PLEA STGO 2022

November 22 - 25, 2022

WILL CITIES SURVIVE?

The future of sustainable buildings and urbanism in the age of emergency.

BOOK OF PROCEEDINGS VOL 1 ONLINE SESSIONS

PLEA STGO 2022

PLEA STGO 2022: WILL CITIES SURVIVE?

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ORGANISED BY

PLEA
Passive and Low Energy Architecture (PLEA)
plea-arch.org

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ABOUT

PLEA Association is an organization engaged in a worldwide discourse on sustainable architecture and urban design through annual international conferences, workshops and publications. It has created a community of several thousand professionals, academics and students from over 40 countries. Participation in PLEA activities is open to all whose work deals with architecture and the built environment, who share our objectives and who attend PLEA events.

PLEA stands for "Passive and Low Energy Architecture", a commitment to the development, documentation and diffusion of the principles of bioclimatic design and the application of natural and innovative techniques for sustainable architecture and urban design.

PLEA serves as an open, international, interdisciplinary forum to promote high quality research, practice and education in environmentally sustainable design.

PLEA is an autonomous, non-profit association of individuals sharing the art, science, planning and design of the built environment.

PLEA pursues its objectives through international conferences and workshops; expert group meetings and consultancies; scientific and technical publications; and architectural competitions and exhibitions.

Since 1982 PLEA has been organizing highly ranked conferences that attract both academia and practicing architects. Past Conferences have taken place in the United States, Europe, South America, Asia, Africa and Australia.

After almost a decade the PLEA conference is coming back to South America, Santiago (Chile), to be organized by the Pontifical Catholic University of Chile (PUC). Inevitably, the theme of PLEA 2022 is inspired by the current pandemic which has put the whole world on alert and makes us rethink our built environment in terms of health and safety. Whereas due to its current social unrest and significant social divide Santiago and South America in general provides a great ground to talk about inequalities and revisit social movements, that spanned around the globe from Lebanon, France to Chile and other countries just before the pandemic hit.

The aim of the PLEA 2022 is to question the whole idea of a city, the way we inhabit and use them generating the definitive inflection point that a sustainable city requires.

GOAL AND THEME

For decades, the climate crisis has been demanding our action and commitment. Numerous efforts to reach an international consensus via climate summits, such as COP25, and Paris Agreement have not had any expected results yet. However, even though the COVID-19 pandemic has intensified the sense of urgency, many talks about climate change were put on hold during 2020, when the new virus put the world on alert.

In no time it has become a global issue and provoked various reactions from political leaders around the world—from absolute denial to the harshest restrictions—adjusting and learning in the process by trial and error.

This process has not been easy as COVID-19 highlighted critical deficiencies in our built environment and urban design. Even though infections battered affluent areas too, the pandemic hit the hardest when the virus reached sectors with high rates of poverty. Dense neighborhoods and overcrowded buildings could facilitate the rapid spread of infections due to the difficulty of generating social distancing and the application of extensive quarantines.

Yet, various changes have been adopted rapidly. Hygiene protocols, wearing masks, social distancing and other strategies has become part of our ordinary life. On top of that, the use of public spaces, streets, parks, homes and all buildings had to be adjusted to control the spread of the virus transforming our habits and conception of them. Numerous studies showed great variations in the use of transportation during the pandemic too. But the questions are: are those changes here to stay? What does the future hold for our built environments?

Some even go as far as to question: Will cities survive? While many intellectuals and academics call for the end of cities (at least as we know them), some stakeholders urge to return to normality, or so-called status quo.

Is this the last opportunity to effectively build a healthy, livable and equitable city? It is clear that cities can no longer be conceived as before and it is time to question the way we inhabit and use them. What are the standards, mechanisms and criteria to define a sustainable city and building? Do they respond to the problems and deficiencies in the age of emergency? History shows us how cities reacted to and changed after health crises similar to COVID-19; this is the time to question everything around us and strive for environmentally sustainable and socially just cities.

The aim of PLEA 2022 is to be a relevant part of the discussion and bring about proposals to the developing and developed world. It is a great chance to talk about the changes that affected cities around the globe since the start of the pandemic and bring the scientific knowledge generated in this short time to the discussion.

Social inequality should also be a part of the debate as both health and climate emergencies may further increase the injustice and, at the same time, the inequality may make such crises worse. Latin America, as the most unequal region, and Chilean case might serve as a great example of such issues and could become a source of inspiration to find the definitive inflection point that a truly sustainable city requires.

WELCOME TO SANTIAGO DE CHILE

Dynamic and cosmopolitan Santiago is a vital and versatile city. Home to many events showcasing the very best of Chilean culture, it also hosts superb international festivals of sound, flavor and color. The Chilean capital breathes new life into all its visitors!

The city's diversity shines through in its many contrasting neighborhoods. Set out to explore the city streets and you'll discover beautiful and original art galleries, design shops and handicraft markets, as well as a great selection of restaurants, bars and cafes. Night owls can enjoy a taste of lively Latino nightlife in hip Bellavista!

Visit downtown Santiago to get a real feel for the city. Learn more about the country in its many fine museums, or wander around the famous Central Market – a gourmet's delight.

Fans of the great outdoors can head for the hills that surround the city and marvel at panoramic views of Santiago with the magnificent Andes as a backdrop. Take the opportunity to grab a picnic and visit one of the city´s many parks.

In Chile there are places that have not seen a drop of rain in decades, while there are others where the rain brings out the green in the millenial forests.

This diversity captivates and surprises its visitors. Because, as a consequence of its geography, Chile has all the climates of the planet and the four seasons are well differentiated. The warmest season is between October and April and the coldest, from May to September.
The temperature in Chile drops down as you travel south. In the north, the heat of the day remains during the day while the nights are quite cold. The central area has more of a Mediterranean climate and the south has lower temperatures and recurring rainfall throughout the year.

The conference will be held at the Centro de Extensión de la Pontificia Universidad Católica de Chile, located at Avenida Libertador Bernardo O'Higgins 390, Santiago, Metropolitan Region. Universidad Católica subway station, Line 1

The Center is located in the center of the city of Santiago, with excellent connectivity to the rest of the city and the most characteristic neighborhoods of the capital, either through the Metro network (Line 1) or other means of public transport such as Transantiago (Santiago's public bus network).

To make your hotel reservations, we recommend looking in the Providencia or Las Condes districts, close to Metro Line 1. We also have some suggestions for accommodation close to the conference venue.

WILL CITIES SURVIVE?: TRACKS

1. Sustainable Urban Development
– Regenerative Design for Healthy and Resilient Cities
– Sustainable Communities, Culture and Society
– Low Carbon Neutral Neighbourhoods, Districts and Cities
– Urban Climate and Outdoor Comfort
– Green Infrastructure
– Urban Design and Adaptation to Climate Change

2. Sustainable Architectural Design
– Resources and Passive Strategies
– Regenerative Design
– Energy Efficient Buildings
– Net-zero Energy and Carbon-neutrality in New and Existing Buildings
– Vernacular and Heritage Retrofit
– Building Design and Adaptation to Climate Change

3. Architecture for Health and Well-being
– Comfort, IAQ & Delight
– Thermal Comfort in Extreme Climates
– IAQ and Health in Times of Covid-19
– Comfort in Public Spaces

4. Sustainable Buildings and Technology
– Renewable Energy Technologies
– Energy Efficient Heating and Cooling Systems
– Low Embodied Carbon Materials
– Circular Economy
– Nature-based Material Solutions
– Water Resource Management and Efficiency

5. Analysis and Methods
– Simulation and Design Tools
– Building Performance Evaluation
– Surveying and Monitoring Methods
– User-building Interaction and Post-occupancy Evaluation

6. Education and Training
– Architectural Training for Sustainability & Research
– Professional Development
– Sustainable Initiatives and Environmental Activism
– Methods and Educational Practices
– Strategies and Tools

7. Challenges for Developing countries
– Energy poverty
– The Informal City
– Climate Change Adaptation
– Affordable Construction and Architecture Strategies
– Urban Planning and Urban Design Policies for Sustainable Development
– Housing and urban Vulnerability

CRISTINA DORADOR

Keynote speaker
CHILE

Between July 2022 and July 2022 she served as a member of Chile's constitutional convention. She is currently back to teaching at the Universidad de Antofagasta.

Chilean scientist, doctor and politician who conducts research in microbiology, microbial ecology, limnology and geomicrobiology. She is also an associate professor in the Department of Biotechnology of the Faculty of Marine Sciences and Natural Resources at the University of Antofagasta. From July 2021 to July 2022 she served as a member of the Constitutional Convention representing District No. 3, which represents the Antofagasta Region.

Her achievements include the coordination in Chile of the Extreme Environments Network for the study of ecosystems in the geographic extremes of Chile and having developed biotechnological tools to value the unique properties of some altiplanic

microbial communities such as resistance to ultraviolet radiation to elaborate cosmetic creams, joining the field of cosmetic Biotechnology. She has also led application projects such as the development of textile material using the photoprotective properties of altiplanic bacteria.

She was a member of the transition council of the National Commission for Scientific and Technological Research in 2019 that gave rise to the National Agency for Research and Development of Chile, and has been recognized nationally and internationally as one of the most relevant researchers in Chile.

ADRIANA ALLEN

Keynote Speaker
ARGENTINA

Professor of Urban Sustainability and Development Planning at The Bartlett Development Planning Unit (DPU), University College London and President of Habitat International Coalition (HIC).

Adriana has over 30 years of international experience in research, graduate teaching, advocacy and consulting in over 25 countries in the global South, she has specialized in the fields of development planning, socio-environmental justice and feminist political ecology.

She is currently President of Habitat International Coalition (HIC), as well as a regular advisor to UN agencies, positions from which she is actively engaged in promoting urban justice through advocacy and policy evidence, social learning and fostering international collaboration both within UCL and globally.Through the lens of risk, water and sanitation, land and housing, food and health, her work examines the interface between everyday city-making practices and planned interventions and their capacity to generate transformative social and environmental relations.

Adopting a feminist political ecology perspective, her work combines qualitative, digital/mapping, and visual research methods to decolonize urban planning practices and elucidate the "cracks" in which transformative planning can be reinvented, nurtured, and pursued. Her work focuses on three interrelated themes: urban justice, everyday city-making, and transformative planning.
Over the years, she has worked at the interface between insurgent practices and planned interventions and their capacity to generate socio-environmentally just cities.

This work stems from her engagement with the analysis of governance approaches to address structural deficits at the interface between "policy-driven" and "needs-driven" approaches and emerging improvements at scale – in water and sanitation, as well as in other areas such as food security, land, housing and health. Since 2008, she has explored the intersection of urbanization and climate change, with a particular focus on the generation and distribution of risks, vulnerabilities and capacities for action in southern cities. A third strand of her research focuses on urban planning as a field of networked governance and pedagogical strategies to decolonize planning education and shape pathways for urban equality.

ANACLAUDIA ROSSBACH

Keynote speaker
BRAZIL

Economist with a track record of more than 20 years working on the issues of slums, social housing and urban policy.

She is currently Director for Latin America and the Caribbean at the Lincoln Land Institute of Policy. She also serves as a member of the editorial board of Vivienda magazine of INFONAVIT – México. And previously she worked as a consultant on housing and urban development issues for the IDB (Inter-American Development Bank).

She worked in the Prefecture of São Paulo, supporting the Brazilian Ministry of Cities in the design and implementation of the Brazilian housing policy. She founded and served on the board of directors of the NGO INTERAÇÃO, which supported the development of high-impact projects in communities in the state of São Paulo and Recife.

As a senior consultant to the World Bank, she provided technical assistance for the development and implementation of Brazilian housing policy and slum upgrading for 10 years, including two major programs: the "PAC Favelas" slum upgrading and the "Minha Casa, Minha Vida" housing subsidy.

She acted as a senior specialist in social housing for the World Bank and other research and project organizations in Brazil and several countries around the world such as the Philippines, China, India, South Africa and Mozambique, among others.

She was Regional Manager for Latin America and the Caribbean for the Cities of Alliance Global Informality Program where the exchange of experiences and knowledge through different networks was consolidated and structured.

The main achievements in Latin America are the Urban Housing Practitioners Hub (UHPH), which brings together practitioners and networks working in the field of social housing. In the global south, multi-sectoral and disciplinary communities of practice on the theme of slum upgrading in the global south with emphasis on the countries: Mexico, Guatemala, El Salvador, Paraguay, Brazil, South Africa and India.

GIANCARLO MAZZANTI

Keynote Speaker
ARGENTINA

Born in Barranquilla, a port city in northern Colombia, Giancarlo Mazzanti is an architect graduated from Pontificia Universidad Javeriana with postgraduate studies in industrial design and architecture in Florence, Italy.

He has been a visiting professor at several Colombian universities, as well as at world-renowned academic institutions such as Harvard, Columbia and Princeton, and is the first Colombian architect to have his works in the permanent collection of the Museum of Modern Art in New York (MoMA) and the Centre Pompidou in Paris.

Giancarlo has more than 30 years of professional experience and his studio, El Equipo Mazzanti has gained notoriety due to its design philosophy based on modules and systems, which generate flexible elements capable of growing and adapting over time, seeking an architecture that is closer to the idea of strategy than to a finite and closed composition. The idea of architecture as an operation was born from exploring the different forms of material and spatial organization, considering concepts such as repetition, the indeterminate, the unfinished, instability, arrangement and patterns.

Equipo Mazzanti also stands out for its research on play and its link to the world of architecture. It is precisely this interest in the play-architecture relationship that has led it to seek new collaborations with professionals from different areas of knowledge, finding new opportunities for cooperation and developing projects and exhibitions that have been presented throughout the world under the We play You play brand.

Social values are at the core of Mazzanti's architecture, who seeks to realize projects that give value to social transformations and build communities. He has dedicated his professional life to improving the quality of life through environmental design and to the idea of social equality.

His work has become a reflection of the current social changes occurring in Latin America and Colombia, demonstrating that good architecture manages to build new identities for cities, towns and inhabitants, transcending reputations of crime and poverty.

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PLEA STGO 2022

PLEA STGO 2022: WILL CITIES SURVIVE?

November 22 - 25, 2022

SUSTAINABLE URBAN DEVELOPMENT

DAY 01
08:30 — 10:00

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PAPERS
1548 / 1542 / 1504 / 1251 / 1536 /
1682

1ST PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Outdoor comfort guidelines for a whole city

Categorising environmental performance of outdoor spaces based on their scale

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ABSTRACT: The cities are so diverse that their open spaces and relevant environmental strategies cannot be generalised, but can they be categorised? An important aspect arising from the theme of the conference, Will Cities Survive, is the need to treat our outdoor spaces effectively. This will not just encourage the use of outdoor spaces due to improved outdoor comfort, but also reduce rising temperatures of our cities due to the heat island effect. But where and how does one start? Through the professional work of the authors, in the last 3 years, there have been several projects where the need to develop city-wide outdoor comfort guidelines was explored. To capture the diverse nature of the city's open spaces in these projects, the authors have used (and are using) the categorisation into Small (S), Medium (M), and Large (L) terminology. Each scale of the outdoor space comes with its inherent opportunities for creating comfortable/habitable spaces but also its inherent environmental performance. As part of the project work, the authors have assessed various environmental parameters that define outdoor comfort and their performance for S, M and L scale of spaces. These have been compiled as part of this document.
KEYWORDS: Outdoor comfort guidelines, the scale of outdoor spaces, environmental performance

1. INTRODUCTION

Why is outdoor comfort important?
Through the author's research and professional work on large masterplans/new cities, there is an evident shift where the design of the outdoor spaces is becoming critical. Covid 19 spread has also been a catalyst for designers to think not just about buildings, but the space between them.
If the outdoor spaces are not designed well, in most climatic conditions, the buildings become islands of comfort and people move from one island to another, any interaction with the masterplan/city itself.

Figure 1 (Left) How untreated outdoor spaces results in buildings becoming islands. (Right) Treatment of outdoor spaces effectively creates a masterplan where all the spaces – buildings and spaces between - are usable and comfortable. Source: Author.

Using Small, Medium and Large as categorisation methodology

Cities are so diverse that their open spaces, inherent environmental performance and relevant environmental strategies cannot be generalised, but can they be categorised?

The authors have previously and continue to explore the idea of categorising the outdoor spaces into small (S), medium (M) and large (L) spaces and creating simplified means of establishing and communicating relevant environmental guidelines for outdoor spaces. The application of idea has already been tested and applied at both masterplan and city-level projects that the authors are currently working on.

This classification model is not new in terms of defining projects of different scales [1] but it was found to form a strong basis for developing respective passive design opportunities for range/diverse scale of outdoor spaces.

An idea similarly explored in the sketch below from [2] where the height to width ratio was varied between an Open Country setting vs a high-density urban environment that resulted in different levels of solar exposure.

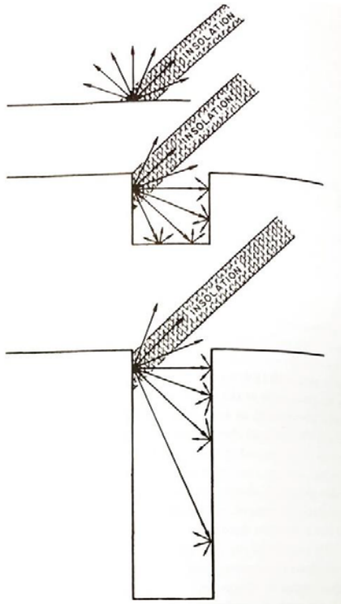


Figure 2 and 3 (Left) Sketch from page 248, figure 7.1 from [1] and using that as a reference for developing the sketch (Right) by the author.

The sketch on the right by the author, introduces different scales to the sketch above, using human as a reference and relating it to the idea of the S, M and L scale of spaces and the inherent environmental performance.

The variation in solar exposure across different scales of spaces (as per the sketch above) can be confirmed from the annual solar exposure analysis (below).

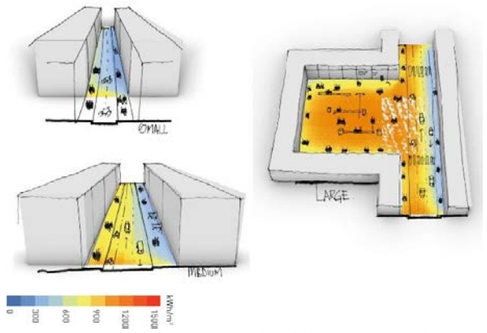
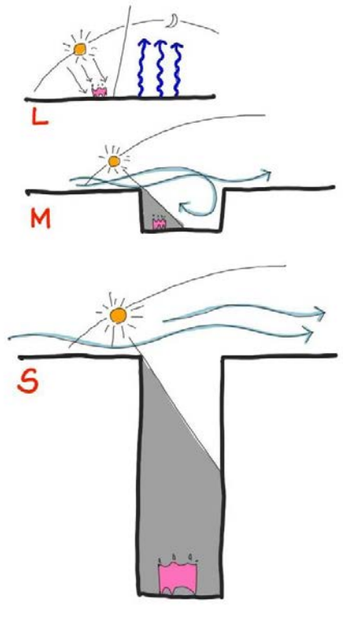


Figure 4: Annual solar exposure for different scales of outdoor spaces. Climate context of London. Simulation tool: Rhino + Grasshopper. Source: Author.

Similarly, various factors that collectively define weather exposure and outdoor comfort were tested as part of previous project work and the same have been compiled in subsequent pages.



2. EVALUATION OF THE IDEA

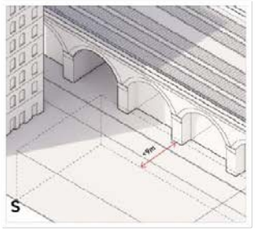
Defining the scale of each of the categories
The scale of the outdoor spaces and what may be considered small, medium, or large could vary depending on the climatic and cultural context.
For the purposes of this research paper and learning from a recent project, the following dimensions for the S, M and L spaces were used for the environmental analysis:

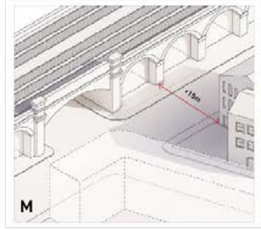
- Small – Less than/up to 9m wide streets
- Medium – between 9 and 15 m
- Large – beyond 15 m streets, including squares, plazas, etc.

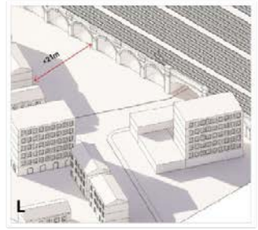
The definition of the scales/sizes also depend on other workstreams and participating/collaborating team members such as urban design and landscape and their relevant design opportunities. The pages below compile outputs of how each of the S, M and L scales of spaces identified above perform against different environmental parameters.

All environmental studies were done using the climatic context of London.

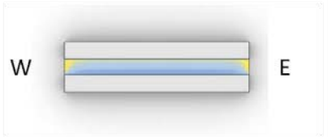
Scale of Spaces

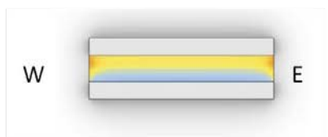


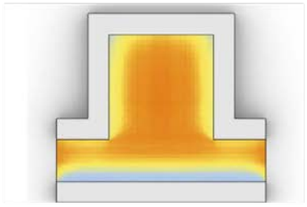




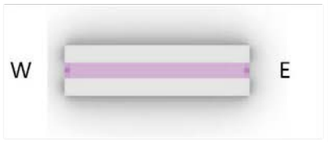
Solar Exposure

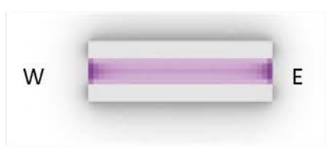


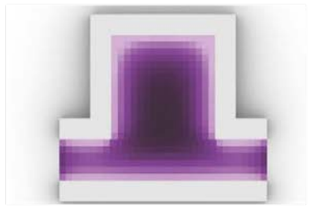




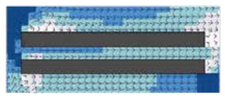
Sky View

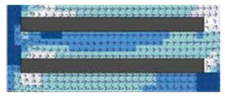


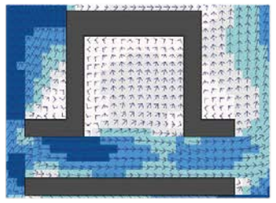




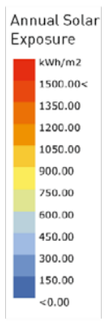
Wind Movement

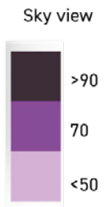


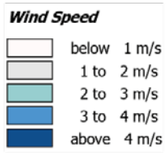




Details on simulations compiled on this page







Solar Exposure analysis:

- Time Period: annual cumulative
- High bound radiation: 1500 kWh/m^2
- Software used: Rhino + Grasshopper

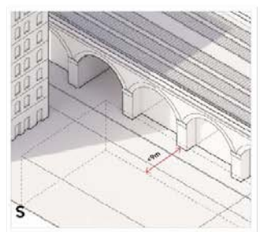
Sky View Factor analysis:

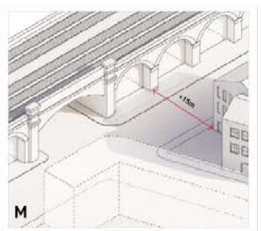
- Time Period: not relevant
- High bound: 100%
- Software used: Rhino + Grasshopper

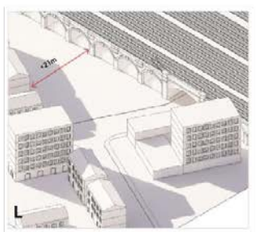
Wind movement:

- Time Period: not relevant
- Direction of wind: Left to right / West to East
- High bound: Unobstructed wind speed of 5m/s
- Software used: ENVI Met 4.5

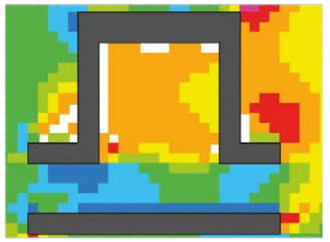
Scale of Spaces



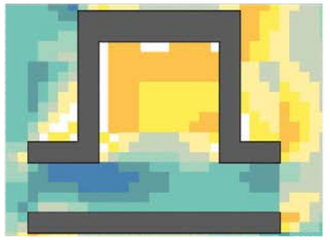




UTCI Summer (at 30°C)



UTCI Winter (at 10°C)



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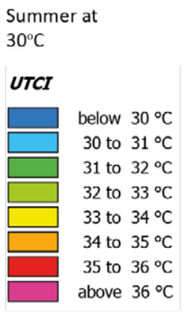

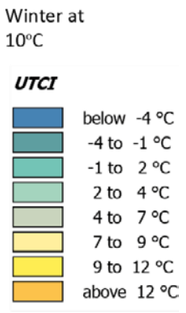

UTCI (Universal Thermal Climate Index):

- Time Period: Summer (30°C) and Winter (10°C)
- Software used: ENVI Met 4.5

Early conclusions from each of the evaluated parameter

Solar Exposure analysis:

- Larger the scale, the higher the solar exposure.
- With an increasing scale from S to M to L, the impact of buildings in creating shade/reducing radiation levels reduces significantly.

Sky View (relevant for daylight availability, general weather exposure – wind, wind + rain, rain, dust storms)

- Larger the space, the lesser protection it gets from the adjacent buildings/structures, the higher the weather exposure.
- During rain, standing in a square has a bigger possibility of getting drenched than moving in a narrow street.

Wind Movement:

- Being a highly directional aspect, the performance of the spaces could vary.
- For the evaluated direction, narrower spaces (S and M) showed a funnelling effect with increased wind speeds.
- While for the Large scale, the winds were generally calmer.

UTCI Summer

- Impact of shade from buildings can be clearly seen in the S and M scale of spaces.
- Large spaces could be significantly uncomfortable due to the combined effect of lack of air movement, high temperature and solar exposure.

UTCI Winter

- Spaces perceived as uncomfortable in summer could be perceived much more comfortable in winter.
- Hence large-scale spaces with higher passive solar gains show a higher perception of comfort.
- S and M scale of spaces, with high wind speeds and limited solar exposure, could be perceived as uncomfortable.

3. OPPORTUNITIES AND LIMITATIONS

Limitations

During both the project work and compiling this research, the authors came across certain limitations to this approach of using S, M and L scale methodology in developing outdoor comfort guidelines. The same have been compiled below:

- Every design team member in a project has a different set of constraints and opportunities. Although in the studies presented above, the authors defined for the wider team what could be the scale of each of the S, M and L scale space based on some initial environmental studies, not every project may offer that level of flexibility/opportunity of integrated design.
- This idea could be seen as oversimplified and not a very critical methodology of capturing the diversity that the open spaces any city could offer.

Opportunities

Having identified the limitations above, the authors would highlight that since most masterplans and wider city-scale projects start with simplified/high-level design ideas rather than extensive details, this methodology could still be easily applied.
Also, it provides a simple and effective design language that is understood and could be easily adopted by wider members of the team. For example, Small (S) scale spaces may offer limited opportunities for landscape design due to the sheer nature of the available space, while a Large (L) scale space like a city square, offers great opportunities for greening and tree plantation/water features.

The authors also acknowledge that certain aspects of the simulations/tests compiled in the document may not be critically defined. But the author's intention while compiling this research was to *highlight the differences/comparisons* in environmental performance that comes with different scale of spaces (S, M or L) rather than the absolute value/performance.

4. CONCLUSION

This paper documents a methodology that the authors have been using while developing outdoor comfort guidelines for the large masterplan and city-level projects. The paper starts by identifying the need for creating comfortable outdoor spaces for increased outdoor occupancy and reduced heat island effect.

While the focus of the paper is to evaluate and compare the performance of Small (S), Medium (M) and Large (L) scale-spaces in a city (London in case of this paper) and use this methodology of developing outdoor comfort guidelines based on the scale of spaces.

Simplifying and categorising the highly complex performance of outdoor spaces using just the S, M and L methodology also comes with its limitations. But in the author's experience, it offers a highly effective, easy to communicate and widely accepted tool for design teams to start early thinking and decision making for large scale projects.

The authors will continue to develop and learn from this methodology as part of current and future projects.

ACKNOWLEDGEMENTS

The authors would like to thank PDP London, the design lead on the project which was used for the simulation results compiled in this document.

The authors are thankful to ENVI Met and its CEO, Daniela Bruse and CDO, Prof. Dr. Michael Bruse, for their continued support and encouragement in studio 4215's research and work on outdoor comfort.

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1. OMA, Rem Koolhaas, Bruce Mau. 1995. S,M,L,XL. The Monacelli Press.
2. Baruch Givoni. 1998. Climate Considerations in Building and Urban Design. Wiley. Page 248.

Heat countermeasures guideline with facilities planning and design strategies for children in Japan

Field measurement study on outdoor thermal environment of children's height level at kindergarten

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[2] Tokyo Polytechnic University

ABSTRACT: The urban heat island (UHI) becomes a serious environmental problem in Japan. Varies mitigation measures are designed and strategically introduced into urban outdoor space to reduce the heat related risks. However, few researches focused on the thermal comfort of the environment at children's height level (less than 1.0 m). Even children share the same space with the adults, they are closer to the ground and receive more amount of radiation heat from the ground, and thus they are exposed to higher risk of heat-related problems compared with adults. The goal of the study aims for developing a thermal environment design guideline to mitigate heat risk for children, in consideration of the outdoor climate features in their height level. To investigate the difference of outdoor thermal environment between the height levels of adults and children, we conducted field measurement at the courtyard of a kindergarten in japan, and compared the related environmental factors at between the height of children and adults. The result shows that the comfort of the height of the child level in the garden is worse than that of the adult level, and the upward long-wave radiation from the ground surface is the major factor that affect the thermal comfort of the activity space of children.
KEYWORDS: Outdoor thermal comfort, Children's activity space, Field Measurement Study, Kindergarten

1. INTRODUCTION

The increasing urbanization leads to the increasing area of asphalt and concrete by replacing the vegetation and natural surfaces. These cause higher air temperature in the city than the surrounding area, which is called "urban heat island" (UHI). The UHI becomes a serious environmental problem and results in an increasing number of mortality due to heat stroke. Figure1 shows the number of death due to heat stroke in recent years in Japan[1)]. It reveals that, the number of death due to the heat stroke is significantly increased from 2018 compared with those during 2013 - 2017. This means the UHI becomes a critical social problem in Japan, especially in the densely built area, such as Tokyo, Osaka, Nagoya and Fukuoka. Figure 2 is the number of heatstroke patients who used the Emergency Medical Services (EMS) in each province during the summer, in 2021 and 2022 Japan. It shows that the number for those four densely built areas are high.

The Ministry of environment publishes a guideline that different mitigation measures are designed and strategically introduced into urban outdoor space to reduce the related risks. However, most measures are designed and discussed by considering the thermal comfort of the environment at 1.5 m above the ground or higher[2)], with less attention on the children's height level (less than 1.0 m). Even children share the same space with the adults, they are closer to the ground and receive more amount of radiation heat from the ground, and thus they are exposed to higher risk of heat-related problems compared with adults. Figure3 shows the percentage of the place where the heat stroke happened for different ages. It suggests that for children, over half of heat stroke occurs in outdoor space. Therefore, the mitigation measures for outdoor space should be investigated by including the consideration of children.

Figure 1:
Number of death due to the heat stroke in Japan

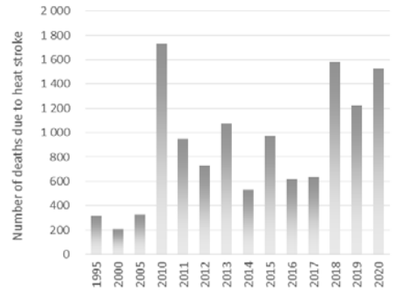
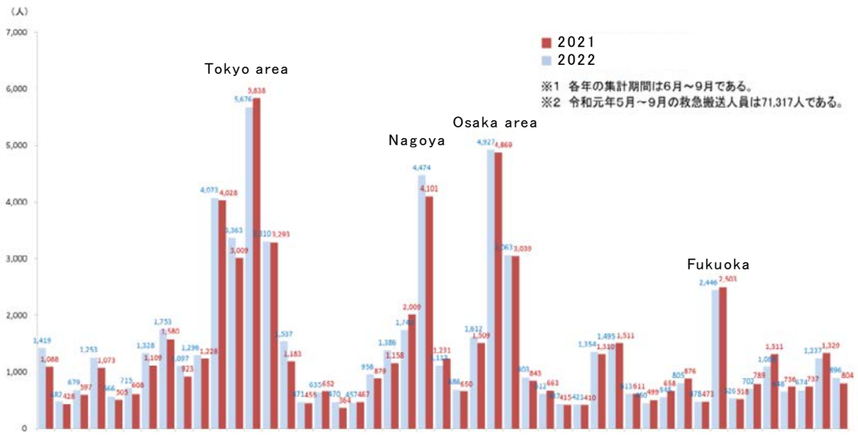


Figure 2:
Number of heatstroke patients by EMS of every province



The ultimate goal of the study aims for developing a thermal environment design guideline to mitigate heat risk for children, in consideration of the outdoor climate features in their height level and provide a thermally safe and healthy outdoor environment for children. As the first step, to investigate the difference of outdoor thermal environment between the height levels of adults and children, we conducted field measurement at the courtyard of a kindergarten, and compared the related environmental factors at both the height of children and adults.

Figure 3:
Place that heat stroke happened for different ages.

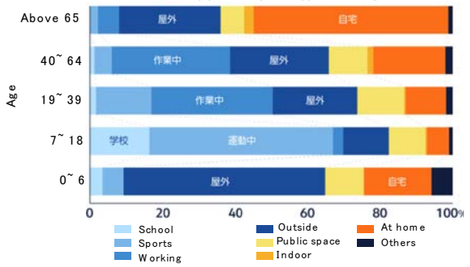
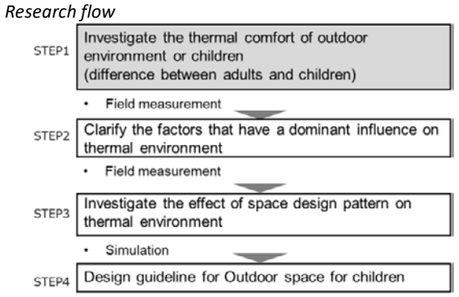


Figure 4:
Research flow



2.AIM AND SCOPE

Fiure4 shows the research flow for the study, including the main steps as below. This paper mainly focused on the step1) and 2):

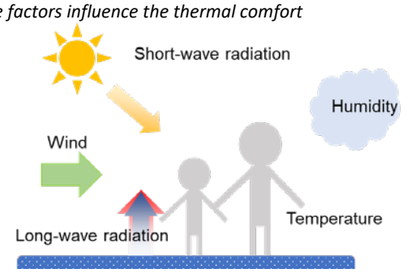
1)Investigate the difference of outdoor thermal environment at the height level of children and adults

The researches of outdoor thermal comfort are usually focused on the height of 1.5m, which is close to the breathing height of the adult. However, the average height of children between 4~5 years in Japan is about 110 cm, and their centre of gravity is around 0.6 m. Even the children stay and share the same space with adults, they are closer to the ground, there thermal environment is different from the adult. This research firstly takes a field measurement study in a kindergarten and clarifies the environmental difference of between the children and adult.

2)Clarify the environmental factors that have a dominant influence on thermal environment at the children's height level

As shown in Figure5, the radiations are considered as one of the mean factors to affect the thermal comfort at different heights. Therefore, this research take field measurement on the radiation conditions at the heights of the children and adults using black globe which receives the radiation from all directions. For the children height, (1) downward shortwave, (2) upward shortwave, (3) downward longwave and (4) upward longwave were measured separately to understand the type and direction of radiation that plays a dominant influence on thermal environment at the children's height level

Figure5
The factors influence the thermal comfort

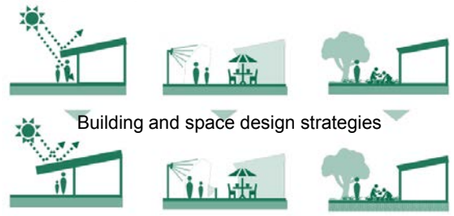


3)Investigate the effect of space design pattern on thermal environment at the children's height level

Most of the kindergartens in Japan introduce heat countermeasures to cool down the activity space. Mist, shading, sprinkle water are the most widely used methods. We conduct measurement on grass, sand and asphalt with the various heat countermeasures that used in kindergartens to confirm its effect on both children and adults height. As the example, Figure6 shows the field measurement of shading effect on sand and grass.

Figure6
Field measurement of shading effect

Figure 7:
Design guideline for outdoor space

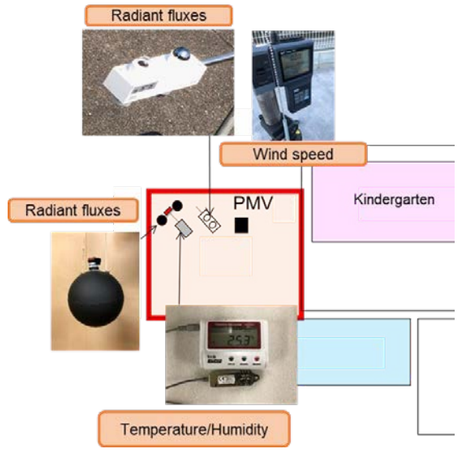


4)Design guideline for outdoor space for children

The simulation will be adopted for further study. We will study the different effect of the heat island mitigation measures that installed in the urban space, such as mist, shading and greenery and discuss the relationship between the urban space designs. Finally, the study will make a guideline for outdoor space for children, showed in Figure7.

Figure8
Research field

Figure9
Measurement items and instruments



3.MEASURENMENT OUTLINE

3.1 The place of field measurement

The research field is a kindergarten in Kanagawa ken, Japan. The area of the garden for kindergarten is about 80 m2 and the ground surface is covered with sand, which is showed in Figure8. It is a typical type for most of the kindergartens in Japan.

Figure10
Measurement instruments for children and adults

3.2 Measurement items and instruments

In order to understand the thermal environment of the children's activity space, we measured the four elements of the thermal environment: temperature, relative humidity, wind speed, and radiation. The layout of the setting point is shown in Figure9. For comparison, the same elements were measured at the activity space of adult too. The height for measurement for adult activity space is set in the height of 1.5m, and for children is set at the height of 0.6. Figure10 shows the measurement for both children and adults. The measurement elements, instruments and their accuracy are listed in Table1.

Table 1:
Measurement items, instruments and accuracy

Measured parameters	Instruments	Range	Accuracy
Air temperature	Thermometer (TR-72nw)	-25～70℃	±0.3℃
Relative humidity		0～99%RH	±2.5%
Wind speed (m/s)	AM-101	0～1m/s 1～5m/s	± 0.1m/s ± 0.5m/s
Radiant fluxes	Globe thermometer	0～70℃	±1.0℃
	Shortwave and longwave radiant fluxes (Upward and downward)	Shortwave: 285～3000mm Longwave: 3～50 μ m	< 0.5%

Figure 11:
Temperature of the day

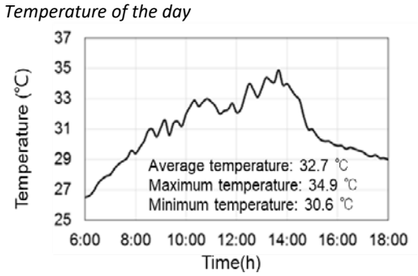
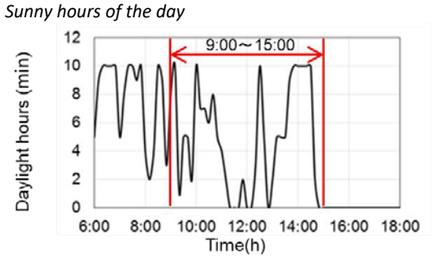


Figure 12:
Sunny hours of the day



3.3 Measurement time and schedule

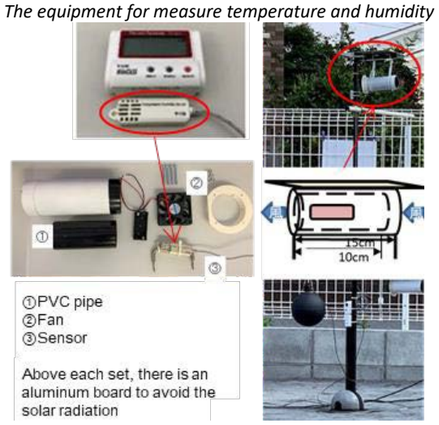
The measurement is conducted on August 22 (Saturday), 2020, during the summer, continued from 9: 00-15: 00. The weather conditions are showed in figure11 and figure12. The average temperature is 32.7℃. Total sunny hours and cloudy hours are around 3.0 hours.

4. RESULT OF FIELD MEASUREMENT

4.1 Temperature and humidity

The Thermometer (TR-72nw) is adopted to measure the temperature and humidity. To avoid the effect of radiation, the equipment is set as shown in Figure13, a doble-PVC pipe installed with a fan for ventilation. There are two sets of the equipment. One is set on the height of 0.6m above the ground to measure the temperature and humidity of children's activity space. The other one is set at the height of 1.5m for adult's activity space.

Figure 13:
The equipment for measure temperature and humidity



The results are showed in Figure14. Between 10am to 2pm, the average temperature of children's activity space is 33.5 ℃, which is 1.0 ℃ higher than that of adult's activity space. The average humidity of children's activity space is 56.2%, which is 2.2% lower than that of adult's space.

4.2 Shortwave and longwave radiant heat fluxes

The radiation is an important parameter that effects the thermal comfort of the outdoor space. The outdoor space receives the radiation directly from the sun and indirectly from the surrounding objects and the ground. In order to clarify the factor which mostly affects the children's activity space, two types of measurement equipment are adopted to measure the radiation, globe thermometer and shortwave and longwave radiant fluxes (Upward and downward)). The measurement equipment is shown in Figure 15. The globe thermometer is used for measuring the total radiation from all directions, while shortwave and longwave radiant fluxes are separately measured in two directions, upward and downward.

Figure 14:
The temperature and humidity for children and adult

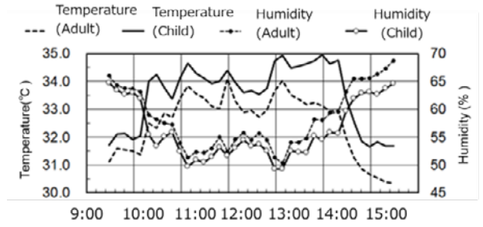


Figure 15:
Equipment for measuring radiation

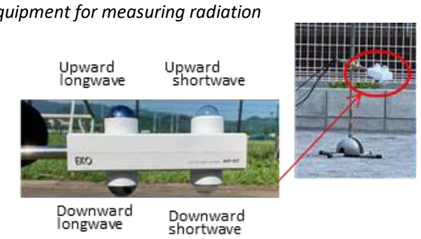


Figure16
Shortwave radiation

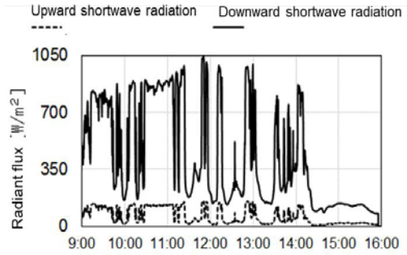
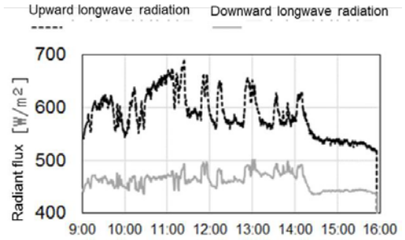


Figure17
Longwave radiation



The result is shown in Figure16, Figure17 and Table2. The average upward longwave radiation from 10:00 to 14:00 is 544 W / m^2, which is the highest among the four types of radiations. It means upward longwave radiation emitted from the ground surface plays more significant role than other radiation components on the thermal comfort environment of the children's height level.

Table 2:
Shortwave and longwave radiant heat fluxes (Upward and downward)

	Average W/m^2	Max W/m^2	Min W/m^2
Downward shortwave radiation	397	1044	77
Upward shortwave radiation	56	153	2
Downward longwave radiation	428	503	435
Upward long-wave radiation	544	690	347

4.3 Mean radiation temperature

Main radiant temperature (MRT) is calculated by using the results of globe temperatures at 0.6m and 1.5m as shown in Figure18.

MRT = $\theta g + 2.35\sqrt{v} \cdot (\theta g - \theta)$ (1)

θg: Globe tempreature [℃]、
θ :Temperature [℃]
: Wind speed [m/s]

Figure18
Equipment for measuring mean radiation temperature

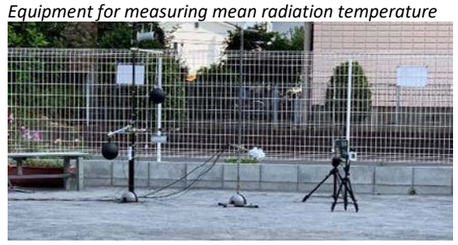


Figure19
Result of MRT

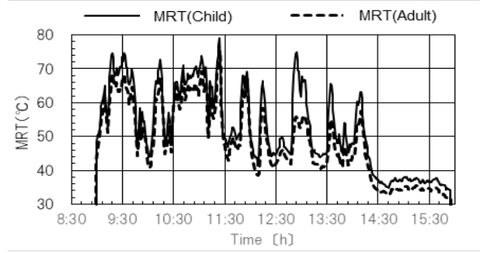


Figure19 and Table3 shows the mean radiation temperature (MRT) at the height of the child level and the height of the adult level. For child-level, the average value of MRTs from 10:00 to 14:00 is 55.7°C with the maximum value 69.6°C, and the minimum value 43.7 °C. At the same time, for adult-level, the average value of is 54.9°C, while maximum 68.3°C, and the minimum 44.5°C. The height of the child level shows a higher value than the height of the adult level. Children are more affected by radiation from the ground than adults.

Table3
MRT for children and adults

	MRT （℃）	
	Children(1.5m)	Adults (0.6m)
Average	52.8	52.3
Max	69.6	68.3
Min	36.8	37.4

Figure20
*Result of SET**

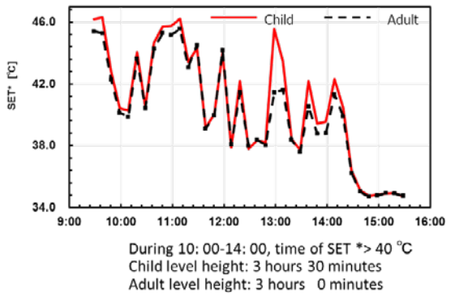


Table4
MRT for children and adults

	SET* （℃）	
	Children(1.5m)	Adults (0.6m)
Average	40.6	40.2
Max	46.3	45.6
Min	34.7	34.7

4.4 The standard new effective temperature (SET*)

The Standard New Effective Temperature(SET*) is an index for thermal comfort. It is calculated from the environmental factors of temperature, humidity, wind speed, and radiation, and clothing status and the metabolism. If the SET * value is 40 ° C or higher, it means the environment is very hot and very uncomfortable, with a higher risk of getting heat stroke[3].

For calculating SET*, the 10 minutes average values of temperature, humidity and MRT is used, and the wind speed is 0.2 m/s. In addition, the values for adults and children are set as the average value of adults and children for height, weight, and body surface area. For adults, the average height and weight of Japanese men in their 20s are 171.9 cm and 67.3 kg. For children, the average height and weight of 5 are 110.2. cm, 19.2 kg. The body surface area of adults and children was calculated by using Dupore's formula (body surface area = 0.007184 x height $^{0.725}$ x body weight $^{0.425}$) with average height and weight.

Figure20 shows the result of SET * at the height of the child level and the adult level. Table 4 shows the results of the average, maximum and minimum values of SET * from 10:00 to 14:00. For the child-level, the average value of SET * from 10:00 to 14:00 is 41.6 ° C, the maximum value 46.2 ° C, and the minimum value 37.7 ° C.

The amount of time when the value of SET* is higher than 40℃(thermally extremely uncomfort condition) during 10:00～14:00 of children is 3.5hours while adult is 3 hours. This reveals that children are exposed in a serious thermal condition.

5. CONCLUSION

Through field measurement study of the outdoor thermal environment in the kindergarten garden, the findings are as below:

(1) Between 10am to 2pm, the average temperature of children's activity space is 1.0 ℃ higher than the average temperature of adult's activity space.
(2) The average upward longwave that emitted from the ground surface radiation is the highest among the four types of radiations. It plays significant role on the thermal comfort environment of the children's height level.
(3) The MRT of the height of the children is 0.8℃ higher than adults, which means they are more affected by radiation from the surroundings.
(4) The amount of time when the value of SET* is higher than 40℃is longer at the height level of children, which reveals that children are in a serious thermal condition.

Above all, the comfort of the height of the child level in the garden is worse than that of the adult level. It is necessary to consider measures against heat in the garden, focusing on the activity space of children.

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3. https://j-kana.or.jp/member/pdf/faq/kaitekisei-nokagaku.pdf

PLEA SANTIAGO 2022
Will Cities Survive?

Investigating outdoor thermal comfort for children play affordances in urban areas
A case of Jaipur, India

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ABSTRACT: This study investigates the impact of microclimate on outdoor play areas at neighbourhood level. It is known that urban surfaces (i.e. hardscape and softscape) contributes towards increased thermal discomfort in the outdoor surroundings. This limits the usage of our open spaces in addition to increasing urban density and reducing availability of open areas. While pandemic has laid emphasis on judicious and conscious utilization of our open areas. Quality of space needs to encourage higher play affordances along with optimum thermal comfort. The former ensures nature of play-ability and the latter contributes towards conducive environment for play-ability to happen. The methodology adopted includes: 1. Evidence based affordances mapping of the most active and least active play zones along with perceptual interviews; 2. Field survey of micro-meteorological parameters like surface temperature Ts, air temperature Ta, globe temperature Tg, relative humidity Rh and Wind speed V; 3. Simulating Physiological Equivalent Temperature PET using Rayman Pro and Envimet, for thermal stress evaluation. Results indicate increased thermal stress and low affordance as an indicator of reduced outdoor play activities in the current spatial layout. This study will help the designers, landscape architects to use thermal comfort as a tool for designing quality play environment.
KEYWORDS: Affordance, Children play, Outdoor Thermal Comfort, Urban heat stress

1. INTRODUCTION

Interaction with outdoor environment can affect physical, social and cognitive development in children [1]. Studies indicate that contact with nature or natural elements can shape ones behaviour and help an individual to become sensitive and conscious of their surroundings [2]. However limited availabilty of open space, poorly designed play-spaces, strict school timetables, and exposure to digital gadgets have forced children to stay indoors. This situation worsened during lockdown, where play had become optional. The pandemic has laid emphasis on judicious and conscious utilization of our open areas.

1.1 Affordance in play

Quality of space is a function of spatial organization which can encourage better play opportunities ensuring nature of play-ability in an environment. Gibson suggests, children perceive functional properties or affordance more than the physical forms of their surrounding landscapes [3]. Studies have shown that, affordances are the potentials, provided or perceived from the environmental features by an individual [4]. Therefore, higher affordability of a given space would mean diverse play prospects for children. Designers have key role in creating environments which are compatible with physical and social skills of the user. However quality play space designs can protect childhood and play relationship in these trying times. According to Kytta the affordances can be categorised into perceived, utilised and shaped [5]. The sequence in which children experience the environments lets them perceive the space in a certain way; and then use them in multiple ways; and then finally shape them based on its ability to be moulded. However, these affordances and interactions with the environment can be positive i.e. *topophillia* or negative i.e. *topophobia* [6]. They can generate curiosity and satisfaction or the experiences can lead to fear and risks. Further the concept of affordance in our designed environments can be evaluated in two ways:

Objective affordances: potential possibilities created by the space components, which the designer brings to the environment for the activities designed for the users.

Subjective affordances. the ones that are formed together with users' creativity and skills to use for the spatial components [4].

1.2 Thermal comfort in play areas

It is known that urban surfaces (i.e. hardscape and softscape) contribute towards increased thermal discomfort in the outdoor surroundings.

More and more areas are converted into hardscapes for eg. internal roads, parking lots, plaza etc. which adds to heat absorption particularly in hot and dry climate. This limits the usage of our open spaces in addition to increasing urban density and reducing availability of open areas. Quality of space needs to contribute towards creating conducive environment for play-ability to happen especially in case of children as they are more sensitive to thermal variation. When ambient temperatures exceed that of the skin, an influx of thermal energy from the environment increases thermal stress which results in reduced physical performance and an in-creased risk of developing heat-related illness [7].

Uncomfortable outdoor thermal conditions can affect the number of children, duration of visits, and activity levels of play [8]. A balance of hardscape and softscape is crucial for reducing heat gain in residential areas. In order to design spaces for children, one must first know the child, know about the nature of his relationship with the environment and understand the importance of this relationship, know about the needs and demands of the child and his developmental process, and evaluate the opportunities that the environment offers to satisfy the child's needs and demands, and only then should one create spaces in accordance with the design principles [9].

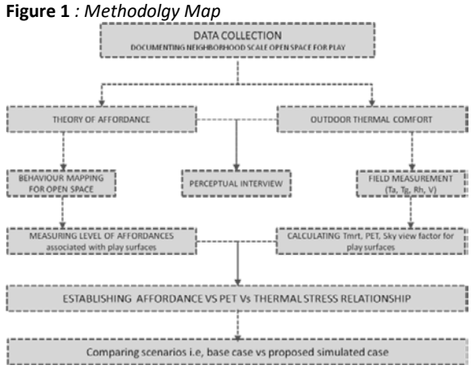
The aim of this study is to assess the neighbourhood open space for children with respect to the spatial affordances offered and its thermal comfort associated. It is crucial for to design spaces for children that encourage them to play. Play-ability of a space must be considered as foremost priority towards designing and not become incidental outcome. The designers can create engaging environment which can perform under varying the climatic conditions.

2. METHODOLOGY

The novelty of this study is that it considers the evidence-based spatial preference for play at neighbourhood level and further investigates the thermal comfort based on affordability (Figure 1). An age group between 6-12 years i.e. middle childhood is considered for the study because they can communicate their ideas easily and the skills acquired at this stage are useful for life.

The data collection was based on field survey, mapping and simulating software Rayman Pro. The device used for field measurements are Extech HT30 Heat Stress WBGT Meter, Fluke 971 temperature humidity meter and Meco 961 digital anemometer. The software Envi Met 5.0 was used for developing thermal simulations scenarios.

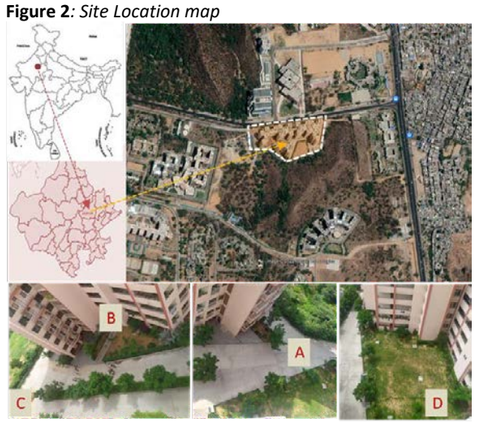
Figure 1 : *Methodolgy Map*



2.1 Study area characterization

The study was carried out in Jaipur, Rajasthan, India, with coordinates 26.9124° N, 75.7873° E. The city lies on the edge of Aravalli Mountains. Based on the 'Energy conservation and building code' user guide, the city climate is classified as a Composite climate (ECBC, 2017). The study area consists of a neighbourhood level open space surrounded by residential blocks (G+10). It is estimated to have 150 households with a population of 600 persons approximately. The study area is 3.6 acres with the central open space with 75% of land under hardscape and rest 25% under softscape. The building is on stilts and the ground floor is utilized for parking. The outdoor area has a double lane road with a median in the centre and fragmented softscape areas as shown in Figure 2. This area is considered for study because most of newer development have poorly designed outdoor spaces which hardly gets utilised for play.

Figure 2: *Site Location map*



2.2 Behaviour Mapping

The spatial characteristics of the open space was analysed by mapping play interactions and activities carried out. The attendance and behaviour was documented during morning (i.e. 09:00 hrs), afternoon (i.e. 14:00 hrs) and evening (i.e. 19:00 hrs.). Majority of children played during the evening hours due to school, tuitions and other engagements. Figure 3 documents the site scenario based upon 5 days observation in evening at 19:00 hrs i.e., after sunset. It is observed:

- It was evident that the concrete road, parking area were most frequently used by children in the event of play
- The peripheral loop around the buildings was majorly used for cycling and skating.
- Key locations of benches, toe walls and kerbs became gathering spots for light play or when they took time off their intense play.
- It is interesting to note that the green areas were rarely utilized for play.

Figure 3: *Behaviour Mapping of the neighbourhood*

This study enables to identify zones of the most active areas and the least active play areas with respect to space usage and attendance. Based on several play opportunities available at the 5 zones, the affordances associated were identified and tabulated in Figure 4. The spatial quality or the design of these zones makes it usable or dysfunctional. These zones are:

Zone A: It is on the access road which is majorly used for vehicular movement and cycling. For children it acts as large open area to perform play.

Zone B : It lies in the small green pocket adjacent to the building making it very accessible. This area consists of trees, hedges, shrubs and loose soil which attract the children to play, pause and hide during a game.

Zone C: It is on the access road which is majorly used for vehicular movement and cycling. For children it acts as widest open area to perform play and celebrations.

Zone D: It is the biggest green open space, but unmaintained. During late evenings this area remains unlit discouraging the children to play.

Zone E: It lies in the parking lot and very frequently used area. The stilts and parked vehicles allow the children to hide and create shortcuts. The parapet walls in the lot attract the children to climb, jump, perform act, rest and hide in this area. Several instances of children colliding with moving cars or two wheelers have been observed in this area.

Figure 4: *Affordance observed in different zones*

Zone	Space component	Objective Affordance	Subjective Affordance	Affordance level	Negative affordance	Attendance level weekend
A	Concrete road Hard scape Unshaded	Driving, Walking, Cycling	cycling/skating (3), running, playing football, chain chase, sitting ,jumping, darwing	8	04 (slipping, tripping, collision, burn)	0 0 35
B	Garden Softscape Fully shaded	Playing, resting,	fetching ball, plucking leaves, hanging from branches, soil modelling, soil ball throw, collecting stones and pebbles,sitting on ledge, dancing/ performing, jumping,hiding, resting, growing plants	15	01 (Insect bite)	7 0 14
C	Concrete road Hard scape Partially Shaded	Driving, Walking, Cycling	playing with soil in the planter bed, running, playing with ball, sitting on bench, standing on bench, balancing on bench, hiding behind planter,	8	04 (slipping, tripping, collision, burn)	3 0 39
D	Lawn Softscape Partially Shaded	Playing, resting, walking	fetching ball, plucking leaves, hanging from branches, growing plants	4	01 (Insect bite)	0 0 2
E	Parking Lot Hard scape Fully shaded	car parking	climbing, balancing on wall, sitting, resting, jumping, hide & seek, running, performing, dancing,	9	04 (slipping, tripping, collision)	23 0 37

2.3 Perceptual Interview

A total of n=36 respondents age group between 6-12 years were questioned about their play preference & experience as shown in Figure 5.

Figure 5: *Questionnaire for survey*

PLAY EXPERIENCE

1. How long do you play during weekdays?
   a) Less than 1hour b) 1-2 hours c) 2-4 hours d) Greater than 4hours
3. How long do you play during weekends/holidays?
   a) Less than 1hour b) 1-2 hours c) 2-4 hours d) Greater than 4hours
3. Where do you play the most?
   a) On the road b) Parking lot c) Green areas
4. Where do you get hurt the most?
   a) On the road b) Parking lot c) Green areas
5. What are your major play activities?
   a) Playing chase, running, jumping, ball sport etc.
   b) Cycling or skating
   c) Walking or light play
   d) Sitting and playing
6. How do you imagine your dream playspace to be like?
   a) Full of equipment likes swings slides seesaw etc.
   b) Playing in Sand, splashing water, climbing trees and rolling on grass
   c) Continuous large playground
   d) Current open space
7. Did you play outside during the lockdown period?
   a) Always b) Sometimes c) Never

THERMAL PERCEPTION

8. Do you play in sun? Yes..... No.....
9. If No, why don't you play during the day time?
   a) It is very hot b) It is very cold c) Parents do not allow d) Lots of homework
10. Before playing how do you feel?
    a) Very hot b) Hot c) Comfortable d) Cool e) Very Cold
11. After playing how do you feel?
    a) Very hot b) Hot c) Comfortable d) Cool e) Very Cold

2.4 Micrometeorological measurements

The analysis and observations were based on data acquired through objective measurement of

climatic parameters and software simulations. The first set of observations was based on onsite data collection carried out at 5 zones identified for affordance as shown in figure 6. The second set of observations were carried through software simulation. PET for all observation points were computed using RayMan pro [10] [11]. Air temperature, relative humidity, wind speed, and cloud cover are considered for calculating TMRT values as described in Eq. (1).

$$Tmrt = Tg + 0.237 \times (V)^{0.5} \times (Tg - Ta) \quad (1)$$

where, Tg is globe temperature in °C, V is wind speed in m/s, Ta is air temperature. The clo value considered for study is 0.5 based upon clothing [12]. Since majority of children were engaged in intense play activities their metabolic rate considered for PET calculation was 150 W/sqm [12] [13]. Based on heat stress range as provided by Matzarakis, PET can be used to identify the stressed areas on site as shown in Figure 7[10] [11].

Figure 6: *Field measurement of Air temperature, Globe temperature and Relative Humidity in different zones*

2.5 Motivation

Based on earlier research on affordance, it was found that natural areas provided children with greater interactions with plants, water, soil, topography and understanding of ecology [14]. The landscape interventions in the urban areas can help in creating cooler environments as well as stimulating play areas using bio climatic design strategies. In order to reduce the heat stress and stay well below the burn thresholds of outdoor materials, an ideation with natural materials, shading along with play preferred components like the trees, waterbody, and mouldable objects can be developed. This ideation can be simulated using Envi Met to understand the effect of bioclimatic design on thermal environment.

2.6 Simulation input

Software simulations were made using Envi met 5.0.1 and Rayman. Meteorological data such as weather file was used as an input (sky cover, wind velocity, air temperature, and relative humidity) for the Envi met 5.0.1 simulation. The computational domain covers a horizontal area of 200 m x 100 m and a vertical height of 36 m.

Figure 7: *Physiological Equivalent Temperature, Surface Temperature, mean radiant temperature and associated thermal stress*

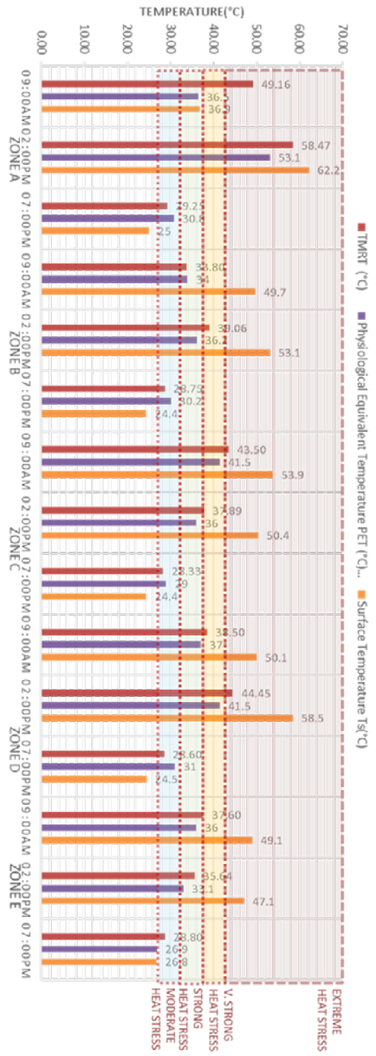


Table 1 – *Summary of input parameters in Simulation*

	Input data	Value
1	**Domain features**	
	Location	26.91°N, 75.78° E
	Elevation (msl)	431m
	Domain size	50*50*30
	Grids spatial resolution	Horizontally:7 m; Vertically: 4 m
	Climate	Composite as per ECBC, hot-dry summers & mild winters
2	**Simulation timing**	
	Simulation day	2022.10.08 & 2021.06.21
	Simulation period	05:00 a.m. for 24 hours
3	**Meteorological data**	
	Dry Bulb Temperature	14°C to 32°C in winter and 30°C to 42°C
	Relative Humidity	15% to 50% in winter and 30% to 50% in summer
	Wind Speed	2.0 (m/s)
	Wind Direction	270 degrees (west)
	Cloud cover	0
	Receptor height	1.4 meter from GL

3. RESULTS

The results obtained from the perceptual interview, behaviour mapping of the site and thermal comfort calculation indicate the interdependence between play and outdoor thermal stress for respective areas as shown in Figure 7. Following can be inferred:

- More than 85% of the respondents spend 2-4 hours for outdoor play and engage in high intensity activities like running, playing chase, ball sports etc. and therefore exhibited sweating, rigorous breathing and need to drink water.
- Based on their space usage and attendance it was observed that less than 20% kids preferred to play in sun. Rest of children found it too hot and uncomfortable, as a result played outside after sunset, when the heat stress reduces. The surface temperature of most used hardscape material i.e concrete for play exceeded its burn threshold of 48°C for 10-minute contact, 56°C for 1 minute contact and 60°C for 5 second contact duration [12].
- It is observed from figure 7 that majority of the site area falls under moderate to high thermal stress when the average air temperature recorded was 33°C [11]. Furthermore, it can be predicted that during summers when the air temperature reaches 44°C, the same area will undergo extreme stress making it highly unsafe for kids to play outdoor.

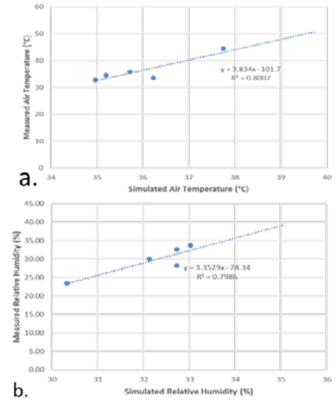
It is interesting to note that most respondents preferred to play in the hardscape areas in spite of high thermal stress. This is because of high affordability of continuous open space or the only available space in this case. However, respondents have indicated their displeasure about the hard surface of the road as they get hurt due to falling, tripping slipping etc. during play. This suggests the designers to understand spatial requirement and use materials that are safe and play friendly.

The softscape areas with elements like trees, shrubs, lawn and, soil etc. have been very scarcely used for playing. On the contrary previous studies have indicated high affordability of natural elements over artificial ones, but in this case use of softscape areas are negligible. This might be due to parental restriction to play in green areas after sunset. Also, the softscape areas are not well lit and gets darker during evenings creating negative affordances to play. However, these respondents when enquired about their play preferences; majority expressed their desire to play with natural materials like sand, water trees, shrubs and playgrounds (*maidan*).

3.1. Model validation

A quantitative measure of the model performance was conducted considering the data in all measurement points/receptors and calculating the correlation coefficients (R2), the root means square error (RMSE). Obtained results for 8th October 2021 are reported in Figure 8 and demonstrate a satisfactory performance of the model, with R square over 0.80, 0.79.

Figure 8: *Relationship between simulated and measured data of air temperature (a) and relative humidity (b), on 8th October,2021 at 14:00 hrs.*



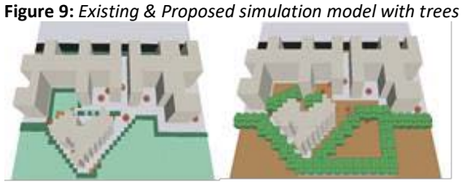
3.2 Model trees configuration

The proposed ideation is developed with dense spherical medium trees with 11m canopy diameter, and replacement of concrete road with soil as shown in figure 9.

Figure 10 shows the air temperature distribution for summer solstice i.e., 21st June 2021 at 1400 hours and at a height of 1.4m. The afternoon reading specifically for the play area is selected as it reaches maximum temperature i.e up to 44°C and

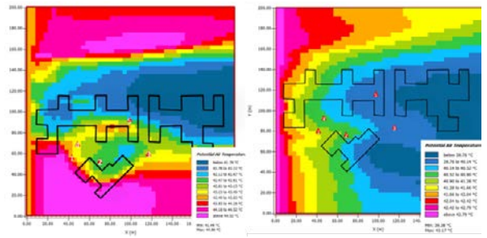
relative humidity of 27%. This is also the time after school hours when most children are available at home.

Figure 9: *Existing & Proposed simulation model with trees*



It is assumed that thermally comfortable play area can attract children to play outdoors. The summer air temperature for existing model ranges between Ta max 44.8°C and Ta min 41.44°C; while in the case of proposed model, Ta max 41.28°C and Ta min 39.3°C. Concerning the summer heat mitigation effect of the greening scenarios, results show benefits provided by the proposed green scenario compared to the base case, with average Ta reduction of 3°C and increase in relative humidity by 15-20 %.

Figure 10: *Distribution of Air temperature, for existing (left) model proposed (right) simulation model with large trees*



4. CONCLUSION

The present-day play pattern has forced children to play in nature deficit conditions and unfriendly environment. The sun exposure in moderation is beneficial for the overall health of children especially for curing vitamin D deficiency. However extreme exposure can lead to adverse effect on health, sun burns, skin allergy and skin burn due to surface material. Bioclimatic design strategies using natural elements like vegetation, water sand etc. can be used to reduce excessive heat gain and thermal stress during extreme temperatures. Further study on effectiveness of each of the bioclimatic strategy can be conducted. The spatial understanding and use of natural elements that can offer high affordability for creative and free play should be integrated as part of playground design, reducing the dependence on mundane equipment. Thus, appropriate design of outdoor play areas can motivate and encourage children to play, while ensuring high affordability and thermal comfort.

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Investigating scientific selection of trees for maintaining thermal comfort in an asymmetric urban street

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ABSTRACT: The reconfiguration of trees into the urban street is one of the strategies for regulating pedestrian thermal comfort. However, indigenous trees of different morphological property have variable thermal comfort potential. While scientific basis of tree selection in the urban designing process is scarce, the appropriate classification of trees should be primarily based on tree form indicators like canopy density, tree height, trunk height and crown diameter etc. The aim of the present study is to investigate interrelationship of urban street attributes and trees morphology. The thermal interaction of an urban street characterized by varying aspect ratio (AR) and the existing tree morphology is mapped. Empirical measurement was carried out at 5 sections along 360 meter long and 18 m wide street. Mean radiant temperature MRT and physiological equivalent temperature PET for all observation points were computed using ENVI MET. The correlation between resulted PET shows that Aspect Ratio and tree morphology indicators are major influencing factors determining the street environment. Statistics represents that tree morphology significantly affect the physiological equivalent temperature (PET) of the street. Thus, appropriate tree selection according to varying street aspect ratio is important in attaining thermal comfort in an asymmetrical street.
KEYWORDS: Asymmetrical Street canyon Aspect ratio Outdoor thermal comfort (UHI) PET Tree forms

1. INTRODUCTION

The world is increasingly becoming urban with a projected growth of 68 % until 2050 (Department of Economic and Social Affairs, 2018), which suggests increase in urban areas as well as urban heat. Outdoor spaces affect pedestrian discomfort considerably. Currently streets accommodate up to 35 percent of outdoor spaces (Shashua Bar et al, 2012), strategic design solutions for outdoor environment can control urban heat Island effect at pedestrian level. In order to improve microclimatic conditions in the existing urban fabric without reconstituting the entire built, green coverage becomes one of the potential strategies out of the three aspects: albedo enhancement, increased green cover and implementing 'cool roof' (R. Emmanuel et al, 2007). Occurrence of recent commercial constructions along street has surged the intention of removing existing native tree species while entirely neglecting their environmental values especially their role in providing shade and comfort. Trees improves thermal conditions by combining solar attenuation and evaporative cooling capacity at pedestrian level (Diana Bowler et al, 2015). However scientific basis of tree selection in the urban designing process is scarce and is mostly an outcome of random selection. Indigenous trees of different morphological property have varied thermal comfort potential (Wiebke Klemm et al, 2015). The appropriate classification of trees in urban street should be primarily based on morphological indicators like canopy density, tree height, trunk height and crown diameter etc. (Eniolu Morakinyo et al, 2020).

1.1. Asymmetric urban street

The major challenge in the urban context lies due to asymmetricity of built forms. The street canyons are classified as symmetrical or asymmetrical if bounding buildings are of equal or unequal heights, respectively (Ahmad K et al, 2005). According to Johnson and Emanuel (Emmanuel R et al, 2006) each urban configuration has a varied influence on the microclimate at street level. Therefore, such asymmetricity in the street aspect ratio must be investigated individually to find heat stress areas. The present study has divided 18-meter-wide urban canyon into three components i.e., two sidewalks (3m) at both edges of the street, and a wide dedicated vehicular lane (12m) in the centre. However previous studies carried for an outdoor environment (such as urban park, residential quarter, urban canyon), have proved that urban greenery and vegetation are important in reducing thermal discomfort, there is need to know the influence of urban greenery for asymmetrical building aspect ratio.

This study aims, to investigate evidence-based tree selection approach which compares the effects of varied tree species characteristics by performing site survey and numerical simulation of different

scenarios. Specifically, we attempt to answer the following question, what is difference in magnitude of thermal improvement by specific tree species in an asymmetrical street.

2. METHODOLOGY

The quantitative analysis was done through parameterization of two variables: urban building form and the urban tree forms; and the interaction between them in an urban street. This process is carried out in two steps, the first was achieved through a field study whilst the second were explored though a Envi-Met 5.0.1 simulation-based study between dependent and independent variables Table 1. Study indicates that the physical parameters of existing trees on the street differ in their canopy density, tree height, trunk height and crown diameter and coverage levels. The physical parameters like sky view factor & aspect ratio of the built form depends upon its geometric relations with the street.

Table 1:
Methodology Map

Quantifying the thermal improvement of the street.
Parameterization of independent variables.
Interrelationship of building form with tree form and their physical parameter like, canopy density, tree height, trunk height and crown diameter.
Field study to explore the variation of Tg (Globe temperature), Ta (Air temperature), Rh (Relative humidity) and Ws (Wind speed) in the street.
Numerical simulation to find Mean radiant temperature MRT and physiological equivalent temperature PET for all observation points and validation with field study.

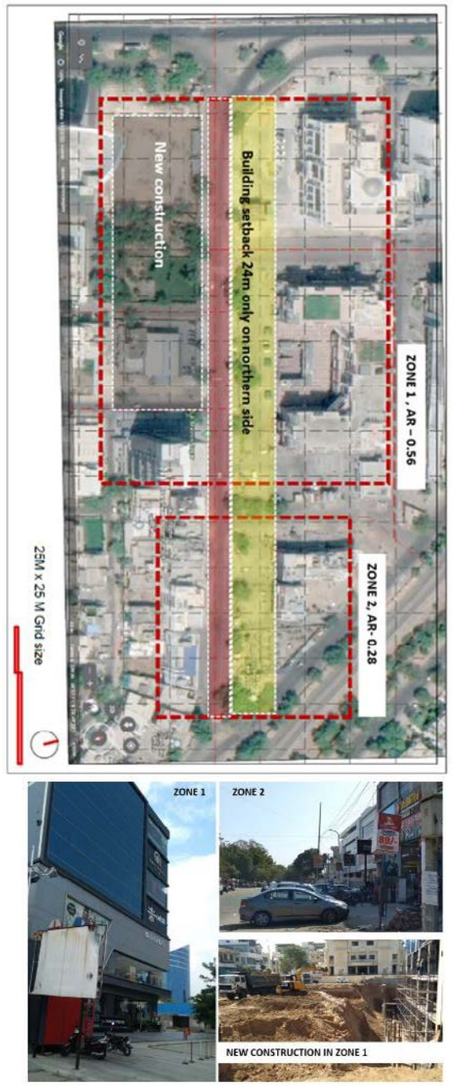
2.1. Study area characterization

The study was carried out in Jaipur city (coordinates 26.9124° N, 75.7873° E.), India, and as per the 'Energy conservation and building code' user guide, the city climate is classified as a Composite climate (ECBC, 2017) Figure 1. The street chosen for study lies in a busy commercial center. It majorly comprises of retail like shopping malls, restaurants & cafeteria, theatres, street food vendors etc. The street receives heavy traffic and footfall all throughout the day. The street is 360 m in length and 18-meter wide which is divided in two equal length sub zones: zone 1 having aspect ratio 0.28 and zone 2 having aspect ratio 0.56. Table 2.

Table 2:
Existing street details

Zone	Street length	Street width	Additional Setback	Building ht.	AR
1	180m	18 m	24 m	24 m (6 floors)	0.56
2	180m	18 m	24 m	12 m (3 floors)	0.28

Figure 1:
Site Map of Studied Street canyon with actual site images of zone 1 and zone 2.



2.2. Micrometeorological measurements

Empirical measurements were taken at regular intervals., 5 points on both sides of the street. As the trees were not located in an orderly manner, separate readings were taken specifically under the 7 trees present on site. The mapped trees species listed in the table are not only indigenous but are very commonly found along road plantation throughout the urban plantation in Indian cities. These readings will help in understanding the heat distribution all along the street (Ministry of Environment F. a., 2021). The first set of observations was done using objective measurement of climatic parameters like, Tg (Globe temperature), Ta (Air temperature), Rh (Relative humidity) and Ws (Wind speed) of the site. Thermal comfort parameter i.e., Mean radiant temperature (Tmrt) is obtained using several using above collected data as described in Eq. (1).

$$Tmrt = Tg + 0.237 \times (V)^{0.5} \times (Tg - Ta). \quad (1)$$

where, Tg is globe temperature in °C, V is wind speed in m/s, Ta is air temperature. Tree canopy cover is recorded using spherical Densio-meter (Sarah Binte S.P.Ali, Thermal comfort in urban open spaces: Objective assessment and subjective perception study in tropical city of Bhopal India, 2018). The second set of observations were carried through software simulations using Envi met 5.0.1 and Rayman (M.Matzarakis et al, Modelling radiation fluxes in simple and complex environments-Application of the RayMan model,, 2006) (M.Matzarakis et al, Modelling radiation fluxes in simple and complex environments - Application of the RayMan model,, 2010). Meteorological data such as the weather file was used as an input (sky cover, wind velocity, air temperature, and relative humidity) for the Envi met 5.0.1 simulation. Table 3.

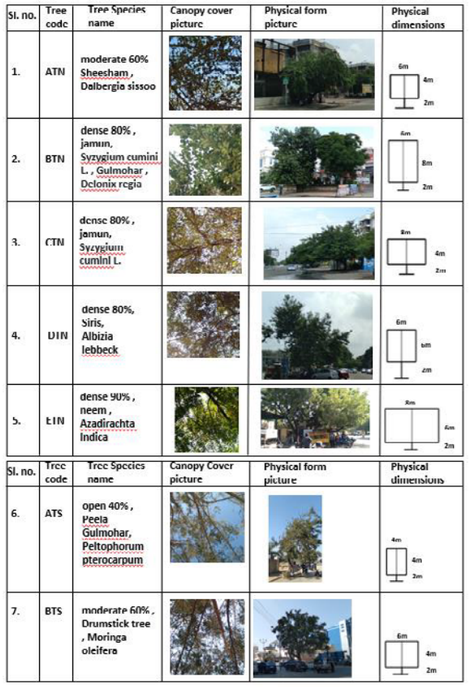
Table 3:
Summary of input parameters in Simulation

Domain features	
Location	26.91°N, 75.78° E
Elevation (m asl)	431m
Domain size	50*50*30
Grids spatial resolution	Horizontally:7 m; Vertically: 4 m
Climate	Composite as per ECBC, hot and dry summers and mild winters
Simulation timing	
Simulation day	2022.02.21 & 2021.06.21
Simulation period	11:00 a.m. for 24 hours
Meteorological data	
Dry Bulb Temperature	14°C to 32°C winter& 28°C 44°C
Relative Humidity	15% to 45% in winter and 20% to 70% in summer
Wind Speed	1.0 (m/s)
Wind Direction	270 degrees (west)
Cloud cover	0
Receptor height	1.4 meter from GL

2.3. Classification of studied trees morphology

Selection of trees in urban areas for their thermal performance is dependent on the foliage characteristics and mature tree canopy shape (Sarah Binte S.P.Ali, Assessment of the impact of urban tree canopy on microclimate in Bhopal: A devised low-cost traverse methodology, 2019). For modelling purpose, three categories of tree canopy densities were identified in the study area according to Forest Survey of India (Ministry of Environment F. a., 2015) Classification of tree canopy densities are as follows: canopy cover <40%, between 40 and 70%, and >70%. Seven tree species with different canopy characteristics and canopy coverage levels were studied: The basic characteristics of the seven tree species are shown in Figure 2.

Figure 2:
Basic physical character of studied tree species



Trees species present on the northern side of the road are Dalbergia sissoo (sheesham), Syzigium cumini (jamun), Delonix regia (Gulmohar), Albizia lebbekk (Shirish) and Azadirachta indica (Neem). The trees present on the southern side are Peltophorum pterocarpum (peela gulmohar) and Moringa oliefera (Drumsticks). It is important to note that south side of the street remains shaded all time due to adjacent buildings.

2.4. Data Monitoring

Extech HT30 WBGT meter with a hot wire probe of diameter 40 mm was used for measuring heat stress (WBGT), Air temperature (Ta), Globe

Temperature (Tg), Relative humidity (Rh). Meco 961P was used for measuring Air velocity in m/s. The measurements were taken at 1.4 m from the ground as per ASHRAE-55, 2010 standard. The tree Canopy Density is defined as the proportion of sky hemisphere obscured by vegetation when viewed from a single point. The spherical densio-meter is simply a convex mirror with grid-overlay (96 vertices) that is used to measure tree/forest canopy closure [13].

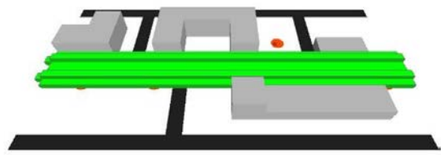
2.5. Re-Configuration of Model trees in street

A modelled is developed with East-West orientation. The computational domain covers a horizontal area of 400 m x 200 m and a vertical height of 30m. In total two different scenarios with regard to trees specie and numbers were simulated on the selected, summer day (21.06.2021) to assess the street thermal comfort conditions.

Case 1: As the base model, with existing building aspect ratio and street trees. A Street canyon of two different aspects ratios were modelled. AR=0.28 refer to shallow canyon while AR=0.56 is typical of medium canyon. Here mild (01 m/s) wind condition with 270 degree (west side) is imposed. The building was all assumed to be made of brick blocks with RCC structural frame while the streets are mainly made of Asphalt.

Case 2: As per the existing tree mapped in the site, one medium tree species (Neem, Azadirachta Indica a deciduous tree) is finalized out of all other 7 options. A Based on current limitation of urban street canyon the selection of tree type should have followed: a). The form should be optimized to follow the urban planning guideline with leaf area density (LAD 3). A tree with cylindrical shape canopy and crown diameter of 11m and trunk height of 4m. Total 50 trees included in one side of the street edge. The trees are placed at approx. 8m interval with up to 30 percent overlapping crown. The comparison among the cases could reveal the impact of selected tree species in current street canyon figure 4.

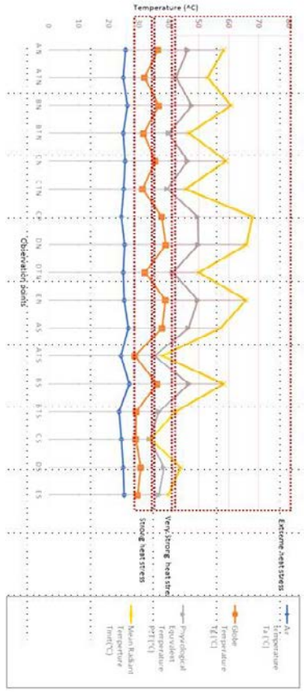
Figure 4:
Iterated case with medium tree species (Neem, Azadirachta Indica).



3. RESULTS

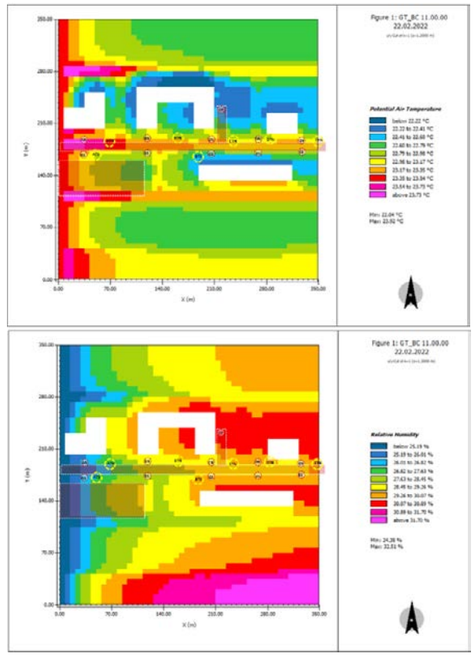
In this section the model validation of simulated and field study has been performed. The variability of air temperature, relative humidity, Mean Radiant Temperature (Tmrt) and physiological equivalent temperature (PET) under tree canopy density on street thermal comfort was discussed during the field visit in the period 11:00 for winter day 21st February. Thermal conditions were significantly under the influence of tree cover during the afternoon hours. Tmrt and PET appeared to be significantly related to the tree canopy cover. Low percentage tree canopy cover (say, 40%) in street lowers Tmrt by 5.0 to 9.0°C and PET by 2.0°C. High percentage canopy cover (say, 80%) reduced Tmrt by 5.0 to 9.0°C and PET by 2.0°C to 4.0°C. Reason of lower temperature ranges even in sparse tree canopy is mostly due to mutual building shade from south side Figure 5.

Figure 5:
Distribution of observed Ta, Tg, Tmrt, PET at a height of 1.4 m at 11:00, with tree and without tree spots



The EnviMet model was simulated with no tree options and validated considering the predicted air temperature and relative humidity during field visit in the period 11:00 for winter day 21st February Figure 6.

Figure 6:
Distribution of potential air temperature, relative humidity at a height of 1.4 m at 11:00 in, base case model i.e., without trees for 21st February 2022.



A quantitative measure of the model performance was conducted considering the data in all measurement points/receptors and calculating the correlation coefficients (R2), the root means square error (RMSE). Obtained results are demonstrate a satisfactory performance of the model, with R square over 0.78,0.76 Figure 7 and Figure 8.

Figure 7:
Simulated and measured data of air temperature

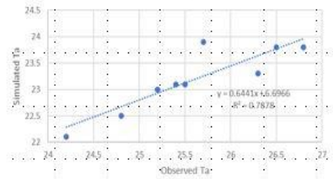
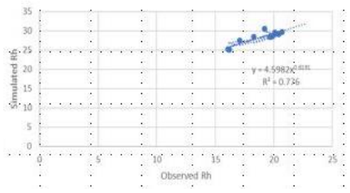


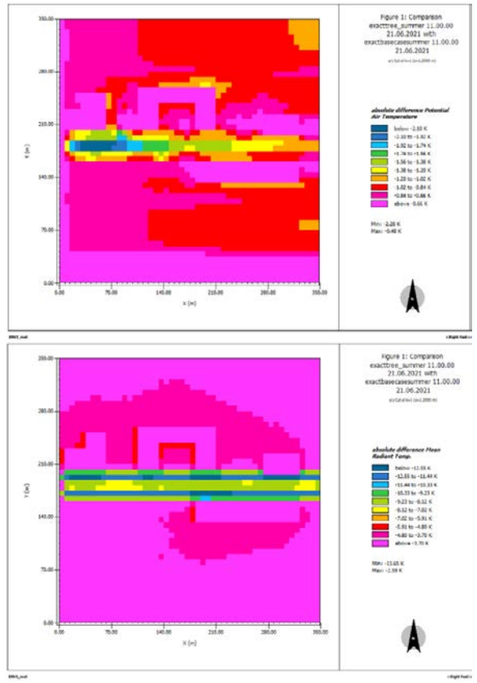
Figure 8:
Simulated and measured data relative humidity.



3.2. Impact of Green scenario

This section shows the evolution and magnitude of the simulation results with experimented trees (Saeid Teshnehdel et al, 2020) for peak summer season for 11:00 am in morning in terms of Ta,Rh and Tmrt are reported for a height of 1.4 m agl to approximate the human-biometeorological reference height (E. H. Mayer, 1993) and presented as: (i) 2-D maps with coloured-coded ranges extracted from LEONARDO tool included in Envi-Met Figure 9.

Figure 9:
Difference of air temperature, mean radiant temperature, at a height of 1.4 m at 11:00. in the hot summer day 21st June 2022, medium trees with base case (without trees).



This tool provides the overlapping of two sets of data for same spots while it shows the difference of ranges between them as delta k values. For current project it was the base model (without trees) and model with medium tree (Neem, Azadirachta Indica) selected above. It shows the distribution of the air temperature, relative humidity and Tmrt at 11:00 (21.06.2021), for the base case model and greenery scenario with trees. The Ta range is 39.9 - 43.2 degree C, Tmrt 64.10 – 86.6 degree C and that for RH is 48.5–55.8 % in summer for base case model. Concerning the summer heat mitigation effect of the greening scenarios, results show benefits provided by the green scenario compared to the base case, with average Ta reduction of respectively 1.5 -degree, average increase of relative humidity by 9% and average Tmrt reduction of 7.5-degree Celsius Table 4.

Table 4:
Zone wise Summary of Ta, Rh, Tmrt

Zones	Average Ta reduction	Average inc. of Rh	Average Tmrt reduction
Zone 1	1.3°C -1.9°C	2 %	9°C-11°C
Zone 2	1.2°C -1.4°C	2%	7°C-9°C

4.CONCLUSION

In this study, we employed a micro-scale numerical model, to investigate the impact of experimented tree selected in asymmetrical street canyon under composite climate (hot and humid) condition. The intensification of green coverage in urban scenario is essential for the overall urban microclimate condition. However extreme exposure of heat stroke can lead to adverse effect on exotic street trees due to their sensitive morphological character. Current investigation represents that tree morphology and urban form significantly affect the PET of the street. Thus, appropriate tree selection for future plantation according to varying street edge and aspect ratio is important in attaining thermal comfort in an asymmetrical street. As the northern part receives direct radiation in the morning and evening, the high canopy density trees or High absorptivity building shading devices can be implemented for reducing the impact of direct solar radiation while for the southern edge where the late afternoon solar radiation falls the low canopy density trees or less numbers of high canopy density trees can be proposed. Therefore, for the current street scenario the optimization can be achieved by adding a dense canopy i.e., LAD 3 deciduous medium size tree more than five times in numbers from existing scenario to avoid excessive heat stress in summer session.

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The environmental gentrification process and the microclimate

Case study in the federal district

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ABSTRACT: In this paper environmental gentrification appears as one of the effects of the accelerated urban process. This phenomenon tends to reinforce inequality in the social and environmental fields of cities. Based on this finding, the aim of the essay is to compare data on the microclimatic effects of environmental gentrification in areas of Brasília (DF) – the third most populous city in Brazil. The area selected was the model 108/508 block, Asa Sul, and the Morro Azul occupation in São Sebastião (DF), satellite city. For data collection, climate measurements were carried out in the morning, afternoon, and evening, in order to measure temperature, relative humidity, lighting and CO2 concentration. The result of the study showed that in the model block 108/508, Asa Sul – central area with a high concentration of vegetation – the climatic conditions favor the occurrence of a mild climate, while in the Morro Azul occupation, São Sebastião, the climatic conditions favor the occurrence of a dry climate with higher temperatures.
KEYWORDS: Environmental Gentrification; Microclimate; Vegetation; Planned Urban Spaces; Sustainable.

1. INTRODUCTION

This article starts from an investigation about the impact of environmental gentrification on urban microclimates. The aim of the study is to compare data on the microclimatic effects of environmental gentrification in areas of Brasília (DF) – the third most populous city in Brazil. It is a theoretical approach that seeks to highlight the relationship between the existence or non-existence of bucolic areas, disordered urban growth and microclimate. The model block 108/308 Asa Sul and the occupation of Morro Azul in the satellite city of São Sebastião (DF) were selected as the study area. The analysis of urban microclimate and its relationship with the process of environmental gentrification allows connecting the study of climatic factors to the effects caused by socio-spatial and environmental segregation resulting from rapid urban growth.

Design solutions for climate change caused by different forms of urban occupation demand continuous knowledge by professionals in the field of Architecture and Urbanism, as well as by public policy managers, when preparing urban, social and environmental works in consolidated areas, new and, mainly, in urban areas as a result of the process of social segregation.

Environmental issues should be considered fundamental in the elaboration of an urban project, since the lack of communication between environmental capital and the others (social, technological, economic and ecological) affects sustainable development as pointed out at the United Nations Conference - Our Common Future, 1987.

There is a surge of interest in how to combine the demands of modern life and society with a healthy natural environment. Scholars are committed to making the most of natural resources such as sun, wind and vegetation. The possibility that humans can benefit from natural cooling and evapotranspiration from vegetation instead of artificial air conditioning, humidifiers or any other energy-consuming device has generated interest in the development of passive cooling environments. [2].

Thus, the quantitative and qualitative study of microclimatic issues and the environmental gentrification process and its characteristics can collaborate for the preservation of natural resources, such as native vegetation, in urban projects, as well as for the elaboration of environmental and social policies aimed at the social classes vulnerable people, who are often limited in their right to live in an urban space that provides environmental quality.

In the qualitative study, information about a problem, trends of thought, opinions and hypotheses are provided in correlation with the quantitative aspects - these associated with the generation of data or objective information - can be transformed into usable statistics and can guarantee the participation of the target audience, as well as

the effectiveness in the political actions to be implemented.

In order to fit the analysis involving all the mentioned fields, the study uses a bibliographic review about the evolution of urban occupation in Brasília-DF and the urban microclimate - covering issues related to temperatures, winds, densities and to vegetation. Likewise, maps with the geographical, environmental, urban and morphological characteristics of the Federal District will be used.

For data collection, climatic measurements of the temperature were carried out, in the morning, afternoon and evening, in November 2021. From the collection, the different influences of anthropic action and the maintenance of vegetation cover in each area were examined regarding the criteria of thermal exchange, evapotranspiration and urban morphology.

2. ENVIRONMENTAL GENTRIFICATION

The United Nations Human Settlements Program (UN-Habitat), in its report, State of Latin American and Caribbean Cities 2012, pointed out that the region is the most urbanized in the world – where about 80% of the population lives in cities, which is expected to reach 90% by 2050 [14].

The document addressed topics such as economic development, housing, public spaces, basic urban services, the environment and urban governance. Likewise, he spoke about the problems arising from the rapid process of urbanization, such as poverty, segregation, income inequality, climate problems, violence, gender disparity and sanitation.

In this accelerated urban process, the urban event called gentrification, a term coined by the English sociologist Ruth Glass, in 1964, to describe a socio-spatial transformation in London, gains strength. The author observed that a traditionally popular area was transformed into a noble region for the middle class. She found that new inhabitants, new costs, new housing segmentations and a new ambience appeared in the neighborhood. Thus, for Glass, the process of gentrification of a spatiality began, because, with the transformation, also came the social segregation of the working classes. This conceptualization won the years and reached the present day in new manifestations of gentrification, driven by space capitalism and neoliberalism. There was an intensification of the expropriation process observed in the 60's by Glass [5].

The transformations of cities create displacements, inequalities and new materialities due to urban policies and the logic of real estate production. On a regular basis, megaprojects are built in areas close to popular neighborhoods, revaluing urban land and inducing the displacement of residents, due to increased taxes, real estate pressure, gentrification and the loss of neighborhood identity. This process results from the neoliberal model and it is from it that the fragmentation of urban spaces takes place, generating socio-spatial inequalities [3].

In this context, social demands went beyond purely demographic issues and began to demand environmental justice as well. As a result of the event identified by Glass, the concept of green gentrification was launched by authors Kenneth A. Gould and Tammy L. Lewis, in the book Green Gentrification: Urban sustainability and the struggle for environmental justice [6].

We situate the concept of green gentrification within broad social processes that produce and reproduce inequality in society. We use the term green gentrification to describe a subset of urban gentrification. The green gentrification process. The green gentrification process is initiated by ecological initiatives that create or restore environmental amenities. Environmental amenities attract wealthier groups of residents and drive out low-income residents, creating green gentrification [6].

The debate on green gentrification, in the field of urban analysis, has its interface with sociology. According to Acselrad, the locational issue is a strategic part for the appropriation and reproduction of capital in the territory. It is in areas of greater socioeconomic deprivation and/or inhabited by social and ethnic groups without access to the decision-making spheres of the State and the market that the lack of investment in sanitation infrastructure, the absence of policies to control toxic waste deposits, risky housing, desertification, among other factors, contributing to their poor living and working environmental conditions.

To designate this phenomenon of disproportionate imposition of environmental risks on populations less endowed with financial, political and informational resources, the term environmental injustice was consecrated. As a counterpoint, the notion of environmental justice was coined to name a future life framework in which this environmental dimension of social injustice will be overcome [1].

In this search for environmental and social justice, but without being confused with the already established concept of green gentrification, the expression “environmental gentrification” is proposed, in an innovative way, which seeks to describe inequality in the social and environmental field of urban spaces due to the removal of vegetation due to large densification and soil sealing, among other socio-environmental and economic factors.

These changes, historically, have always affected man's relationship with the environment. The 1987 Brundtland Report conceives of sustainable development as meeting current needs without compromising the ability of future generations to meet their own needs.

This report brings the notion that the sustainability element encompasses social, technological, economic and environmental capital. In this sense, the report works on the idea that sustainability must contemplate social and environmental equity and that the change to reach sustainable development requires a transformation in the field of all capitals.

Within this scenario, Brasília suffers from disorderly demographic expansion and the process of environmental gentrification, which results in an appropriation of natural resources and impetuous social segregation.

At the height of the accelerated urbanization process, the Federal District, in a systemic way, has experienced the process of environmental gentrification, which leads to microclimatic changes, causing consequences for the urban environment, such as the absence of green areas, rising temperatures, reductions in in air humidity and changes in water absorption by soils.

2.1 Spatial expansion of the Federal District

Planned for 500 thousand inhabitants, Brasília-DF is today the third city in Brazil, with almost three million inhabitants and with 33 Administrative Regions. This accelerated growth results in urban and environmental problems, such as disorderly expansion, slums, environmental pollution, vegetation fragmentation, water shortages and mobility problems [10]. The population evolution of the Federal District, from the 60s to the present day, demonstrates a growing urban sprawl.

The history of the spatial organization of the DF was marked by the creation, often without urban planning and in areas distant several kilometers from the center, the Plano Piloto, of urban centers. Some of these RAs, in turn, grew, initially, disorderly and poorly equipped, suffering from the lack of infrastructure to guarantee the basic needs of the citizen, such as basic sanitation, water supply, medical assistance, transport and, overloading thus, the Plano Piloto, where most jobs, education and health services are concentrated [11].

The accelerated and disorganized way in which the administrative regions of the Federal District have been expanding, impacts the entire urban context and, especially, the microclimate and the individual's quality of life. This is because one of the effects of this unplanned expansion is the excessive consumption of the vegetation that makes up the soil.

The removal of vegetation cover causes changes in the environment, reflecting in a chain of consequences that influence the quality of the urban environment [11]. There is a relationship between the quality of the environment in which the individual is inserted and the quality of his life. This factor (the urban and quality of life) affected by the accelerated and unplanned expansion of the areas and the city population.

Claims for housing and urban resources end up affecting the entire urban landscape and, in search of space, the poorest populations are at a disadvantage. Many communities are formed through invasions and irregular occupations, almost always inadequate, deprived of services and infrastructure. In these cases, planning, which aims at the sustainability and health of the environment, is moved to the background, which can drastically affect the quality of the environment and, therefore, the quality of life of the population [4].

The negative effects of this disordered and repulsive consumption of urban space characterize environmental gentrification - a phenomenon that impacts the life of the individual inserted in the lowest strata of society. In these cases, this individual tends to be repelled from the consolidated centers and from the better-structured areas in terms of basic sanitation, transport, public facilities such as schools and hospitals, and, of course, from the bucolic areas.

As the urbanization process increases, well-designed urban management is required for cities to have sustainable development. This organization is rare, on the contrary, as mentioned, it has had a devastating effect in low-income places, where the pace of urbanization is projected to be faster [14].

In this context, “Transforming our world: The 2030 agenda for sustainable development” has, among its 17 objectives, “to make cities and human settlements inclusive, safe, resilient and sustainable” (11th objective) [14].

These objectives serve as a complementary basis for the elaboration of public policies aimed at inclusive urban management, with a focus on sustainability, the individual's quality of life and the right to the city. There is a need for a holistic knowledge of urban demands so that the parameters of global urbanization can be understood.

The landscape is a reflection of the relationship between man and his surroundings. In this sense, it is designed and constituted from the real needs of the individual and the environment in which he is inserted. The landscape organization criteria are questioned and modified according to the evolutionary process of society, science and techniques [9].

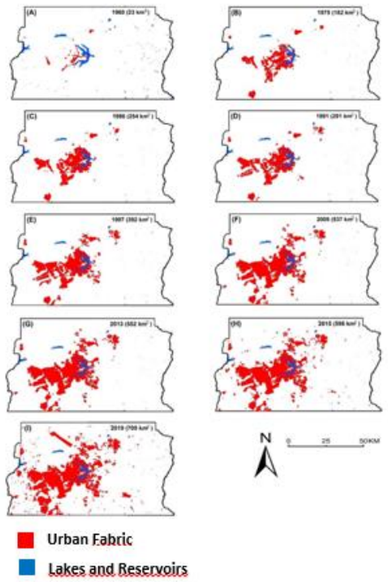
If it is possible to identify the elements that make up our visible surroundings, to identify their origin and development, their interrelationships and their specific manifestations in each place, it must be recognized that these elements are not lasting, but, on the contrary, are in continuous development. and incessant mutation. In the same way, individual or collective experience is also subject to continuous variations, to a dynamic that derives from the historical process of qualification, on which the most varied factors affect, from the evolution of political, economic and social relations, to the the development of techniques, arts, religions, philosophy [9].

To understand the main trends in urbanization in the coming years in the Federal District, it is important to know the patterns, vectors and impacts on the landscape. The growth of spatial patterns of urbanization in Brasília-DF in recent decades can be observed by analyzing the map

"Evolution of the urban sprawl of the Federal District in the period 1960-2019".

Figura 1:

Evolution of the urban area of the Federal District in the period 1960-2019 – Source: Codeplan; 2021



The urban sprawl considers the entire area where there are occupations with urban characteristics, such as a high degree of soil impermeability, high population density and the presence of traffic infrastructure. The map shows urban expansion in the years 1960, 1975, 1986, 1991, 1997, 2009, 2012, 2015 and 2019, which represents the first years of creation of Brasília-DF to the present day.

There is a high urban sprawl in the Federal District, which accumulates almost 97% of the population living in urban areas [8]. The urban dimension, as a social fact, makes the community depend on resources and environmental conditions from the built environment, without, however, eliminating the natural environment.

The discussion of the quality of the urban environment gains strength in the current scenario, when humanity starts to face the negative effects of the last two hundred years of population and economic growth, which caused ecological imbalance and the degradation of the physical and social environment [7].

On the track of occupation of the Federal District, the issue of environmental quality has been affected by irregular land consumption, the emergence of condominiums and residential occupations without infrastructure, the increase in demand for water, sanitation, and the removal of vegetation cover [13]. In the sphere of vegetation, in the last six decades, the impact is enormous. Approximately 60% of the Federal District's natural vegetation has been reduced to make room for urban centers, agricultural areas, and pastures [14].

In this way, the evolution of the urban layout and the drastic way in which the vegetation has been consumed by the disorderly occupation can be observed. There is, therefore, a need to requalify the urban space, in a more democratic way, understanding the influences that the bucolic environment exerts on the quality of life of the individual and the urban microclimate.

2.2 Planned and disorderly urban occupation – SQS 108/308 Asa Sul and Morro Azul

The choice of model block SQS 108/308 (Fig.2) was made due to its planned urban structure, representing the example of a superblock that is closest to the original concept proposed by Lucio Costa, having a road system with a single entrance for vehicles, buildings with pilotis, pedestrian freedom of movement, green areas and a densely wooded outline. On the opposite side, there is Morro Azul (Fig. 3), an urban occupation located in the administrative region of São Sebastião and characterized by the absence of urban planning and vegetation.

Figure 2:

Google Earth Image of SQS 108/308 Asa Sul.

Figure 3:

Google Earth Image of Morro Azul.

In these urban areas, temperatures, thermal exchanges, and the presence of vegetation were analyzed. Data collection took place in November, a period in which Brasília's climate is defined as hot-humid, marked by summer rains.

The capture of thermographic images took place in residential and commercial areas and in different shifts – morning, afternoon, and evening. In the images of the thermographic camera, it was possible to observe a scale of heating, being the biggest heating of the asphalt and vehicles, followed by the buildings. It is also noted that the greater presence of vegetation (evapotranspiration) in SQS 108/308 provided milder temperatures than the temperatures collected in Morro Azul, where there is absence of vegetation, disorderly land occupation and increased in built-up areas and population density.

To analyze the thermal field, the information collected is arranged as shown in the following images.

Figure 4:

Thermal images of SQS 108/308 Asa Sul.

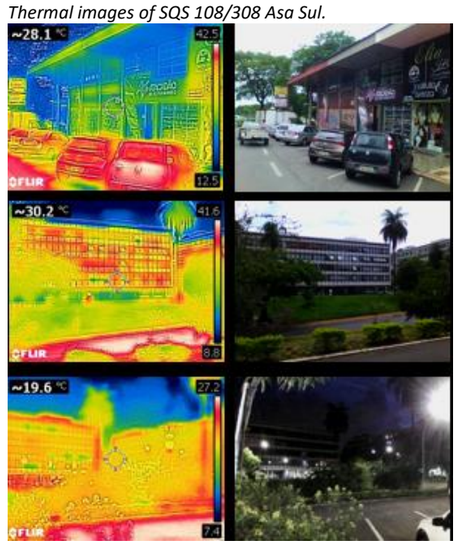
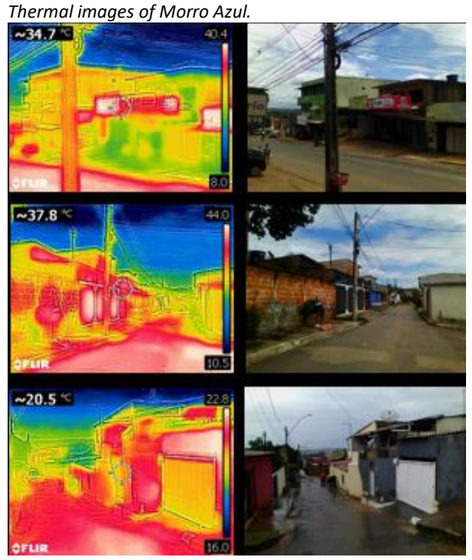


Figure 5:

Thermal images of Morro Azul.



In a comparative analysis of the images from the Thermographic Camera of SQS 108/308 and the images of Morro Azul, it was possible to observe a variation in temperature in the three shifts collected. In SQS 108/308, in the morning the maximum temperature was 28.1°C, in the afternoon 30.2°C and at evening the temperature collected was 19.6°C (Fig. 4). In Morro Azul, the maximum temperature in the morning was 34.7°C; in the afternoon it presented a temperature of 37.8°C and at evening a temperature of 20.5°C (Fig. 5).

Affiliation between greenway and street canyon aspect ratio
In ameliorating street canyon microclimate of residential Dhaka

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ABSTRACT: Emerging roads and wrecked foliage have harshly affected tropical Dhaka's microclimate. These newly widened roads are thermally uncomfortable for pedestrians with raised dry-bulb-temperature (DBT) and mean-radiant-temperature (T_{mrt}). Tropical research portrays the deepest street-canyons thermally comfortable. Aspect-ratio increment lessens canyon temperatures. Integrated greenways (linear pedestrian open-spaces built along lush-green or stream) on Dhaka's Street-canyons reduce DBT and T_{mrt}, 7.03-10.30 K and 5.76-31.36 K respectively and increase (RH) 7.90-18.47 %. This research explores the affiliation between street-canyon aspect-ratio (h/w) and greenways microclimatic heightening in terms of DBT, RH, WS and T_{mrt} in residential Dhaka. Smart-Sensor-AR-807 Temperature-Humidity-Clock and Zephyrus-Wind-Meter investigated microclimatic parameters at Dhaka's eight bare and greenway street-canyons in summer-days from 10:00-17:00 hours. Envi-met-5.0.2-software simulated 12-scenarios for shallow, mid-shallow and uniform bare and greenway canyons from 10:00-17:00 hours on the hottest summer day. This research elucidates that, tropical greenways enhance microclimatic thermal-comfort highest consorting NS and EW mid-shallow street-canyons, where 0.5<h/w<1 mostly. However, in few exemptions, greenways deliver excellent thermal comfort consorting uniform and shallow canyons, where h/w=1 and <0.5. This study culminates that, detailed insight of the relationships between greenways microclimatic thermal-comfort enhancement aptitude and street-canyon aspect-ratios including street-canyon orientation could landmark designing thermally comfortable tropical greenway street-canyons for urban pedestrians.
KEYWORDS: Affiliation, Greenway, Street canyon microclimate, Aspect ratio, Pedestrian thermal comfort.

1. PROLOGUE

In tropical Dhaka, roads are emerging in a volcanic speed. In 2021, the roads are widened chopping down intense foliage. Like several altered areas, being a lower middle-class neighbourhood, lacking accessible green, the microclimate of Mirpur, Pallabi, Section-12 of Dhaka is severely affected from the shift. Presently, these roads are thermally uncomfortable for pedestrians from raised dry bulb temperature (DBT) and mean radiant temperature (T_{mrt}) with lessened relative humidity (RH). Tropical studies reveal that the deepest street canyons are thermally comfortable and an increase in aspect ratio leads to lower canyon temperatures [1,2]. Street canyon is the core of urban residential. Street canyon aspect ratio, namely height-to-width ratio (h/w) and street orientation are vital city microclimatic parameters [3,4]. Research reveals that integrated greenways (linear open spaces built along lush green, stream, or alike features for non-motorized users) on Dhaka's Street canyons enhance microclimate reducing DBT and T_{mrt} 7.03-10.30 K, and 5.76-31.36 K respectively and increasing RH 7.90-18.47 % offering pedestrian thermal comfort [5,6,7].

The affiliation between street canyon aspect ratio and greenways microclimatic heightening is crucial at ensuring effective greenway exertion on Dhaka's Street canyons. Research hinted a relation between greenway and aspect ratio [5,6,7]. However, no study explored the role of street canyon aspect ratio in greenways microclimatic enhancement elaborately. This research seeks to explore the affiliation between street canyon aspect ratio and greenways microclimatic heightening in terms of DBT, RH, WS (Wind Speed) and T_{mrt} in residential Dhaka.

2. METHODOLOGY

Field investigations were steered in 13 points of 8 street canyons for bare (B) and vestige tiny green (G) or greenway (Gr) points in hot August days, 2021. Smart-Sensor-AR-807 Temperature Humidity Clock and Zephyrus Wind Meter measured DBT, RH and WS at 1.5 m height (pedestrian level) from 10:00-17:00 hours. Envi-met-5.0.2 software ran simulations at twelve different scenarios modelling bare and greenways for shallow, mid shallow or deeper and uniform street canyons from 10:00-17:00 hours, on 16 April, the hottest day of 2021. Microclimatic parameters (DBT, RH, WS, T_{mrt}) were compared for potential bare and greenway street canyons to specify the relation between greenways microclimatic boost and street canyon aspect ratio.

Through the thermal images it was possible to obtain the radiant temperature of the urban surface and to verify a high temperature variation in the places and shifts collected in the morning of 6.6°C, in the afternoon of 7.6°C and in the evening period of 0.9°C. Likewise, it was possible to demonstrate the difference in thermal comfort between more wooded and less wooded areas. In the same way, it was shown that with urban densification, there is a reduction in the natural ground cover and, at the same time, an increase in waterproofed areas.

3. CONCLUSION

There was a direct relationship between the removal of vegetation cover, the waterproofing of the soil, the disorganized densification of the space and the modification of the factors that make up the urban microclimate. In the same way, it was noticed that there is a connection between the process of "environmental gentrification" and the alteration of the elements that form the urban microclimate. It proved to be relevant to identify the temperatures of urban surfaces as an initial factor for the study of sustainable urban development, especially in areas of irregular occupation that demand active government action in terms of structuring or restructuring infrastructure. Also, the study of temperatures in structured areas and areas that still need structuring planning, shows the local population the importance of green areas for the quality of the microclimate, habitability and for the preservation of natural vegetation.

Inequality in the social and environmental field of urban spaces, due to the removal of vegetation during large densification and soil sealing, among other socio-environmental and economic factors, can be observed in the phenomenon of accelerated urbanization in the Federal District. When analyzing the evolution of the consumption of the natural landscape and the temperatures in SQS 108/308 and Morro Azul, it was found that to reformulate it, through a plural and inclusive process, it would be necessary to reach new criteria and meet the various phases of socio-economic development of the city and its people, and it is essential to remain adaptable to the most recent proposals, both at the individual and collective levels, for sustainable urban quality and life.

At this juncture, the process of environmental gentrification could be removed if there was a construction of the landscape through urban requalification, in a more democratic way, considering the influences that the public environment exerts on the private sphere and on people's lives.

It was identified that the urban landscape needs to be built on plural bases, including the histories, needs and culture of the individual so that it (the landscape) does not follow the segregationist rationality, according to the insulated areas commonly destined for the lower social classes.

Finally, it should be pointed that the process of democratic improvement of the urban landscape, in response to the issue of environmental gentrification, could be established on an inclusive basis, aimed, effectively, at the quality of the urban landscape. It could also be based on the maintenance and reconstruction of areas of vegetation, favoring the urban microclimate and environmental sustainability. In this way, integrated environmental actions between the public power and the individual would create democratic instruments capable of enabling the realization of the right to the city.

In a preliminary basis, it is expected that this study will serve as a foundation for future and depper research, both with regard to the space-time cut and the aspects of resources used.

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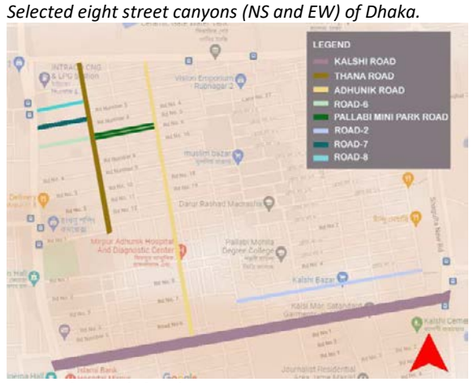
3. FIELD INVESTIGATION

Field survey investigated 13 points (Fig. 2) of 8 potential street canyons (Fig. 1) of Section-12, Pallabi (Area:17 km^2; Latitude: 23.495°N; Longitude: 90.215°E) at Mirpur, Dhaka. Buildings are mostly of six stories (18m height). Grid iron patterned roads ensues primary, secondary, and tertiary hierarchy. This lower middle-wage high density residential area, of sparse vegetation, huge asphalt road and concrete footpath is exposed to high DBT and T_{mrt}.

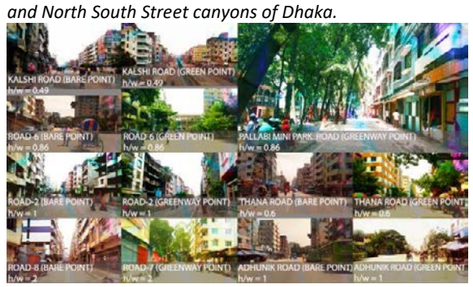
Figure 1:
Selected eight street canyons (NS and EW) of Dhaka.



Note: NS= North South, EW=East West.

East West (EW) street canyons are Kalshi Road (*B* vs *G*), Road-6 (*B* vs *G*), Road-6 (*B*) vs Pallabi Minipark Road (*Gr*), Road-2 (*B* vs *Gr*), Road-8 (*B*) vs Road-7 (*Gr*) covering h/w: 0.49, 0.86, 0.86, 1 and 2 in turn. North South (NS) Roads are Thana Road (*B* vs *G*) and Adhunik Road (*B* vs *G*) covering h/w: 0.6 and 1. h/w: 1, <0.5 and 2 denotes uniform, shallow and deep street canyons in turn [5].

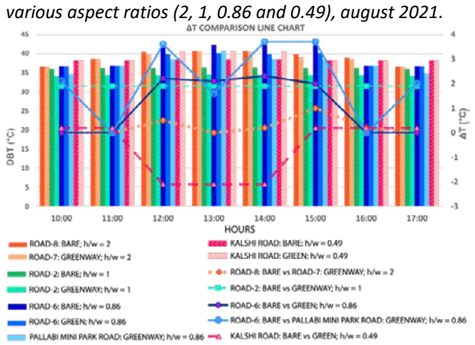
Figure 2:
Thirteen Bare, Green and Greenway points of East West and North South Street canyons of Dhaka.



3.1 ΔT (DBT Difference) Comparison

At EW Street canyons of h/w: 0.49 (B vs G), 0.86 (B vs G), 0.86 (B vs Gr), 1 (B vs Gr) and 2 (B vs Gr); average ΔT (DBT Difference) registered -0.7, 1.1, 2.1, 1.9 and 0.2 K in turn (Fig. 3). Average DBT range were 38.4 vs 39; 39.5 vs 38.4; 39.5 vs 37.4; 36.2 vs 34.3 and 39 vs 38.8 °C from 10.00-17.00 hours. In NS street canyons of h/w: 0.6 (B vs G) and 1 (B vs G); average ΔT registered 3.1 and 0.7 K; in turn. Average DBT range were 40.7 vs 37.6 and 36.9 vs 36.2 °C in turn from 10.00-17.00 hours. Both EW and NS canyons showed lower average DBT in green (G) or greenway (Gr) canyons than bare (B) canyons excluding EW canyon of h/w: 0.49.

Figure 3:
ΔT comparison (B vs G/Gr) among EW street canyons of various aspect ratios (2, 1, 0.86 and 0.49), august 2021.

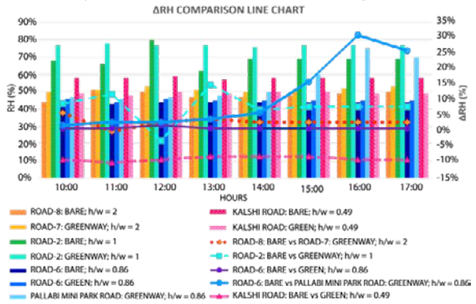


Note: ΔT-DBT Difference; DBT-Dry Bulb Temperature; EW-East West; B-Bare; G-Green; Gr-Greenway; h/w-Street canyon aspect ratio.

3.2 ΔRH (RH Difference) Comparison

At EW Street canyons of h/w: 0.49 (G vs B), 0.86 (G vs B), 0.86 (Gr vs B), 1 (Gr vs B) and 2 (Gr vs B); average ΔRH logged -9, 1, 11, 8 and 3 % in turn (Fig. 4). Average RH range were 49 vs 58; 45 vs 44; 55 vs 44; 77 vs 69 and 51 vs 48 % in turn from 10.00-17.00 hours. At NS street canyons of h/w: 0.6 (G vs B) and 1 (G vs B); average ΔRH logged 3.8 and 2.1 % in turn. Average RH range were 46.3 vs 42.5 and 61.8 vs 59.75 % in turn from 10.00-17.00 hours. Both EW and NS canyons logged greater average RH at G or Gr canyons than B canyons except EW canyon of h/w: 0.49.

Figure 4:
ΔRH comparison (B vs G/Gr) among EW street canyons of various aspect ratios (2, 1, 0.86 and 0.49), august 2021.

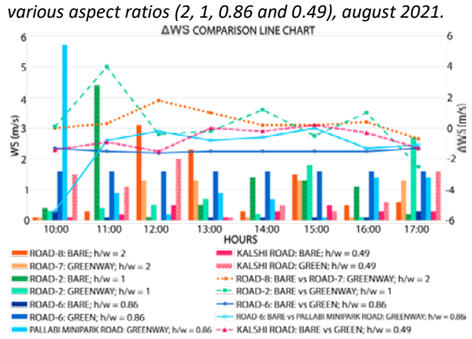


Note: ΔRH-RH Difference; RH-Relative Humidity; EW-East West; B-Bare; G-Green; Gr-Greenway.

3.3 ΔWS (WS Difference) Comparison

At EW Street canyons of h/w: 0.49 (B vs G), 0.86 (B vs G), 0.86 (B vs Gr), 1 (B vs Gr) and 2 (B vs Gr); average ΔWS were logged -0.7, -1.5, -1.3, 0 and 0.2 m/s respectively (Fig. 5). Where average WS range were 0.3 vs 1; 0.1 vs 1.6; 0.1 vs 1.4; 0.9 vs 0.9 and 0.9 vs 0.7 m/s respectively from 10.00 to 17.00 hours. At NS street canyons of h/w: 0.6 (B vs G) and 1 (B vs G); average ΔWS were logged 0.4 and -0.1 m/s respectively. Where average WS range were 0.8 vs 0.5 and 0.6 vs 0.7 m/s respectively from 10.00 to 17.00 hours. Both EW and NS canyons showed greater average WS at G or Gr canyons than B canyons mostly.

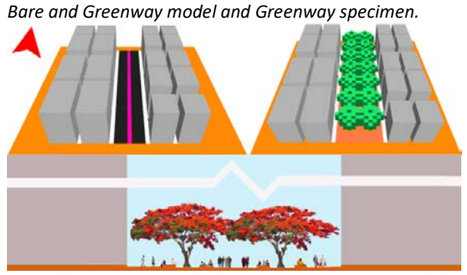
Figure 5:
ΔWS comparison (B vs G/Gr) among EW street canyons of various aspect ratios (2, 1, 0.86 and 0.49), august 2021.



Note: ΔWS-WS Difference; WS-Wind Speed; EW-East West; B-Bare; G-Green; Gr-Greenway. h/w-Aspect Ratio.

4. SIMULATION STUDY

Figure 6:
Bare and Greenway model and Greenway specimen.



Note: Street canyon simulation model: Bare (Top left); Greenway (Top Right); Greenway specimen (Bottom).

Given, EW roads are residential access roads. Thana road was simulated as suitable NS street canyon for greenway application alternatively without disrupting the residential access (Fig. 6). As EW canyons, Road-6 was simulated leaving the access roads on both sides of the street canyons, applying the greenways in the middle. NS canyons simulated 6 potential scenarios; h/w: 0.49, 0.6 and 1 for bare and greenway (Fig. 6). EW canyons simulated 6 potential scenarios; h/w: 0.49, 0.86 and 1 for bare and greenway. Permeable Interlocking Concrete Pavement (PICP) and densely planted Delonix regia were applied for greenway street canyon model. As PICP lessens DBT and T_{mrt} around 12 K and Delonix regia (Krisnochura) reduces DBT and increases RH in summer days augmenting pedestrian thermal comfort [6].

4.1 ΔT (DBT difference) comparison

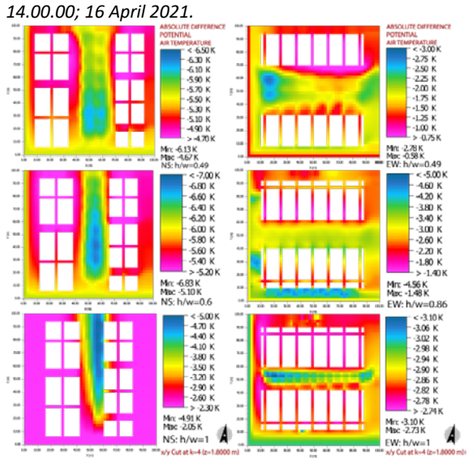
NS Street Canyon Bare (B) vs Greenway (Gr):

In h/w: 0.49 (B vs Gr), 0.6 (B vs Gr) and 1 (B vs Gr); average ΔT registered 5.6, 6.4 and 3.9 K in turn (Fig. 7). Where average DBT were 43.9 vs 38.3, 43.4 vs 37 and 38.9 vs 35 °C in turn from 11.00-17.00 hours.

EW Street Canyon Bare (B) vs Greenway (Gr):

In h/w: 0.49 (B vs Gr), 0.86 (B vs Gr) and 1 (B vs Gr); average ΔT were logged 2.2, 3.4 and 3 K in turn from 11.00-17.00 hours (Fig. 7). Where average DBT were 40.7 vs 38.5, 40.9 vs 37.4 and 37.2 vs 34.2 °C respectively from 11.00 to 17.00 hours.

Figure 7:
ΔT comparison map: NS: h/w: 0.49, 0.6 and 1 (Left); and EW: h/w: 0.49, 0.86 and 1 (Right); street canyons (greenway vs bare); respectively from top to bottom, 14.00.00; 16 April 2021.



Note: NS-North South; *EW-East West;* h/w-street canyon aspect ratio; ΔT-DBT Difference.

4.2 ΔT_{mrt} (T_{mrt} Difference) comparison

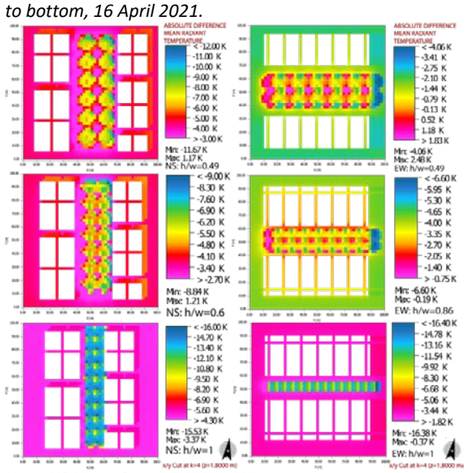
NS Street Canyon Bare (B) vs Greenway (Gr):

In h/w: 0.49 (B vs Gr), 0.6 (B vs Gr) and 1 (B vs Gr); average ΔT_{mrt} were logged 6.7, 3.6 and 13.6 K in turn from 11.00-17.00 hours (Fig. 8). Where average T_{mrt} were 63.4 vs 56.7, 61.7 vs 58.1 and 56.9 vs 43.3 °C in turn from 11.00 to 17.00 hours.

EW Street Canyon Bare (B) vs Greenway (Gr):

In h/w: 0.49 (B vs Gr), 0.86 (B vs Gr) and 1 (B vs Gr); average ΔT_{mrt} were logged 1.1, 1.6 and 6.8 K in turn from 11.00-17.00 hours (Fig. 8). Where average T_{mrt} were 46.7 vs 45.6, 44.2 vs 42.6 and 54.8 vs 48 °C respectively from 11.00 to 17.00 hours.

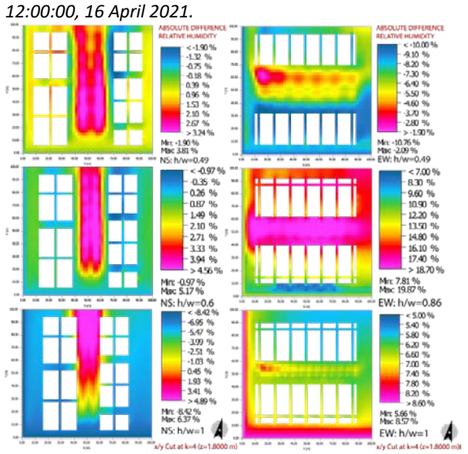
Figure 8:
ΔT_{mrt} comparison map: 13:00:00: NS: h/w: 0.49, 0.6 and 1 (Left); and 15:00:00: EW: h/w: 0.49, 0.86 and 1 (Right); Street canyons (greenway vs bare); respectively from top to bottom, 16 April 2021.



Note: NS-North South; EW-East West; h/w-street canyon aspect ratio; ΔT_{mrt}-T_{mrt} Difference.

4.3 ΔRH (Relative Humidity difference) comparison

Figure 9:
ΔRH comparison map: NS: h/w: 0.49, 0.6 and 1 (Left); and EW: h/w: 0.49, 0.86 and 1 (Right); Street canyons (greenway vs bare); respectively from top to bottom, 12:00:00, 16 April 2021.



Note: NS-North South; EW-East West; h/w-Street Canyon Aspect Ratio; ΔRH-Relative Humidity Difference

NS Street Canyon Greenway (G) vs Bare (B):

In h/w: 0.49 (Gr vs B), 0.6 (Gr vs B) and 1 (Gr vs B); average ΔRH were logged 1.8, 2.9 and -3.2 % in turn (Fig. 9). Where average RH were 52.5 vs 50.8, 54.5 vs 51.7 and 48.9 vs 52.1 % in turn from 11.00 to 17.00 hours. Average RH were greater in greenways canyons than bare canyons. However, the average RH were lower in NS greenways than bare canyons for h/w=1 from 14.00-17.00 hours.

EW Street Canyon Greenway (G) vs Bare (B):

In h/w: 0.49 (Gr vs GB), 0.86 (Gr vs B) and 1 (Gr vs B); average ΔRH were logged -5.6, 13.7 and 9.3 % in turn (Fig. 9). Where average RH were 45.6 vs 51.2, 54.2 vs 40.5 and 70.1 vs 60.8 % in turn from 11.00 - 17.00 hours. Average RH were greater in greenways canyons than bare ones. Yet average RH were lower in EW greenways than bare canyons for h/w = 0.49.

4.4 ΔWS (Wind Speed difference) comparison

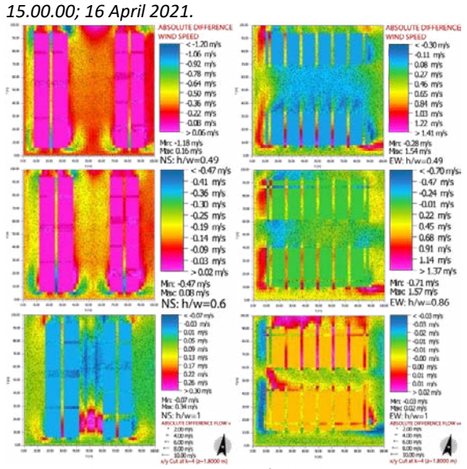
NS Street Canyon Bare (B) vs Greenway (Gr):

In h/w: 0.49 (B vs Gr), 0.6 (B vs Gr) and 1 (B vs Gr); average ΔWS registered 0.3, 0.2 and -0.04 m/s in turn (Fig. 10). When average WS were 1 vs 0.6, 0.9 vs 0.8 and 0.79 vs 0.83 m/s in turn from 11.00-17.00 hours. Average WS were lower in greenways canyons than bare ones. Yet average WS was higher in NS greenways than bare canyons for h/w=1.

EW Street Canyon Greenway (Gr) vs Bare (B):

At EW street canyons, h/w: 0.49 (Gr vs B), 0.86 (Gr vs B) and 1 (Gr vs B); average ΔWS were logged 0.05, 0.09 and -0.03 m/s in turn (Fig. 10). Where average WS were 0.3 vs 0.2, 0.2 vs 0.1 and 0.2 vs 0.3 m/s in turn from 11.00 to 17.00 hours. The average WS were higher at greenway street canyons than bare canyons. However, the average WS were lower in greenways than bare street canyons for h/w = 1.

Figure 10:
ΔWS comparison map: NS: h/w: 0.49, 0.6 and 1 (Left); and EW: h/w: 0.49, 0.86 and 1 (Right); Street canyons (greenway vs bare); respectively from top to bottom, 15.00.00; 16 April 2021.



Note: NS-North South; EW=East West; h/w-Street Canyon Aspect Ratio; ΔWS -Wind Speed Difference

5. DISCUSSION

Field and simulation study clarifies greenways Cooling Effect (CE) on DBT; Decrement Effect (DE) on T_{mrt}; Increment Effect (IE) on RH; Decrement Effect (DE) and Increment Effect (IE) on WS of street canyon microclimate of various aspect ratios.

5.1 Greenways CE on DBT

Field study reveals that for EW street canyons, greenways cooling effect (CE) or lessening DBT, increases with h/w from shallow (h/w=0.49) to mid shallow (h/w=0.86) street canyons (Eq. 1). Then, greenways CE decreases with h/w from mid shallow (h/w=0.86) to deep (h/w=2) canyons (Eq. 2). In alternative cases, greenways CE increases with h/w from shallow (h/w=0.49) to uniform (h/w=1) street canyon (Eq. 3). Later, greenways CE decreases with h/w from uniform (h/w=1) to deep (h/w=2) street canyons (Eq. 4). In contrast, for NS Street canyons, greenways CE decreases with h/w from mid shallow (>0.5) to uniform (1) street canyons (Eq. 5).

Simulation study clarifies that for NS street canyons, greenways CE increases with h/w from shallow (h/w=0.49) to mid-shallow (h/w=0.6) canyon (Eq.6). Later it decreases with h/w from mid shallow (h/w=0.6) to uniform (1) canyon (Eq. 7).

EW simulation reveals that CE of greenway increases with h/w from shallow (h/w=0.49) to mid-shallow (h/w=0.86) street canyon (Eq. 8). Later, CE decreases a little with h/w from mid shallow (0.86) to uniform (h/w=1) canyon, still it remains greater than shallow (h/w=0.49) street canyons (Eq. 9).

5.2 Greenways DE on T_{mrt}

Simulation study reveals that for NS street canyons, greenways T_{mrt} decrement effect (DE) declines with h/w from shallow (h/w=0.49) to mid shallow (h/w=0.6) street canyons (Eq. 10). Later, Greenways T_{mrt} decrement effect (DE) increases with h/w from mid shallow (0.6) to uniform (1) canyons (Eq. 11). For EW canyons greenways T_{mrt} decrement effect (DE) increases with h/w from shallow (h/w=0.49) to uniform (1) canyons (Eq. 12).

5.3 Greenways IE on RH

Field study clarifies that for EW street canyons, greenways RH Increment Effect (IE) increases with h/w from shallow (h/w=0.49) to mid shallow (h/w=0.86) street canyons (Eq. 13). Later, Greenways IE on RH decreases from mid shallow (h/w=0.86) to deep (h/w=2) street canyons (Eq. 14).

Alternatively, Greenways IE on RH increases with h/w from shallow (h/w=0.49) to uniform (h/w=1) street canyons (Eq. 15). Later, greenways IE on RH decreases with h/w from uniform (h/w=1) to deep (h/w=2) street canyons (Eq. 16).

Simulation study reveals that for NS canyons, greenways RH Increment Effect (IE) increases with h/w from shallow (h/w=0.49) to mid shallow (h/w=0.6) canyons (Eq. 17). Later, greenways IE on RH starts decreasing with h/w from mid shallow (h/w=0.6) to uniform (h/w=1) canyon (Eq. 18).

At EW canyons, greenways RH Increment Effect (IE) increases with h/w from shallow (h/w=0.49) to mid shallow (0.86) canyon (Eq.19). Later, greenways IE on RH starts reducing with h/w from mid shallow (h/w=0.86) to uniform (h/w=1) canyon (Eq. 20).

5.4 Greenways IE and DE on WS

Field study reveals that for EW canyons, greenways WS increment effect (IE) increases with h/w from shallow (h/w=0.49) to mid shallow (h/w=0.86) canyons (Eq. 21). At uniform street canyons greenways IE or DE on WS remains zero. Later, greenways WS Decrement Effect (DE) starts revealing and increases with h/w from uniform (h/w=1) to deep street (h/w=2) canyon (Eq. 22). In contrast, for NS canyons greenways DE on WS reveals at mid shallow (h/w=0.6) canyons. Alternatively, greenways IE on WS reveals at uniform (h/w=1) canyons.

Simulation study clarifies that for NS canyons, greenways WS Decrement Effect (DE) decreases with h/w from shallow (h/w=.49) to mid shallow (h/w=0.6) canyons (Eq. 23). Later, greenways WS Increment Effect (IE) starts revealing with h/w from mid shallow (h/w=0.6) to uniform (h/w=1) street canyons (Eq. 24). Greenways WS decrement effect (DE) declines with h/w from shallow (h/w=0.49) to uniform (h/w=1) canyons (Eq. 25). Thus, greenway provides better thermally comfortable WS from shallow to uniform NS street canyons.

At EW street canyons, Greenways WS increment effect (IE) increases with h/w from shallow (h/w<0.5) to mid shallow (h/w=0.86) canyons (Eq. 26). Later, greenways WS Decrement Effect (DE) starts revealing with h/w from mid shallow (h/w>0.5) to uniform (h/w=1) canyons (Eq. 27).

These finding agrees with several research [8]. Yet, some studies [9] found the formation of three varied flow regimes inside a street canyon of h/w= 0.16, 0.25 and 1, namely isolated roughness, wake interference and skimming flow in turn. Conversely, other field studies [10,11] in street canyon with h/w= 1.5 and 0.8 detected no evidence of vortex formation for ambient WS less than 1.5-2.0 m/s.

6. EQUATIONS

Equations for CE (Cooling Effect) of DBT, DE (Decrement Effect) of T_{mrt}, IE (Increment Effect) of RH, DE (Decrement Effect) and IE (Increment Effect) of WS are illustrated below.

6.1 CE of DBT

$$(h/w)_{greenway} \alpha (CE)_{DBT} \quad (1)$$

Where h/w = <0.5 to <1; for EW street canyons.

$$(h/w)_{greenway} \alpha (1/CE)_{DBT} \quad (2)$$

Where h/w = >0.5 to 2; for EW street canyons.
Alternatively.

$$(h/w)_{greenway} \alpha (CE)_{DBT} \quad (3)$$

Where h/w = <0.5 to 1; for EW street canyons.

(h/w) $_{greenway}$ α (1/CE) $_{DBT}$ (4)
Where h/w = 1 to 2; for EW street canyons.
(h/w) $_{greenway}$ α (1/CE) $_{DBT}$ (5)
Where h/w = >0.5 to 1; for NS Street canyons.
(h/w) $_{greenway}$ α (CE)$_{DBT}$ (6)
Where h/w = <0.5 to <1; for NS street canyon.
(h/w) $_{greenway}$ α (1/CE) $_{DBT}$ (7)
Where h/w = >0.5 to 1; for NS street canyon.
(h/w) $_{greenway}$ α (CE)$_{DBT}$ (8)
Where h/w = <0.5 to <1; EW street canyon.
(h/w) $_{greenway}$ α (1/CE) $_{DBT}$ (9)
Where h/w = >0.5 to 1; EW street canyon.

6.2 DE of T_{mrt}

(h/w) $_{greenway}$ α 1/(DE) $_{Tmrt}$ (10)
Where h/w = <0.5 to <1; NS street canyons.
(h/w) $_{greenway}$ α (DE)$_{Tmrt}$ (11)
Where h/w = >0.5 to 1; for NS street canyon.
(h/w) $_{greenway}$ α (DE)$_{Tmrt}$ (12)
Where h/w = <0.5 to 1; for EW Street canyons.

6.3 IE of RH

(h/w) $_{greenway}$ α (IE)$_{RH}$ (13)
Where h/w = <0.5 to <1; for EW Street canyons.
(h/w) $_{greenway}$ α (1/IE) $_{RH}$ (14)
Where h/w = >0.5 to 2; for EW Street canyons.
(h/w) $_{greenway}$ α (IE)$_{RH}$ (15)
Where h/w = <0.5 to 1; for EW Street canyons.
(h/w) $_{greenway}$ α (1/IE) $_{RH}$ (16)
Where h/w = 1 to 2; for EW Street canyons.
(h/w) $_{greenway}$ α (IE)$_{RH}$ (17)
Where h/w = <0.5 to <1; for NS Street canyons.
(h/w) $_{greenway}$ α (1/IE) $_{RH}$ (18)
Where h/w = >0.5 to 1; for NS Street canyons.
(h/w) $_{greenway}$ α (IE)$_{RH}$ (19)
Where h/w = <0.5 to <1; for EW Street canyons.
(h/w) $_{greenway}$ α (1/IE) $_{RH}$ (20)
Where h/w = >0.5 to 1; for EW Street canyons.

6.4 IE and DE of WS

(h/w) $_{greenway}$ α (IE) $_{WS}$ (21)
Where h/w = <0.5 to <1; for EW Street canyons.
(h/w) $_{greenway}$ α (DE) $_{WS}$ (22)
Where h/w = >1 to 2; for EW Street canyons.
(h/w) $_{greenway}$ α (1/DE) ws (23)
Where h/w = <0.5 to 0.6; for NS Street canyons.
(h/w) $_{greenway}$ α (IE) $_{WS}$ (24)
Where h/w = >0.6 to 1; for NS Street canyons.
(h/w) $_{greenway}$ α (1/DE) $_{WS}$ (25)
Where h/w = <0.5 to 1; for NS Street canyons.
(h/w) $_{greenway}$ α (IE)$_{WS}$ (26)
Where h/w = <0.5 to <1; for EW Street canyons.
(h/w) $_{greenway}$ α (DE)$_{WS}$ (27)
Where h/w = >0.86 to 1; for NS Street canyons.

Above discourse clarifies that for tropical climate, in ameliorating microclimatic thermal comfort (decreasing DBT and T_{mrt}, increasing RH and WS) greenways work best for both EW and NS mid shallow street canyons, where 0.5<h/w<1 mostly. However, in one or two exceptional cases greenways deliver better results for different street canyon aspect ratios as following. Greenways show: greater cooling effect in EW uniform (h/w=1) street canyon; greater decrement effect on T_{mrt} in EW uniform (h/w=1) canyons and NS shallow (h/w<0.5) and uniform (h/w=1) canyons; greater increment effect on RH in EW uniform (h/w=1) canyons; and greater increment effect on WS in NS uniform (h/w=1) street canyons.

7. CONCLUSION

This research culminates that for tropical climate in enhancing microclimatic thermal comfort (reducing DBT and T_{mrt}, raising RH and WS) greenways work greatest consorting both NS and EW mid shallow street canyons, where 0.5<h/w<1 mostly. However, in few exceptional cases, greenways show great results with uniform and shallow street canyons, where h/w=1 and <0.5. This study concludes that for tropical cities, detail understanding of the relationships between greenways microclimatic enhancement capacity (lowering DBT, T_{mrt}, raising RH and WS) and street canyon aspect ratios including street canyon orientation could lead to a milestone in designing effecting urban greenway street canyons to deliver pedestrian thermal comfort to the urbanites. However, these affiliations are complicated enough to wreathe in a single string.

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WILL CITIES SURVIVE?

Teaching program for local climate-response design

A case study on vernacular house renovation in hot-humid climates

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ABSTRACT: Following the rapid development and urbanization in China over the last decades, sustainable renovation of urban residences will become an important issue. This study attempted to develop an architectural teaching program integrating the study of local climate, vernacular buildings, climate responsive design strategies, and simulation tools. A local house in a high-density neighborhood in a historical area in Guangzhou, China, in a hot-humid climate area was selected for renovation in this teaching program. The investigations of urban neighborhood development, the construction and climate-responsive characteristics of the vernacular houses, long-term thermal environment characteristics, and sustainable design strategies were conducted before the design project. The concept of an "active house" with appropriate standards reflecting these field studies was incorporated into the concept design. The students' works presented the understanding of the characteristics of a hot-humid climate, responsive strategies of the local buildings, preliminary methodologies on micro-climate analysis, and technologies supporting sustainable building design. Thus, this study provided a valuable approach on the adequate pedagogy for a research-integrated design studio within the context of sustainable architectural education development.

KEYWORDS: Architecture education, vernacular house, climate response, renovation, hot-humid climate

1. Introduction

Urban residences in China built over 20 years ago are faced with the problems of living quality and will ultimately require renovation [1]. Sustainable renovation will be an important issue in the process of urban development. From the perspective of architectural and urban planning education, the number of teaching programs that focus on urban building renovation, urban infrastructure development, the community and its habitants, and urban resilience has increased in recent years in different universities across China.

This study attempted to develop a teaching program for sustainable architectural renovation design by integrating the study of local climate, vernacular buildings, climate-responsive design strategies, and simulation tools. The adequate pedagogy for a research-integrated design studio along with a multimethod approach have been developed in some teaching projects [2–3]. The value of "design thinking" is an essential core of architectural design projects that encourages students to respond to real problems in practice and guide them in developing an innovative framework for problem solving [4]. Technologies and tools are integrated in the teaching and design processes as well. An interdisciplinary approach is also encouraged in the pedagogy of architectural design studios to achieve holistic designs [5].

The research practice–oriented training project, which was parallel to the regular teaching program, was supported by the university and applied by undergraduate students in their 2nd and 3rd years. One project team included 6–8 students. The study goal, schedule, and job assignment were discussed and executed by the students with their tutors. The program spanned one year.

2. Methodology

2.1 Structure of the teaching program

The project was conducted in the following steps:

- Neighborhood and building quality investigation
- Study of local climate response strategies via theoretical and field studies
- Field measurements and evaluation of the thermal environment
- Study of sustainable building design guidelines based on the Active House (AH) standards
- Building performance simulations and evaluations

2.2 Study objects: the vernacular house in a high-density neighborhood

The teaching program was based on vernacular houses that had been built over 70 years ago in a historical area in Guangzhou, China. The high-density neighborhoods were formed in the 18th to 19th century due to harbor development. The layout of the neighborhood, in which each house was arranged side by side with a shared wall, limited the building height and retained the character of urban morphology over the decades (see Fig. 1).

The program encouraged students to investigate urban morphology and understand its impact on the people living in the high-density community as well as the micro-climate characteristics.

The investigation methods included site surveying, scale measurements, interviews with the residents, mappings, and drawings.

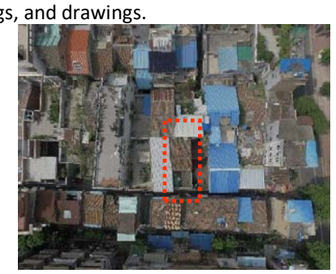


Figure 1: Bird's-eye view of the neighborhood.

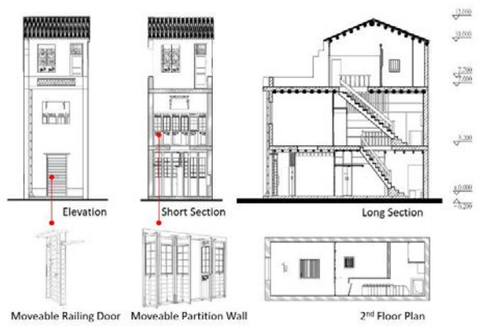


Figure 2: Building floor plan, elevation, section, and some details (measured and redrawn by students).

2.3 Investigation of the house

The vernacular house in this study was named "Bamboo House" in Guangzhou due to its narrow, long layout of floorplans (4m width and 15m length; see Fig. 2), which shared both brick walls with the neighboring houses. These Bamboo Houses were built for both living and cargo storage in the last decades in similar settings in Hongkong, Rotterdam, and Singapore [6].

Field studies were conducted to measure and redraw the layout and details of the study building. Some constructions and materials with specific functions or decorations were recorded and integrated into three-dimensional models as well. Since the house was built over 70 years ago, some renovations or changes had been made in different decades. Field investigations were also encouraged to analyze the changes following the changing residents, activities, and modern living requirements [7].

2.4 Thermal environment measurements

To gain a deeper understanding of the local climate and thermal environment, the students took field measurements of the thermal indices in the Bamboo House. The equipment used was a HOBO data logger (U23 Pro v2) and HD32.3 with a globe thermometer probe and an omnidirectional hot wire probe. These were installed at a height of 1.5m on each floor of the house. Comparably, a HOBO data logger with a shading shield, cup anemometer, and solar irradiation probe was installed outside the house. The measurements took place from Jan to Aug 2021, covering the transitional and hottest months in the hot-humid climate [8]. A thermal imager allowed the students to take images from the street and the building to gain a more intuitive understanding of the effects of the street canyon as well as the building materials.

The dates of the field measurements will provide a better understanding of the indoor thermal quality and subsequently lead to the development of a climate-responsive renovation design.

2.5 Sustainable design strategies

Theoretical understanding, cases studies, and building technologies are important considerations in sustainable architecture studies. Considering the connection between study and practice, some standards and guidelines are necessary to understand. However, this requires substantial time to explain the chapters, terms, and clauses. In this teaching program, the design goal was set following a competition named AH competition in China.

The International Alliance of Active House was established in 2005. Throughout the cycle of design, construction, and use of residential buildings, AH standards advocate the architectural concept of energy conservation and environmental protection as the premise, building health and comfort as the core, and well-being of the occupants as the goal [9].

Active House standards were promoted in China in the last two years, and the Assessment Standard for Active House in China (ASAH) was published in 2020 [10] and introduced to the students to provide a more integrated perspective on architectural design that considers the balance between sustainability and human comfort.

3. Results and discussion

3.1 Perspective on urban housing

3.1.1 Neighborhood and community

(1) Scale of the street

One of the challenges of housing renovation is the high-density nature of the neighborhood. The width of the streets is 2–4m. Sections were analyzed by students,

and the aspect ratio of the street was found to be approximately 1.7–7.2 (see Fig. 3). The narrow street space limits the amount of daylight and natural ventilation for the houses. The students discussed the renovation design strategy and agreed that a better space arrangement should consider not only efficiency but also the relationship between the house and the street.

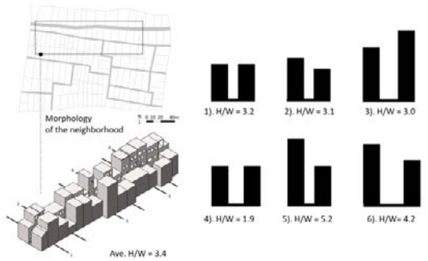


Figure 3: Sections of the street.

(2) Private and public interaction

A social perspective was introduced to reveal the interaction between private and public spaces in the narrow street. The spontaneous, shared activities of the residents in the streets are worth studying and lead to a much more active relationship between the private and public space in future renovation designs. Students were encouraged to see how the residents used their space and how this changes the quality of the street (Fig. 4).

(3) Greenery

Different scales of greenery were found in the street to utilize the different spaces. Most greenery was planted and placed in public spaces by the residents. Some semi-private spaces included some greenery that was placed in front of the entrance of the buildings, even when the width of such space was limited to 0.5–2m. This kind of shared space provides the possibility for social interaction between neighborhood inhabitants, especially for the elderly and kids. The usage of greenery and space provided a good example of providing and sharing public space even in high-density neighborhoods.

(4) Entrances

Entrances with steps and canopies also revealed some interesting information about the street. The drainage system of the historical district was poorly constructed, and the streets face the risk of flooding from heavy rains in the summer. Thus, two or three steps were built to create a higher ground floor level. Canopies also provided protection from the rain in front of the entrances.

(5) Windows and facilities

Observations also found many external features of the houses. Windows were guarded by railings set 30–40cm outside the windows and provide some additional space for storage or plantings as well. Air conditioning units installed outside the houses with different shading blinds are also popular. Religious features were also found on the wall or near the entrances of the houses, such as small containers for prayer activities and some religious drawings.

Figure 4: Observations of street space usage.

Street observations aim to better understand residents' actual lives, their local habits, awareness of private and public spaces, and other social perspectives in the dense neighborhood. These observations will also provide some valuable insights into the renovation design that considers the residents both inside and outside the houses.

3.1.2 Bamboo House

(1) Space

The typical Bamboo House was built at a height of 2–3 floors. To increase the amount of daylight and natural ventilation, a vertical patio was typically included in the middle or end of the floor plan. However, the patio of the study building had been closed and replaced with a kitchen, bathroom, and bedroom on different floors due to the increased need for living space. The collapse of the original space model caused some indoor environmental problems, such as a lack of daylight and ventilation in the house, and the materials incurred damage as a result of the moisture. The living space was also divided into rooms on the 1st and 2nd floors and decreased the living quality (see Fig. 5).

(2) Construction and materials

The Bamboo House was mainly constructed with brick and timber. Both brick walls limit the width and span of the house to no higher than 4 m. Dense beams were separated by a distance of 0.4–0.8m support the timber floor. The building's roof was constructed with timber beam and tiles. The partition walls of the rooms were produced with craftsmanship and include abundant decorations and different opening methods (all or half opening).

Some additional features were found that were meant to accommodate the hot-humid climate, such as a roof window and a semi-open space to increase natural ventilation.

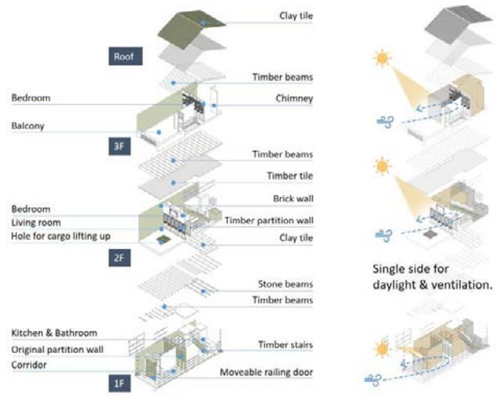


Figure 5: Observation of the construction and materials, daylight, and ventilation of the Bamboo House.

3.2 Perspective on thermal environment

3.2.1 Evaluation of the street canyon

Field measurements helped understand the thermal environment of the house and the neighborhood. The difference in the ground surface temperature was measured up to 5.1℃ in the afternoon on a summer day (see Fig. 6). The streets in the neighborhood are mainly oriented in the east-west direction. Thus, the deep street canyon may reduce solar irradiation, but limit the wind flow at the pedestrian level.

a. Photo of the street. **b.** Thermal image of the street.

Figure 6: Street surface temperature.

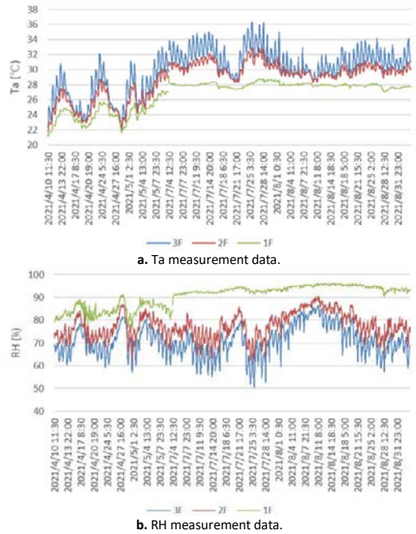
3.2.2 Evaluation on the indoor thermal environment

Results revealed that the air temperature (Ta), relative humidity (RH), and globe temperature (Tg) showed significant differences between the upper and lower floors (see Table 1 and Fig. 7). The difference in average Ta, RH, and Tg between the third (3F) and first (1F) floors were 2.9℃, 17%, and 2.4℃ in spring, respectively, and 3.2℃, 19.8%, and 2.4℃ in summer, respectively. The wind velocity (Va) was kept lower than 0.2 m/s in all the test points because the windows were always closed and there was no vertical patio to provide natural ventilation.

A psychrometric chart was created to provide a thermal comfort analysis for the house. Results revealed that the house was not comfortable most of time (see Fig. 8). Simple strategies, such as natural ventilation can improve indoor thermal comfort. Thus, the renovation design will consider strategies for thermal comfort optimization based on the field measurements.

Table 1. Average Ta, RH, and Tg data in spring and summer

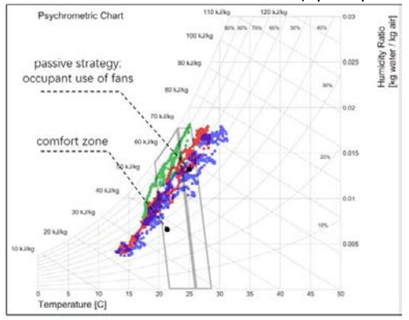
Indices	Spring			Summer		
	1F	2F	3F	1F	2F	3F
Ta (℃)	20.2	21.8	23.1	26.7	28.7	29.9
RH (%)	78.6	66.7	61.6	90.6	77.6	70.8
Tg (℃)	20.5	24.1	22.9	28.0	31.3	30.4



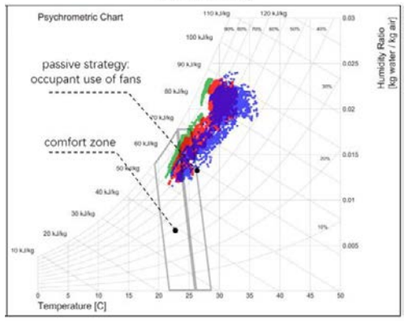
a. Ta measurement data.

b. RH measurement data.

Figure 7: Ta and RH measurements data (Apr–Sep 2021).



a. Jan, Mar–May



b. July–Sep

Figure 8: Psychrometric chart analysis (Mar–Sep 2021).

3.3 Renovation design strategies

Following the students' field studies and measurements of the thermal environment, the characteristics and problems of the Bamboo House were identified and led to the development of renovation design strategies.

3.3.1 ASAH guidelines

The renovation design was guided by the ASAH [10]. Adaptability to the hot-humid climate is an important principle in the renovation design. Four aspects of ASAH guidelines were given to integrate into the design process (see Fig.9).

Responding to the poor natural ventilation of the existing house, the space design will consider a strategy that includes a vertical patio, controllable roof window, and wind inlet openings. The problem of overheating on the third floor requires better roof insulation construction and shading devices. The habits of the local residents, such as greenery, religious space, and air conditioning would be considered in the space design as well.

Activeness	Comfort
• Hot-humid climate response • Atrium for natural ventilation and daylight • Sensitive, automatic controllable roof window and shading devices	• Improvement in natural ventilation and indoor thermal comfort • Daylight improvement • Vertical greenery • Noise reduction
Energy	**Environment**
• Roof PV panels • Cooling results in energy reduction in summer	• Reuse of construction components and materials • Rainwater storage and reuse • Street space improvement

Figure 9: Strategies based on the ASAH guidelines.

3.3.2 Space and users

The design process of the space layout is diagrammed in Fig. 10. The house will contain a family of three generations (1 + 2 + 1). Considering the limitations of the site and its volume, the bedrooms and living rooms were arranged vertically (1 floor for the elders, 2 floors for the child, and 3 floors for the couple). To improve communication, the three levels of the floor were shifted one-half floor vertically and connected with the stairs, furniture, and structure (see steps a–c in Fig. 10). To increase the amount of natural ventilation and daylight of the house, two vertical patios were added in the front and back sides. On the front side, a semi-open space with a grilling door, vertical greenery, and religious space was provided to satisfy residents' local habits as well as improve the street space (see steps d–e in Fig. 10). Windows and openings were set around vertical patios to increase the amount of daylight (see step f in Fig. 10).

3.3.3 Simulations

Building environment simulation tools (Ladybug and Honeybee in Grasshopper design software.) were introduced in the teaching project. Weather data including temperature, relative humidity, and wind rose of one year were distributed and compared with the field measurement data (see Fig.11). Simulations of daylight and wind velocity were launched. Results revealed significant improvements in the amount of daylight in the main indoor space on different floors (see Fig.12).

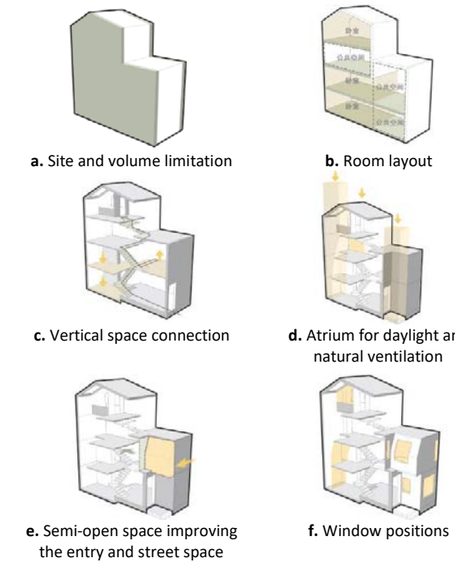


Figure 10: Design process diagram of the new Bamboo House.

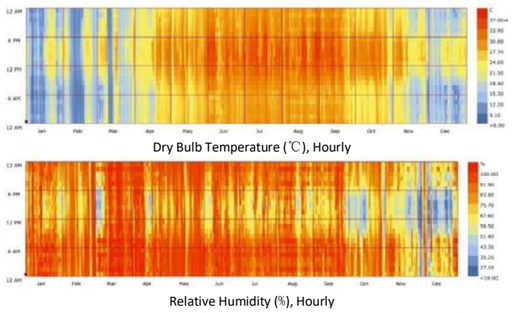


Figure 11: Ta and RH of one year in GZ in weather data file.

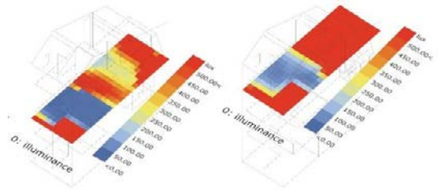


Figure 12: Daylight simulation results of three main floors.

3.3.4 Technologies

Based on the space arrangement, some technologies were integrated in the renovation design (see Fig.13-15).

(1) Photovoltaic (PV) panels: As the house is located in a dense environment and share both walls with the neighboring houses, the potential for energy collection is mainly on the roof. The design of the roof was integrated with PV panels (26 m^2) facing south. The PV panels were calculated to provide an average of approximately 85.75 kWh per month and satisfy 30.5% of the energy cost of a four-person family.

(2) Green wall: Considering the lack of a green area in the neighborhood, the design project intended to provide the option of incorporating greenery into the house via a green roof and interior green wall. The green roof was set on the terrace, and the green wall was set on the wall of ventilated atrium, where the natural daylight improved the indoor space quality for different rooms.

(3) Shading devices: The dimension of the windows on the roof and top floor were maximized to increase the natural ventilation and daylight for the interior, and the controllable shading devices helped prevent overheating in summer days according to the results of the measurements.

(4) Water treatment: Rainwater was designed to be collected and reused for greenery in this project due to Guangzhou's rich rainwater supply. Rainwater collection is also a resilience strategy to reduce street drainage in such a dense neighborhood during the rainy season.

Figure 13: Section of the house.

4. CONCLUSION

This study attempted to develop an architectural teaching program integrating different aspects of sustainable building design. The students' works presented an understanding of the characteristics of a hot-humid climate, responsive strategies of vernacular buildings, preliminary methodologies on micro-climate analysis, and sustainable building guidelines. Simulation tools that support the optimization of the design project are necessary for future improvements.

ACKNOWLEDGEMENTS

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Figure 14: Floorplans of the house.

Figure 15: Rendering of the interior space.

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Enhancement of cultural heritage awareness and sustainability of the built environment through academic education

The HERSUS project

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ABSTRACT: Culture is increasingly regarded as one of the pillars of sustainability, along with Environment, Economy and Society, while the preservation of built heritage emerges as an indispensable component for the sustainable development of cities. Sustainability of the built environment and cultural heritage preservation are critical interrelated aspects of Architecture and Urban design; they nevertheless are usually considered as distinct fields in higher education and professional practice. The paper discusses the outcomes of the initial stages of the HERSUS project, which brings together researchers from Schools of Architecture in five European countries under the scope of enhancing awareness of cultural heritage and sustainability of the built environment in academic studies of Architecture and Urban Design. The project supports the collaborators in generating high-quality programs of studies, through international cooperation across cultures and problem-solving processes. The study presented here is informed by a review of Architecture/Urban Design curricula and seeks to develop an interpretative and evaluative analysis on the state of learning of sustainability and cultural heritage in academic education. This is done through the analysis of responses received by expert professionals and students in the context of a survey on the state of art in educating sustainability and heritage.
KEYWORDS: Cultural Heritage, Sustainability, Architectural Education, HERSUS project

1. INTRODUCTION

Culture is increasingly regarded as one of the pillars of sustainability, along with Environment, Economy and Society, while the preservation of built heritage emerges as an indispensable component for the sustainable development of cities [1,2,3]. Sustainability of the built environment and cultural heritage preservation are critical and interrelated aspects of Architecture and Urban design; they nevertheless are usually considered as distinct fields in higher education and professional practice.

The paper discusses the outcomes of the initial research stages of the HERSUS project, which brings together researchers from Schools of Architecture in five European countries under the scope of enhancing awareness of cultural heritage and sustainability of the built environment in academic studies of Architecture and Urban Design. The project supports the collaborating institutions in generating high-quality programs of studies, based on international cooperation across different cultures and interactive problem-solving processes. The study presented here is informed by a review of Architecture/Urban Design curricula [4] and seeks to develop an interpretative and evaluative analysis on the state of learning of sustainability and cultural heritage in academic education. This is done through the analysis of responses received by expert professionals and students in the context of a survey on the state of art in educating sustainability and heritage [5].

The primary research questions of the study focus, first, on the degree of awareness of students and experts regarding the significance of enhancing built environment sustainability and cultural heritage issues in education and practice, second, on determining the level of understanding and the potential of applying the concepts of sustainability and heritage in architectural and urban design, and third, on finding efficient methods to include sustainability and heritage knowledge in the current or in new academic curricula. The research includes two inquiry-based perspectives, which constitute its main innovation elements. The first explores the students' perception on their acquired competences and on potential employers' expectations of competencies that are valuable in the practical and professional work field. The second poses questions about learning behaviours and pertinence of design approaches.

2. METHODOLOGY

The survey is based on the dissemination of two online questionnaires within the participating countries (Serbia, Italy, Cyprus, Greece and Spain). The first questionnaire addresses experts in cultural heritage conservation and in sustainable environmental design, who are occupied in academic institutions, public administration, and the private sector, having specific roles as educators, practitioners, policy makers in government or local authorities (members or consultants), decision makers in public administration (ephorates, ministries etc) and decision makers in NGOs or professional societies. Experts are selected by their academic background, professional profile, years of experience and contributions to academia. The second questionnaire is directed to students at master level studies, PhD researchers and recent alumni from academic institutions in the five countries, inquiring about their experience from attended study programs, their options, and expectations in the professional field. It was disseminated through courses at architecture schools, academic websites and social media, and addressed a range of related disciplines. The survey analysis is conducted separately for each country, sequentially variations derive between the national and the international summed outcome.

Both questionnaires are structured in distinct sections; a background section on the respondents' profiles aiming to confirm a balanced sample, a section on the awareness of sustainability and heritage issues in professional practice, research and academic studies and a section on competences related to sustainability and heritage in practice. The experts' questionnaire includes one more section on their expectations from academic programs. Most questions for experts are open-type, appropriate for oral interviews, subject to qualitative analysis. Questions for students are of quantitative nature (numerical values, checkboxes, ratings) appropriate for statistical analysis of a larger sample of responses.

The questionnaires were prepared in English by A.U.Th. HERSUS team through consultation among all HERSUS partners and translated into four more languages (Serbian, Italian, Greek and Spanish). The two multilingual questionnaires were transferred to online survey forms in the Lime Survey software tool [6] and distributed to the recipients through webpage links. The online survey was available to respondents for a period of three weeks in April 2021. Analysis of the results, in each country, was performed by the respective HERSUS partners.

3. RESULTS AND DISCUSSION

The international survey reflects the views of 56 experts and 766 students on issues regarding the developed awareness on the importance of sustainability of the built environment and heritage, in education and practice, the level of understanding of concepts related to sustainability and heritage in the field of urban and architectural design and the relevant design scales, the most effective ways to include relevant knowledge in the existing curricula, the competences students develop through their studies and the expectations in the professional field.

The experts' background data indicates a slight imbalance among their professional profiles with lower contribution from practitioners and higher contribution of decision makers in NGOs/professional societies. This imbalance can be attributed to the "role" that the experts themselves chose for this question, which may be different from the "role" HERSUS teams envisaged for them when addressing them. Most experts declare architecture and urban planning as their main filed of work while construction detailing, landscape design and urban design are considered as complementary fields. Furthermore, above 50% of the experts have more than 20 years of experience in the field, ensuring high quality feedback.

According to the background data from the student survey, the distribution of results reveals higher contributions from female participants, a balanced contribution in terms of age groups, and higher participation of 2nd Cycle Students (immediate target group). A high contribution of Alumni justifies the HERSUS teams' decision to include them as one of the target groups and allows variation of the results. Overall, these can be commented on, in the local context of each country, but nevertheless represent a balanced and diverse sample.

The responses of 10 experts and 120 students in Greece, representing 18.5% and 15.7% of the total sample are the focus of further analysis hereinafter.

Figure 1:
Total of experts' responses in the five countries on the proportion of different design scales in their field of work.

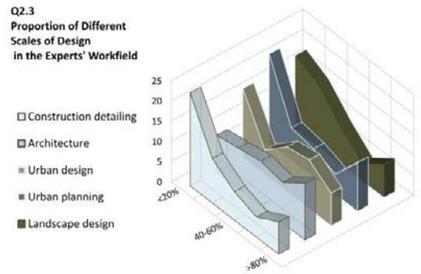
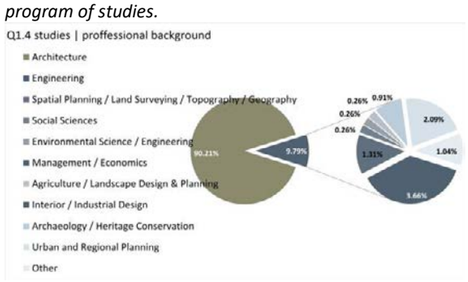


Figure 2:
Total of students' responses in the five countries on (a) their educational or professional background and (b) program of studies.



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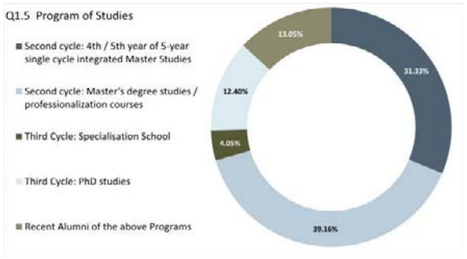


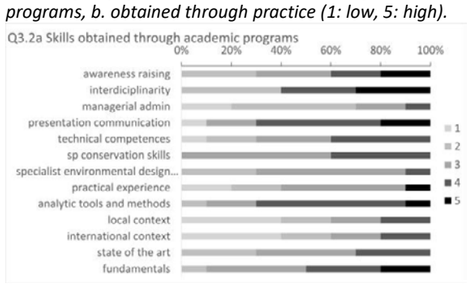
b

3.1 Experts' questionnaire results

Among all experts' profiles and projects, there is different emphasis on the importance of sustainability or heritage, while neither one is entirely disregarded. Experts converge in that their colleagues and collaborators are specialized mainly through postgraduate programs, and that the concepts of sustainability and heritage are well addressed in such programs yet they are not correlated. They suggest that interdisciplinarity, which is essential within professional practice, is missing in academic education and should be improved through cooperation between study programs and the public sector (Ephorates, public authorities, etc). They often point out fragmentary knowledge by colleagues without specialisation, and lack of training in terms of management and legislation issues, social parameters and hands-on experience (Figure 3). They appear satisfied from their cooperation with graduates of 5-year Architecture and related specialisation postgraduate programs acknowledging architecture graduates as the most knowledgeable on matters of sustainability and heritage with regards to related disciplines/ engineering professions.

The Greek Experts suggest that "Methods of Knowledge transfer" (e.g. lectures seminars, literature reviews) should form the highest proportion of academic studies focusing on the two fields, while indicating that "Practical and technical training" (e.g. laboratory work, fieldwork, internship, software and ICT tutorials, site visits) are also important. Most of them express the need to link academic education with professional practice, suggesting the enhancement of design studios and specialized intensive workshops, through interdisciplinary education with the involvement of relevant stakeholders, institutions, and professionals in postgraduate studies in bridging the gap. Experts' responses indicate that their perception on the relevance of key concepts of Sustainability and Heritage with different scales of design depends largely on their own practice, nevertheless, they all express the wish for more systematic efforts to correlate the concepts of the two fields both at undergraduate and postgraduate studies.

Figure 3:
Greek Experts' responses on the level of skills and knowledge of graduates a. obtained through academic programs, b. obtained through practice (1: low, 5: high).



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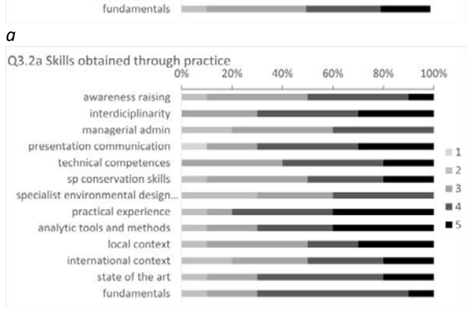


b

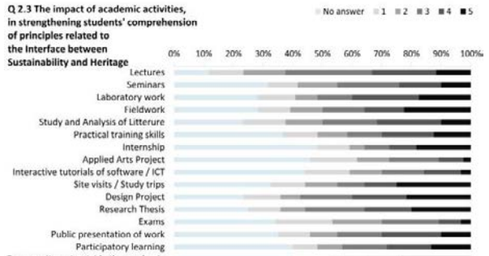
3.2 Students' questionnaire results

With regards to the courses in academic curriculums focusing mainly on sustainability and cultural heritage or raising issues that pertain to the two, there is a divergence of views in the international sample and students in Greece indicate that such courses are included in the integrated Masters' curriculums in larger proportions than those observed across all HERSUS countries (Figure 4). According to Greek students, heritage-related Master's programs are more inclusive of the two disciplines while sustainability-related Postgraduate programs of study are able to better interface the two disciplines in the context of interdisciplinary courses (focusing equally on sustainability and heritage).

Figure 4:
Available courses in the existing programs of studies according to Greek students' responses

	Responses		Focus of Studies			Taught Courses of the curriculum	Courses focusing mainly on Documentation Conservation Restoration of Cultural Heritage		Courses focusing mainly on Sustainability / Environmental Design		Courses focusing both on Sustainability & Cultural Heritage		Courses raising issues of Sustainability / Environmental Design / Planning		Courses raising issues of the value/appreciation or dialogue with the National / International Historic Context	
	number	% of total samples	Architecture	Heritage	Sustainability	Median	Median	% of total courses	Median	% of total courses	Median	% of total courses	Median	% of total courses	Median	% of total courses
4th / 5th year of 5-year single cycle integrated Master Studies	72	9.4%	87.5%	6.9%	5.6%	46	4	8.7%	3	6.5%	1	2.2%	3	6.5%	3	6.5%
Master's degree studies / professionalization courses	16	2.1%	0.0%	0.0%	100.0%	4	0	0.0%	4	100.0%	1	25.0%	4	100.0%	0	0.0%
	7	0.9%	0.0%	100.0%	0.0%	13	7	53.8%	1	7.7%	1	7.7%	1	7.7%	2	15.4%
	6	0.8%	100.0%	0.0%	0.0%	24	3	12.5%	2	8.3%	2	8.3%	3	12.5%	3	12.5%

Figure 5:
Academic activities enhancing students grasp of principles related to both sustainability and heritage a. students' responses in Greece, b. students' responses across the five countries (1:low, 5:high).



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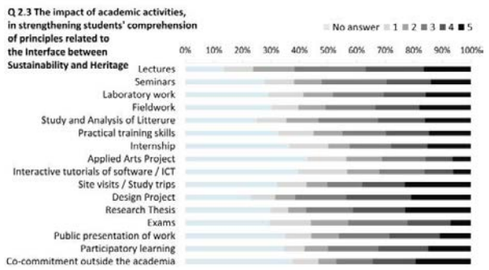


b

In line with the international sample, among all academic activities, the design studio is considered vital for the comprehension of both sustainability and heritage issues, while students also highly rate lectures, laboratory work, site visits, fieldwork, research thesis and co-commitment outside academia, revealing a preference for a hands-on approach to learning (Figure 5).

Regarding key concepts of sustainability and heritage applicable in different scales of design, students highly rate "restoration" and "comfort" for architectural design, "regeneration", "resilience" and "energy conscious design" in the urban scale and "nature-based solutions" and "microclimate improvement" for landscape design.

On the assessment of skills and competences obtained from curricula dealing with sustainability and/or cultural heritage, students' responses highlight the knowledge of fundamentals, awareness-raising, and presentation and communication skills are their most prevalent qualities while they seem less confident on skills transgressing the two disciplines. Students believe that the same skills, with the addition of technical competences, improve their employability in the professional arena. Furthermore, they recognise they have little knowledge of the international context in terms of the two disciplines and also consider this parameter of least significance in terms of employability potential.

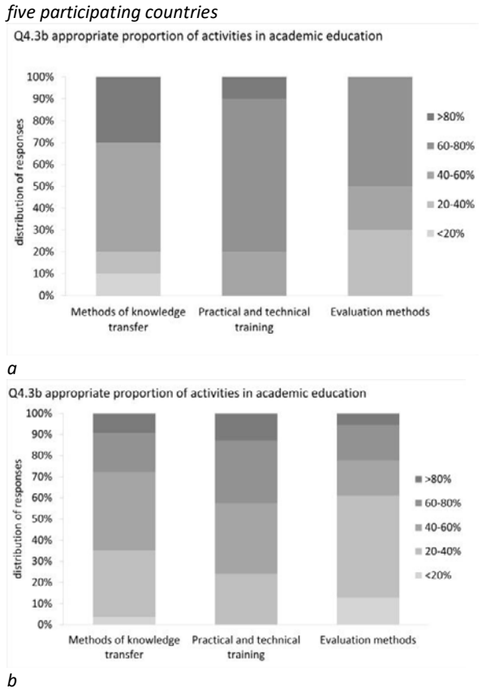
3.3 Common ground and divergence

Regarding "Presence and awareness of sustainability and heritage in education and practice" the survey results indicate that postgraduate specialization programs offer more integral knowledge on sustainability and heritage issues than integrated masters 5-year programs which nevertheless offer adequate knowledge of the basic principles. However, academic programs lack interdisciplinarity and practical training and diverge on the approach to link sustainability and cultural heritage. Most experts consider

sustainability and cultural heritage pivotal issues in their research or practice.

In evaluating academic activities, students indicate a preference for a hands-on approach to learning. They rank highly activities as "Lectures" and "Design project" for the impact on comprehending key principles of sustainability and heritage but are less confident in activities that enhance their comprehension of issues pertaining to the interface of heritage and sustainability. Experts consider "Practical and technical training" activities as most effective academic tools as well as certain "Methods of knowledge transfer" and agree with students on the low impact of "Evaluation methods" on consolidating knowledge (Figure 6).

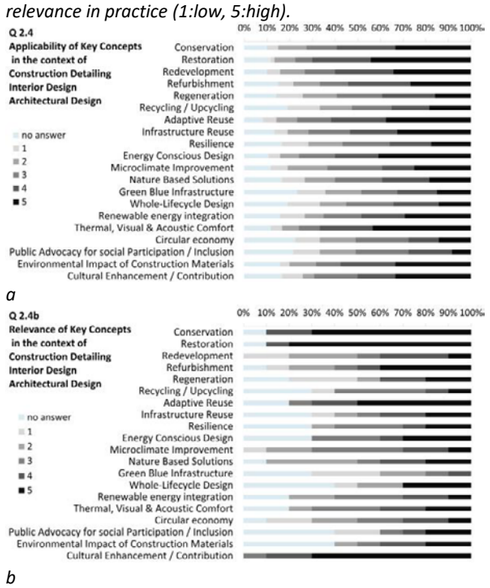
Figure 6:
Experts' views on the appropriate proportion of academic activities in architectural education a. in Greece, b. in the five participating countries



Students' views on the competences obtained through their studies reveal a lack of transversality and multidisciplinary specialist skills transgressing the domains of sustainability and cultural heritage. They also consider the skills obtained through their studies as the most relevant in terms of employability assets. Experts agree with students in adequate presentation - communication skills, technical skills, knowledge of fundamentals as well as on the lack of managerial skills, practical experience and field training. Experts' ratings also indicate a high contribution of practice in consolidating most of the skills of graduates, some implying that academic education offers the basis of knowledge which is further developed through professional practice.

The students' responses on the applicability of sustainability and heritage concepts in different scales of design, indicate (similar to the total sample across the five countries) a wide range of key concepts perceived as applicable to design scales, highlighting that the concepts related to conservation, restoration, cultural enhancement, along with key concepts of sustainability, are more relevant at the building scale, but their rankings are weaker at the urban and landscape scales. Experts reveal a different perspective than students on the applicability of key concepts across different design scales as they exclude some key concepts not relevant to their own everyday practice. There is a consensus with students' views mostly on heritage related key concepts in the Architectural design scale (Figure 7).

Figure 7:
Key concepts of sustainability and heritage in the context of architectural design a. Greek students' perception on their applicability and b. Greek experts' views on their relevance in practice (1:low, 5:high).



For the improvement of architectural education in terms of sustainability and heritage, experts propose a hands-on interdisciplinary approach, practical training and involvement of relevant stakeholders, institutions, and professionals in specialized programs to address the gap between education and practice and to enhance graduates' profiles in the labour market. They also emphasize the need to correlate the concepts of sustainability and heritage in the study programs.

At the international level, experts and students in different countries find that the "available courses" in Architecture Diploma programs are mainly focused on Architecture, leaving in a second place Heritage and afterwards Sustainability (Spain), they consider Sustainability a topic related to technological aspects, while Cultural Heritage a topic linked to a historical, social, cultural and multidisciplinary approach (Italy) and that the concepts of sustainability and/ or cultural heritage are not adequately integrated in the main body of their architectural academic studies (Cyprus). Experts' opinions in different countries vary on the degree of the awareness of colleagues and collaborators on the principles of sustainability and heritage, noting a higher degree of awareness in younger generations due to more integral learning experience (Spain) or that it may depend on the field that each professional works on (Italy). A variation of experts' views across HERSUS countries is noted through responses pointing out the significance of the link between Society and Culture in their activities (Italy), the limited depth of expertise in the concepts of sustainability and heritage in professional practice revealed by simplifications and trivialization (Spain) and the need to upgrade traditional conservational concepts in line with challenges posed by aspects of sustainability (Serbia).

4. CONCLUSION

The analysis of the questionnaire surveys conducted in Greece revealed similarities and differences between the views of experts and students and with the international sample. Major common concerns are the link of academic education with professional practice, the interdisciplinarity in education and the systematic correlation between concepts of sustainability and heritage. Hands on approaches, practical training and inclusion of professionals and educators from multiple fields along with other relevant stakeholders in architecture study programs have been initially identified as potential improvement methods. Moreover, a more profound integration of notions related to the sustainable development of the built environment and the preservation of cultural heritage consolidated in merged postgraduate programs is regarded as a step towards a holistic approach to engage with the interface of the two disciplines. Further analysis of the surveys can highlight views and preferences based on different respondent profiles as well as variations on the perception of sustainability and heritage concepts within the participating countries or the education curricula.

ACKNOWLEDGEMENTS

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Impact of large-scale training program to engage a public institution on energy efficiency actions

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ABSTRACT: To achieve ambitious energy efficiency objectives, large public institutions face challenges to embark employees and building users. In this regard, the French Social Security deploys actions to raise awareness among a large number of internal stakeholders, in order to increase acceptance, participation, and responsibility to bring about behavioural change on energy efficiency. The paper presents the results of the programme Impulsion2021, a large-scale awareness-raising program that targeted 5800 employees. The program consisted of several phases: a) identify participants, b) develop learning material, c) plan and execute the communication campaign d) facilitate internal communities, and e) measure and analysis of participatory results. This paper presents and focuses on the impact that an awareness-raising programme had on the willingness of employees to commit 1) to go further in their skills development via other training formats 2) implement a new in-house tool to support the implementation of operating in renovation work.
KEYWORDS: Energy, Comfort, Awareness

1. INTRODUCTION

The building sector now accounts for 44% of the energy consumed in France and is one of the main drivers of climate challenges. One-third of real estate emissions come from buildings in the tertiary sector, i.e., 34 Mt CO_2e, according to the report on the state of the environment. Between 1990 and 2017, greenhouse gasses (GHG) emissions from buildings in the tertiary sector increased by 8%, which can be explained in particular by the significant expansion of the tertiary surface area, by almost 50% over the period **[1].**

However, since 2009, the sector's energy consumption has been decreasing by an average of about 2% each year, due to energy efficiency improvements and the use of less carbon-based energy. [2].

In 2019, the French government set out a new regulation to accelerate the performance improvement energy consumption via the Tertiary Eco Energy decree. The decree sets rather ambitious targets for energy consumption thresholds and energy reduction. The decree concerns all buildings with a surface area of 1000m^2 or more that are used for tertiary purposes. It thus concerns offices, educational buildings, administrations, hotels, shops, etc. The objective of reducing the energy consumption of buildings is set at -40% by 2030, -50% by 2040 and -60% by 2050 **[2].**

Moreover, the Ministry of Ecological Transition has since 2005, put in place a nationwide program to support massive renovation: the CEE program (Energy Savings Certificates). This scheme is based on a three-year obligation to achieve energy savings imposed by the public authorities on energy suppliers. The energy suppliers are thus encouraged to actively promote energy efficiency among their energy consumers client-base: households, local authorities or professionals to comply with their obligation.

CEEs are awarded, under certain conditions, by the Ministry of Energy to eligible actors that carry out energy-saving operations. These actions can be carried out in all sectors of activity (residential, tertiary, industrial, agricultural, transport, etc.), on the property of eligible parties, and/or with third parties. Standardised operation sheets, defined by decree, are drawn up to facilitate the setting up of energy-saving actions.

Since the second period of the CEE scheme, capacity building and innovation programmes have been added as potential activities financed by CEE certificates **[3].** The objective is that non-technical actions can also contribute to the control and reduction of energy consumption.

This article presents the results and follow-up initiatives of a large-scale awareness-raising and capacity-building programme, branded Impulsion2021, which targets 5800 employees of the French Social security to support the drive towards low energy consumption in buildings.

2. Context of Project

With a building stock of 4.5 million m² spread over more than 3,700 buildings, most of which have high energy consumption, and 145,000 employees, the Social Security system is a privileged field of experimentation for the implementation of awareness-raising and capacity building actions with a strong potential impact towards its energy transition strategy **[4].**

In order to meet the objective of energy efficiency targets set by the Social Security in its CSR strategy, it is necessary to raise awareness and participation among the greatest number of internal stakeholders **[5].** Thus, the need to promote behavioural change among Social Security employees, and to bring about new practices among operational staff through in-depth knowledge of the subject coupled with a playful and educational approach.

Although collective awareness of the environmental impact of buildings is not new in this institution, it would seem appropriate for an actor as that of the Social Security, given its size, to trigger potential energy savings by the mobilisation of its internal stakeholders (e.g., occupants and operators).

The Social Security system deployed the program across the institution, which is composed of four complementary and independent branches: Health Insurance (in charge of the health system and accidents at work), Family Allowances (in charge of supporting families throughout their lives: children, solidarity, housing assistance, etc.), Retirement Insurance (in charge of collecting and paying pensions) and Collection (in charge of collecting contributions from companies to finance the other three branches); where each branch manages their teams, buildings and training policy internally and individually. Within the institution, the Union of National Social Security Funds (UCANSS) is the entity responsible for carrying the tasks of common interest within the French Social Security (e.g., professional training, collective bargaining, national examinations, and competitions).

Thus, the challenge is on how to propose training and participatory activities at the institution level with various user profiles.

3. Methodology

The French Social Security has been committed to the issues of sustainable development and CSR for several years. As such, the programme Impulsion2021 supplements the institution's environmental training to take action at its role and level. To ensure maximum impact of the programme the followed a methodology:

a) Identify the population to take part in the deployment of the programme.

b) Design a specific training content.

c) Implement the communication campaign.

d) Deploy and support the different communities of the four branches of the institution.

The training was deployed with the support of the Union of National Social Security Funds (UCANSS),

Throughout the programme, its progress was evaluated according to several key indicators: the participation of the different social security branches, the satisfaction rate of the employees who followed the MOOCs, the number of participants in the participatory workshops, and finally the number of exchanges and interactions that took place between branches by the end of the programme **[6].** The main objective of the programme was to initiate concrete actions to improve the energy efficiency of the Social Security's building stock.

4. Implementation

4.1. Identify the population to participate in the deployment of the programme

Two audiences were targeted: a) the Institution's employees (the occupants of the buildings, as they use the premises on a daily basis and have a direct impact in the buildings), and b) the Institution's real estate professionals/experts (include the asset managers, real estate directors, maintenance or project manager).

Within a universe of 140,000 employees, an initial target of 5% of employees was defined for both types of users, where 5300 were general employees, and 500 were real estate professionals. This number is expected to grow in the next years.

In terms of planning, the programme started in September 2019, the online courses were available from June 2020 until December 2021, webinars and workshops were carried out between October 2020 and December 2021, and the main Forum took place in March 2021.

4.2. Design the training content

The programme included two main training courses targeted at each population: a) an “Introduction to Energy Transition” for the general employee population, and b) on “Optimising your Building” for the real estate professionals.

The training content was presented as massive open online courses (MOOCs) with diverse means of engagement (videos, polls, dynamic presentations, chat forum, webinars, etc). A Learning Management System (LMS) platform was used for the e-learning and forum, and other collaborative tools (Klaxoon, and

WebinarJam/MS Teams) for online workshops and interactive sessions. The MOOCs included videos specifically tailored for the programme, and complementary videos from other governmental agencies promoting energy efficiency in the public sector (ADEME, Ministry of Ecological Transition, etc.). The content was co-constructed by a Technical Committee (conformed by the UCANSS and representatives of each branch).

1) Creation of course:

A training and awareness-raising course entitled Introduction to the energy transition (MOOC 1) was created to address the 5300 Social Security employees with the main objective to present action that employees can carry out in their organisations. MOOC 1 was divided into four weeks with four key learning objectives (table I).

This course also integrated links to different initiatives carried out by the different branches to increase cross-communication (a challenge within such a large institution). The activities within each module focused on individual eco-actions, which enabled participants to identify concrete measures they could do in the office or at home in order to reduce the energy consumption in buildings.

2) Creation of the course: Optimising your Building

A training course entitled Optimizing your Building (MOOC 2) aimed at 500 site managers was created to clarify the opportunities and challenges of property management to accelerate the energy transition of the Social Security's property assets. MOOC 2 was divided into four weeks with four objectives (table II):

TABLE II
LEARNING OBJECTIVES OF MOOC 2

Week	Learning objective
1	Defining the challenges of climate change and energy transition (*common for both MOOCs*)
2	Understand the regulatory context related to the challenges of the energy transition and the ambitions of the Social Security
3	Know the tools to reduce the energy consumption of a tertiary building
4	Recognise the internal relays to drive the energy transition in the Social Security building stock

The activities (videos, quiz, forum, presentations) were design to address the learning objectives of each week.

MOOC 2 provided real estate professionals/experts with regulatory information on the energy transition for buildings, possible levers for action (e.g., optimisation of technical systems, monitoring solutions, efficient renovation approach, etc.), and successful case studies that showcase various solutions to improve building performance.

The ambition of the programme was to produce coherent, fun, and impactful content material that could reach a large population and be widely disseminated within the institution. In this context, UCANSS and its partners, in charge of the conception, paid particular attention to the script and language of the content in order to make it easy to follow, and at the same time provide in-depth examples for the most seasoned participants [7].

In this regard, the beginning of each MOOCs starts with a common general presentation on the challenges of climate change, the energy transition, and its specific application to social security. Subsequently, each course follows its specific structure (tables I and II), where MOOC 1 (aimed at general employees) focused on individual eco-actions and the means for collective involvement in an energy-saving approach, and MOOC 2 presented the regulatory challenges and framework on the energy transition for the built environment and a list with concrete operation actions to implement. At the end of each MOOC an evaluation was carried out to assess perceived satisfaction, motivation to do the course, and knowledge [8] [9].

Figure 1: Example of training content

4.3. Implementation of the communication campaign around the project

The Social Security, with four main independent branches that oversee 300 local offices, is a complex organisation. Thus, it was important to establish a project governance (steering committee) and to coordinate, communicate and reach all stakeholders. The committee was in charge of validating the main orientations of the programme, the monitoring, and the progress of the awareness-raising and participatory actions. The Steering Committees made it possible to streamline communication of the project among social security organisations, and in particular to register the employees.

Securing the target number of participants was a key concern as it required significant support and commitment from managers. To address this, the directors of each national social security branch took part in several communication [10] [11]. The videos presented: a) a call to participate by the national branches, and b) the institution's strategy towards energy transition. This initial call helped secured over 2000 participants as of June 2021.

After June 2021, we managed to deploy another animation campaign to the targeted audience of the institution. We organised different webinars and workshop in order to maximise the interactions. We also decided to put an emphasis on the sensibilisation side of the project aimed at the general public.

4.4. Deployment & support of the different communities

The main challenge of the project lay in its transversal ambition to provide training, awareness-raising, and participatory activities that are known to all the offices within the Institution and large demographics (e.g., age, education level, role) [12].

To support this deployment over the different communities, the programme provided a centralised e-learning platform complementary to the tools already in place in the institution. This made it possible to deploy the courses, solicit feedback from participants, exchange document and good practices, and communicate on upcoming events (webinars and workshops). It also allowed for a different form of outreach to raise awareness on other environmental issues and relay exemplary actions already in place in the organisations.

The exchange between participants was reinforced by the distribution of a weekly newsletter to share additional content (articles, quizzes, internal news, events, etc.). This channel was 100% collaborative and allowed participants to propose content to be shared in the newsletter so that everyone can take ownership of the programme and the topics covered (eco-actions, training, awareness-raising events, etc.).

During the deployment of the courses, three other main types of events were organised to ensure that concrete actions were taken by participants after completion of the courses, specifically for the group of real estate professionals.

5. IMPACT

The dissemination of the digital training proposed within the framework of the Impulsion2021 programme has led the various Social Security bodies to carry out several new initiatives within the Institution. Indeed, the significant increase in the number of employees made aware of the issues has made it possible to place the challenges of the energy transition at the heart of the concerns of many employees. UCANSS has then set up new activities for the organisations to help them in the operational implementation of these new ambitions.

The program led to a new intern impulsion on the development of new activities for the institution, in order to concretise the implementation of new ambitions linked to the energy reduction.

5.1. Webinars on shared experiences

In 2021, after the awareness-raising sessions and following the participants' requests (around 20 of them requesting more exchanges between professionals internally) to continue learning about energy transition issues, 3 internal experience-sharing webinars were set up. These webinars aimed to share concrete feedback on the potential implementation of the actions proposed in the short and medium-term to identify and develop solutions adapted to the Social Security's real estate assets.

For example, a webinar on the strategies put in place to communicate on eco-actions to be implemented in the office was offered to 150 SR ambassadors in the Social Security organisations. Additional webinars were organised on the new French regulations (Eco-…) to reduce energy consumption by 40% before 2030); but also on the challenges of operating and maintaining buildings.

5.2. Workshops on Innovative Solutions

To strengthen the technical knowledge of the programme, participatory workshops were organised. 200 participants were invited to small groups workshops of about 20 people per session. Around 20 innovative solutions linked to energy performance were presented in these workshops. For example:

- Energy performance monitoring solutions for buildings
- Innovative heating solutions
- Free cooling solutions
- etc.

Participants exchanged their feasibility for the social security's buildings. These workshops allowed participants to discover new solutions to integrate into the renovation planning of their assets. It also provided an opportunity to share experiences and to understand what needs to be anticipated in order to implement this type of solution (possible preparatory work, legal aspects, search for funding opportunities, technical information, etc.).

5.3. National Forum for the Social Security and the Public Sector

In March 2021, an Energy Transition Forum was organised to exchange ideas and experiences with other French institutions in the public sector [13]. Its objective was twofold:

- To inspire through a programme rich in content and varied in its formats around the issues related to the reduction of energy consumption and the carbon footprint of the public tertiary sector on a national scale;
- To connect by putting people in touch with an ecosystem of players (companies, start-ups) offering innovative solutions.

The 3-day forum counted with 4 roundtables, 5 workshops, 50 technical solution pitch sessions, 960 participants, 240 Business-2-Business meetings. It enabled participants to identify and exchange innovative solutions in the field of energy transition. The conclusion of the forum opened channels that have led to requests for proposals (RFP) for the implementation of some of the solutions identified.

5.4. Decision-making tool for energy work and personalised support

Another output action consisted of a methodology and a tool to help the 300 asset managers within the institution to implement innovative solutions for their buildings and to reduce their energy footprint.

Figure 2: Example of Social Security building

This tool is based on 60 action sheets containing concrete solutions in terms of 4 types of actions: building works, maintenance and operation processes improvement, awareness-raising solutions, and building management.

These 60-solution sheets have integrated the impacts, associated costs, technical prerequisites, and return on investment of each solution. These asset managers can effectively understand the issues in each sheet and, above all, provide them with the technical keys to implement them. To be more user-friendly, the institution proposed a decision support tool to choose the most suitable solutions according to the characteristics of their building and their needs.

The tool allows the automatic selection of solutions that will reduce the energy bill, improve the well-being of the occupants and, above all, comply with the various regulations governing the building.

This tool was widely shared during December 2021 within the Institution and today, of the 300 organisations more than 30 have already been able to generate an operational action plan.

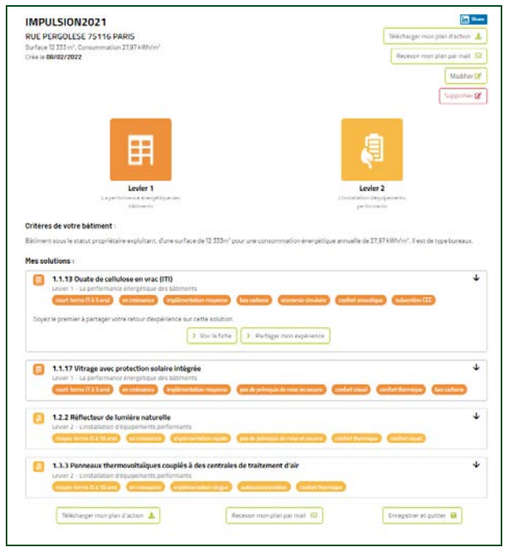

Figure 3: Example of action plan

6. Next steps

Based on this experience the Union of National Social Security Funds aims to offer tailor-made support to organisations that would like to be assisted in implementing innovative solutions and that lack the internal skills to do so effectively. This support will provide assistance in defining the scope of the necessary work, sourcing the relevant partners to implement these solutions, drafting the necessary contract documents for the establishment of a public invitation to tender, monitoring and delivering the work. The objective is the renovation of 500 buildings in 2022-2023.

7. CONCLUSION

The paper shows the results of the experience of a large-scale training and stakeholder engagement initiative within a public institution with a large building stock and significant energy consumption with potential reduction. The methodology and results show the impact of a continuous and specific training program in engaging around 5.000 employees to carry out energy efficiency actions. The training material and output are currently being deployed and used by the different branches of the institution. This awareness-raising programme had an impact on the willingness of employees to commit themselves more strongly to energy efficiency and, in particular, 1) to go further in their skills development via other training formats 2) to have new in-house tools and support dedicated to the implementation of more efficient operating strategies or renovation work.

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The role of universities on forming social inclusive and sustainable environments

The importance of university social responsibility

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ABSTRACT: This paper aims to explore and emphasize the importance of universities as social and sustainable actors of urban change. In this sense and to better understand this context, the main structure conceived for this paper is composed by an introduction and a brief contextualization of the role of the universities, based on the definition and concepts of University Social Responsibility (USR), Sustainable Development and the University Social Networks. The case study of Mapping San Siro (MSS) is highlighted as an example of the role of universities and its challenges to seek for urban regeneration and more inclusive cities. This case also reinforce the role that universities can play as agents in the development of mutual learning between them and communities. As a conclusion, the reflexive thinking presented herein demonstrates how important is the role of universities in co-producing knowledge and in enriching the educational process in order to achieve changes in the society.
KEYWORDS: Universities, Social Responsibility, Sustainable Development, Communities, Urban Regeneration

1. INTRODUCTION

Currently the world is facing issues on economic, social, environmental and cultural aspects in a more revolutionary connected way than in years before. One of the main challenges is to identify which among possible actors could be the leaders of future changes facing these aspects and their role in society.

In this regard, over the years, universities are progressively building and playing an important role, through new research strategies linked towards social responsibility within communities. These new strategies are based on the concept of expanding research, teaching and learning beyond the boundaries of the university campus. Universities are being considered as "at the forefront of scientific and technological advances in undertaking global research and educating future leaders and professionals. Universities deliver impactful knowledge in every sector across all nations and act as anchors in the communities they serve nationally and internationally" [1]. The issue regarding universities and social responsibility takes on a greater relevance compared to the past. Around the world, there are many universities exchanging knowledge and experiences concerning how they are acting with their communities.

Therefore, more than training qualified personnel, universities can become responsible actors in boosting social cohesion and forming inclusive and sustainable environments.

Thus, this paper proposes a general discussion and analysis of the role of universities as agents for introduction of social responsibility in the context of community urban regeneration. To fulfil this role, universities face challenges in political, cultural, social, economic and environmental aspects. Therefore, it is important to address how this role is being built and how the impact of its actions is being perceived.

2. THE ROLE OF UNIVERSITIES

It is important to highlight that "Urban and metropolitan areas face unique challenges in serving the multifaceted needs of their communities, but also have advantages that create some of the world's greatest universities... Urban university-community engagement enriches metropolitan communities while strengthening the universities' core commitment to teaching and research" [2].

Universities are increasingly becoming organizations that seek to comprise social and civic aspects in their areas of research, in particular, in the area of for social urban regeneration.

In this sense, the universities in general are adapting their action strategies according to the local needs of their cities and communities, therefore playing a role as responsible training agents of inclusive and sustainable environments.

The role of universities is becoming more socially active through promoting co-production of knowledge and new innovative educational practices combining the engagement of students and communities to build a better society.

In what follows, the related aspects of social responsibility and sustainable urban development supporting the role of universities are addressed. Next, a case study to demonstrating how this role can be practiced is presented.

3. ON UNIVERSITY SOCIAL RESPONSIBILITY (USR)

The scenario of the higher education importance along with the approach of how academic services can take into account the needs of people and society has been growing in recent years and being addressed in the literature.

In this sense, University Social Responsibility (USR) as an approach that provide a better connection between the university and the needs of society can play an important role.

It is important to mention, that the field of university social responsibility (USR), in the past decades has gain a big repercussion, especially in relation to the application of corporate social responsibility (CSR) in the business sector. Therefore, in relation to the maximization of profits not being a common objective among universities, educational services and commercial activities, it became necessary to explore the notion of university social responsibility (USR) for research and academic practice.

Universities' attention to social responsibility began in the late 1990s. The main focus was on environmental protection in response to sustainable development and also with the approach of urban living laboratories to contribute as an experimental environment for universities.

In 1998, at the UNESCO [3] World Conference on Higher Education a call for the re-evaluation of educational policies for the new millennium was elaborated, in order to recognize the importance of the social dimension of universities by training qualified graduates and responsible citizens by creating opportunities for students to build their own sense of social responsibility. Furthermore, the 1999 World Declaration highlights the importance of social responsibility and the education matters in social-cultural and economic development.

Therefore, the awareness of social responsibility is connected with the third stream[1] or third mission, which aims at working with employers and community groups as part of teaching and research of universities.

[1] Third Stream is an international concept that "Traces an emerging role of universities in innovation processes. Such processes require a more collaborative approach with other sectors and the gradual extension of this from working with the private sector to the consideration of collective actors working on civil society issues" (Millican et al., 2014), (Laredo, 2007).

Although the concept of USR is spreading faster around the world, its design basis is still under development. Currently, USR can be considered as an engine of educational policies that relate the fundamental objectives of universities with the environment they are acting. From a practical perspective, the sense of the USR is to contribute to the quality of life, by promoting knowledge of social utility. It is worth mentioning that the USR requires "a two-way perspective between universities and society, which involves directly multiplying the critical uses of knowledge in society and the economy" [4].

Moreover, in the global northern region the USR terminology is also known as "civic engagement" or "community engagement", then used to describe the impacts of higher education institutions on public and community activities. In practice, it may be associated to "a more encompassing concept, one that includes the social impacts of the full range of university functions, and includes corporate social responsibility issues such as the energy efficiency of building design, employment policies, purchasing and financial management" [4].

Therefore, USR is not only focused on its impacts on teaching, research and service missions, but also on its practices and policies encompassing the fields of social, economic, cultural and environmental dimensions.

3.1 University Social Networks

Organizations around the world, together with universities, are developing different types of Networks to promote social responsibility.

Social responsibility is englobed in other kinds of terminology like, public or civic engagement, community engagement and universities engaged through community based learning.

Actually, universities must be one of the agents in the search for a better world. As they are considered places that hold knowledge and can promote "activities which are ethical, inclusive, and beneficial to the public; that emphasize environmental conservation, sustainability, and balanced social development that promote welfare and quality of life of people, especially the needy and vulnerable populations; and committed to build a better world" [4].

In sequence, it will be highlighted, among others as important as, four internationally recognized network organizations that promote social responsibility.

3.2 The Talloires Network

The Talloires Network is an international association of institutions with more than 400 coalition universities and spread across 78 countries and it is composed by an elected 14-member Steering Committee. Formed by heads of higher

education institutions, heads of national or regional higher education networks for university civic engagement and student representatives.

It was founded in 2005 at the Tailloires conference at Tufts European Centre in France. This was the first international reunion of heads of universities committed to engage civic and social responsibility of higher education.

The network contributes for global civic movement among universities based on three areas of analysis and action, which are: research, practice and education. These actions are addressed to publish research, to support the practice of civic engagement and educate graduate students at Tufts to the course of civic engagement.

3.3 USR University Social Responsibility Network

On October 9th, 2015, the Hong Kong Polytechnic University (PolyU) with eleven other universities across the world formed the USR Network to provide guidance and tools to make the world a better place.

The USR Network serves as a platform that connects and cultivates partnership between members and promotes activities such as global awareness of URS, global student engagement, staff training, research on global issues and publications.

The University's Social Responsibility strengthens institutional capacity to develop solutions that address the economic, social and environmental issues of society.

3.4 NCCPE National Co-ordinating Centre for Public Engagement

The National Co-ordinating Centre for Public Engagement (NCCPE) was established in 2008 as part of the Beacons for Public Engagement [5] initiative and cooperates to promote and support engagement of universities with the public.

This support is based in different types of services, such as consultancy, professional development, engage competition, engage conference, engage watermark, research for journal, manifesto for public engagement and projects.

The NCCPE is hosted by University of Bristol and the University of the West of England and is funded by UK Research and Innovation.

The term of public engagement appeared in the beginning of 2000s in the UK Higher Education Policy Lexicon as a way to understand the development of community's life.

Engaging with public is a strategy that is becoming essential for higher education in terms of strengthening responsibility, accountability, relevance and building trust.

Moreover, it is important to highlight that NCCPE support community-university partnerships as a way to create mutual benefits among them and to develop a two-way exchange of knowledge, experiences and skills between universities and communities.

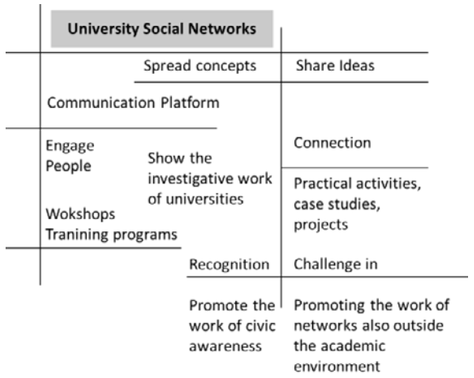
3.5 CUMU Coalition of Urban and Metropolitan Universities

The Coalition of Urban and Metropolitan Universities (CUMU) is an international organization of universities located in metropolitan areas. It was stablished in 1989 at Wright State University by a group of metropolitan institutions leaders to define and disseminate the concepts of university-community engagement by using their campuses as a place to develop education, research and to serve the local communities.

Moreover, several activities and strategies that support research are developed in order to exchange institutional engagement and public information.

Since 2018, an increasing number of CUMU member institutions have been recognized for encouraging community engagement effort located in the metropolitan areas with aim to boost partnership formation and community development.

In addition, these University Networks are important in promoting, articulating and disseminating the idea, concept and the investigative work of universities and their impact on activities carried out with the public. However, it is still a challenge to publicize the work and be



recognized not only in the academic environment. The (Fig. 1) illustrate a diagram of the general and common aspects of the networks.

Figure 1:
Note: Image developed by the author, 2021.

4. ON SUSTAINABLE DEVELOPMENT

The concept of sustainable development was launched and recognized worldwide in the second version of the United Nations Conference on Environment and Development (UNCED), held in June 1992 in the city of Rio de Janeiro (Agenda 21).

This concept embraces the relationship between environment and development, which seeks for balancing the social, economic and environmental limitations that the world faces.

Later on, in September 2015 in the city of New York the 2030 Agenda for Sustainable Development was adopted by all United Nations Member States, which "provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries - developed and developing - in a global partnership"[6].

Actually, universities are considered as facilitators in adopting the SDGs (Sustainable Development Goals) at a sustainable strategic level, connecting higher education to business, industry, health, community and entrepreneurs.

Since then, universities around the world are promoting new ways of thinking about sustainable actions. In this sense, it is common to frame the role of universities as living laboratories for other universities, communities and cities as a way of implementing these actions, which seek sustainable development and social responsibility beyond the limits of university campuses.

This terminology can be defined and exemplified "As model that become a part of transformative institutional change that draws on both top-down and bottom-up strategies in pursuit of sustainable development" [1].

Moreover, living laboratories constitute "a form of experimental governance, whereby stakeholders develop and test new technologies and ways of living to address the challenges of climate change and urban sustainability" [7].

In addition, the main idea of these living labs is to create the opportunity to bring together professors, researchers, students, university staff and facilities, stakeholders and the community, in rethinking new strategies and co-producing knowledge to address sustainability and services in the settings of the real world.

Finally, it is important to emphasise that "in order for universities to realise their potential to address sustainability challenges they need new frameworks that synthesise their core business or research, teaching and social responsibility. Living labs provide new ways of working that can systematically frame co-production opportunities to achieve just that" [7].

5. MAPPING SAN SIRO (MSS) CASE STUDY

The complex of contemporary cities and their urban dynamics and challenges are demanding from Higher Education Institutions (HEIs) new approach in the process of teaching and learning in order to plan cities for social inclusion.

Urban regeneration conception[2] and the local development of marginal and peripheral areas in the last decades have become more inclusive, due to the presence of different actors, consisting of "citizens and local organizations, considered able to interpret and bring out local resources and competencies, essential to develop successful interventions, especially in an era of scarce availability of funds" [8].

Concerning the achievement of urban regeneration in fragile communities, there is an urgent call for social responsibility and civic engagement from universities, through the development of tools able to support and transform "local citizens and organizations in truly empowered actors, able to promote and control changes, but also to claim for effective institutional support" [8].

Today in Italy, the university system already encompass different concepts related to innovation, culture and social responsibility, the so-called Third Mission. To reinforce social, cultural, educational perspectives, Polytechnic of Milan, through the Polisocial Programme is involved in the repositioning and regeneration not just of its on campuses, but also of the urban areas and cities where it is present.

The Mapping San Siro (MSS) project is an example of how university and communities are working together in the development of new forms of learning, new skills, co-production of knowledge in order to find alternatives for urban regeneration and improvement of quality of life.

Beyond that, MSS is considered as an "urban living lab" experiment based on co-research, co-design and local co-production of knowledge and aims "at experimenting a pedagogical environment based on grounded, interactive, action-oriented and hybrid learning, reflecting how new approaches can enrich the experience of educational practices for the inclusive city" [9].

The neighbourhood of San Siro is located in a west area close to the central part of the city of Milan, which can be characterized as an urban marginal context. Despite its diverse living demands and urban issues, it shows up as a wealthy and active environment that "civil society takes action, promoting interventions and projects, in term of social innovation, practices and bottom up

[2] "the urban regeneration approach, widely recognised as a comprehensive and integrated vision and plan to solve the multi-faceted problems of urban areas and to improve the economic, physical, social and environmental conditions of deprived areas" [Barosio et al., 2016, 369].

responses to its needs, desires and expectations" [9].

Furthermore, the neighbourhood can be considered a fragile area, due to the issues related to social-spatial inequalities, cultural challenges and the conditions of the house's stock. It is worth mention that this area is marginal and problematic considering the "living conditions: urban decay and blight exacerbate already existing problems, such as disadvantage, social exclusion, poverty, and the coexistence of different populations and cultures" [9].

The fact of considering San Siro as a learning context in building networks and developed resources, which can be recognized by local organizations networks, composed by community groups, non-governmental organizations and local institutions. These actors work aiming the common-good for the neighbourhood by providing better conditions for living, social inclusion and cohesion. Although, this network is considered fragmented and provided by lack of resources, it plays an relevant and dual role that deals with "everyday problems, and having a proactive role in terms of the production of shared visions for the future transformation of the neighbourhood" [9]. In addition, together with the network, other resource players that can be considered are the initiatives promoted by residents and local public institutions.

Therefore, the MSS project is an action research and learning process that seeks to achieve and share mutual knowledge between university and the neighbourhood, which combines research activities and teaching practice focusing on social responsibility and civic engagement approach.

The MSS project started in 2013 under the coordination of Francesca Cognetti from the Department of Architecture and Urban Studies (DAStU) of Polytechnic of Milan and with the participation of Liliana Padovani from IUAV University of Venice and is supported by DAStU and the Polisocial Program[3].

The first activity developed was a workshop to recognize local conditions and physical analysis in order to understand, which intervention and actions could provide social and urban transformation for the local community.

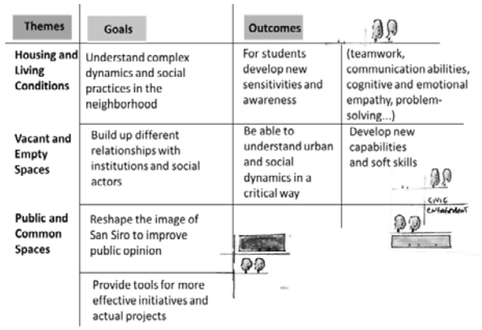
The work developed by the workshop was continued in a second phase by a group of students, young researchers and teachers, in order to understand how the knowledge and expertise from academia could interact with the inhabitants and community partners. Moreover, the engagement experience offered to the students allowed them to improve their critical thinking and social competences to understand the complexity of urban and social issues.

The second phase was based on three thematic, composed by: living conditions; courtyards and public spaces; and empty residential spaces.

In 2014 another step to continue the activities of the MSS project was taken by the provision and the use of a physical space in the neighbourhood provided by the Regional Agency for Public Housing of Lombardy (ALER). The space was called Trentametriquadri and it was located in Abbiati 4.

Therefore, this location could motivate a change on the research methodology leading to the development of an innovative pedagogical environment. The Trentametriquadri became a living lab of interaction and exchange between the university and community, where "local partners and residents gave access to information, data, facts and products about the dynamics occurring in the neighbourhood" [9]. The (Fig. 2) illustrate a Diagram of the MSS themes, goals and outcomes.

Figure 2:



Note: Image developed by the author based on archival material accessed in 2021.

Later, in 2019 as an initiative of Polisocial Programme this laboratory was transferred to the space named Off Campus (The Cantiere per le periferie) in via Gigante. This physical space was the first among other two: Off Campus Nolo and Off Campus Corvetto located in other peripheral areas of the city of Milan.

The Off Campus activities are composed by research: education and culture; co-design; neighbourhood archive; coordination of Sansheros local network; and legal help desk and legality education.

The active network of Off Campus San Siro is formed among others by: Bocconi University, Region Lombardy Department Social policies, housing and disability and ALER Milano, Foundations and Companies, local network Sansheros and the Municipality of Milan.

On the other hand, the development of this experience as a living lab can be considered an innovative pedagogical environment, enriched by the possibility of having a physical space inside the neighbourhood. In this sense, this project was a way of demonstrating to the residents of the neighbourhood the possibility of an open window, in order to build connections and knowledge, share ideas and understand the daily life, their needs in fragile urban areas.

Most of the projects developed were focused on small interventions like on public and abandonment spaces, concerning its urban regeneration with the participation of local organizations and inhabitants.

As an example, one can mention the Via Gigante: street front and courtyard redesign, at Off Campus space. The idea of this project was to redesign empty spaces in the neighbourhood as a possibility to provide spaces for new uses, new activities and to recognize transformations of the public spaces.

This project was developed with an interdisciplinary approach together with The West Road Project (WRP) and it was conceived as a participatory laboratory between the university and the inhabitants, with aim to share and care for common places.

It is important to emphasize that there are still some social, environment and economic challenges to be faced. Despite of the lack of more general political and institutional support, the role of the university in these local communities can indeed provide a positive impact, in order to give them a voice and the possibility that things can change. Moreover, the creation of a common knowledge and the improvement of the academic skills by learning within a real context are important aspects to be highlighted.

6. CONCLUSION

This paper aimed to explore the important role of universities as agents for social and sustainable urban regeneration, through exploring concepts of social responsibility, sustainable development and university social network. Furthermore, by describing a case study, one aim to demonstrate and reinforce the role of universities as agents for the development of mutual learning between institutions and communities, by seeking to build more social and sustainable environments.

The Mapping San Siro (MSS) case study is a good example of how the universities are putting into practice their important role by promotion of social and civic engagement as a strategy to deal with the issues of local communities in order to achieve urban regeneration.

To conclude, the role of universities are important and necessary to guide and build better and safe environments. Although the pathway is still a challenge, the outcomes and positive impacts can be noted even with small changes, gathering efforts of all actors involved.

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Innovative teaching methods for regenerative materials

Being less bad is simply not good enough

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ABSTRACT: It is time to go beyond sustainability. Alternative solutions out of local resources such as earth, bio-based and reused materials are emerging all over the world and are triggering regenerative outputs, thanks to their capacity to contribute to the restoration and improvement of the surrounding natural and social environment. However, they are not widespread in the construction sector due to lack of information on the side of decision makers and lack of competence on the side of practitioners. This paper describes the teaching methods of a new teaching Program on Regenerative Materials addressed to decision makers and building practitioners. It analyses why the teaching format used here is efficient to teach regenerative approaches in the building sector.
KEYWORDS: Teaching Methods, Active learning, Regenerative Materials, Earth, Bio-based, Re-used,

1. INTRODUCTION

The Certificate of Advanced Studies "CAS ETH in Regenerative Materials – Essentials", an international training programme launched by ETH Zurich, aims to tackle this problem [1]. It offers knowledge and skills to question our conventional construction techniques and to promote regenerative materials from resource extraction to construction site, building operation and end-of-use of the building materials. The Program focuses on tools and methods to manage projects using earth, bio-based and reused materials with efficiency and creativity in order to contribute to the necessary ecological and social transition in the construction sector.

The paper describes the teaching methods developed and used in this Program. It analyses why the teaching format is so important to ensure an efficient teaching of regenerative approaches in the building sector.

2. STURCTURE OF THE PROGRAM

The program is structured with five Modules, of one week each, distributed over one semester. The Modules cover the essential knowledge on the use of earth, bio-based and reused building materials from resource extraction to construction site, building operation and end-of-use of the building materials. Each Module combines the six teaching methods developed in the following sections.

2.1 Module 1: Discovering Regenerative Materials

Regenerative materials come in a wide variety of forms and compositions, from raw materials to industrialized construction systems. The Module introduces the basics of Regenerative Principles and Life Cycle Analysis (LCA) and presents the diversity of Regenerative Materials from the physico-chemical properties of grains, clays and fibres, to inspiring reference projects. The projects are chosen for their overall architectural quality, their aesthetic value and the fact they are using building systems adapted to the socio-economic situation and the resource availability of their territory. Both vernacular construction and new buildings are confronted in this Module. Meeting some of the designers, builders or users allow discussions on legislative barriers they had to face, how to involve the inhabitants and how to analyse the stakeholder configuration of the project.

2.2 Module 2: Earth construction

Earth construction is attracting attention in contemporary construction thanks to its aesthetic value, its environmental benefit, the high comfort levels it offers and the positive impact on the health of the users. New regulations and new innovations, combining traditional techniques with modern construction systems, were recently developed. This has already changed the paradigm of earth construction.

This Module gives an overview of the different techniques of earth construction. It focuses on the material itself (composition, rheology, implementation) when used as rammed earth, poured earth or earth plaster applications and addresses its structural behaviour when used for a load-bearing structures or under seismic conditions. Guests and discussions help identifying the challenges of using local resources, assessing their environmental impacts, defining specific production line or implementing a prefabrication process. Fig. 1 shows an example of hands-on organised during Module 2.

Figure 1: Module 2: Hands-on - Poured Earth

2.3 Module 3: Bio-based construction

The market of buildings with straw, bamboo, hemp or any waste from plant harvesting has grown almost exponentially in the last decades.

The Module aims to offer a solid knowledge on the use of bio-based materials in buildings, from the material composition and microstructure, to the constructive details of main techniques. Based on results from dynamical assessment models, it also presents the building physics principles required to understand hygrothermal behaviour of bio-based insulation materials and their environmental impact (considering their carbon segregation). Through built examples, potentials and limitations of these techniques are presented to the participants, confronting them to the latest regulations, the best practice of last decades, the specifications for public market and the most recent research results and industrial developments.

2.4 Module 4: Re-valuing the building stock

New construction represents only one or two percent of constructions per year in European countries. Re-valuing the existing building stock is therefore a priority. For heritage conservation as well as for energy retrofit of dwellings, using Regenerative Materials represents a promising solution.

The re-use of materials from demolitions or refurbishments of existing buildings is on the rise. The question is no longer to identify existing practices, but rather to apply selection filters to highlight only the best or pioneering practices.

The Module aims to challenge the conventional building design to maximize its potential for later reuse and support the necessary retrofit of the building stock with low-carbon materials.

2.5 Module 5: Project exercise

During the last Module the participants have to work in small groups to propose a Regenerative Strategy on an existing buildings that is going to be renovated in the near future. The proposals of each group are presented during a final review on the last day of the Program.

3. TARGET AUDIENCE

This CAS in Regenerative Materials is geared towards the needs of professionals who want to deepen and question their existing practice in order to develop more regenerative approaches. The target audiences are project managers, engineers, architects, building contractors, members of city technical services, NGO representatives. A limited group of professionals (around 15 participants) is selected to favor intense interactions and high quality learning considering background, age, gender, field and level of expertise, as well as the probable impact in the field they may have in the future.

4. TEACHING METHODS

The aim of this paper is not to discuss the content of this teaching but the methods used to ensure an efficient and long-lasting impact on the professional development of the participants. The long-term strategy is to support the dissemination of rigorous information on Regenerative Materials and their use in the building industry to reinforce the network of stakeholders in this field on a large scale.

This teaching program combines six specific and complementary teaching methods presented in the following sub-sections.

4.1 Theoretical and Experimental lectures

Theoretical lectures are the basic substance of most of the high-level education. However, if they are not combined with other ways of teaching, the participants may not engage actively and they may stay somewhat detached from the subject. When teaching about earth, bio-based and re-used materials, it is crucial to confront the participants with samples and let them explore some properties through simple experiments. Our senses are very powerful tools to analyses composition and specificities of materials. A time to reflect and discuss the theory, sensations or observation has a key role to play in the learning process. Short sessions, with breaks or changes in the room configuration should be preferred.

Participating in a lecture is not only about the content itself but also about the person you have the chance to meet. Therefore, the teaching team is very

important and should be composed of acknowledged experts in the field with complementary approaches origin and background (designer, entrepreneur, researcher, developer, artist…). This is even more important for a teaching on Regenerative Materials, as the market is booming with many sparse initiatives.

Ideally, all courses should supply handouts even if it is limited to the slides used during the presentations.

4.2 Digital Guest Lectures (public)

The pandemic situation offered a great opportunity to develop online communications. The fact Regenerative Materials are still not widespread in the construction sector makes it sometime difficult to find local experts on every topics. In addition, well-known pioneers or famous practitioners have often no possibilities to travel for a lecture.

The format of digital public lecture allows reaching out a larger scope of contributors and can be easily shared with a broader audience. For each Module, one or two public lectures of approximately one hour are proposed. They can be followed online be a large public and are recorded to be viewed later by those who were not available. The lecturer then stay another hour for a more private discussion with the direct participants of the Program.

4.3 Hands-on exercises

For Regenerative Materials, hands-on exercises are a vital opportunity to understand the right composition and water content of various earth or bio-sourced mixes, to learn how to feel the right compaction level, how to cut, transport or implement building products. These exercises can be focused on the material scale or organized to produce wall elements (and connections). They can also be organized on a real construction site, as it is done in this Program to introduce the complexity of re-using building elements from a refurbishment, as illustrated on Fig. 2.

These activities give a valuable insight on the tools used during the construction process and the time and efforts (energy) needed for each steps.

Figure 2: Module 4: Hands-on – Re-use

4.4 Visits of inspiring projects

During each Module, a visit of exemplary buildings is organized. The focus of the visit is in line with the topic of the Module. The visits are conducted by the architect, an entrepreneur or the client, and, when it is possible, meeting the users usually leads to inspiring discussions too.

To be confronted with an existing building is crucial to acknowledge the global project and the place given to Regenerative Materials, as well as the way the materials are connected to the others and the architectural impact of finished surfaces.

Meeting with the stakeholder involved in the projects is found to be an excellent way to grasp the complexity of the decision process and importance of a good coordination during the construction phases.

4.5 Participative engagement

Through all activities, the participants are supported to have a dynamical interaction between them, the organizing team and the guests. Time for questions and answers at the end of each activities has to be planned.

Round Table are also frequently organized with a special selection of guests who combine their expertise in an open discussion with the participants. This is a great way to cross different points of view and show that decision making always need a fine tuning between stakeholders.

The participants of previous editions of the Program are sometimes invited as guests to highlight the fact that each individual has a role to play in the change of paradigm we are facing today.

Figure 3: Participative engagement

4.6 Project-based learning

In the building industry, many buildings are to be refurbished but this often increases the complexity of the design and brings more constraints to the implementation phase. This is exactly why such projects are chosen in this case. In deed, this complexity tend to decrease the motivation to use Regenerative Materials and implies a strong commitment throughout the decision making process.

At the end of the Program, the participants are asked to gather the knowledge they were confronted to and apply it in a real project. As it happens in most of the projects, small groups are formed to brainstorm and elaborate a strategy to optimize the use of Regenerative Materials.

During this process, the groups have the opportunity to meet with special guests with complementary expertise in short but intensive consultancy periods.

After a week of group work, the groups present their strategy in front of a jury compose with the organizing team of the Program, stakeholder involved in the project proposed and experts that participated in the some of the activities organized along the Program.

5. SPECIAL FEATURES

The activities presented in the previous section are the core of this teaching Program on Regenerative Materials. However, they should be combined to the following features to guarantee a long-term effect on the participants.

5.1 Handouts

Ideally, the courses should all supply handout and reading references. A platform was developed to gather all the handouts, tools, links or complementary documents and share them with the participants.

At the beginning of each Module, the participants also receive a Booklet (A5 format) with all the necessary information corresponding to this Module. In addition, they receive a complementary Booklet with a selection list of reference books that they may want to read at one point. These books are, for the most part, available for borrowing at any time during the Program.

5.2 Evaluations and reporting

The feedback of the participants is very valuable. At the end of each Module, they are asked to fill an evaluation form to identify the strengths and weaknesses of each activities. This is followed by an informal discussion that closes the week.

The forms should allow to point out which teaching method was the most efficient, to reveal which guests had the most impact and what can be adapt to improve the global organisation. The results are analysed and used the next year when defining the program of the new edition.

To ensure the long-term improvement of the teaching, a report is written annually. The report contains the complete program, a list of participants and contributors, as well as the results from the evaluation, a financial review and general comments. This report is used internally.

Figure 3: Closure Event: Alumni and teaching team

5.3 Alumni

The CAS in Regenerative Materials is relatively short (five weeks spread on one semester) but intensive and it must have long-term impact on the participants. To favour the contacts between the participants of each editions, some participants of previous editions are invited to contribute to the new edition. Ideally, the participants should meet at each Module at least one of the alumni.

At the end of the last Module, a Closure event is organized where all alumni, all contributors and the member of the organizing team are invited to join. Fig. 3 shows the group that met at the end of the second edition. This time for networking is a key moment of the Program.

5.4 External communication

This Program aims to contribute to the shift in the building industry that has already started. The number of participants is reduced, but an appropriate communication on the activities organized during this Program, some being open to the public, can influence a larger scope of stakeholders.

To do so, different media are combined: Instagram, Facebook, LinkedIn and Vimeo accounts, mailing list and Slack channels.

6. OUTREACH

The organizing team is constantly renewing its effort to connect the ideas conveyed by the Program to the efforts of other organizations, groups, individuals with interest in the development of Regenerative Materials.

The participants are selected on different criteria.

One of them is the probable impact in the field they may have in the future. Some of them come from large architectural or engineering offices or representatives from public bodies.

The Program started in 2020 and already almost 50 experimented professionals chose to take part in it. Around 20% of those who finished the Program found a new position where they benefit from what they learned on Regenerative Materials and actively contribute to development of Regenerative Materials in building sector. For example: one received a teaching position in Swiss Federal Institute of Technology Lausanne EPFL (CH), another one was hired by the University of Art and Design Linz (AT) to take part in the organization of the Program BASEhabitat, a third one was chosen as director of Cirkla, the Swiss association of all actors of reuse.

Most of the other still work in the same structure as before and share with their colleagues their new expertise. It is also interesting to note that the group formed during the first edition created a collective called "Rethink Materials". This collective has already received funding for a research project and is organizing workshops on the reuse of building materials. The group formed during the second edition are still keeping contact too: two of them collaborated, together with a participant of the first edition and a guest invited for the closure of the second edition, on an architectural competition where they obtained the third position; another one decided to write a book with us, the Module 6 he says.

7. SIMILAR PROGRAMS

The first steps when defining the scope of this Program was to analyse the offer for equivalent teaching. Here are five examples:

- the postgraduate programs in earth construction of CRAterre – ENSA Grenoble [2];
- the numerous courses on specific construction systems: straw bale, liquid earth, light earth, fibres, etc. of amàco - Atelier Matère à construire [3];
- the MSc on innovative structural materials of the University of Bath [4];
- the MAS BASEhabitat at the Kunz Universität Linz [5];
- the teaching programs on circular retrofit of VUB - Vrije Universiteit Brussels [6].

Most of the "competitors" that were found focus on earth materials, for its architectural aspects, the preservation of cultural heritage or in the context of emerging countries in a rural context. Engineering aspects of Regenerative Materials are barely addressed. The only few teaching programs found on this topic are focused on structural aspects. Moreover, even if some of the teachings in this field uses design-built workshops, none of them combines equivalent teaching methods, as implemented in the CAS in Regenerative Materials. In addition, none of them combines knowledge on earth, bio-based and re-used materials.

8. FUTURE EVOLUTIONS

The innovation of the CAS in Regenerative Materials lies in the way six specific and complementary teaching methods are combined to ensure an efficient and long-lasting impact on the professional development of the participants. Of course, the content of a Program has a major influence on the quality of the teaching, but this aspect falls out of the scope of this paper.

The long-term strategy is to support the dissemination of rigorous information on Regenerative Materials and their use in the building industry to reinforce the network of stakeholders in this field on a large scale. To this end, this Program will be soon associated to three new teaching Programs on Regenerative Materials.

The "CAS ETH in Regenerative Materials – Hygrothermal Specialisation", starting in autumn 2023, will be organized during four weeks spread on one semester. It will focus on the hygrothermal specificities of Regenerative Material to optimize the combination of earth, bio-based and re-used materials in buildings. High quality envelops using straw bales or light mixes combining a mineral binder, as lime or clay, to bio-sourced materials, as hemp, wood, straw or any waste from plant harvesting, will be analysed in detail. The participants will acquire result-oriented skills in terms of thermal efficiency and humidity regulation to ensure a high comfort with a positive impact on energy consumption, carbon emission, health and biodiversity. After this Program, they will have the skills to participate in the hygrothermal dimensioning of long-lasting buildings or infrastructures.

The "CAS ETH in Regenerative Materials – Structural Specialisation", starting in autumn 2024, will be organized during four weeks spread on one semester. It will focus on the structural specificities of Regenerative Material to optimize the combination of earth, bio-based and re-used materials in buildings. Existing load bearing structure using rammed earth, straw bales or bamboo will be analysed in detail. The participants will acquire result-oriented skills in terms of structural calculation to ensure long-lasting buildings or infrastructures with a positive impact on energy consumption, carbon emission, health and biodiversity.

When combining two of these Programs, the participants will have the opportunity to apply for the Diploma of Advanced Studies "DAS ETH in Regenerative Materials – Hygrothermal Specialisation" during which they will be working on a personal project with the supervision of relevant experts. The workload is spread on one semester. At the end of the period, a jury will evaluate the Regenerative strategy they propose to apply to this project.

Furthermore, to disseminate the knowledge on Regenerative Materials on an even larger scale, in particular to participants from emerging countries that have not the opportunity to come to Zurich (CH), a MOOC is currently being developed on this topic.

9. DISCUSSION

The CAS in Regenerative Materials focuses on tools and methods to manage projects using earth, bio-based and reused materials with efficiency and creativity in order to contribute to the necessary ecological and social transition in the construction sector.

The aim of this paper is not to discuss the actual content of this Program but the teaching methods used to ensure an efficient and long-lasting impact on the professional development of the participants. Moreover, it aims to reinforce the network of stakeholders in this field on a larger scale.

The teaching methods used in this Program are, of course, used in other teachings, indeed, active learning methodology is a powerful way to change the traditional teacher-centered classroom into the newer student-centered approach to learning and increase the knowledge retention of the participants.

The innovation of this Program lies in the way these teaching methods are combined and used as "cognitive activators" [7] to disseminate the fast developing knowledge on Regenerative Materials.

In addition, the author believes that this active pedagogy is perfectly fitting the needs of teachings on earth, bio-based and re-used materials. All our senses have to be activated to really understand the impact of the theory on design and implementation practices. Hands-on, visits of reference buildings and problem-solving activities in small groups have no match to encourage the participant engaging with Regenerative approach.

The Program is still young, it started in January 2020. In, each edition, even each Module, new observation are made to improve the quality and efficiency of the teaching. The feedback of the participants in their evaluation is really important from this point of view. This is an on-going process and the Program will still evolved. Reinventing the way we teach Regenerative Materials is part of the new paradigm that we are facing, as we have to reinvent our building models and our organisation [8].

10. CONCLUSION

This paper describes the teaching methods of a new teaching Program on Regenerative Materials addressed to decision makers and building practitioners. It analyse why the teaching format used here is efficient to teach regenerative approaches in the building sector.

Being less bad is simply not good enough! This is usually applied to the way we build, but it should also apply to the way we lead our organisations and the way as this paper wishes to demonstrate.

So, let's update our built environment combining earth, bio-based and reused materials and using regenerative approaches.

ACKNOWLEDGMENT

The authors of this paper express their deep gratitude to ETH Zurich and in particular, to the School of Continuing Education of ETH for their administrative and financial support and the enthusiasm they showed when developing this Program. In addition, our grateful thanks are also extended to the Ricola Foundation for their financial support and the opportunity they give to some participants to follow the Program through scholarships. Last but not least, the authors of this paper wish to thank the motivated participants from previous editions, the member of the Chair of Sustainable Construction and all contributors who accepted to share their knowledge and expertise during this Program.

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Bioclimatic Physics Program Attachable on Design Studio

Teaching Package about Climatic Design Study in Education

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[2] Freelance

ABSTRACT: It is getting common that various building performance simulation (BPS) tools or computational design methods support architect's creative works. However, scientific thinking and attitude are not discussed much enough in some design studios. It is because various types of tools are designed user-friendly but include a lot of black boxes. That's why users don't need to care about the detail of the calculation procedure. As a result, it brings the situation that users don't require scientific knowledge. The authors put priority to apply simulation methods to develop scientific thinking by interpreting the design with removing complexity as much as possible. The authors developed and proposed the short program entitled "Bioclimatic Physics Program" in which environmental simulation is carried out with students' ideas and supports to develop scientific understanding. The developed program was tested in practice and analysed its feasibility. The remarkable response from the students was that they were inspired by experience of the design process with numerical evidence. As well as visualization by simulation, scientific discussion can be the key factor in this program. In conclusion, it is identified that students recognize the impact of design on the environment and feel the possibility of bioclimatic physics rather than constraint.
KEYWORDS: education, building performance simulation, scientific attitude, bioclimatic design, passive control

1. INTRODUCTION

1.1 Simulation-based design in education

Recently, it is getting common that computational design methods support architect's creative works. Building Performance Simulation (BPS) tools generate numerical or visual output which help architect understand physical phenomena happened in own design. As well as practical projects, the tools are applied in design studio courses in universities.

1.2 Competence for simulation-based design

When students or architects handle BPS tools in design work, they need to have, at least, three competencies (Table 1., left).

- create study models
- analyse the results from simulation
- design with the simulation results

The first competence, way of creating study model, is usually covered in exercise or workshop in education. The third competence could be enhanced through practical discussion in design studios or projects.

1.3 Simulation applied in education

In general, an opportunity to train scientific thinking and attitude is not enough involved in design studio. In addition, many of BPS tools are designed user-friendly, and easy to generate outputs. In other words, BPS tools include a lot of black boxes. This fact may bring the situation that users don't need to care about the causal relationship between design parameters and the results in detail. As a result, the users miss chance train scientific thinking and attitude. However, some users feel that it is difficult for them how to understand the simulation results and how it should be reflected to own design. The authors put priority to apply simulation methods to develop scientific thinking by interpreting the design with removing complexity as much as possible. Therefore, the authors developed and proposed the short program entitled "Bioclimatic Physics Program" in which environmental simulations are carried out with students' ideas and support to develop scientific understanding.

Table1: Three Processes of simulation-based design, the required competences at each stage, and educational program in which students practice the competences

	Simulation based Design	Required Competence	In Education
1	Create Study Models	Handle the software	Tool Exercise
2	Analyse the Results from Simulation	Scientific Attitude	Bioclimatic Physics (Proposed)
3	Design with the Results	Architectural Design	Practice in Design Studio

2. METHODOLOGY

2.1 Bioclimatic Physics Program

Bioclimatic Physics Program (Fig 1.) was developed based on research and teaching experience by the authors [1,2]. The program was tested in practice and analysed its feasibility under the series of lecture for master level architectural students.

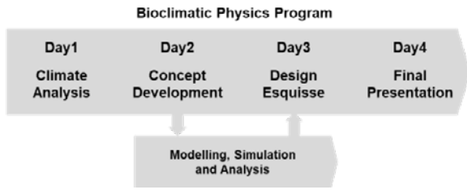

Figure 1: Procedure of Bioclimatic Physics Program

2.2 Small project assignment

The lecture time assigned for the test was only four modules (three hours per module for four weeks). The size of the student group was 18. The authors need to handle twelve hours with small project assignments for teaching the basics of building physics. The project assignment was provided as planning campus community space for learning students under three different cities, such as Hyderabad (Pakistan, semi-arid tropic climate), Singapore (Tropical climate), and Kigali (Rwanda, Savanna climate). Climate profiles of three region are shown in Fig 2 (Psychrometric chart, total irradiation). The computational study models and preliminary calculations were done by the educators (it means authors in this case) for the discussion. The simulated results were provided at the lecture one week before the final presentation. By indicating the simulation results, the students could see what will happen with their ideas (Fig 4,6).

3. RESULTS

3.1 Environmental design keyword collection

The outcomes from the students' concept development indicated the fact that they know the environmental design theories such as stack effect, evaporation cooling, natural ventilation, solar shading, etc., for creating built environment under the target climate. However, their concept development for environmental design was done as "keyword collection". Some students didn't comprehend clearly how the theory performs and the reason why it works under the target climate. In addition, most of them didn't deepen their ideas to solve trade-off relationships among lighting,

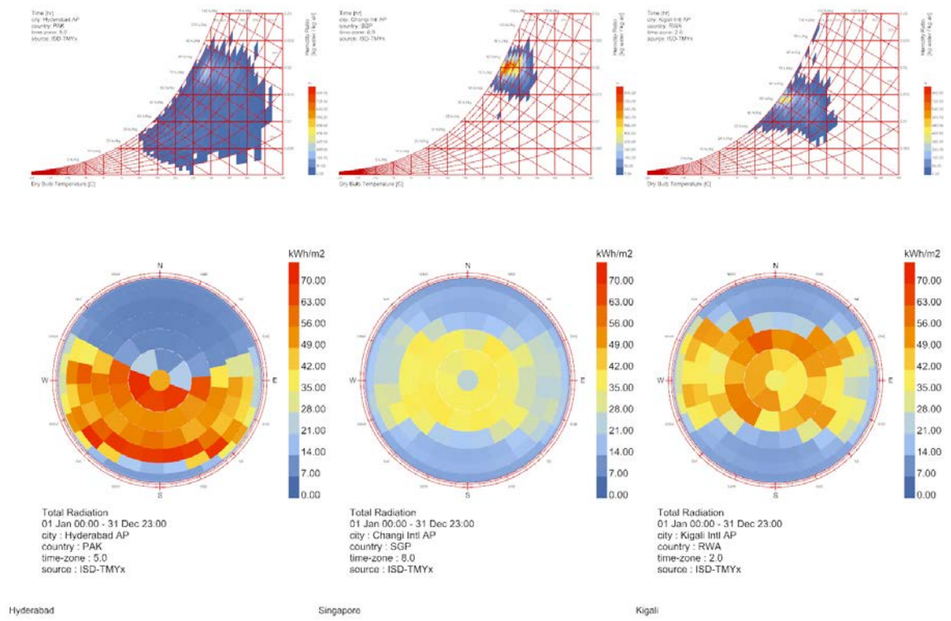

Figure 2: Climate Profile of three locations (up: Psychrometric chart, bottom: total irradiation)

heating, and ventilation. It is needed that supporting to achieve perform as expected, instead of environmental design as keyword collection. For the support, simulation-based design study will be appropriated.

3.3 Case1: Darker than imagined

Figs 3 and 4 show the case that one student group who chose Kigali as the target site. Through the climate analysis using sun path diagram, they noticed that the sunlight comes from top because the location is near the equator. They planned the triangle shape as roof geometry and mud as a roof material to avoid too much heat gain from the sun. They mainly focused on the only thermal situation and made their concept with the drawing (Fig 3). The lighting simulation output supported their visual understanding how much dark it is (Fig 4). The simulation results provided them with clues on how to solve the balance between designing a lighting environment and a thermal environment.

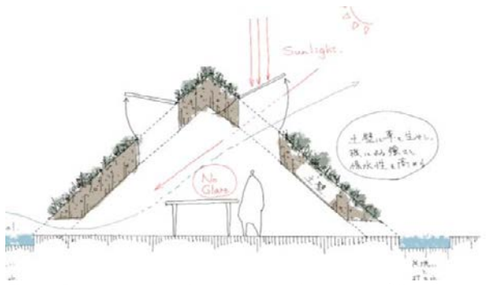

Figure 3: concept drawing by the student group (Kigali)

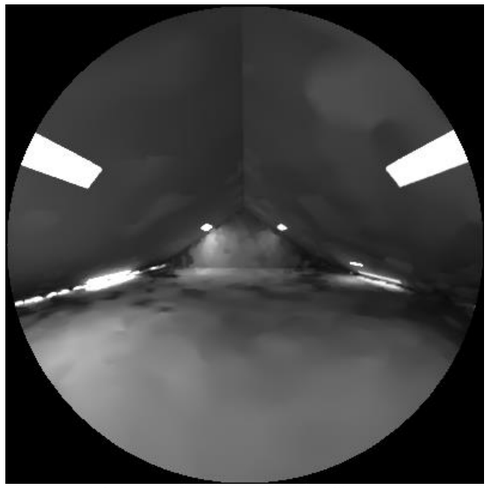

Figure 4: Lighting rendering interior (Kigali)

3.4 Case2: Less effective than expected

Figs 5 and 6 show the case with the other student group. Their concept drawing (Fig 5) showed the idea to control the amount of solar irradiation under the Kigali climate by changing the inclining angle. The idea came from their analysis using sun path diagram. After analysing solar radiation with simulation model (Fig 6), the student group noticed that the impact of their ideas on controlling solar radiation is less effective than expected. It is found that the process of analysing their ideas with simulation models is important to develop environmental design skills in education.

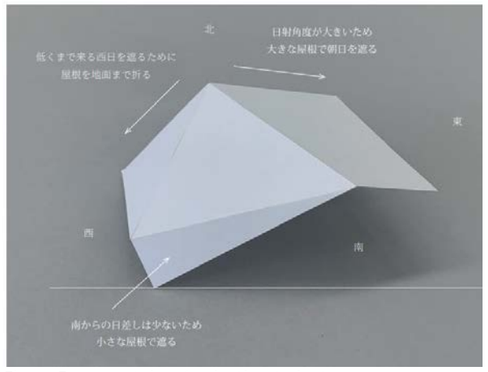

Figure 5: concept drawing by the student group

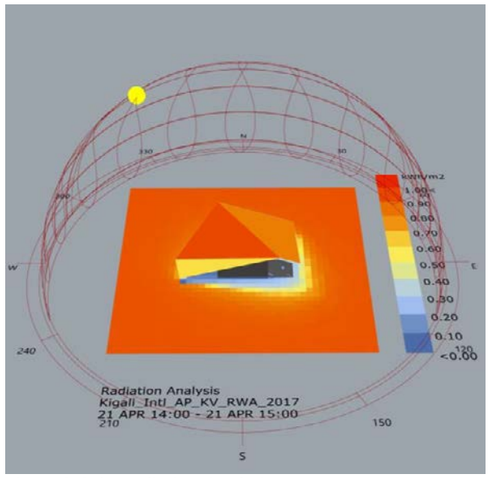

Figure 6: Solar radiation simulation

3.5 Thoughts of the students after the lecture

On the last day of lecture series, the questionnaire survey was carried out. The students were asked “what have you acquired through the series of lectures?” at the last session. From the questionnaire result, it is found that simulation results helped their imagination and students felt interesting in integrating scientific thinking and creative thinking.

4. DISCUSSION

4.1 Knowledge

In the most case of architectural education in Japan, the fundamental knowledge is provided in the preliminary series of courses, for example, grade 1-3. It means that architectural students have basic knowledge regarding building physics or environmental design methods. However, there is seldom no opportunity to learn how to apply this knowledge in practice, for example, through the design studio works. As a result, the knowledge can be shown in their projects as a checklist of environmental design techniques. It can be recognized that this is a hinder to develop skill creating effectively performed design. Most of the cases, the environmental courses focus on the training lectures to use computational simulation tools. The course in which the students can develop their competence to handle simulation tools is expected by both students and professionals. The proposed program challenged to provide opportunity to connect knowledge and practice regarding environmental design with limited time.

4.2 Scientific analysis

Environmental design sometimes requires the competence to calculate the design performance with a series of mathematical equations. To provide feasible results within limited time through design process, most of simulation tools can be handled as easy as possible. Therefore, the simulation tools hide mathematic equation in back. As a result, the students miss a chance to develop their environmental design knowledge from simulation outputs. Architect is not required scientific competence equal to scientist, but the similar competence is basically required when they apply simulation results into their design. In education, especially most of architectural program in Japanese architectural school, scientific competence development is missing. The proposed program challenged to provide interpretation how to get understanding of scientific discussion from simulation outputs. The challenge is to use 3D geometric models made by the students for simulation. To simulate environmental analysis within limited time (1 week between two lectures), the simulation model needs to be prepared effectively.

4.3 Concept of “comfort”

It is common in environmental design, in general, to create thermally comfortable environment. During the lectures, it is observed that students use the word “comfortable space” easily in their description. However, the authors have a feeling that “acceptable environment” is better to focus because “comfort” is not always an essential requirement, but it means that “not uncomfortable situation” is required.

4.4 Reputation

Students felt the difference between their expectation and the simulation result. Simulation with their idea models can be a useful learning material if having analysis and discussion process. They recognize that this difference can be a good opportunity to test their knowledge into design. It is positively taken that activity to show the output from simulation by lecturer before developing the skills to handle simulation tools. The trial which is described in this article is just four-days lectures, so the cyclic study between design study and simulation is limited. It is found that there is a demand to apply the program into design studio.

5. CONCLUSION

The article described the Bioclimatic Physics Program developed and tested. The remarkable response from the participating students was that they were inspired by their own experience of the design process with numerical evidence. The reputation of simulation and design study is expected in their design studios. As well as visualization by simulation, design study with scientific discussion can be the key factor. It is identified that students recognize the impact of design on the environment and feel the possibility of bioclimatic physics rather than constraint. In the future steps, the program will be attached in the early stage of design studio projects and monitor its process of design improvement.

ACKNOWLEDGEMENTS

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PLEA STGO 2022

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3RD PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Designing for thermal comfort

Lessons learnt from different latitudes, longitudes, and altitudes

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ABSTRACT: With a view to promoting sustainable architecture and provide strategies for energy efficient buildings that will cope with climate change, this paper intends to discover commonalities among an eclectic group of research activities on thermal comfort, in different geographical, climatic, and cultural contexts. Among other things, one main finding is that long-standing strategies such as thermal mass and purposeful ventilation are still optimal solutions for low energy and comfortable buildings in the various contexts presented.

KEYWORDS: Thermal comfort, ventilation, thermal mass, vernacular architecture, innovation in buildings.

1. INTRODUCTION

The studies of thermal comfort over recent years have continuously updated our understanding as knowledge unfolds. One main driver for this is the compelling need to design buildings where energy demand is reduced while still maintaining thermal comfort for its occupants. To improve indoor thermal conditions, new technologies and new materials are being used in buildings, which can affect comfort conditions.

This paper intends to respond to the following question: *is it possible to draw commonalities among an eclectic group of research activities on thermal comfort?*

2. METHODS

This paper is intended to collate different studies on thermal comfort and synthesise common findings. Data were collected at different climate zones and from different types of buildings, either through experimental tests or case studies (see Table 1). First, each thermal comfort study with its specificities, methods, and findings will be presented. Then, a critical analysis will be performed of each study, extrapolating their main contributions to the themes of thermal mass and ventilation. Finally, the results of each study will be framed within the analytical framework presented in Figure 1.

Table 1:
Thermal comfort studies considered in this paper

Country	Climate zone	Building type	Type of study
UK	Cfb	residential	Multi-case study
Germany	Dfb	offices	Exp.& case study
Canada	Dfb	offices	Experimental
Peru	BWh	residential	Experimental
Chile	Csb	offices	Multi-case study
Ecuador	Csb	residential	Case study

In terms of validity, it should be emphasised that this paper considers the main findings of each study and the validity that each study has attained within its own domain. As a result, conclusions will be drawn accounting for generalisations made within each study, and research quality standards relating to each method and approach used.

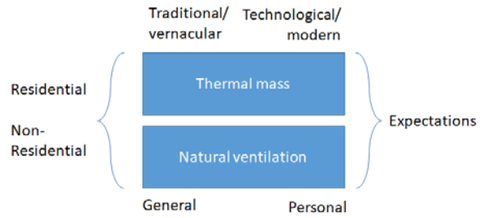

Figure 1:
Analytical framework.

3. RESULTS

3.1 Study in the United Kingdom (UK)

The study considered four highly energy efficient homes: two homes with thermal mass exposed, one Passivhaus home with modern methods of construction, and one refurbished pre-1919 traditional Victorian terrace house. Such homes constitute exemplary cases of highly energy efficient homes. Due to its climate, homes in this country have historically been heating intensive, and governmental recommendations and policies favour a fabric-first approach, in which most of the energy demand reduction is achieved by reducing the overall building's skin conductivity, increasing airtightness values to unprecedented values, and managing air quality ventilation (i.e., to extract water vapour and indoor air pollutants) via mechanical ventilation with heat recovery. The study aimed to evaluate whether energy efficient homes are providing comfort with little or no use of energy during winter, as well as throughout the changing seasons [1]. Data was collected over 11 months, including monitoring the main environmental parameters such as air temperature and relative humidity, delivering a seasonal post-occupancy evaluation questionnaire, and a thermal comfort sensation questionnaire submitted at different times throughout the study.

From this study, it emerged that all homes were positively evaluated by the occupants in winter. However, three out of four homes overheated in summer, with different degrees of intensity and severity. One of the main triggers found was the absence of solar shading, which tends to be absent in the traditional UK residential stock due to the mild British summers and predominantly overcast weather. Another trigger for overheating was found in the absence of cooling ventilation.

Traditionally, homes in the UK are characterised by remarkably high values of air permeability (around 10-15 ACH 50Pa) with a consequent (new) need to cool homes. The study indicated that highly energy efficient homes respond quicker to heat gains. However, contextual factors interfered with window-opening, among these, there were security concerns (windows located on the ground floor), outdoor pollution, and the mistaken idea that mechanical ventilation would also provide the necessary air changes to reduce temperatures. Such conditions converge in a latent new potential for energy demand for cooling. It became clear that more feedback from recently built case studies is of paramount importance to inform future designs of new highly energy efficient homes.

3.2 Study in Germany

This study is part of an ongoing project in which the impacts of personal comfort systems on thermal comfort and energy efficiency are investigated. The project is located in a free-running office building in southern Germany. Together with ambitious renovation measures, an innovative personal ceiling fan - which is integrated into an acoustic panel - was installed in the building and combined with passive cooling solutions, such as night ventilation and automated window shadings. Both monitoring and survey campaigns and a series of experimental studies were carried out to support the analysis of thermal comfort.

In the experimental studies, the air velocities provided by the ceiling fan were analysed in relation to comfort preferences and compared to standards [2]. The focus of the monitoring campaign was to evaluate the performance of the ceiling fans and night ventilation in real-world conditions, and further to better understand employees' interactions with the system. Based on the monitoring data, a building simulation study was carried out to compare the implemented solution with other passive and active cooling strategies in terms of economic viability, energy consumption, and thermal comfort. A series of questionnaires were delivered to the building employees before and after the building renovation to capture, among other things, thermal comfort votes and satisfaction with the indoor climatic conditions. The impact of the building renovation and the acceptance of the installed ceiling fans were also evaluated.

The implementation of this passive cooling solution – a combination of night ventilation and personal ceiling fans – showed a positive impact on thermal comfort as well as low energy consumption. Laboratory results indicated that air movement provided via the ceiling fans allowed the acceptability of indoor conditions up to 31°C. Moreover, the possibility of personal control extended occupants' thermal comfort ranges. Results from the survey campaign showed an increase in satisfaction with the room temperature after the renovation. The ceiling fan was positively evaluated with respect to its effectiveness to increase thermal comfort at the workplace. The simulation study showed that the increasing investment cost by installing personal ceiling fans can be partially compensated by a productivity improvement resulting from the increase in employees' comfort. One of the limitations of this study is related to the positive psychological impact of personally controlled ceiling fans that could not be accounted for in the economic viability analysis.

While the economic viability of the use of night ventilation in refurbished buildings is evident, the viability of ceiling fans in moderate climate zones is limited. Further research on warmer environments and a reduction in the investment costs for integrated ceiling fans may justify the economic viability of this solution. Within the context of global warming, cooling loads are expected to increase in the future, therefore personal ventilation seems a possible path to enhance comfort levels whilst allowing for low energy consumption.

The combination of different research methods allowed a comprehensive understanding of the performance of the proposed cooling solution and provided a methodical approach during the research process. For instance, the results of the experimental study were used as a reference for the position of the ceiling fans in each workspace. Results from the building monitoring served as validation for the simulation study, which allowed a case-specific sensitivity analysis of different cooling strategies. Furthermore, the psychological analysis through questionnaires supported the predicted thermal comfort obtained from comfort models and

provided a better understanding of employees' comfort preferences and expectations regarding new technologies.

3.3 Study in Canada

The goal of this study was to evaluate the thermal and energy performance of an innovative, flexible cooling system that can be installed as a retrofit solution in a typical office building. The study was performed in a test room in Toronto, Canada [3], during the 2021 summer season. The test room was fully exposed to outdoor environmental conditions and was solely conditioned by radiant ceiling panels (RCP) incorporating macro-encapsulated phase change materials (PCM). The experiments were focused on evaluating the ability of the RCP-PCM system to shift cooling loads to off-peak hours, measuring its heat removal capacity and the resulting indoor thermal environment. A 100 W heater was installed in the room (at a height of 0.7 m) to simulate heat gains from an occupant. Internal heat gains also included one 60 W laptop placed on a small desk inside the room and the lighting fixtures (four 4-ft. 30 W LED wraparound fixtures). The schedules for the internal heat gains (heater, laptop, and lighting fixtures) corresponded to a typical office workday schedule (from 8:00 to 18:00).

Two operation modes were evaluated, i.e., passive mode or PCM melting/heating cycle (no water flow) and active mode or PCM freezing/cooling cycle (cold water flow). The system operated in passive mode during occupied hours (8:00 to 18:00). As a result, the RCP-PCM panels passively absorbed internal heat gains (heater, laptop, and lights) and solar gains during this period. On the other hand, the system operated in active mode only during unoccupied hours (from 18:00 to 8:00) to evaluate its ability to shift the load to off-peak hours (e.g., night-time). During active mode, the heat absorbed by the RPC-PCM panels during the passive mode was discharged by circulating water from the cold generation system. In this way, the incorporated PCM was regenerated (solidified) before starting the next occupied period.

Indoor thermal conditions were monitored using a delta Ohm HD 32.3 instrument, which measured radiant temperature, air temperature, humidity, and airspeed in the centre of the room at a height of 1.1 m. The heat flow rate between the radiant cooling surface and the room was also measured using heat flux sensors installed on the bottom surface of the RCP-PCM panel (facing the room). The radiant surface temperature was also measured using negative temperature coefficient (NTC) glass-encapsulated thermistors. The monitoring data was also used to validate a building-system simulation model. The validated model was used to compare the performance of the proposed solution with a conventional all-air system in terms of energy consumption and thermal comfort.

The results obtained in this study indicate that by incorporating PCM into standard RCP, the radiant system displayed a heat removal profile similar to high-thermal mass radiant systems such as Thermo Active Building Systems (TABS). This means that the RCP-PCM can effectively shift cooling loads to off-peak periods while maintaining acceptable thermal comfort conditions (i.e., $-0.5 < PMV < 0.5$). This load-shifting capability of the RCP-PCM system can be of great help in planning demand-side management (DSM) strategies for increased penetration of renewable electricity in building cooling applications. Simulation results showed that in the evaluated climate (hot and humid), annual energy savings of around 34% were obtained by using the RCP-PCM system instead of the conventional all-air system while maintaining room conditions within the limits of human thermal comfort ($-0.5 < PMV < 0.5$) for more than 90% of the total occupation periods.

3.4 Study in Peru

This study monitored three test rooms located in the town of San Pedro de Lloc, on the north coast of Peru, very close to the equator, with a markedly vertical solar path and a subtropical desert climate [4]. The objective was to combine different types of roofs to identify the most efficient solar control strategies: light roof (corrugated fibre cement sheets), roof with insulation (EPS), roof with thermal mass (mud layer over reeds), and roof with thermal mass plus insulation (EPS+mud layer). Such options were evaluated with and without shade (also known as 'double roof'). The test rooms were built with the three most widely used materials in the region: light walls (wooden boards), medium mass walls (concrete blocks), and high thermal mass walls (adobe). Firstly, the test of roofs made it possible to verify the hypothesis that the simplest, cheapest, and most effective strategy is to provide shade via a double roof. Then, it was observed that the concurring effects of strategies on the roof (such as thermal mass, insulation, and shading) progressively improved the thermal performance of the test rooms. Additionally, an aspect that was equally or more decisive in achieving comfort conditions inside was the presence of thermal mass in the walls. The high-thermal mass strategy was combined with moderate levels of ventilation (between 4 and 5 ACH) and high-positioned ventilation openings, to ensure the removal of warm indoor air during the day, and the cooling of the mass during the night. The above findings are closely related to what has already been learned from vernacular architecture in this area, to which are added certain occupants' habits such as siesta during the hottest hours of the day. In such cases, ventilation is limited to a minimum during the hottest hours as well as ventilating when temperatures are more pleasant.

It is also important to recognize that the strategy of thermal mass with controlled ventilation often does not coincide with those suggested and validated for other latitudes, in which considerable emphasis is placed on ventilation under the associated conditions of temperature and relative humidity [5, 6]. This can be explained by the fact that in proximity to the equator, summer nights are markedly longer than those at higher latitudes; this allows for both less heating of the mass during the day and greater cooling capacity during the night, which ultimately increases the value of the thermal mass at these climates and latitudes.

Thus, traditional architecture is valued as a reference, especially in unique climates close to the equator and with particularities both in altitude (Andes Mountains) and in the presence of cold marine currents (north Chile and coast of Peru). There is a need to investigate further in these areas to design in such a way that prevents discomfort or waste of energy; this should avoid imitating both the aesthetics of foreign architecture as well as thermal strategies that are valid in other areas (often counterproductive in specific contexts).

3.5 Study Chile

This study was performed on eighteen office buildings in Concepción and Santiago [7]. On-site fieldwork, including a thermal comfort survey with simultaneous measurement of environmental conditions, was carried out during a single day in winter, spring, and summer. The buildings offer varied opportunities for thermal adaptation to the occupants: in Concepción, mostly operable windows, whereas in Santiago, adjusting the HVAC thermostat is more common.

The longitudinal survey recorded the thermal comfort perception (sensation, preference, and acceptability) but also the occupants' actions and perceptions of their opportunities to operate the control elements. The survey attempted to collect different environmental and temporal conditions where actions could occur, to contrast them against the contextual factors. The personal factors (age and sex) were gathered through a characterization questionnaire, while the spatial factors (layout, orientation, distance to control element) were recorded during the fieldwork.

The results showed that comfort temperature had a wider seasonal variation in buildings where occupants are allowed to operate windows. In this sense, ventilation is key to improving thermal comfort: if operable windows exist, the occupants tend to use them. However, they need to be aware that they could use them. Contextual factors such as office layout, age, or seniority influence the window operation. Knowing the conditions and constraints under which an action can be performed is useful to generating a more tailored design that better coincides with reality and strives for greater user well-being while optimising energy use. Moreover, from this study, it has emerged that in office spaces, coexistence implies not only different thermal requirements, but also different thermal expectations [8]. Although this study could be subject to self-reporting bias, some strategies were adapted to minimise this. First, the survey was performed face-to-face at the same time with observations in the field, allowing the availability and state of the control elements to be checked. Second, the questionnaires were grouped by participant, allowing their profile to be unified, and avoiding potential errors in isolated answers. In this sense, it is important to note that this survey was designed to identify patterns rather than register the exact moments of the actions.

This mixed methodology allowed rich information to be gathered in a non-expensive or intrusive way, something common in thermal comfort studies, being a powerful alternative to occupant behaviour studies. In southern America, research in understanding occupant behaviour is scarce, and personal adaptation in these climatic and socio-cultural contexts is still the subject of research. Combining monitoring at the right time, surveys fitted to the purpose with questions that allow several analyses and using skills like programming not only to process but to extract data are paths to optimising research in a context generally lacking economic resources for large data collection campaigns or laboratory studies.

3.6 Study in Ecuador

A thermal comfort study was conducted in Quito-Ecuador. The research combined cross-sectional thermal comfort surveys and thermal performance simulations of residential buildings [9]. Due to the city's location and topography, wider variability in thermal comfort responses was expected from the differences in altitude rather than the differences in weather conditions. Thus, data were collected in three parishes located between 2400 and 3000 metres that lay within a radius of 40 km. Dwellings in the studied area mainly operate under free-running conditions; hence, occupants mainly rely on passive design strategies and adaptive solutions to restore

comfort. The three monitored typologies correspond to dwellings built with (a) asbestos/zinc in the roof and hollow concrete blocks in walls, (b) cast-concrete roof and hollow concrete blocks, and (c) clay tiles, used almost exclusively in vernacular or traditional architecture in the highlands, combined with adobe walls. Based on archetypes' relative thermal mass, Typology A is herein referred to as light, Typology B as medium, and Typology C as high-thermal mass construction. Monitoring data revealed a narrow mean thermal oscillation in medium and high-thermal mass construction whereas in lightweight constructions (Typology B), the incident solar radiation significantly impacts the maximum daily temperature, as confirmed by the high and significant correlation of the indoor temperature with the outdoor temperature and solar radiation. Furthermore, occupants at higher altitude perceived indoor air movement to be uncomfortable, even though the relative air movements were within the range of 0.25 m/s and 0.35 m/s at the three locations.

On-site surveys and monitoring were the main research methods used to evaluate thermal comfort and indoor environmental performance in residential buildings. Besides the known benefits of on-site data collection, we were able to gain additional value from observations and diversity of subjects. The observations at each dwelling and discussions with participants added to the understanding of occupants' behaviour in the studied locations. However, one should not underestimate how time-consuming and demanding it is to collect individual comfort votes from different subjects. Furthermore, participants' recruitment should be coordinated and arranged in advance with organisations and institutions having direct and trustful access to the target population.

4. DISCUSSION

In this section, a critical and comparative analysis is performed to find commonalities concerning thermal mass and ventilation from the studies presented, as summarised in Table 2.

With regard to **thermal mass**, including the use of radiant ceiling panels (RCP) has been demonstrated to be the most valid strategy to provide comfort by optimising the effect of solar radiation, and enhancing the reduction of indoor temperatures if night cooling is adopted. However, many lightweight buildings are currently being constructed in which this type of strategy cannot be applied. The study conducted in Canada shows that the use of PCM can represent an interesting solution in lightweight buildings since its heat storage capacity allows cooling/heating loads to be shifted off-peak hours. Nevertheless, the studies presented clearly show the limitations to the employment of night cooling provided by the climate, at least in some locations. For instance, in the UK, night cooling may not be an option for other immediate contextual reasons, such as heat islands, security concerns, or city noise. In such cases, a suitable way to provide cooling during the night can be through the circulation of cold water, as in the case of the RCP with thermal energy storage. Water is a much more efficient heat transfer medium than air, which is commonly used in night ventilation strategies.

It is important to underline the limitations to the use of thermal mass as a sustainable option; specifically, one must count on the fact that high heat capacity construction materials (such as concrete, bricks and tiles) are high in embodied carbon because of the large volume of emissions released in their production, though one might well defend the longevity of such materials, especially when compared to the expected life span of more ecological materials. A balance to this dichotomy can be found in the local availability of traditional solutions high in thermal mass (adobe, mudbricks, rammed earth) and the potential economic benefits to communities who produce them.

With regard to **ventilation**, it has been found that there is a necessity to specify its particular purpose. In the UK study, high levels of energy efficiency resulted in an increased need for cooling ventilation, and this was necessary for both thermal mass as well as lightweight constructions. However, contextual constraints made night cooling unavailable at times. The study in Germany showed that cooling ventilation can be provided via personal ceiling fans, consequently extending the thermal acceptability of indoor conditions. Both studies related to energy efficient buildings, where 'ventilation' should be distinguished as either air-quality ventilation (pollutants dilution, moisture control) and cooling ventilation (lowering internal temperatures). The study in Chile showed that providing the possibility of window-opening is essential for thermal acceptability, though users must not only have control of window opening but should also be aware that such an option is available to them. This last finding applies to residences, especially innovative designs such as highly energy efficient homes, where a widespread unawareness of control of indoor environmental quality was observed. Also, the Peruvian and Ecuadorian studies showed the importance of ventilation management in combination with thermal mass. While thermal mass materials (in the roofs) showed a significant improvement in indoor temperature (narrow daily oscillation) at latitudes close to the equator, as characterised by a markedly vertical solar path and the consequent longer portion for night cooling. Also, people at higher altitudes are more sensitive to air movement. As a result, the ventilation strategy should be managed carefully to prevent (a) mass saturation, and (b) thermal unacceptability (too cold). Importantly, specific weather conditions offered in altitudes and latitudes and not considered by international standards. Therefore, designers should be critical of such standards and also consider what thermal strategies have previously been successful in specific contexts. Finally, the role of occupants to effectively have natural ventilation is crucial. The studies above showed this is an aspect to consider in the building design, especially in climatic contexts where natural ventilation is possible in order to provide both air quality ventilation and cooling ventilation when necessary.

Table 2:
Findings framed in the framework provided

		study
thermal mass	Thermal mass is an optimal strategy to reduce the internal thermal oscillation when combined with solar shading and cooling ventilation.	UK, Peru, Ecuador
	The use of phase change materials can be used to increase the thermal mass of lightweight buildings.	Canada
	When night cooling is not a reliable option, cooling can be obtained through the circulation of cold water in radiant ceiling panels.	Canada
Natural ventilation	High levels of energy efficiency (airtightness) resulted in increased demand for cooling ventilation in both heavyweight and lightweight constructions with no solar shading.	UK
	At higher altitudes (3000 m), occupants are more sensitive to air movement.	Ecuador
	Increased air movement, together with personal control, enhanced the thermal comfort of occupants.	Germany
	Personal control and opportunity perception increase occupants' interactions with windows for ventilation.	Chile

A final reflection is devoted to the methodologies used in the analysed studies. Thermal comfort surveys and post-occupancy evaluations have encountered limitations when adopting a standardised questionnaire. In such studies, the questionnaires have benefitted from adaptations that purposely target the contexts. Finally, most studies presented in this paper adopted a mixed-methods approach where the environmental data collected or generated was interpreted in light of occupant surveys and observations of peoples' habits and cultures. This quality of the research allows for is conclusions to be usable for designers.

5. CONCLUSIONS

From this study, it can be concluded that the most effective strategies to provide comfort are the ones valid in traditional buildings and that can be maintained while improving their performance. However, it is noted that modern architecture and new advances in building construction tend to move away from traditional designs to adhere to lighter and cheaper methods of construction, as well as often introducing counterproductive automation of window opening, restricting adaptive possibilities to occupants. Finally, when it comes to traditional buildings, designers must acknowledge that standardised definitions of comfort can disregard more efficient strategies to provide comfort. The risk of such design practice is to neglect the opportunities offered by contexts, in particular, all those regions benefitting from a pleasant climate, with opportunities to design buildings that may provide a fair and delightful thermal experience.

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Thermal benefit of conventional mud walls in tropics

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ABSTRACT: This paper explores the thermal properties of mud walls in two different aspects. First, the thermal properties of mud walls within different climatic zones. Second is the thermal property of mud walls with different conventional walling material. Thus, two cases were studied to analyze the local mud houses in two major climatic zones; wet and dry in Sri Lanka while three cases (bricks, mud, cement blocks) were selected for the study of variations in each material. Thermal simulation analysis was employed as the means of comparison. From the readings obtained for temperature and relative humidity, Derob-LTH analysis was carried out to find out the thermal properties: thermal conductivity and specific heat capacity of mud. Further, the analysis was justified through the survey questionnaire, which was carried out in both wet and dry zones. The study concludes that mud houses have more occupant friendly indoor environments and more effective performance in dry zone than the wet zone. Further, it was proved that mud walls have less indoor temperature than brick or cement block walls during day time. As a result, it can be concluded that utilization of correct materials could make the buildings comfortable for its occupants.
KEYWORDS: Local mud walls, Tropical Climate, Thermal properties, Occupant Satisfaction, Computer Simulation.

1. INTRODUCTION

Most of the countries with tropical climatic conditions in Asia are experiencing rapid development in infrastructure. This phenomenon produces thermal discomfort associated with built environments. The use of air conditioning is gradually becoming a fashion due to its affordability resulting from improved economic standards and reduced capital cost for air conditioners (Mallik, 1996). This is not a desirable situation in long term basis, since any increase in the use of electricity; generated using fossil fuels can increase greenhouse gas emissions and further aggravate the potential for global warming. Recent mounting concern for environmental issues triggered by buildings has made people think on how architecture can respond more appropriately to the environment once again. The "Thermal Problem", which encompasses the relationship between energy consumption and comfort, has currently become a critical issue in Sri Lanka as a developing country located in equatorial tropics.

According to Givoni (1998), thermal comfort is defined operationally as the range of climatic conditions considered comfortable and acceptable to humans. The sensation of thermal comfort, and the occupant's satisfaction or dissatisfaction, depends in their interaction and response to certain physical influences. It was explained as the absence of two basic sensations of discomfort: a thermal sensation of heat, and a sensation of skin wettedness (Givoni, 1998). Babara, Christian and Emmanuel (2014) also defined thermal comfort as the physical and psychological wellness of an individual when temperature, relative humidity, and air movement conditions are favourable for the activity that has to be developed. From all the definitions, thermal comfort is achievable when 'temperature' is under control. In most thermal comfort studies, temperature have been indicated as the most important parameter since it is temperature, that actually determines how occupants feel within spaces (Koranteng, Essel and Amos-abanyie ,2015). Air temperature is often taken as the main design parameter for thermal comfort. Hence it is essential for occupants‟ well-being, productivity and efficiency (Adebamowo and Akande, 2010). Heidari and Sharples (2002) have suggested that air temperature alone is a good indicator.

When discussing about the indoor thermal comfort building envelope receives great attention in today's world. The envelope of a building protects the interior space from the harsh exterior conditions. Consequently, the wall material of buildings does have an effect on the temperature within the interior space (Koranteng, Essel and Amos-abanyie ,2015). As a result, ancient building technologies were reconsidered, as they were carefully invented and used, assuring the sustainability of the environment. Most of these technologies were based on the natural materials, which were taken from the natural world. For instance, in a research on the thermal conductivity of building fabrics, (Soebarto, 2009) discovered that mud has a high thermal conductivity. With the passage of time, and within the warm humid climatic conditions, there is gradual heat deterioration from the building fabric. The rate at which heat is transferred through the external envelope of a building is expressed as a U value. Heat always flows from a warm area to a cold area and each material component of the external envelope of a building transfers heat at different rates. (Advice series, 2010). This rate depends on the thermal mass of the building material.

The thermal mass of a building material describes the ability of that material to absorb heat, store, and later release it either outdoor or indoor. The time delay due to the thermal mass is known as a time lag. The thicker and more resistive the material, the longer it will take for heat waves to pass through. The reduction in cyclical temperature on the inside surface compared to the outside surface is known as the decrement.(Time Lag and Decrement Factor, 2015.) In order to be effective as a thermal mass, a material must have a high heat capacity, a moderate conductance, a moderate density, and a high emissivity. It is also important that the material serve a functional (structural or architectural) purpose in the building (Haglund and Rathmann, 1996).

When considered there have been a lot of natural materials which have played an important role in the traditional architecture. They are used to make up building elements using technological processes that have evolved over many centuries to create a distinctive style of architecture. "Earth", being the most renowned building material that used in the construction from early period much research work has been carried out to recognize the authentic performance of the mud houses in many climatic contexts. Justifying the historical recognition and the wide usage of earth, Cofirman et al. (1990) stated that earth as mud bricks, have been used in the construction of shelters for thousands of years, and at present, one third of the world's population lives in mud constructions. When developing countries alone are considered, this percentage increases to 50%. (Houben, 1994 & Vega et al, 2011).

In this context, ancient building technologies were reconsidered, as they were carefully invented and used, assuring the sustainability of the environment which were based on the natural materials. The history of mud houses in Sri Lanka spans from the first settlement, using the principle of "Wattle and Daub" walling method with thatched roof. During the colonial period and thereafter, other methods of earth building construction were introduced; such as adobe blocks and rammed earth buildings. (Bogahawatte,1993) Further, mud has been the only building material known in ancient Sri Lanka until fire brick and stone masonry was introduced by India around the third century B.C. (Wijesekara, 2012)

Other than the cost effectiveness, the rich thermal properties of mud encourage the communities to use it, in their habitats. The natural air-conditioning effect of mud houses (Martin et al., 2010 & Saldivar et al., 2005) known as the thermal flywheel effect (Duffin & Greg, 1984) is used in houses in Yeman as not only for the people in hot developing countries, but also for those in cold industrialized countries in Europe and America for their special features (Eben, 1990).

Earth has high thermal capacity which could store much heat when it is absorbed during the day. Thus, in day time, the interior of the mud house is cold relative to the outside. The ability of transmitting heat strongly depends on water content of clay and highly saturated clay has high thermal conductivity. When the outdoor temperature starts to go up, mud walls tend to heat and thus water in the clay is evaporated and heat loss occurs in the form of latent heat. As a result, inside wall surface temperature is dropped and; the indoor temperature is maintained at a lower value or at a steady state. (Sldivar et al. 2005)

Thiwari and Chel (2008) have further investigated on thermal performance and embodied energy analysis of an existing eco-friendly and low embodied energy vault roof passive house located in India. Thermal models were developed based on mathematical methods and compared with the experimental data to verify it. It has found that the annual heating and cooling energy saving potential of the mud-house was determined as 1481 kW h/year and 1813 kW h/year respectively for New Delhi composite climate which is higher saving compared with other structures. Embodied energy calculation was performed for the house and it was presented that it has a lower embodied energy and this will lead to shorter payback time in terms of energy and low emission of CO_2.

However, today we are experiencing the repercussions due to modern and sophisticated technologies. Therefore, a need to reverse back to the ancient technologies with relevant modifications to suite the contemporary needs has risen. The research was mainly carried out to find out the real thermal performance of one of the most popular ancient technology; mud wall construction, with the modifications and to understand the suitability and the acceptability of the technology by the local community, with compared to other popular existing walling methods.

2. METHODOLOGY

The research was conducted with the key objectives to examine and compare the thermal performance of local mud houses within wet and dry zones, find out the thermal properties: thermal conductivity and specific heat capacity of the mud walls, understand the thermal performance of mud walls with compared to the existing walling techniques: brick and cement blocks, understand occupants' satisfaction level on their habitat in both wet and dry zone and to identify the best climatic zone to setup Mud houses, by improving the existing living conditions of the mud houses.

As the first step a detailed literature survey was conducted to identify the use of mud in early periods in global and local built contexts as a sustainable building material. Following the initial literature survey, field investigations were conducted to identify the thermal performance and properties of mud as a sustainable building material in local context. For the field investigations, the case studies were selected from two different climatic zones in the tropical Sri Lankan context (figure 1 & 2). As case studies mud house from each wet and dry zone were selected with similar floor area, walling type, roof and floor finish and readings were taken with respect to temperature and relative humidity in both indoor and outdoor, covering 12 hours from 6.00 am to 6.00 pm at every 30 minutes intervals. Readings were analysed using DEROB - LTH computer software to identify the thermal properties of mud used in the two different contexts.

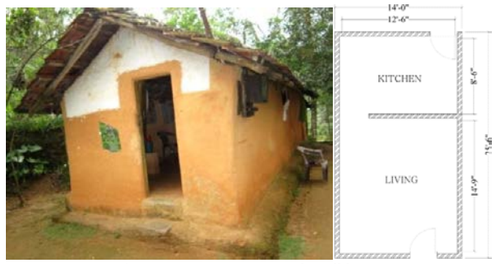

Figure 1: Wet Zone mud wall house

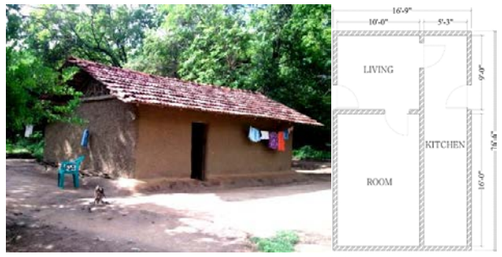

Figure 2: Dry Zone mud wall house

Further, a questionnaire survey was carried out in both wet and dry zones to validate the results obtained from the DEROB-LTH. 35 randomly selected houses from each zone were considered for the data analysis. The collected data from the questionnaire survey was analysed by scaling their preferences and compared with the measured data and analysed results of DEROB modelling. Finally, results were compared to understand the thermal performance of mud houses in wet and dry zones and to find out any relationship with the occupants' responses to physical readings of the indoor environment of the house.

Consequently**,** based on the thermal properties; thermal conductivity and specific heat of mud derived from the on-site investigations and software simulation, a two-storey mud wall house was modelled and simulated using DEROB-LTH to investigate the thermal performance. Same house model was simulated with brick walls and cement walls and the thermal performance of each wall type was compared.

3 DATA ANALYSIS

3.1 Field measurements

Figure 3 & 4 depicts the temperature and humidity variation in wet zone and dry zone. From the field measurements it is clear that there is a tendency of indoor temperature reaching higher than outdoor temperature during morning hours and reducing during day time and again increasing in the latter part of the day.

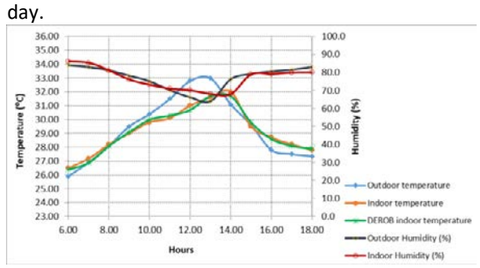

Figure 3: Temperature and Humidity variation in wet zone

In wet zone, temperature peaks were indicated one hour before dry zone and it was lower than 2.0^{o}C. Further, 45 minutes of time lag and 0.97 of decrement factor was observed in wet zone while one hour of time lag and 0.95 of decrement factor was observed in dry zone. This was mainly due to moisture variation between wet and dry zones.

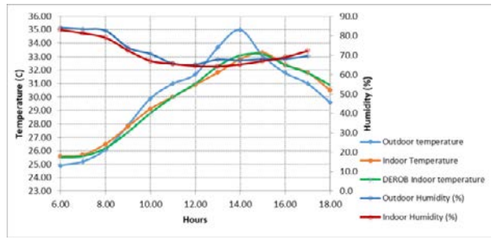

Figure 4: Temperature and Humidity variation in dry zone

3.2 Identifying the thermal properties of local mud walls

Thermal properties of clay were determined by calibrating DEROB-LTH models using actual outdoor and indoor temperature and the indoor temperature obtained from DEROB calibration (figure 5 & 6). Thermal conductivity and specific heat capacity of clay was adjusted according to the indoor temperature of actual values and values from DEROB-LTH software. Then finally, real values for thermal conductivity and specific heat capacity of clay in both wet and dry zone were obtained.

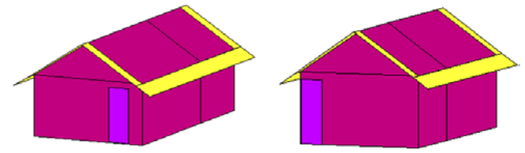

Figure 5: DEROB models for dry zone mud house

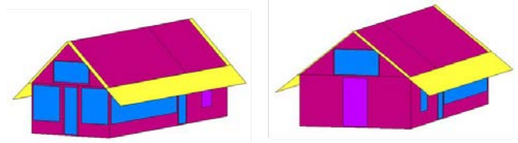

Figure 6: DEROB models for wet zone mud house

From the Derob-LTH results, it was found that mud walls of the house in dry zone has less thermal conductivity than mud walls of the house in wet zone.

Table 1 : Thermal properties of mud from DEROB analysis

Zone	Conductivity (W/m.k)	Specific heat (Wh/kg.k)
Wet zone house	0.41	0.20
Dry zone house	0.37	0.31

Since mud walls in dry zone shows high specific heat capacity than wet zone house it is evident that thermal properties of mud walls in dry zone can perform more effectively than in the wet zone.

3.2 Questionnaire survey

Questionnaire survey was carried out to find out how occupants feel the temperature and moisture within the day and night in wet and dry seasons and the overall satisfaction of living in a mud house. According to the results occupants in dry zone feel much more comfortable in their houses and experience less temperature inside the house. Similarly, they do not feel moisture during rainy season; where in different performances can be seen in wet zone by feeling more moisture during rainy season (figure 7 & 8).

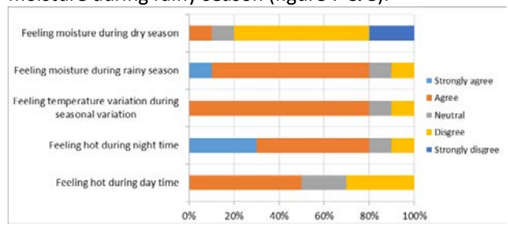

Figure 7: Occupant perception of temperature and moisture variation in wet zone

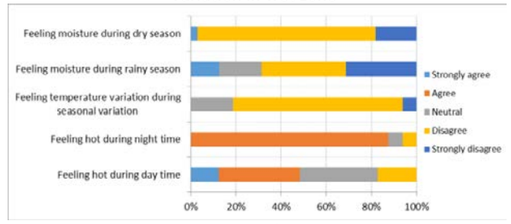

Figure 8: Occupant perception of temperature and moisture variation in dry zone

Overall 95% of the sample in dry zone liked, living in their mud houses, where only 50% of the sample were satisfied in wet zone (figure 9).

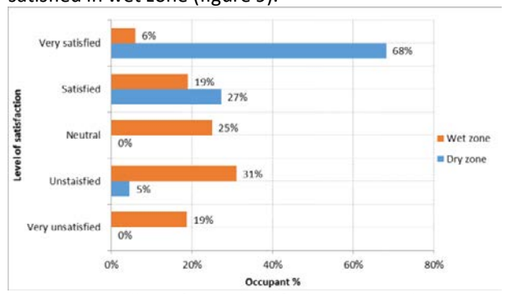

Figure 9: Overall satisfaction level for living in mud house

3.2 Comparison of thermal performance of walling materials

For the comparison of thermal performance of different materials, a two storey house was modeled and simulated by changing the different walling material; mud walls, brick walls and cement block walls (figure 10). Location of the house was assumed to be

Colombo. Two volume in both ground and upper floors were compared varying the walling types.

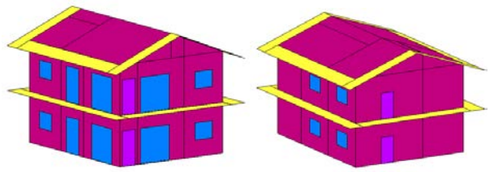

Figure 10: Two storey house modeled using software

Table 2: Specifications for two storey DEROB model

Item	Specification
Floor (Ground floor & first floor)	Slab thickness – 150mm. 2m earth layer below the ground level
Roof	Calicut tiles roofing. Ceiling under the roof. 300mm air gap.
Walls	Cement plastered
Floor to floor height	3m

Assuming that the house is located in Colombo, the main commercial hub of the country and the appropriate climatic file was used with the thermal properties that were found during the previous analysis for clay (Table 3) (Halwatura and Jayasinghe,2007).

Table 3: Material Properties (Halwatura and Jayasinghe, 2007)

Material	Conductivity (w/m.k)	Specific heat (wh/kg.k)	Density (kg/m^3)
Concrete	1.7	0.24	2300
RC. Concrete	1.28	0.26	2100
Cement mortar	0.93	0.29	1800
Brick	0.5	0.2	1300
Air Space at 21 C	0.024	0.28	1.201
Sand	0.4	0.24	1700
Earth	1.4	0.22	1300
Burnt clay Brick	0.7	0.15	1400
Cement plaster	1.3	0.28	2000
Calicut tile	0.9	0.24	1900
Ceiling sheet	0.22	0.26	900
Timber	0.16	0.7	800
Clay	0.45	0.25	1900
Cement block	0.95	0.1	2000

Each volume in both ground and upper floors were compared varying the walling types. According to figure 11, in ground floor, all three types of walls shows similar performance throughout the day, but cement walls shows lesser temperature during the morning hours and it reaches to a higher-level during day time and again decrements during evening than brick and mud walls. Overall, there are considerable temperature differences between outdoor temperature and indoor temperature in all three types of houses.

In the first floor, almost similar thermal performances are shown in all three houses, where in cement walls have lowest temperature during morning hours and it is lesser than outdoor temperature. Further, during day time, when compared to all three wall types, mud walls show the lowest indoor temperature and the difference shows as 1^{o}C than cement walls. This was mainly due to the high thermal conductivity and less specific heat capacity of cement than clay.

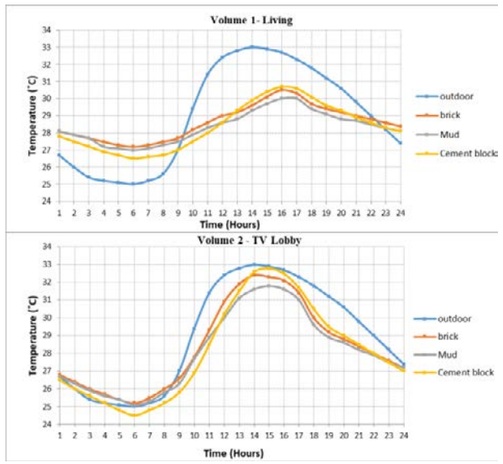

Figure 11: comparison of other walling materials – ground floor and upper floor

Similarly, the temperature in mud walls reduces during the daytime than cement and brick walls. This is mainly due to the high thermal mass and the moisture content in the mud which also contributes to maintaining the indoor temperature and to keep it in lower range over the day.

4. CONCLUSION

This research was carried out to understand the thermal performance of mud walls with compared to conventional walling materials; bricks and cement blocks in the country. Further, it was analyzed, how mud houses perform in wet and dry climatic zones to meet the level of occupants' satisfaction. During the research, two similar types of mud houses were selected in dry and wet zones as the experimental model for the study. Using on site measurements and Derob-LTH simulations, thermal conductivity and specific heat capacity in mud walls were found.

The study concludes that mud houses have more occupant friendly indoor environments and more effective performance in dry zone than the wet zone. Further, it was proved that mud walls have less indoor temperature than brick or cement block walls during day time. The results further concluded that mud houses perform extremely well in dry zone providing maximum comfort to the occupants.

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Including indoor vertical greening installation influence in building thermal and energy use simulations

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ABSTRACT: The thermal load on urban buildings is expected to increase owing to the adverse influence of a warming climate. As means to address such heat-related risks, green infrastructure enhancements have been widely supported in recent times, while the challenge of realising enhancements in densely built cities has demanded the consideration of vegetated architectural features. Although early efforts promoted horizontal greening, 'vertical greening' has gained increased prominence in recent times. This paper examines the hypothesis that this typology serves to enhance the climate resilience of urban built environments, and does so by presenting an analysis pathway including a novel one-dimensional model (VGM) coupled with the TRNSYS modelling framework to estimate the microclimate and energy use implications of their implementation. The pathway's application at an indoor atrium study highlighted the installation to contribute to a net annual space-conditioning energy consumption saving when air-conditioning was simulated.

KEYWORDS: vertical greening; vertical greening model; sheltered environments; microclimate modification; space-conditioning energy use; atrium case study

1. INTRODUCTION

To address ever-worsening heat-related risks in cities, green infrastructure enhancements are widely supported. The challenge of achieving enhancements in densely constructed cities however has compelled the consideration of vegetated architectural features [1,2]. Early efforts promoted horizontal greening (i.e., greenroofing), although in recent years 'vertical greening' (VG) has gained increased attention to exploit the underutilised vertical surfaces of urban buildings [3]. This paper is concerned with the hypothesis that VG and its two principal categories of green façades (GF) and living walls (LW), serve to enhance climate resilience in urban built environments. This is examined here by approximating the influence of an indoor installation on the thermal and energy use estimates of the host building, and does so by coupling a novel one-dimensional vertical greening model (VGM) to the TRNSYS building energy model of the selected case study [4]. This study is named here as the indoor atrium in the David Attenborough Building (DAB) sited in Cambridge, England (temperate, Cfb).

This four-storey atrium's northwest surface is host to a three-storey living wall installation that is 13 m-high and 91 m^2 in area, with ~8,750 evergreen plants from twenty-four species planted onto a soil-based, modular interlocking crate system [5], (see Figure 1). The atrium at present is naturally ventilated.

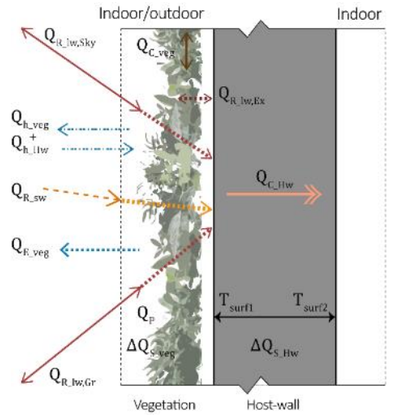
a) b)

Figure 1. Extract from the DAB section showing the four-storey atrium volume (a); and the living wall in its current state (b).

2. METHODOLOGY

To approximate the influence of the above-described DAB indoor installation, the novel VGM and TRNSYS coupling pathway introduced and validated in [4] was implemented. This VGM considers the inclusion of a vertical greening system as the addition of a 'layer(s)' to the face of an existing host-wall construction. For direct green façades this takes the form of a 'plant layer' with a defined canopy depth (z_{veg}) and leaf area index (LAI), while for living walls a saturated 'substrate layer' is also included between the plant layer and the existing host structure. This simplified layered representation was coded in MATLAB as the VGM to calculate one-dimensional flux from vegetated façade constructions (Figure 2), which can then be coupled with a TRNSYS model of a building construction to receive surface flux and temperature modifications [4]. This coupled pathway can be used to study the impact of including such installations, typically as either influence on comfort parameter modifications or space-conditioning energy use implications. The latter is considered in this paper for the DAB case study.

Direct green façade (GF)



Living wall (LW)

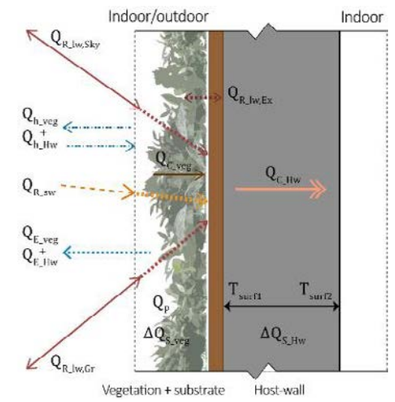


Figure 2. Vertical greening (direct green façade and living wall) energy interactions included in the VGM [4].

Where,

$Q_{R_{sw}}$	Shortwave solar radiation gain (outdoor); or attenuated transmission and/or artificial lighting gain (indoor)
$Q_{R_{lw}}$	Total longwave gain
$Q_{R_{lw_{Gr}}}$	Longwave gain from ground
$Q_{R_{lw_{Sky}}}$	Longwave gain from sky
$Q_{R_{lw_{CS}}}$	Longwave gain from contextual surfaces present (outdoor); or exchanges with contextual bounding surfaces (indoor)
$Q_{R_{lw_{Ex}}}$	Longwave exchange between plant leaves and host-wall (with GF), or substrate (with LW)
$Q_{R_{lw_{veg}}}$	Longwave emissions
$Q_{h_{veg}}$	Sensible heat convection
$Q_{E_{veg}}$	Latent heat convection from transpiration
Q_P	Biochemical storage from plant photosynthesis
$Q_{C_{veg}}$	Conduction through stems to the supporting host layer (with LW) or ground (with GF)
$\Delta Q_{S_{veg}}$	Storage in plant matter

The DAB configuration was accordingly simulated in TRNSYS, with and without vertical greening interventions applied as described by the scenarios presented in Table 1. The resulting Impact was then quantified and reported as vertical greening surface flux and space-conditioning energy consumption modifications.

Table 1. Simulated DAB case study scenarios.

Scenario		Status	Space-conditioning	
			Atrium	*Adjoining room*†
Bw-Nv	Bare wall in atrium	Hypothetical	*Nv*	Heating only
Bw-AC		Hypothetical	Cooling	Heating + cooling (AC)
GF-VGM-Nv	Green façade (GF)	Hypothetical	*Nv*	Heating only
GF-VGM-AC		Hypothetical	*AC*	Heating + cooling
LW-VGM-Nv	Living wall (LW)	Existing	*Nv*	Heating only
LW-VGM-AC		Hypothetical	*AC*	Heating + cooling

Notes: †Room directly behind installation. Suffixes '***-Nv***' = natural ventilation; and '***-AC***' = cooling added/air-conditioned.

3. FINDINGS

3.1 Surface temperatures

Surface temperature modifications were assessed with reference to mean temperatures from leaf (T_{leaf}), host or substrate (T_{Hw} | T_{sub}), and TRNSYS output for the host-wall facing the DAB atrium volume (T_{surf_1}). The summertime data as expected presented much warmer temperature means. The level 2 (L02) midlevel wall section notably presented the warmest for the summer and winter *Nv* and *AC* datasets. This suggested the significance of disproportionate internal gains, with relatively greater received by the midlevel from surrounding occupied zones; the effect of which was pronounced during the heating period than in the summer.

3.2 Surface flux

The annual surface flux results showed that the mean net flux out of the walls (and into the atrium space) had substantially decreased following vertical greening application, relative to the bare wall (*Bw*) simulation and under both space-conditioning scenarios (Figure 3). With green façade addition the net annual flux was directed into the installation for day and night-time durations, while with living wall application this was valid for the daytime only. The inward flux was mostly affected by the summer mean, which was directed inwards for all vertical greening scenarios. Winter mean flux in contrast was always in the outward direction for all scenarios.

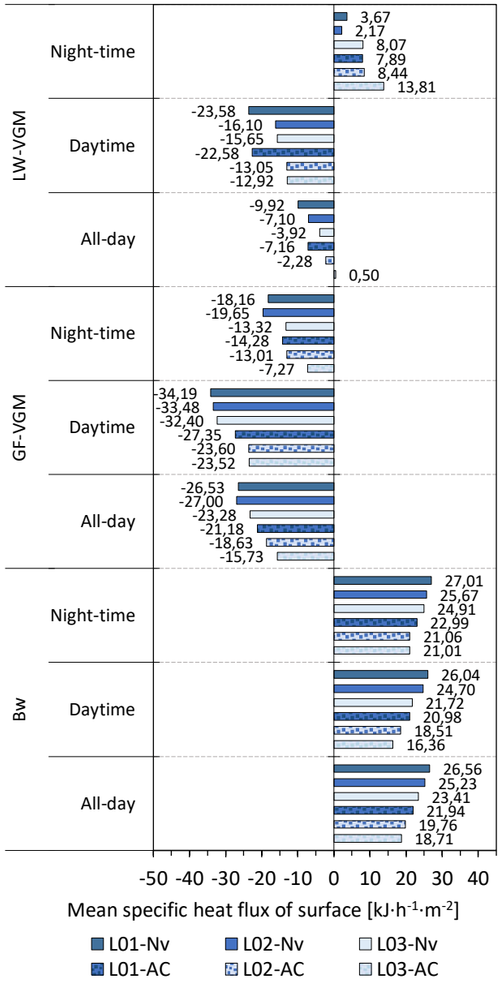


Figure 3. DAB, annual mean specific surface flux for walls, by floor level and scenarios.

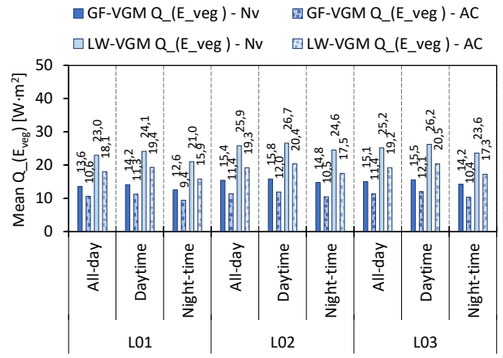


Figure 4. DAB, summer mean vegetation latent flux contributions by floor levels and scenarios.

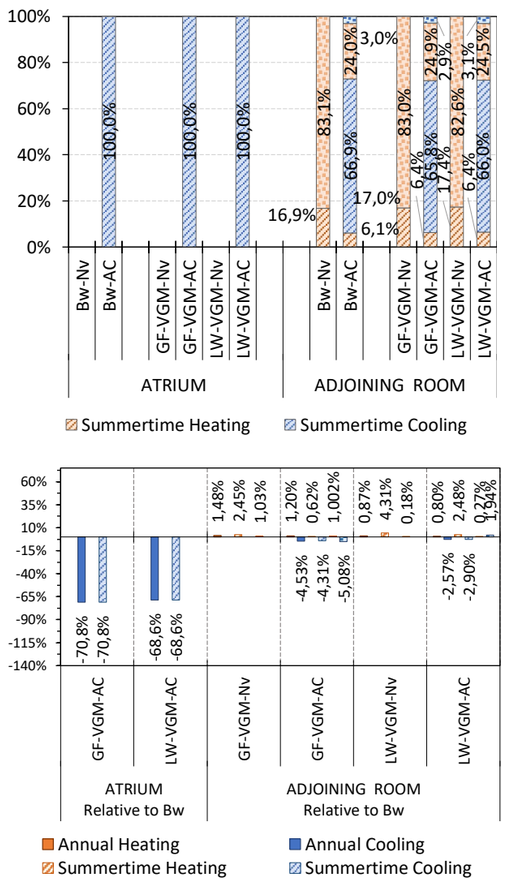


Figure 5. DAB, annual mean energy usage representation for scenarios (above); and space-conditioning energy consumption modifications for rooms and scenarios (below).

3.3 Energy use

The surface flux modifications of vertical greening application impacted on space-conditioning energy consumption of the scenarios. Both green façade and living wall application marginally increased annual heating energy consumption in the adjoining room under the natural ventilation (*Nv*) scenario by 1.48 and 0.87% respectively, and by 1.20 and 0.80% under the air-conditioned (*AC*) scenario (Figure 5). Living wall application therefore presented a relatively lower annual increase than with green façade application, which suggested influence from the wintertime insulating function of the additional substrate layer. The annual increase however was mostly contributed to by the summertime increase, with living wall application presenting greater contribution than green façade application to suggest the significance of increased heat loss from greater evapotranspiration at the living wall surface. With the *AC* scenario adjoining room cooling energy, both green façade and living wall application decreased annual consumption by 4.53 and 2.57% respectively, owing largely to summertime reductions (i.e., increased heat loss to the atrium). Green façade application in this regard was more beneficial with cooling consumption reductions offered in both summer and winter, which in turn suggested that the insulation uplift of the living wall substrate to have countered some of its surface cooling benefit.

4. DISCUSSION

The DAB case study atrium is an indoor volume that can be modelled within the TRNSYS environment to calculate surface and spatial energy balances. In addition to surface metrics, airnode metrics including space-conditioning loads were as a result available for discussing vertical greening thermal performance and influence. The representation of the atrium in the model however presented limitations that must be acknowledged and considered when interpreting results.

For such atrium arrangements as at the DAB where multiple airnodes are coupled, TRNSYS documentation recommends longwave radiation exchange to be calculated with the 'detailed view-factor method'. However, as the VGM is applied as an overriding surface gain, only the standard 'Starnode model' can be applied at present. This means that longwave exchanges from other atrium zones and multiple reflections within the zone are not included (this has marginal contribution to deviation). Furthermore, no airmass balance is calculated between the coupled atrium zones, which means that vertical flux exchanges resulting from buoyancy flow are not included (relatively greater contribution to deviation). These limitations mean that the TRNSYS approximation of this atrium environment is relatively coarser than reality, which then feedbacks to the VGM estimation [4].

4.1 Thermal performance

With the DAB indoor study, the central location of the atrium within the building's general arrangement, and the disparity in occupational demands of adjoining spaces, means that an energy deficit within the atrium volume is expected. This means that the dominant flux direction from the adjoining rooms will be into the atrium volume; from the said rooms, through the shared partywalls, and in the case of the vertical greening host, through to its outer surface represented by the installation. The occurrence of this is validated by the simulated vertical greening surface temperature at all floor levels (i.e., T_{surf_1}) being always cooler than the other side of the wall facing into the adjoining rooms (i.e., T_{surf_2}).

The addition of the hypothetical vertical greening installation served to decrease the mean flux into the DAB atrium volume, and thereby reduce mean T_{surf_1}, and increase the $T_{surf_1} - T_{surf_2}$ difference relative to the bare host wall scenario (i.e., *Bw*). The flux reduction was negative (i.e., into the wall) during the summertime to highlight a heat sinking or cooling influence for the atrium volume. This influence was best demonstrated with reference to the air-conditioned scenario (*AC*), where it contributed to substantial reductions in cooling energy consumption. With the adjoining rooms, atrium vertical greening addition also served to increase the drawing or sinking of energy from the said rooms. Relatively higher outward flux/heat loss in this manner resulted in the increased heating demand and consumption simulated for these rooms; while when the *AC* scenario was considered a beneficial reduction in cooling energy consumption was simulated. The flux modifications presented were therefore beneficial in the summer, although an adverse influence in winter (given that the installations are evergreen and provide continuous ecosystem service provision). With both the atrium and adjoining rooms, the marginally better performance simulated with the green façade installation relative to the living wall is attributed to the influence of the heat storage properties of the latter's substrate. This was exemplified by mean T_{surf_1}, where living wall means were marginally warmer than with green façade application.

The above highlighted the partitioning of the installation surface flux as latent flux to contribute towards a cooling energy consumption reduction for the DAB atrium. Examining net annual expenditure however revealed that this saving only materialised with the *AC* scenarios (possible future state), with green façade application providing a greater saving (71%), than with living wall application (69%). The adjacent rooms in contrast reported only marginal net energy use savings, with green façade application again providing a greater 2.0% saving, than the 1.1% with living wall application. The natural ventilation (*Nv*) scenarios highlighted that net

energy use for the adjacent room increased by a larger 1.5% with green façade application, than 0.9% with living wall application (given that the atrium included no space-conditioning energy demands). These net consumption results highlighted the relative significance of installation siting within a given building's arrangement, while the influence of the living wall substrate zone and its thermal properties had significant bearing on whether the installation presented a net benefit.

4.2 Humidity influence

Any increase in surface latent flux translates to increases in proximate absolute (AH) and relative humidity (RH), with subsequent diffusion into the surrounding microclimate. The DAB atrium simulation data highlighted an uplift in surface vapour flux following vertical greening application, with daytime evapotranspiration output as the largest contributor (plant transpiration at night is minimal as stomata are closed, [6,7]).

Summer output at the installation was significantly greater than in winter. This is explained by the ratio between the slope of the saturation vapour pressure function and air pressure, rapidly increasing with background air temperature, which in turn means that the latent flux is dominated by radiant energy input, received most during the summer [7]. The greater vegetation contribution from living walls relative to green façades is attributed to the former's plant profile, which has a greater LAI and canopy depth (z_{veg}); while the overall greater latent flux contribution from living walls is attributed to the additional flux from its saturated substrate.

Humidity additions could remain trapped in sheltered environments if background wind velocities and resultant humidity advection is minimal [3,8]. This in turn could present a challenge to both the health and comfort of occupants of such sheltered environments by increasing fungal colony-forming units (CFU) [9], while also increasing risk of thermal discomfort to occupants by inhibiting evaporative cooling from perspiration [3]. These risks are far greater in indoor environments such as at the DAB, where the atrium could be considered as a near closed system with only controlled ventilation. The dissipation of contributions is somewhat aided by the presence of a prevailing stack-flow, as identified by previous monitoring results [5,8,10]. This however is unique to the spatial arrangement of the atrium system, and not relatable to all indoor application environments. In generic sheltered environments the necessity for providing enhanced ventilation flow paths is therefore a key consideration of vertical greening installation design and siting. This will not only mitigate risks from humidity accumulation but will also serve to enhance the plant evaporative flux (and living wall substrate) by keeping the foliage coupled to relatively desaturated airflow.

5. CONCLUSION

This paper presented the application of a novel one-dimensional VGM coupled with TRNSYS, to approximate the influence of an indoor VG installation on the thermal and energy use estimates of the host building (i.e., the DAB). The application of this coupling highlighted vertical greening addition to present a net annual space-conditioning energy consumption saving when air-conditioning was considered (69 or 71% for the atrium and 1.1 or 2.0% for the rooms behind, with either living wall or green façade application respectively). The current natural ventilation and heating only profile however presented a modest net increase resulting from the wintertime cooling influence provided by the evergreen installation (0.9 or 1.5% for the rooms behind with living wall or green façade application respectively). Green façade application therefore had greater influence on net annual space-conditioning energy consumption at this indoor study than with living wall addition.

6. ACKNOWLEDGEMENTS

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PLEA 2022 SANTIAGO
Will Cities Survive?

Evaluating energy efficiency in housing

Tools for a 30% reduction of conventional energy in social housing

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ABSTRACT: This paper presents the tools used to evaluate social housing projects that were developed to show the feasibility of achieving a 30 % reduction of conventional energy demand. Eight projects in different climate zones and latitudes. The project proposes four levels of energy efficiency, comparing existing housing projects with improved thermal insulation, better bioclimatic design and integration of renewable energy systems. The designs were developed by different provincial housing authorities so a series of evaluation tools were developed to check the improvements and promote designer participation. The results show the differing levels of energy reductions and the performance variations of design strategies according to climate and solar radiation over the wide range of latitudes and altitudes found in Argentina. The results show that the objectives are feasible with different levels of efficiency in the wide range of conditions analysed.
KEYWORDS: Social housing, design tools, thermal insulation, solar collectors, bioclimatic regions.

1. INTRODUCTION

This paper presents the development of tools to evaluate and promote energy efficient social housing projects, aiming to achieve a 30 % reduction of conventional energy in Argentina [1]. Thermal standards for social housing have remained largely unchanged over the past 30 years, while the private sector has limited and ineffective standards [2]. By 2017, the combination of falling national fossil fuel production and increasing demand, encouraged by partial subsidies lead to importation, contributing to the national economic crisis. In Argentina, 38 % of final energy demand corresponds to the building sector, with housing responsible for 27 % of the total [3]. The current world energy crisis, post-Covid and the Russia-Ukraine conflict has added further urgency to improve energy efficiency in housing, especially for the low-income sector.

There is an urgent need to reduce energy demand through greater efficiency in the housing sector to reduce imports, subsidies and economic impacts. The housing sector in Argentina is highly dependent on gas, which supplies 71% of the total energy demand for heating, cooking and water heating. 27 % of the rest is electricity, but 48% of the electricity is generated using gas, so an additional 13 % should be added, bringing the total dependence on the housing sector on gas to 84 %. As imports are growing, the higher cost of imported gas, compared with local extraction, has a high social and economic impact. Therefore, the object of the study is to evaluate the contribution of energy efficiency in new social housing.

The project aims to test the effectiveness of new improved energy standards, such as IRAM 11900, housing energy performance and other IRAM Standards [4, 5, 6, and 7]. These advances require improved implementation and evaluation in housing developments in different regions, representative of the wide climatic range of the country.

This paper presents the evaluation process undertaken to test and validate improved design and construction and the development of tools to predict future savings in three key areas, better thermal insulation of roofs, walls and windows, improved bioclimatic architectural design and passive solar systems, and the incorporation of renewable energy for solar water heating and PV electricity. The resulting reduction of green-house gas emissions is also estimated.

2. PROJECT DEVELOPMENT

2.1. Experimental design

The project involves the design and evaluation of houses in 8 different climates, with 4 different thermal performance standards and 4 different plot orientations. This requires a total of 120 units to compare results with each variable. Each project located in different provinces has 16 housing units with the following design requirements implemented in four designs in plots with access from four different orientation:

1. A nearby large housing development of about 80 units without improved thermal insulation is used as a control to compare energy demand with improved housing.

2. Four housing units with the same design as the existing project, but incorporating substantially improved thermal insulation in walls, roof and windows.
3. Four housing units with improved bioclimatic and solar design as well as improve insulation, using strategies such as form, orientation, grouping, window size and location.
4. Four units with the same design as level 3, but with the addition of renewable energy installations such as solar water heaters and PV modules.

2.2. Climate data

Table 1 shows the location and climate of the 8 final locations, with basic data such as latitude, height above sea level and heating degree days.

Table 1. Locations of the housing projects with latitude, altitude and annual degree days (base 18° C), climate and temperature range.

Location and province	Latitude	Altitude, m	Degree days	Climate Zone, IRAM 11603 [5] and subzone (temperature range).
1. Formosa, Formosa.	26°	60	40	Ib. Very warm, low range
2. Tafí Viejo, Tucuman	26°	481	481	IIB. Warm, low temperature range.
3. Salta Capital, Salta	25°	1225	703	IIIa. Temperate upland, high range.
4- San Martin, Mendoza	33°	820	1135	IVa. Temperate, cool, high range
5. San Nicolas, Buenos Aires	33°	30	909	IIIb. Temperate, low range.
6. Rawson Chubut.	43°	40	1673	IVc. Cool temperate.
7. Zapala, Neuquén.	47°	600	2800	VI. Very cold
8. Ushuaia, Tierra del Fuego.	55°	14	4485	VI. Very cold

See locations in Figure 1.

During project development, 4 locations were modified, requiring new climatic data and solar radiation estimates for the new sites in different towns and latitudes, especially for locations without nearby meteorological stations; latitude and height above sea level were used to estimate adjustments the temperature, while the solar atlas for Argentina [6] was used to obtain values using ground-based measurements.

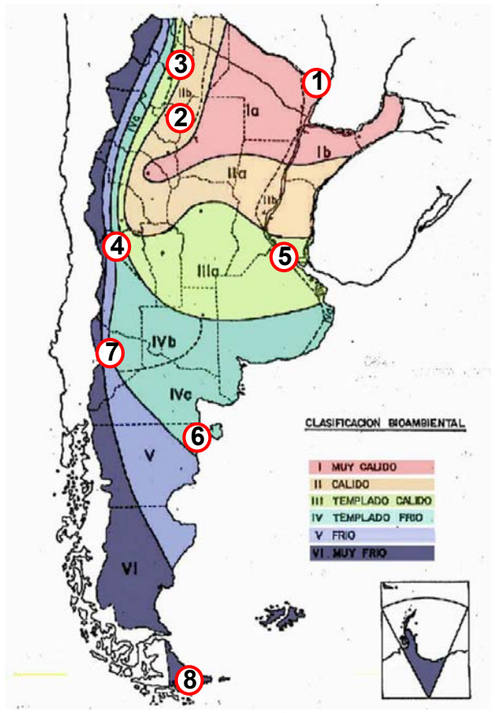

Figure 1. Bioclimatic zones of Argentina, based on IRAM Standard 11603, with the locations of projects evaluated in this study. Numbers refer to Table 1.

The latitudes of the projects studied range from the warm humid subtropical region in the north of the country, latitude 23° S, to high latitude cold climates at latitude 55° S and upland regions above 1000 m. To illustrate the very wide range of climates, the location in Formosa has a latitude equivalent to the north of Africa, while Ushuaia has a similar latitude to the south of Sweden. The degree days, base 18° C, show the wide climate variation with limited heating requirement in the north, as the example of Formosa shows with less than 45 degree days, and Ushuaia in the south has nearly 4500 degree days.

In addition to the evaluation of potential conventional energy saving, the project aims to promote improved conventional design and construction in the different Provincial Housing Institutes selected for this study and, encourage them to use the same tools to evaluate their proposals without additional external support.

2.3. Spreadsheets

The evaluation tools were developed and applied to achieve a rapid evaluation of multiple and evolving projects, using electronic spreadsheets. These tools include the following characteristic and advantages:

- Databases for all required variables are included, with selection of options from pull-down list, ensuring the selection of valid data and ease of use.
- Spread sheets are not executable and files have a limited size without macros so they can be sent by e-mail
- Saving multiple copies can record variations and alternatives to document the results of evolving designs.
- A simple colour code identifies input variables, fixed values and results.
- Numerical values and graphs show results immediately after each data input to evaluate each variable, facilitating parametric studies.

The spreadsheets, specially developed or adapted for this project, cover the following complementary areas of energy performance:

- Thermal transmittance for each opaque building component is calculated and compared to levels of performance specified by national standards [4, 7] and as well as the additional requirements for social housing. The spreadsheets can also estimate time-lag, decrement factor, and thermal admittance, with similar procedures to OPAQUE (Milne, 2013).
- Conventional energy demand for heating is calculated, considering internal gains from occupants, conventional energy use and other gains, such as solar gains and metabolic heat, based in the method of IRAM Standard 11604 [XX] according to the building envelope [5].
- Hourly indoor temperatures and eventual summer cooling demand for each room are based on solar and internal gains, steady state and periodic heat performance and ventilation strategies, using the admittance method [XX]. This tool is used to check for summer overheating and explore design options to reduce or totally avoid the need for artificial cooling.
- Solar water heating contribution to reduce conventional energy demand is calculated according to the efficiency of conventional water heaters, efficiency of solar collectors, orientation and tilt, surface area, storage capacity and typical daily hot water demand. The resulting conventional energy demand and greenhouse gas emissions are calculated according to combination of conventional heaters and solar collectors using the f-chart method.
- Grid connected PV panels are evaluated to estimate the annual useful energy generation, according to slope, orientation, size and PV technology [xx].

In addition to energy demand and potential savings, the tools show 'in use' economic benefits and reductions in greenhouse gas emissions, according to the current residential tariffs and national emission factors for gas and electricity published by the Secretary of State for Energy.

The following methods are used to calculate other energy requirements for gas cooking and electrical appliances and lighting. The estimate the energy demand for cooking uses a relation with average monthly temperatures (Gil, 2018) as higher monthly temperatures are associated with lower cooking demand. A proportion of the cooking energy contributes to heating demand in winter. The electricity demand for lighting and appliances is estimated using average national household values, checked against household surveys of the central region. A constant value is used for all locations as data for regional differences is not available.

3. RESULTS

Monthly conventional energy demand depends on the heating or cooling demand, considering solar and internal gains, as well as energy for cooking, hot water and electricity use. The results vary widely in different climatic locations, due to building technology adopted, variations in design and installations efficiency with conventional or renewable energy. Overall, the average reduction in conventional energy demand is just over 30%, with important variations responding to different climate conditions and solar energy intensities. The savings are greatest in colder climates such as Zapala and Ushuaia which also have the highest energy demand. Climates such Mendoza and Salta with favourable solar energy also perform well.

Figure 2 shows the results of percentage energy savings obtained in Mendoza, compared with the reference case. This temperate mid-latitude climate has favourable solar radiation. Figure 3 shows the reduction of gas demand for water heating using a solar collector, with the same surface area and two different generic technologies, local production of flat plate collectors or imported evacuated tubes. The later have higher efficiency and lower costs but cannot be repaired.

It should be noted that although most large cities have gas distribution, Formosa does not have an urban gas distribution network and most housing units have electrically heated water.

Finally, Figure 4 shows the annual output of electric energy for a square metre of a grid connected PV module for different locations using net metering. This option is now available following new national legislation, although some provincial authorities have not yet approved the adoption of 'distributed generation'. The complex requirements to approve connections tend to discourage small domestic applications. Another problem detected is the need to avoid partial shading of the modules as partial shadows can reduce output significantly.

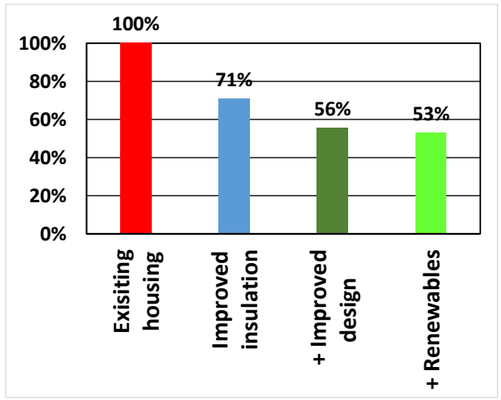

Figure 2: Percentage of the demand for conventional energy, compared with existing housing, 100% in the case of Mendoza, Latitude 32° Sur.

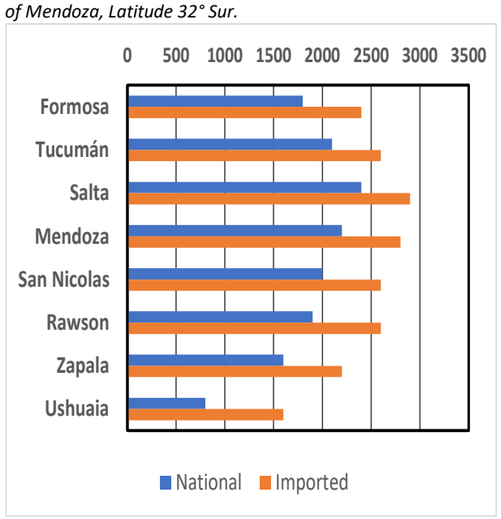

Figure 3. Annual contribution of solar collectors to reduce gas demand in kWh/año with national production of flat plate collectors and imported evacuated tube collectors, with the same surface area in all cases.

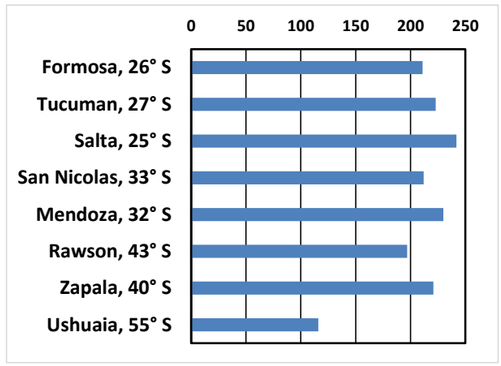

Figure 4: Output from 1m2 of PV module, in kWh / year, in locations with different latitudes and solar resources

4. DISCUSSION

Results show different cost-benefit outcomes according to climatic regions. The investment in improved energy efficiency in social housing can be evaluated with different criteria. In terms of the national energy situation, the need to reduce imported gas is critical, and energy efficiency will also reduce the existing requirement for gas and electricity subsidies. From the point of view of the occupants, energy costs are also important, but the requirements for heating and cooling installations are also relevant as this cost is not financed by the national or provincial authorities. The benefit of improved comfort in hot climates are primarily social as low-income families may have difficulties in installing and maintaining air conditioning units.

The provincial authorities have different priorities, The number of housing units produced by the provincial housing authority may be more important than the inclusion of energy efficiency measures. The reduction of national subsidies will increase energy costs and increase the provincial and municipal taxes included as a proportion of this amount. So, part of the national saving on energy subsidies produces a transfer of resources to the provinces.

As heating dominates the total energy demand in the centre and south of the country, thermal insulation is the most cost effective as the heating requirement increases. So, investments in cold climates such as Zapala and Ushuaia are most effective in reducing energy demand, while in warmer climates with low energy demand have lower absolute energy savings. However, the social benefits need to be considered.

As figure 3 shows, PV panels have similar outputs from close to the tropics to the higher mid latitudes, 24° to 45°, despite variations in cloud cover and solar incidence angles. But PV modules in Ushuaia, latitude 55°, have half the output of the favourable central region, due to high cloud cover, low angle sun and shading from mountains.

Therefore, investments in PV modules in this location do not provide a reasonable return and improved insulation allows similar energy saving and reduction in green-house gases at lower cost. The spreadsheet tools allow this analysis at an early stage in project development, avoiding later design changes. However, the electrical installation for later PV installations can be incorporated at low cost, allowing the eventual addition of PV modules when costs are lower in the future.

Solar water heaters show greater variation as the results depend on the initial water temperature as well as outdoor air temperature and solar radiation intensity. In low latitudes with high outdoor air temperatures, little energy is required to raise water temperature, indeed many low-income households shower with cold water This results in a lower reduction of conventional energy and lower benefits in reduction of greenhouse gases than in temperate climates.

As a result of the energy efficiency measures studied in this project, the thermal insulation standards for social housing have been improved, and the standard for establishing thermal insulation levels of wall and roofs have also been improved to allow a progressive improvement over time. At the start of the project, the standard established for thermal insulation is 'C', the lowest level which aims to avoid condensation problems. As a result of the studies, the level has been improved to 'B' of IRAM Standard 11604. The proyect also introduced a new intermediate level 'A-B' to achieve further improvements in performance,

6. CONCLUSIONES

The most important contribution to the reduction of conventional energy is thermal insulation with an overall reduction on conventional energy by 12-25 %, without affecting the quality of life of the occupants. This is followed by improved architectural design by about 10-15 % and grouping of houses at the urban scale, 3-6 %. This allows the achievement of a reduction of the conventional energy demand by 30-44 %. Although the aim of the project is to achieve a percentage reduction, the absolute saving is more important than the relative difference, as total energy is highly dependent on heating demand. This varies greatly as the degree days shown in table 1 show.

Energy savings from improved insulation are greatest and most cost effective in cold high latitude climates. However, improved insulation provides important social benefits in warm low latitude climates in summer and winter months.

The application of the tools allows the evaluation of a large number of projects in different climatic zones in a short period of time. This is important to incorporate the favourable results during the design process and avoid decisions that not do not achieve energy efficiency. The evaluation tools presented in this paper are important to inform the designers and allow a wider participation in the implementation of energy efficient design resources.

The improvement of new social housing will have an important impact on the energy demand and the quality of life of the occupants, this will support the progressive improvement of the housing stock for this sector in the long term. However, this will not affect the existing housing stock or the new housing in the private sector.

The results presented in this study were obtained by the application of the evaluation and optimization tools that contribute to the promotion of sustainability in social housing. The same tools can be applied in the private sector and the evaluation of improvements of the existing housing stock, the most important challenge to achieve a significant reduction of the energy demand, control of emissions and an improvement of the quality of life.

The paper shows that a 30% reduction in the conventional energy demand of new housing is technically possible, using available measure of energy efficiency. The cost for the eight housing projects was estimated was estimated at about 10%, thought in certain cases the cost of improved thermal insulation was estimated to be the same as the cost of conventional construction. The next challenge is to implement the measures through political and economic decisions to achieve the social and environmental benefits that contribute to the promotion of liveable cities and sustainable development.

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PLEA SANTIAGO 2022
Will Cities Survive?

Influence of mass and insulation in building retrofitting

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ABSTRACT: The building envelope of old buildings is usually composed of a single layer with high mass and without thermal insulation, which characterizes its thermal behaviour. Retrofit actions tend to accomplish with thermal building regulations by adding a thermal insulation layer in the building envelope, but the effects of mass and thermal inertia are usually ignored. In this work, we monitored two single-family houses located next to each other for one year. They are comparable in size, composition, and orientation, but were built with one hundred years of difference. The façade of the old house (House 1) has a single layer of stone. The newer house (House 2) has a multi-layer façade with thermal insulation. The annual results of temperature have not presented significant differences. But, in the winter and summer week, under free-running operation, House 1 presented less temperature fluctuation compared with House 2. In winter, the mean temperature was similar, but in summer House 1 remained cooler than House 2. These results indicate that the effects of mass in the thermal behaviour of old buildings should be considered before undertaking retrofit actions and the addition of a thermal insulation layer.
KEYWORDS: Mass, thermal insulation, retrofitting, thermal inertia, building stock

1. INTRODUCTION

Urban areas have increased in number and extension in the last century. This is a phenomenon affecting worldwide that implies an environmental impact on land use and material resources. At the same time, cities count on consolidated urban fabrics with buildings that have not exhausted their lifespan yet. In Spain, according to the population and housing census carried out in 2011 [1], 793.401 dwellings were built before 1900, an 8% of the total in 2011. If we consider the dwellings built before 1950, the number raises to 2.072.302, which represents 21% of the building stock [2]. Old buildings are often abandoned or demolished. However, they could be reused for similar or different purposes if they are in acceptable condition. Retrofit actions add value to existing buildings by smartly updating them to current requirements.

The year of construction gives important information for old building retrofitting because it determines the building system, especially the characteristics of the envelope. This part of the building is where thermal exchanges take place and has an influence on the building's thermal behaviour. Most old buildings are characterized by heavy façades composed of a single layer made of stone or brickwork, providing them with high building mass. In old constructions, façades used to be heavy structural elements that supported the weight of floor slabs which, before the emergence of concrete structures, were not as heavy as today.

Mass and insulation characterize the building envelope. Insulation materials hinder the heat transfer providing high thermal resistance. On the other hand, the main consequence of mass is the delay of the thermal conditions indoors and the reduction of the amplitude of the thermal wave (thermal inertia). Some countries have thermal building regulations that fix the limits of the thermal transmittance (insulation) of the envelope, depending on the harshness of weather and other factors [3]. However, mass is not specifically included in regulations and the thermal performance of the building falls on the thermal transmittance value of the envelope.

When facing the retrofitting of old buildings in compliance with regulations, a low-density thermal insulation layer is usually added inside or outside the envelope [4,5], while mass and its thermal effects tend to be ignored [6]. However, massive walls also produce a certain reduction in the heat flux through the envelope and influence the dynamic behaviour of the building. Therefore, it should be considered before undertaking an integral intervention in the building [7,8].

In this paper, it is questioned to what extent the effect of mass could counteract the effects of thermal insulation in old buildings [9,10]. The objective is to contrast the effects of mass and insulation on buildings' thermal performance. To this end, we measured and compared two houses: one of them is a traditional house with massive walls and the other a contemporary construction with a multilayer insulated façade. We monitored air

temperature and relative humidity in each living room for one year. The situation and characteristics of both houses offer an opportunity for comparison of two different building systems under the same climate conditions. The extended old buildings' stock and the need for real data [11,12,13] are crucial for establishing old buildings' intervention strategies in consolidated urban fabrics.

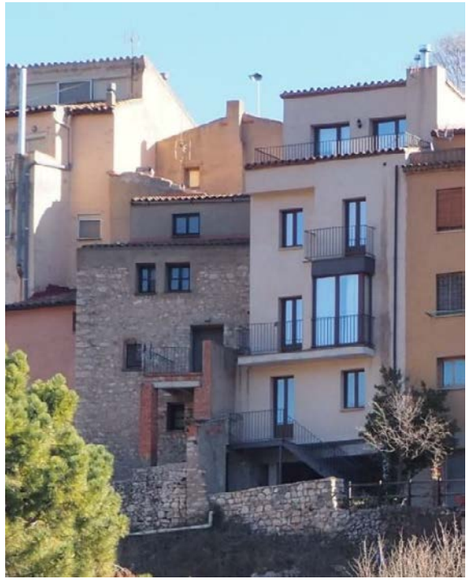
2. METHODOLOGY

2.1 Case of study

The case of study comprises two adjacent terraced single-family houses (House 1 and House 2) in a Spanish small town in the Coastal Catalan Mountain range (40°17'N), 750 m above sea level. According to Köppen's climate classification, this area has a warm-summer Mediterranean climate (Csb). The annual average temperature is 13,3°C with an annual and daily fluctuation of 17,9°C and 10°C, respectively. The annual average humidity is 70,3%. The annual pluviometry is 525 mm/year [14].

Both houses are east-west oriented and have a ground floor, two floors above ground, and two semi-basement floors. The access is on the ground floor; a lobby precedes the living room with an open kitchen. All spaces above ground are thermally conditioned. Their composition, surface, and volume are equivalent (Figure 1, Figure 2, and Figure 3).

Figure 1:
House 1 (left) and House 2 (right), west façade



Even though they are similar in shape and volume, their building systems are different. House 1 was built at the beginning of the 20th century with traditional means. Façade walls are 60 cm thick, with one layer of stone masonry (1,91 W/m²K). Windows have single glazing and wooden frame. House 2 was built in 2015 under thermal regulations and has a multi-layer façade with two ceramic layers (14+7 cm) and 5 cm of polystyrene thermal insulation (U=0,45 W/m²K). High-performance windows with thermal bridge breakage and double glazing complete the façade.

Figure 2:
Floor plan of the houses (in grey, the living room)

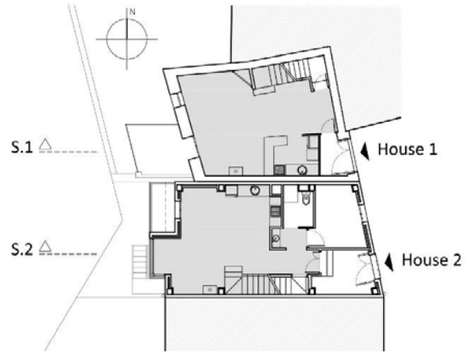
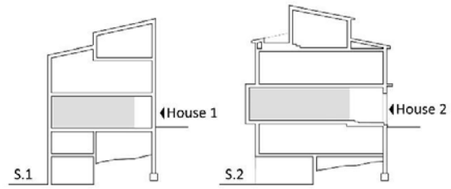


Figure 3:
Section of the houses (in grey, the living room)



Air temperature and relative humidity were monitored for one year in the living room of House 1 and House 2, with an area of 36,4 m² and 34,5 m², respectively. Both spaces have a façade oriented west with openings. The north and south partitions are in contact with other houses. The other partitions (horizontal and vertical) are in contact with indoor spaces. Table 1 and Table 2 show the details of the living-room envelope. For each element, there are four defining parameters: surface (m²), U-value (W/m²K), total mass M of the element (kg), and effective mass M' (kg). M' refers to the mass from the insulation inwards or half of the width if there is no thermal insulation. The listed elements are façades (F), windows (W), partition walls (PW), partitions (P), doors (D), floors (F), and ceilings (C), identified in Figure 4.

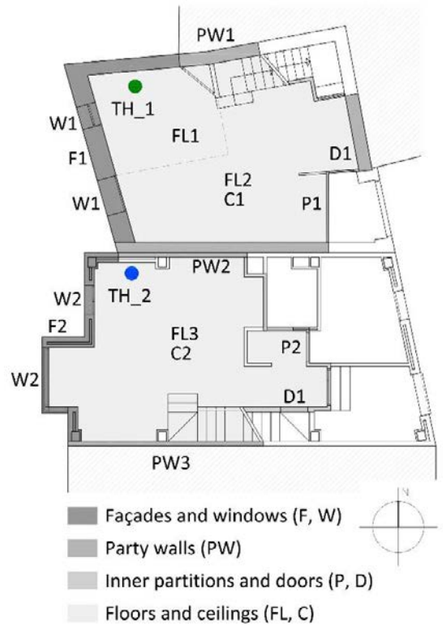
Table 1:
Characteristics of the building envelope, House 1

Code	S (m²)	U-value (W/m²K)	M (kg)	M' (kg)
F1	10,5	1,91	13192	6596
W1	3,1	4,30	77	77
PW1	7,2	-	6057	3028
PW2	14,8	-	14322	12454
P1	11,2	-	558	279
D1	2,8	-	-	-
FL1	8,3	-	2543	1271
FL2	28,1	-	8605	1652
C1	36,4	-	11148	5574
TOTAL	**122,4**	**-**	**56500**	**33581**

Table 2:
Characteristics of the building envelope, House 2

Code	S (m²)	U-value (W/m²K)	M (kg)	M' (kg)
F2	13,0	0,45	2493	849
W2	8,2	2,70	286	286
PW2	10,2	-	9830	1282
PW3	12,8	-	6438	1609
P2	14,2	-	926	463
D1	6,8	-	-	-
FL3	34,6	-	10585	5292
C2	34,6	-	10585	5292
TOTAL	**134,4**	**-**	**41142**	**15075**

Figure 4:
Floor plan with sensors position (TH_1 and TH_2), and identification codes of the envelope elements



2.2 Materials and methods

Data was recorded for one year, from October 2019 to September 2020 with two Data logger TESTO 175 H1. Sensors TH_1 (House 1) and TH_2 (House 2), were placed in an equivalent position on the northwest corner of the living room at 1,5 m height (Figure 4). The sensors were programmed to register values of air temperature (°C) and relative humidity (%) every 20 minutes, starting at the o'clock.

A weather station located 40 m away from the houses, managed by meteoprades.net, provided weather information (764 m altitude, UTM coordinates E 334739, N 4573418). Data obtained from this source were air temperature (°C), relative humidity (%), and solar radiation (W/m²). The timing of weather data registers was synchronized with the sensors.

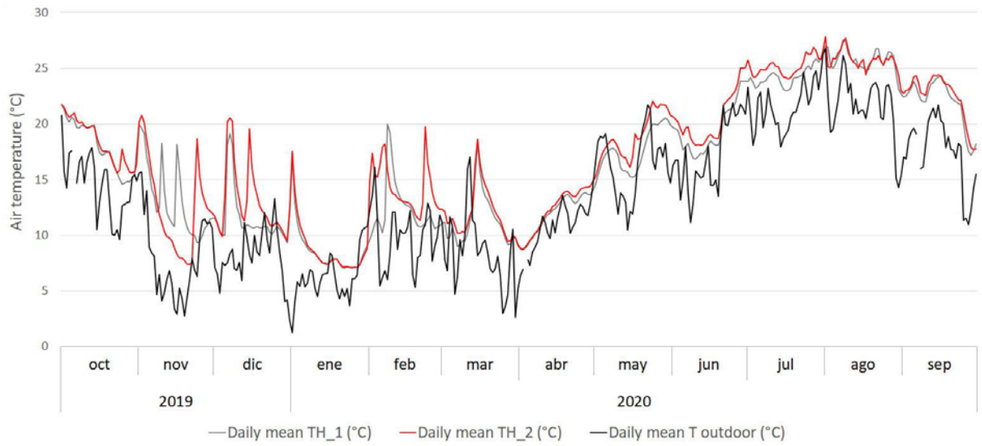
3. RESULTS AND DISCUSSION

The results of air temperature throughout the year show similar thermal behaviour in both houses. Figure 5 shows the daily mean indoor air temperature (House 1 and House 2) and the daily mean outdoor temperature in one year, from October 2019 to September 2020. The annual average temperature measured outside in the year of study was 13,14 °C. The annual average temperature measured in House 1 in the same period was 16,34 °C, and 17,02 °C in House 2. The occupation pattern of each house was not coincident during the year of monitoring, so the resulting mean temperature is influenced by this fact.

The annual variation of air temperature clearly shows the periods with occupation, especially in the winter season when active heating is operating. These days, air temperature reaches a peak value in a few hours, remains steady during the weekend or holiday (the time of stay), and slowly decreases in the following days. In summer, when internal thermal loads are caused only by occupation (there is no air conditioning system), such peak temperature values are not visible.

As houses are used as secondary or vacation homes, the occupation is not continuous all year round. This fact means that there are long periods without occupants, which offer the opportunity to compare the thermal performance of the two houses without the internal thermal loads caused by people or heating systems. In addition, the SARS-CoV-2 pandemic that started in March 2020 also implied a long period of personal confinement in Spain (2 months). Figure 5 shows this period without occupation from mid-March to the end of May.

Figure 5:
Indoor and outdoor daily mean temperature (October 2019 – September 2020)



Despite the similar thermal behaviour in one year, some differences are visible if we look more in detail. To this end, we chose two extreme periods and analysed them, a winter week (10-17/01/2020) and a summer week (8-14/07/2020). In these periods, both houses were in free-running thermal operation and without occupation.

Figure 6 and Figure 7 show the indoor temperature in the selected winter week. The indoor temperature in House 1 and House 2 is low and similar to the outdoor temperature. The mean temperatures are 7,75°C, 7,77°C, and 6,46°C in House 1, House 2, and the outdoor, respectively.

As for the daily temperature fluctuation, there is a small difference. The daily temperature fluctuation is slightly higher than 1°C in House 2 and lower than 1°C in House 1. In addition, House 2 experiments peak temperature values at noon, when the west façade receives solar radiation. House 1 has the same orientation, but the temperature does not increase in the same way.

In general terms, House 2 temperature remains slightly higher than House 1 at midday and slightly lower at night. The amplitude of the thermal wave in the house with higher mass (House 1) is lower than in the house with thermal insulation (House 2). Solar radiation has more influence in House 2 which, at the same time, does not store this heat during the night, since air temperature decreases more than it does in House 1. In House 1 there is less access to solar radiation, but the mass contributes to storing this heat during the night.

Figure 6:
Indoor temperature in the living room of House 1 and House 2 in the winter week (10/01/2020 to 17/01/2020)

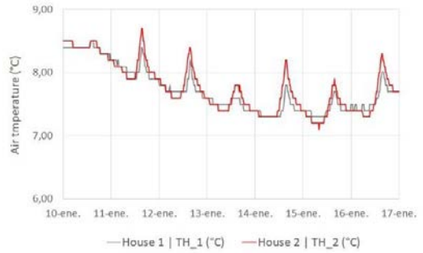
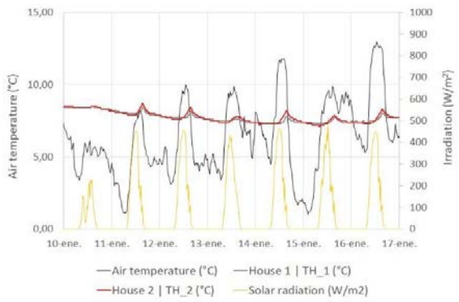


Figure 7:
Outdoor temperature and solar radiation during the winter week (10/01/2020 to 17/01/2020)



In the summer period, this difference is more perceptible. The air temperature in House 1 does not fluctuate as it does in House 2. In the old house, there is a difference of approximately 1°C between day and night. The peak value is reached in the afternoon when the west façade receives solar radiation. Then, the temperature decreases until the early morning when the temperature starts to increase again. In House 2, the temporal evolution of temperatures is similar. However, the peak temperature is higher. On average, the temperature fluctuation raises up to 2°C, with the maximum value in the afternoon. After this moment, the temperature decreases until the early morning of the day after, as it happened in House 1. It is also noticed that, in the summer week, the temperature in House 1 remains all the time clearly under the temperature of House 2. At midday, this difference is around 2°C. The mean temperatures this week, in House 1, House 2, and outside are 24,09°C, 25,03°C, and 20,42°C, respectively. The results show that, in the studied week, the old house remains cooler than the newer house all the time and on average.

Figure 8:
Indoor temperature in the living room of House 1 and House 2 in the summer week (08/07/2020 to 14/07/2020)

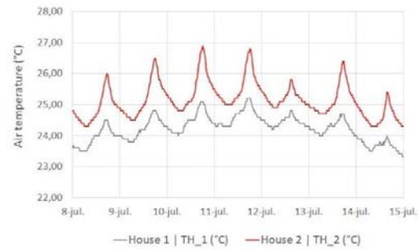
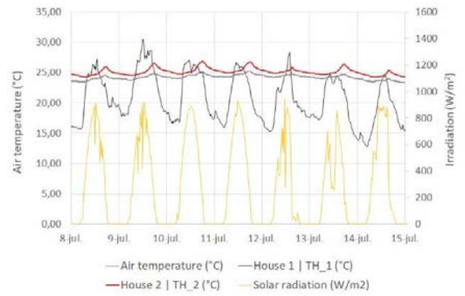


Figure 9:
Outdoor temperature and solar radiation during the summer week (08/07/2020 to 14/07/2020)



The initial hypothesis when starting the study was that the effects of mass and insulation in both houses would clearly appear in the measurements since their values are different. The effective mass (M') of the living room in House 1 is 33581 kg, more than double that of House 2, which is 15075 kg. The repercussion of mass on the volume of House 1 and House 2 is 364,3 and 164,5 kg/m^3 respectively because indoor volumes are very similar (92,2 and 91,7 m^3). Despite this difference, we have not noticed a visible thermal delay in House 1 with respect to House 2. Even though House 1 has a heavier façade than House 2, the mass is not enough to produce this effect. However, it seems to influence thermal fluctuation. The results of the winter and summer week have shown that, under free-running thermal operation, House 1 has a lower thermal amplitude than House 2. In both periods, the daily air temperature fluctuation remains under 1°C in the first case. However, the air temperature in House 2 fluctuates around 2°C in winter and summer. The maximum difference between day and night is produced in summer.

The different thermal amplitude can be attributed to the higher mass of House 1. However, the higher fenestration of House 2 and the access to solar radiation may also have influenced the results. Old houses tend to have small openings with limited access to solar radiation. It means that solar gains and transmittance losses are controlled. However, contemporary houses have higher fenestration surface, which implies that the access to solar radiation is higher but also the transmittance losses. In the studied houses, the envelope surface is comparable (122,4 and 134,4 m^2, in House 1 and 2) but the glazed surface is different, as shown in Table 1 and Table 2 (3,1 and 8,2 m^2 in House 1 and 2). Concerning thermal insulation, we calculated the unitary losses of the elements in contact with the exterior (façade walls and windows) and excluded the adiabatic surfaces. The result was 33,2 W/K in House 1 and 27,9 W/K in House 2. According to that, House 1 has 16% more thermal losses caused by thermal insulation than House 2.

According to the results, mass and the relation between façade walls and openings' surface seems to influence the thermal behaviour under free-running operation. The results show that the mean temperature in winter is similar in both houses but in summer, House 1 remains cooler than House 2 all the time. The higher access to solar radiation of House 2 in winter does not increase the mean temperature with respect to House 1, which has a similar value. However, in summer, the effects of solar radiation are much clear, because the mean temperature in House 2 in the week of study is 1°C higher than House 1. Other studies show that, in mild climates, a high mass is considered positive in summer periods while the benefits are lower in winter periods.

4. CONCLUSIONS

Old buildings with massive walls constitute a treat percentage of the building stock that needs to be updated to actual requirements. Intervention on the thermal envelope, especially in façades, is usually one of the most spread measures in retrofitting actions.

The results obtained in this study show a similar behaviour in two houses with different façade configurations under mild, steady conditions. The differences shown in the winter and summer week are not enough to justify the addition of a thermal insulation layer in the older house (House 1). However, as the analysed period consisted of a winter and a summer week without occupation, a longer interval would be needed to complete the thermal behaviour under other operational conditions.

As a conclusion, the addition of a thermal insulation in the case of historical constructions retrofitting is questioned if the characteristics of the envelope, such as the mass, are not considered previously. It would require checking the type, surface and orientation of openings, along with the physical characteristics of the façade such as mass and thermal transmittance before undertaking expensive and invasive retrofitting actions.

ACKNOWLEDGEMENTS

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A nationwide empirical study of residential electricity use in India

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ABSTRACT: Electricity demand from urban residential buildings in India is projected to rise driven by growth in air conditioning (AC). This paper empirically examines the seasonal variation (summer, winter) of residential electricity use in India using statistical analyses of survey data of 1,537 households with AC units (in the form of room AC units) representing four climatic zones and income groups. The survey data includes information on household characteristics, socio-demographics, cooling and non-cooling appliances, electricity use in summer and winter and level of energy awareness. High income households (n: 507) reported the highest mean monthly summer electricity consumption at 349 kWh followed by middle income households (n: 405) at 272 kWh, while low income households (n: 507) experienced the lowest mean monthly summer electricity consumption of 216 kWh. Mean monthly electricity use in summer was lowest in the milder temperate climate zone as compared to the more extreme composite and warm humid zones. When number of AC units increased from one to three or more ACs, residential electricity consumption (REC) almost doubled across summer and winter seasons. In households where the set-point temperature was 19°C, REC was found to be double that of households with 21°C. Based on the statistical method of Least Absolute Shrinkage and Selection Operator (LASSO) method, family size, floor area (m^2) and non-cooling appliances had the biggest influence on electricity use of AC households. It is vital that residential energy policy considers these factors along with the significant seasonal variation in electricity use prevalent in households with AC units.
KEYWORDS: Residential, Electricity, Survey, Household

1. INTRODUCTION

Cooling demand (mainly in the form of room-air conditioners) has been found to be a key driver of residential energy consumption in India, even though India has one of the lowest access to cooling across the world with per capita cooling consumption at 69kWh [1]. India also has the highest distribution of cooling degree-days anywhere in the world [1]. Rapid urbanization, higher incomes, lifestyle preferences and rising temperatures are driving more Indians to buy space cooling appliances. Complementary to this are the air conditioners sales projections in India which are expected to grow sharply from 42 million in 2019 to 240 million units in 2030 which will further increase the residential electricity demand [2]. In anticipation of this increase, Government of India launched the India Cooling Action Plan (ICAP) in 2019 which aims to reduce cooling demand across all sectors by 20-25% by 2037-38. ICAP projects that households with an AC unit would use AC for eight hours every day for five months a year [2]. The ownership and use of air conditioner (AC) was a key factor in determining the household's electricity demand especially during cooling season.

It is vital to explore characterise residential electricity use in India based on air-conditioning (AC). To date most of the studies have used survey-based approach for a particular region or climatic zone in India. Nationwide studies on residential electricity use in India are missing in Literature. Khosla et al., identified that as more people are exposed to ACs at work or school, AC use was expected to increase by 37%; this is especially concerning if more households adopt home-working post-pandemic [3].

The literature review identified a wide array of variables through studies that characterise residential electricity consumption (REC) for an Indian context. The most commonly used variables were cost of electricity per unit, household characteristics (type of dwelling, ownership of dwelling, age of dwelling, BHK, floor area), non-AC appliances and AC characteristics (BEE star rating, tonnage, age, number of units and usage, year of purchase, condition), physical characteristics and socio-economic characteristics (family size, income, age , gender, education of primary householder) [4-7] The literature review also found that electricity demand summer was highest in the summer months despite prices inelasticity, possibly due to

higher ambient temperatures [8]. It was also found that there was substantial variation in the usage and pattern of electricity use depending on income levels, climate and geography. Climatic variation is especially important since composite, warm-humid and hot-dry climate zones cover approximately 80% of the total geographical area of India and majority of the population live in these climate zones. The density of population in the cold climate zone is low when compared to other climate zones. Similarly, temperate climate zone covers a small geographical area [9, 10]. Debnath et al., captured the variation in usage of AC and other space cooling devices seasonally and found several interesting behaviours based on AC patterns of the residents in the warm-humid region [11]. It is clear although that there are limited empirical studies in India characterising electricity use of AC households across different climatic zones. This nationwide understanding of electricity use and its key drivers is necessary to curtail the rising demand of the residential sector.

To address these gaps, this paper empirically investigates the magnitude and causes of climatic and seasonal variation of residential electricity use using statistical analyses of survey data gathered for 1,537 urban AC households in India. The study also identifies key drivers of residential electricity consumption in AC households to inform energy policy.

2. METHODOLOGY AND DATASET

This study conducted statistical analyses of survey data gathered by the NEEM-CLASP study. The data was gathered using face-to-face interview based questionnaire survey across during 2018-19. Complete dataset was available for 1,537 households with one or more AC units. The households were located in four climatic zones covering composite, warm-humid, hot-dry and temperate zones.

The survey data were checked for inconsistencies in responses (ex: discontinuity in data), straight-line responses to only required questions (ex: neutral to every environment behaviour awareness), odd responses (ex: Only 32 kids in the dwelling with no adults) and missing responses or partially filled forms. Finally, outlier data were removed from further analysis as including these can skew results. Calculation of annual usage hours from energy use per minute, hour, day and month was calculated for all electrical appliances. The selected variables were then checked for data availability using frequency tables for any missing values. The final filtered variables were then checked again for any outliers and other erroneous data.

The households were categorised into Low (LIG)/medium (MIG)/high (HIG) income groups based on the Pradhan Mantri Awas Yojana. Here the LIG households earn an annual income of less than INR 6 lakhs rupees, MIG were grouped under yearly earnings between INR 6-12 lakhs while HIG earns more than INR12 lakhs per annum. Summer and winter period was defined by the perception of the surveyed residents. The survey data was analysed statistically at the overall sample level, climatic zone, income group and seasons to examine the correlation between variables.

2.1 Data variables used for analysis

Pearson correlation analysis was done to identify correlations among variables. LASSO regression was then used to identify the key drivers of seasonal electricity consumption. The survey variables that were analysed are shown in table 1.

Table 1*:*
Key variables used from the survey

Variable group	Variable name and categories
Physical characteristics	Climatic zone (Composite, Temperate, Warm-humid, Hot-dry)
	Type of house (Flats/Apartment in a society, Flats/Apartment-standalone, Villas (gated community), Independent houses/bungalows)
	House size (1BHK, 2BHK,3BHK,4 or more BHK)
	Built up area (m2)
Household characteristics	Income group (LIG, HIG, MIG)
	Family size (Number of residents)
Cooling appliances: Air conditioners	Number of AC units (1AC,2AC, 3 or more AC)
	AC usage hours per night and day
	AC set point temperature(˚ C)
	Type of AC unit (Window, Split with or without inverter technology)
	Age of AC units (< 1 year, 1-5 years, 5-10 years, > 10 years)
	Cooling capacity of AC units (Ton)
	Condition of AC units (First hand, Second hand)
Cooling appliances: non -AC	Number of Fans [Ceiling fans, Wall/table/mounted fans] and desert coolers
Purchasing behaviours	Very concerned about environment and always purchase star rated appliances
	Prefer to purchase star rated appliances
	Somewhat concerned about environment but no purchases on this
	Importance to cost and performance than environment
Energy awareness of environment	Changed appliance settings with respect to weather
	Switch-off Appliances when not in use
	Neither aware nor concerned on environmental issues
Electricity use	Mean monthly electricity use in summer (kWh/month), Mean monthly electricity use in winter (kWh/month)

3. RESULTS

The study sample of 1,537 households was split by income group into 507 HIG households, 625 LIG households and 405 MIG households. About 48% of the household sample occupied independent houses while 52% were based in apartments (standalone or in a society). The mean built-up area was 98 m^2 with a mean of five residents per household. While 37% of the households were located in warm-humid climatic zone and a similar percentage in the composite climate zone, 20% were based in the hot-dry climate zone, and less than 10% of households were in the temperate climate zone. The distribution of households by climate zones broadly represented the distribution of climate zones in India. Across the sample of 1,537 households, the mean monthly summer electricity consumption was found to be 275kWh, which was 32% more than the winter consumption of 186kWh. The distribution of mean monthly electricity consumption in summer and winter at the sample level is shown in Figure 1. The 90th percentile of mean monthly consumption in summer and winter was seven times more than the 10th percentile. Across all percentiles, the mean monthly summer consumption was at least 1.4 times more than the mean monthly consumption in winter.

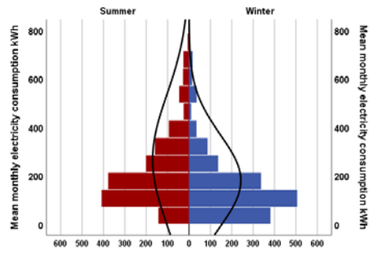

Figure 1:
Distribution of monthly REC across seasons

Across the sample, 90% of the households had one AC unit. Households with three or more AC units consumed around 46% more electricity than households with one AC unit in summer, while households with two AC units consumed 12% more than households with one AC unit. During winter season, households with three or more AC units consumed 57% more than what one AC households consumed. The monthly electricity use almost doubled when number of AC units increased from one or two to three or more AC units irrespective of season.

The highest mean monthly REC for both summer (293kWh) and winter (203kWh) was observed in independent houses/villas and lowest consumption was observed in flats/apartments (standalone or society) (271kWh in summer and 193kWh in winter), since houses are more exposed and wee larger in size. Monthly electricity consumption increased in summer and winter as dwelling size increased from 1BHK to 4 or more BHK, since larger area was cooled. With increase of one bedroom, REC was found to increase by 1.3 times on average in both summer and winter seasons.

3.1 Seasonal electricity consumption across climatic zones

The climatic zones of India as defined by ECBC states that the hot-dry region had the highest mean daily temperature for midday in summer at 42.5°C, followed by composite zone at 37.5°C, warm-humid zone at 32.5°C, and temperate at 32°C and cold zone at 23.5°C. Cold zone had the lowest mean daily temperature in winter at -5°C, followed by hot-dry at 5°C, warm-humid at 7°C, temperate at 17°C and the highest daily mean temperature was observed in composite at 22.5°C. The climatic variation was reflected in the mean monthly electricity consumption across seasons. In summer, highest REC was observed in households located in composite zone (322kWh) while the lowest monthly REC (88 kWh) was in households based in the milder temperate zone. In winter season, mean monthly REC was highest in warm-humid zone (208kWh) and again lowest in the temperate zone (66kWh). The variation in REC across climatic zones was stark - lowest mean monthly REC in the milder climate (temperate zone) was one third of the mean monthly REC in more extreme zones (composite zone/warm-humid).

Despite having highest ambient temperature in summer (45°C) in the hot-dry zone, REC in such households was not higher than households located in the composite or warm-humid zone. This was likely to be due to the fact that households in the temperate zone and hot-dry regions used AC for five hours per day, while households in the warm-humid and composite zones used AC for over six hours per day. Interestingly, more than 90% of all the households in each climatic zones owned only one AC except for temperate zone households where 70% had two AC units.

3.2 Seasonal electricity consumption by income group

Across all income groups, households with less than three AC units, consumed on average 33% more

electricity in summer than in winter. However households with three or more AC units showed a 16% rise in summer consumption as compared to winter, indicating a lower influence of ambient temperatures as households got more affluent (represented by 3 or more AC units).

As shown in Table 2, in summer the low income (LIG) households (n: 625) reported a mean monthly electricity consumption of 216 kWh, followed by the MIG households (n: 405) at a mean monthly electricity consumption of 272 kWh, while the HIG households (n: 507) reported the highest mean electricity consumption at 349 kWh. Thus HIG households consumed 1.6 times more than LIG households in both summer and winter. In winter, the usage of AC was expected to fall drastically especially among LIG, however, the REC did not observe a significant difference among these income groups implying that electricity use in winter was determined by other non-cooling appliances and their usage.

Table 2:
Income group variation of REC

Income group	N	Mean (median) of monthly summer REC (kWh)	Mean (median) of monthly winter REC (kWh)
LIG	625	216 (160)	151 (100)
MIG	405	272 (200)	176(130)
HIG	507	349(250)	238(170)

3.3 Characteristics of cooling appliances

Statistical analysis of survey data revealed that all households owned ceiling fans along with an AC unit. Desert coolers were interestingly not very commonly owned or used among households. Other non-AC space cooling appliances such as table fans, pedestal fans or wall mounted fans were owned by 31% of households with more than three AC units. The prevalence of non-AC cooling appliances indicates that Indian households tend to use a combination of cooling devices through a mixed-mode operation.

Table 3:
Ownership of non-AC space cooling appliances

AC ownership type	Ceiling fans	Table Fans/Pedestal/ Wall Mounted	Desert Coolers
1AC (n:1384)	100%	16%	20%
2AC (n:137)	100%	21%	15%
3 or more AC (n:16)	100%	31%	19%

The most common form of AC system was a split system, where 72% of these AC's were relatively new (less than five years) with a capacity of 1-1.5 ton. The average daily use of AC was found to be 5.6 hours per day across the sample although the timing of AC use was not uniform across the sample. The mean daily AC usage varied from 5 hours in LIG households to 5.9 hours for MIG and 6 hours for HIG. The AC use varied from 5.5 hours for households with one AC, 6.8 hours for households with two AC units and 8.6 hours for households with three or more AC units.

Across various income groups, the set point temperature varied widely ranging from 16°C-28°C. The mean set point temperatures of 21-22°C was observed across all income groups. Interestingly, those who set their mean AC temperatures to 19°C or lower (mostly households with more than three AC units) were predicted to have two times higher AC usage than households with set-point temperatures over 21°C. Among all the households, only 56% of the residents used specifically star rated products while less than 50% took energy saving actions, such as changing appliance settings or switching off appliances when not in use to reduce energy use. Although LIG preferred an EE rated product, more percentage of HIG households actually purchased and used an EE rated product. This could be due to the fact that lower income group (40% of all LIG households) prioritised cost and performance more than HIG (25% of all HIG households prioritised cost and performance) due to financial reasons.

3.4 Correlation between variables

The Pearson coefficient or r value was used to find the strength of the correlation between mean monthly electricity consumption (in summer and winter) and survey variables. The value of r between 0.1-0.3 and 0.3-0.5 shows small to moderate correlation and greater than 0.5 shows a strong correlation. All variables were chosen to be significant at the 0.05 level in analysis.

It was observed that BHK and floor area (dwelling size); family size and family structure were strongly correlated with r>0.5. In order to remove multi-collinearity, redundant variables were removed to avoid overfitting into regression. For example, here floor area and family size were used instead of BHK and family structure since these variable correlations were quite obvious. The strength of correlation between number of fans and number of AC appliance with floor area was found to be of moderate strength, implying that as the number of fans and AC units increase with dwelling size.

3.5 LASSO regression

The variables used for LASSO regression were climatic zones (as dummy variables), income group (as dummy variables), family size, floor area (logarithmically-transformed), number of AC units, number of ceiling fans, number of fans (table/pedestal/wall mounted), number of desert cooler, daily AC use and AC set point temperature. The dependent variable was logarithmically transformed in summer and winter to normalize data for regression. In summer, daily AC use influenced the mean monthly summer REC along with floor area, family size and number of ceiling fans. Variables of daily AC use and set point temperatures were be taken as determinants for winter REC as space cooling use was almost nil in this season [12, 13]. In winter, mean monthly REC was influenced by floor area, family size and number of non-AC space cooling appliance (ceiling fans). Overall, the determinants of mean monthly REC were found to be floor area, family size and non-AC space cooling appliances (ceiling fans).

Table 4:
LASSO regression

p<0.05 Standardised coefficients (Beta)	**Mean monthly summer consumption kWh**	**Mean monthly winter consumption kWh**
Floor area	0.2	0.1
AC day use	0.1	-
Number of ceiling fans	0.1	0.1
Family size	0.1	0.1
Multiple R	0.5	0.5
R square	**0.3**	**0.2**
Adjusted R square	**0.2**	**0.2**
Penalty	**0.12**	**0.12**

4. DISCUSSION

The analysis shows that in households with AC, there is widespread variation of REC by seasons, climate zones, income group, number of AC units, as well as dwelling size and dwelling form. It was found that main factors that affect REC use were floor area, family size and number of non-AC cooling devices like ceiling fans, while in summer daily AC usage hours influenced REC. Households with more than three AC units used AC for longer hours and thereby contribute to a higher REC. This trend was also observed across income groups with highest income groups contributing to a higher REC use. It is important that residential energy policy in India addresses these highest electricity consumers and ensures that the lowest electricity consumers do not rapidly move to these groups. There is thus a need for policies to be customised to different income groups. While financial incentives to purchase energy efficient appliances may not work for more affluent households, these may be appropriate for the lower income groups. For MIG and HIG households, smart management of AC use in line with occupancy and outdoor weather can be encouraged, along with increasing the set point temperature, given the potential electricity savings this change can bring.

Although the Indian Bureau of Energy Efficiency (BEE) recommends 24°C as the set point temperature for AC units, the set point temperature in the study was found to be 19°C - 21°C. Households with set point temperature of 19 °C consumed 1.6 times more electricity than those with 21°C. Given that with every degree rise in set-point temperature around 6% savings could be achieved, this is a tremendous untapped for reducing electricity use, even though it will be a social challenge given the rapidly rising aspiration of higher thermal comfort in urban Indian households.

Based on data analysis conducted from this study, AC usage varied from 5.6 hours to 8.5 hours depending on the number of AC units. This range is higher that what was found by two other Indian studies that identified average daily usage of AC to be around five hours per day (Khosla et al., 2021, Agarwal et al., 2020). However the two studies were conducted at different periods of the year in different cities. In future studies should aim to establish the average daily household AC use at a national level to inform energy models for estimating savings from a reduction in usage hours.

The study also revealed the wide variation in REC across climatic zones, income groups and seasons**.** Residents in hot-dry (highest mean summer outdoor temperature) and temperate zone (70% households owned two AC units) were thriftier in their summer and winter electricity use than residents in composite and warm-humid zone. Space cooling usage in summer across households located within the composite zone was twice as compared to households located in other climatic zones. This variation across space (climatic zone) and time (season) will need to be tackled through customisation of the recently-launched Residental Energy Code in India, especially as climate warms and more households aspire to reach higher levels of comfort (at lower set point temperatures). The Energy Code will need to consider reducing both annual and seasonal use of electricity and how that varies across climatic zones and income groups.

5. CONCLUSION

This study empirically examined the seasonal variation (summer, winter) of residential electricity use in India using statistical analyses of survey data of 1,537 households with AC units representing four climatic zones (composite, hot dry, warm humid and temperate) and different income groups (low,

medium, high). The survey data included information on household characteristics, socio-demographics, cooling and non-cooling appliances, electricity use in summer and winter and level of energy awareness. High income households (n: 507) reported the highest mean monthly summer electricity consumption at 349 kWh followed by middle income households (n: 405) at 272 kWh, while low income households (n: 507) experienced the lowest mean monthly summer electricity consumption of 216 kWh. Mean monthly electricity use in summer was lowest in the milder temperate climate zone as compared to the more extreme composite and warm humid zones. When number of AC units increased from one to three or more ACs, residential electricity consumption (REC) almost doubled across summer and winter seasons. In households where the set-point temperature was 19°C, REC was found to be double that of households with 21°C. The influence of the variables on the electricity consumption was obtained by performing LASSO regression. It was observed that BHK /floor area, family size/number of residents, usage of AC, income group, set-point temperature and number of non-AC cooling appliances were key factors driving the electricity consumption of households.

The study reinforces the need to tackle the growth of AC units among Indian households as climate warms and aspirations for thermal comfort increase. Energy policies should encourage the use of low power consuming space cooling appliances like fans or desert coolers which are also more affordable than AC units. To curtail the rise of residential electricity consumption in India *one size fits all* policy is not likely to work in the Indian context. Instead residential energy policy should address the factors that drive electricity use along with the variation in residential electricity use prevalent across climatic zones, seasons and income groups in India.

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The energy efficiency evaluation on rehabilitated social housing buildings

Machado Vaz neighbourhood, Porto, Portugal

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ABSTRACT: The energy efficiency evaluation as a result of the implementation of rehabilitation works in social housing buildings will be established with the calculation of the two following energy indicators: Global coefficient of heat losses through the building envelope - C(W/ºC) and Gross energy demand for heating - N(kWh). On the rehabilitation of the Machado Vaz Social Housing - this present study case, solar thermal collectors were applicated to the buildings (this was the first housing estate in Portugal equipped with this technology). The installation of solar panel allowed a final energy reduction with the production of domestic hot water throughout the year. At the present study case the energy consumption of two scenarios – pre and post rehabilitation of the buildings- will be presented, also the corresponding domestic hot water production system (AQS (KWh/year)), the savings (€/year) and the CO2 emissions calculation. As a result, it has been verified that despite the total cost of 1.022.654,82 euros of the rehabilitation works on this social housing buildings, an annual improvement of reduction in energy cost of 325.059,33 euros was achieved, which means that this investment will be recovered in a period of less than 4 years.
KEYWORDS: Social housing rehabilitation, Energy efficiency evaluation, "Low cost" social habitation, Solar thermal collectors, Architectural requalification.

1. SOCIAL HOUSING IN THE CITY OF PORTO

This paper attempts to put in evidence the architectural and engineering interventions in rehabilitation of social housing quarters, in order to solve the crucial problems detected (condensation, humidity).

Around the two important metropolitan areas (Lisbon and Porto) it was verified that over than 20% of people live in social housing. A large number of these buildings have an intensive residential use and need a systematic maintenance that is often ignored for economic reasons and also for insufficient planning (Abrantes, 2009).

Thus, the rehabilitation of social housing quarters is undertaken with the purpose of answering to three central questions:

- To solve the existing anomalies that are often caused by rain water infiltrations through the vertical's building envelope, through the roof and through existing cracks in the facades, together with the condensation caused by the lack of insulation and poor existent ventilation.
- To increase the satisfaction and self-esteem of the residents, promoting a modern and higher architectural quality in social quarters.
- To improve thermal comfort and to increase the energy efficiency of the buildings.

As example, two solutions taken from authors' projects, regarding the rehabilitation of social housing quarters, are presented, having in mind that the EU program of investment forces that the housing after the rehabilitation reach more two levels (Abrantes, 2010).

At the present time, the analysis of Santa Luzia Neighbourhood, Porto (Fig. 1, 2 and 3), and its redevelopment project, allowed to study the factors that compromise the urban integration and how the requalification met such conditions.

The project seeks to understand the relationships between the different spatial components in shaping the urban neighbourhood form and the contribution of each of these components to the overall quality of the intervention (Abrantes et Al., 2018).

Each component of the urban space has been designed so that the assembly formed by the new reclassified zones of the design, could be understood as a unit - and not the current sum of road sections, with more or less dispersed buildings

and some voids between both, building an urban fabric.

Figure 1:
Santa Luzia Neighbourhood, Porto (640 dwellings). Before rehabilitation.

Figure 2:
Santa Luzia Neighbourhood, Porto. After the architectural and engineering rehabilitation.

Figure 3:
Santa Luzia Neighbourhood, Porto. After the architectural and engineering rehabilitation.

Regarding a second example - the Vila d'Este Neighbourhood, the analysis of the morphological characteristics of this Neighbourhood in two stages (before and after the physical rehabilitation), allowed us to study the factors that compromised the urban integration, the architectural quality and the residents' satisfaction (Fig. 4, 5).

Figure 4:
Vila d'Este Neighbourhood, Vila Nova de Gaia (2085 dwellings). Before rehabilitation.

The redevelopment meets the full range of objectives which must meet the physical rehabilitation of public space in affordable housing sets. Like in the previous case, each element of the urban space was designed together with all other elements, so that all the parts reformulated in the rehabilitation work can be seen as a unit.

Before upgrading, urban set was only a sum of empty spaces between buildings scattered and fairly disjointed road sections, buildings without quality.

In both examples we can see a big improvement of the architectural design with new energy solutions (Fig. 2, 3 and 5).

Figure 5:
The rehabilitation of Vila d'Este Neighbourhood - Ssome energy solutions have been integrated in the new design of facades.

2. MACHADO VAZ NEIGHBOURHOOD, PORTO. - CASE STUDY.

The present study case concerns one of the urbanizations of "low cost" social residence in the city of Porto, with great visibility and localization next to the North-South highway – the Machado Vaz Neighbourhood (Fig. 6 and 7). Built in 1966, the neighbourhood is a large estate with thirteen blocks comprising two hundred and seventy-two units.

This improvement will positively affect not only its inhabitants and users but also visitors, improving their quality of life and, of course, the urban landscape.

The studied part of the urbanization includes 13 buildings corresponding to 256 dwellings.

Figure 6:
The Machado Vaz Neighbourhood, Porto. Before the architectural and engineering rehabilitation.

Figure 7:
The Machado Vaz Neighbourhood, Porto. Before the architectural and engineering rehabilitation.

For each dwelling, a complete inquiry has been undertaken, followed by planned technical visits to those buildings that presented the major anomalies. The purpose was the diagnosis of these buildings, identifying problems and causes, in order to later reach efficient treatment solutions.

In these 13 buildings we present, 6 have an Northwest/Southeast orientation and 7 have an North East/South-west orientation. There are 3 main size windows: bedrooms - 1,10 m x 1,10 m, living rooms - 2,70 m × 2,0 m; bathrooms - 0,60 m × 0,60 m.

The roof is in tile. and the walls façade are a unique wall of stone. The windows have window frames in wood and single glass.

It is important to note that the integration of the architectural component in rehabilitation must be considered as a major and significant value in the image and functionality of the rehabilitated buildings. It is to be expected that the architectural component of valorisation work will be the key for the acceptance of inhabitants and users of the buildings and therefore it induces self-esteem in people to reinforce their bond with their surroundings. This point constitutes a value that must be assured for all social residences (Abrantes, 2021).

Portuguese social residences are subject to the controlled-costs construction regime for social housing. In what concerns to the present study case, the rehabilitation process was promoted by DomusSocial Municipal Company, in 2017. Next, the main rehabilitation procedures are presented (Fig. 8, 9, 10 and 11):

1. Requalification of the façades with the application of Thin Synthetic Reinforced Coating;
2. Replacing the structure and ceramic cladding of the roofs;
3. Replacing the exterior frames (Fig. 10 and 11);
4. Enclosing the stairwells (Fig. 10 and 11);
5. Treating and requalifying entrance/ staircase surfaces, namely walls and floors;
6. Increasing the unit's ventilation systems;
7. Reformulating the structure of the communal areas to comply with current demands: water, supply, rainwater drainage, electricity, telecoms and cable tv;
8. Installing gas supply infrastructure;
9. Installing solar panels (the first housing estate in Portugal equipped with this technology) (Fig. 9).

Figure 8:
The Machado Vaz Neighbourhood, Porto. After the architectural and engineering rehabilitation.

Figure 9:
Solar panels at Machado Vaz Neighbourhood (after the architectural and engineering rehabilitation).

As regards the buildings´s architectural requalification I would highlight the proposal to close the communal stairwell area with an iron structure at ground level, including a stainless-steel door, laminated safety glass and letter boxes.

On the upper storeys the wells were closed on the front part with windows and on the sides with iron grids (Fig. 10).

The clothes drying areas were enclosed with glass brick walls serving as the base for a ventilation frame and grid with a diffuser for future connection to gas and water heaters (Fig. 11).

Figure 10:
The Machado Vaz Neighbourhood (after the architectural and engineering rehabilitation).

Figure 11:
The Machado Vaz Neighbourhood (after the architectural and engineering rehabilitation).

Also, part of the estate´s exterior areas were requalified to serve as a leisure area and small games field (Fig. 12).

My fundamental thesis is grounded in the fact that I believe human beings and buildings reveal similar behaviour, particularly with regard to pathology.

Pathology is defined as the study of diseases, it comes from Greek pathos - suffering, disease, and logia - science, study of.

I would even venture to affirm that both human beings and buildings are born, they live and they die (Abrantes, 2019).

According to Jean de la Bruyère (a 17th century French philosopher) "There are only three events in a man's life: birth, life and death; he is not conscious of being born, he dies in pain and he forgets to live." I underline "he forgets to live" because it will be decisive for pathology.

Figure 12:
The Machado Vaz Neighbourhood (after the architectural and engineering rehabilitation).

3. ENERGY EFFICIENCY EVALUATION

As a result of the implementation of rehabilitation works in social housing, the energy efficiency evaluation is established with the calculation of the two following energy indicators (Decreto-Lei nº 118/2013, 2021):

1. Global coefficient of heat losses through the building envelope - C(W/ºC), given by the following equation (1):

$$C = \sum U_x \, . \, A_x \qquad (1)$$

where U_x – Coefficient of thermal transmission of the blank and glazed facades and of the roof [W/m²ºC].

A_x – Area of blank and glazed facades and of roof [W/m²ºC].

2. Gross energy demand for heating - N(kWh), given by the following equation (2):

$$N = C \, . \, GD \, . \, 0{,}024 \qquad (2)$$

Where GD - Heating degree days on a basis of 20 ºC (ºC.day).

Regarding the rehabilitation of the present study case - the Machado Vaz Social Housing - solar thermal panels were integrated in the buildings (as mention before, this was a pilot intervention where for the first time, a housing estate in Portugal has been equipped with this technology) (Fig. 13). Considering the production of domestic hot water throughout the year, it was found that the installation of solar panels allowed a final significant energy reduction.

Table 1 presents the estimated cost of the rehabilitation works associated with this intervention and which had energy efficiency-direct effects.

Table 1:
Cost of the rehabilitation works

Works	Quantities	Unit Cost	Total Cost
Facades	6792.88m²	26,02 €/m²	176.750,74 €
Roof	4003.50m²	74,17 €/m²	296.939,60 €
Glazed Areas	2043.89m²	189,43 €/m²	387.174,08 €
Regulating Grids	680un	3,88 €/u	2638,40 €
Solar Panels	146un	766,16 €/u	111.859,36 €
“Storage”	272un	173,87 €/u	47.292,64 €
			1.022.654,82 €

We calculate that the saves are 325.059,33 € per year and the energy consume reduction is 58,25 % per year.

Table 2 presentes the energy consumption of the two scenarios – the pre and post rehabilitation of the buildings – together with the corresponding domestic hot water production system (AQS (KWh/year)), the savings (€/year) and the CO2 emissions calculation (Table 2).

Table 2:
Pre and post rehabilitation scenarios

Rehabilitation Scenarios	Energy (KWh/year)	(€/year)	(Ton CO_2/year)
Pre-Rehab.	2.749.468	558.004,53	395.92
Post-Rehab.	1.147.796	232.945,20	165.28
Savings	1.601.672	325.059,33	230.64
Reduction (%)	58,25 %	58,25 %	58,25 %

Figure 13:
Solar panels view at Machado Vaz Neighbourhood (after the architectural and engineering rehabilitation).

4. CONCLUSION

The three presented interventions focusing the rehabilitation of social housing quarters show how we can solve, in an easy integrated manner, the lack of energy efficiency through technical engineering solutions.

These solutions combined with architectural interventions and the redesign of the buildings will increase the satisfaction and self-esteem of the residents, at the same time qualifying the urban integration of the quarters.

It is important to refer that the integration of the architectural component in rehabilitation must be considered as a major and significant value in the image and functionality final result of the rehabilitated buildings (Efficient Buildings).

It is to expect that the architectural component valorisation work will be the key for the acceptance of inhabitants and users of the buildings and therefore it induces auto-esteem in people to reinforce their bound with their surroundings. This point is, without any doubt, a value that must be assured for all social residence areas (Project X-tendo, 2020).

At the present study case, it has been verified that the rehabilitation works on this social housing buildings had a total cost of 1.022.654,82 euros, but having an annual improvement of reduction in energy cost of 325.059,33 euros, which means that this investment will be recovered in a period of less than 4 years (iBRoad project, Horizon 2020).

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4TH PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Post-Pandemic Campus Return
Evidence-Based Decision-Making for university learning spaces in Egypt

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ABSTRACT: Since March 2020, the pandemic forced higher-education students into remote learning. Since Autumn 2021, universities across the globe, including the American University in Cairo (AUC-Egypt), have set out plans to return to face-to-face instruction. The safety of learning spaces and the control of pathogen transmission are now decisive parameters in the planning and continuation of this physical return. This research presents some of the first findings collected from learning spaces post-COVID return in Egypt. The study gathers data for four learning spaces with varied characteristics and schedules, including CO2 concentration, occupancy, temperature, humidity, and behavioural dimensions such as doors, windows, and HVAC use. The findings highlight that the four spaces generally remained within the temperature and humidity comfort zone during occupied hours. Most of the time, the spaces remained below the 800 ppm threshold proposed for low transmission. With some exceptions, reduced occupancy allowances were also met. However, the ventilation rates estimated for the spaces are considerably low: barely meeting traditional standards and far from the enhanced ventilation proposed in recent COVID guidelines. The outcomes of this research are used to improve the current local and institutional policies to ensure that learning spaces are healthy, comfortable, and safe.
KEYWORDS: Post-COVID, Learning Spaces, CO2 Concentration, Health, Ventilation

1. INTRODUCTION

The environmental quality of enclosed spaces, which is impacted by factors such as air change rate, directly affects occupants' health and well-being and plays a vital role in controlling pathogen transmission. In the context of learning spaces, indoor environmental conditions are critical for student cognitive performance and the health and safety of students who will soon be returning to campuses. Over 3.3 million students are currently enrolled in higher-education institutes in Egypt. Since March 2020, they have been forced to learn remotely due to the global lockdown and rising infection rates, resulting in observable challenges for students, faculty and institutions [1–3]. Remote learning has also created other societal and economic repercussions beyond campuses [4]. As university campuses start their return to face-to-face instruction in the Autumn of 2021, the safety of learning spaces and the control of pathogen transmission are now decisive parameters in the planning and continuation of this return [5].

Since the onset of the pandemic, researchers and policymakers have introduced a variety of responses. Such responses include emergency regulations that call for increased ventilation rates, reduced occupancy, hybrid modalities, and ventilation and disinfection breaks during occupancy [6].

2. AIM AND SCOPE

The research aims to create an evidence-based approach to inform the decision-making process surrounding these issues based on field data, providing reassurance for society and ensuring a post-COVID return that is both safe and comfortable for students and staff. Recent research has outlined that, in spaces where humans are the primary source of CO2 (i.e. through exhaling) in a well-mixed space, CO2 concentration can serve as a proxy for measuring the risk of transmission of COVID and other airborne viruses [7]. Therefore, this study will track the excess CO2 concentration in spaces during and following their use to examine the effectiveness of the existing ventilation. This study investigates learning spaces at The American University in Cairo (AUC)'s New Cairo Campus, which was inaugurated in 2008 and is home to 5,500 students and 1,500 staff and faculty. The campus resumed its face-to-face teaching operations in Autumn 2021.

This research aims to (i) collect and analyse occupant behaviour data, including abiding by maximum occupancy allowances. (ii) Examine the studied spaces' temperature and relative humidity conditions and (iii) measuring CO2 concentrations in studied spaces. (iv) Assess the comparative performance of learning spaces against the health recommendations required to curb the transmission of pathogens, such as COVID-19.

3. METHODOLOGY

We utilise a series of teaching and learning spaces at AUC, develop a monitoring protocol for two weeks before we analyze the data and compare it to the available and published operation guidelines for COVID and other airborne viruses.

3.1 Space Selection

Criteria were developed to select learning spaces that ensured accessibility, suitability for study, and 'standard' characteristics that would enable the broader applicability of finding. With the return to campus in Autumn, AUC introduced new capacities for existing learning spaces that consider social distancing requirements. Thus, four spaces were selected: two studio spaces (S.1 and S.2), one computer lab (Comp), and one classroom (Class). All the selected spaces included operable windows, and all, except the classroom, had central mechanical ventilation – including mechanical fresh air input in the rooms. The classroom only had recirculating fan coil units, with no mechanical injection of fresh air. Table 1 presents the details of the four spaces studied.

Table 1:
Description of investigated spaces

	Std. 1	Std. 2	Comp.	Class
Area (m^2)	141	93	61	86
Volume (m^3)	705	465	305	430
Max Occ.	30	25	20	22
Op. Windows	✓ (2 large)	✓ (2 large)	✓ (1 small)	✓ (4 large)
Doors	✓ (2)	✓ (1)	✓ (1)	✓ (1 – open to outdoor)
Mech. Fresh Air	✓	✓	✓	✓

The university sets the maximum occupancy indicated in Table 1 based on the size of the classroom and its expected use. The teaching and learning spaces selected follow different occupancy schedules and rates.

3.2 Definition of the Monitoring Protocol

The team extracted the course and lecture schedules from the AUC class schedule. Each classroom had a different operation schedule, including classes, studios, and general open-use time for students.

EXTECH Portable Indoor Air Quality CO2 Meter, capable of measuring indoor CO2 concentrations (1 ppm resolution, 5%rdg + 50ppm), dry-bulb temperature (0.1 ºC resolution, +/- 0.6°C), and relative humidity (0.1% resolution, +/-3% Rh from 10 to 90% and +/- 5% for RH below 10 or above 90%). The instrument was calibrated using the kits available from the manufacturer. In-situ CO2 monitoring devices were unavailable on campus, and fitting this equipment in classes was impossible during the experiment.

To overcome the lack of continuous data logging, the main limitation in the study, an extensive monitoring schedule was created:

- Two readings are to be recorded for each measurement point, with a time difference of at least 5 minutes between them.
- For each reading, two-minute time average is used (weighted average calculated by device).
- A minimum of two measurements are to be collected during each scheduled course in the learning space.
- A minimum of two measurements are to be collected after the last scheduled course.
- A maximum of two hours and minimum thirty-minute interval between all measurements (to calculate decay curves).

Table 2 presents the parameters recorded.

Table 2:
Parameters recorded for each measurement point

	Description	Recorded
Temperature	Dry bulb	Highest
Relative humidity	-	Highest
Occupancy	Number of people present in the room	Maximum
Door open	T/F	
Windows Open	T/F	
Mech Vent. or A/C	On/Off	
CO2	PPM	2 min average

3.3 Data collection and analysis

The data collection for this study was set for two weeks, between 28 November 2021 and 11 December 2021. Overall, 3,699 data points were collected for 302 measurement points: 80 for Studio 1, 87 for Studio 2, 63 for the computer lab, and 72 for the classroom.

The collected data was analysed to study the temperature and relative humidity based on ASHRAE 55 [8] and the overall carbon concentration levels, in comparison to the 800 ppm suggested by the UK Scientific Advisory Group for Emergencies (SAGE) [9,10]. The maximum occupancy allowance violations were recorded, and their effect on CO2 accumulation was studied. Additionally, the usefulness of windows, doors and mechanical ventilation on CO2 accumulation was also assessed.

Finally, the ventilation rates for the rooms were calculated using the decay curves method. The process was informed by the recent work published on the topic, including [11–14].We identified periods of zero occupancies following occupied

periods, which mainly happened at the end of each learning day. We utilised the equation proposed by Roulet and Faradini [12], presented in Equation 1:

$$C_N = (C(t) - C(0))/(C(0) - C_o) \quad (1)$$

Where CN is the normalised concentration of CO2 in ppm, C(t) is the measured CO2 concentration at a given time from time zero, C(0) is the CO2 concentration at time 0 (i.e. the start of the decay), and Co is the base concentration. Co was attained by the minimum value of long decay periods for each space (as per [12]). Nonlinear regression was used to estimate the exponential decay curves, with the air changes per hour (ACH) as the equation's exponent – as suggested in [15].

4. RESULTS AND DISCUSSION

4.1 Temperature and Relative Humidity

Figure 1 presents the distribution of the temperature and relative humidity readings from the four spaces throughout the two weeks. The thermal comfort zone highlighted in Figure 1 was obtained through *ASHRAE 55* [8], assuming an internal airspeed of 0.1 m/s, a metabolic rate of 1.0 (writing) and typical winter clothing (1.0 clo) since the study took place in winter.

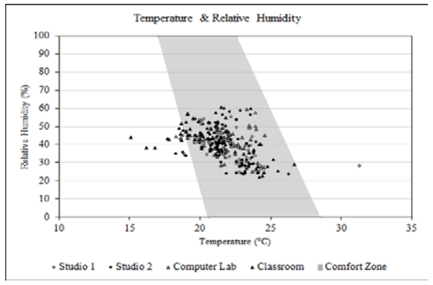


Figure 1:
Temperature and humidity measurements for the four spaces in reference to the comfort zone indicated in ASHRAE 55 [8]

Most of the data points fall within the comfort zone shown in the figure. The expectations mainly occurred in the early morning hours (i.e. first scheduled sessions). Specifically, we identified that the spaces with the windows or door(s) open overnight were more prone to temperatures below the proposed comfort level. However, the spaces were within the expected temperature and humidity comfort conditions.

4.2 General CO_2 Concentrations and Occupancy Allowance Violations

The basic analysis of the CO_2 data for the four spaces is presented in Figure 2. The averages and the upper quartiles for all the spaces fall within the 800 ppm suggested by the UK Scientific Advisory Group for Emergencies (SAGE) [9,10]. However, in some instances, the spaces exceeded this limit. Specifically, Studio 1 exceeded 800 ppm from 5:15PM to 6:15PM on 29 November, following an extended studio session from 2PM to 6:30PM. Again, a similar situation happened on 9 December in the same studio session, starting at 3:15PM.

Studio 2 presents comparable situations, where the CO_2 concentration accumulated to more than 1000 ppm by 6:15PM on 30 November, following a studio session that started at 2PM. The same scenario also appears in the computer lab and the classroom, with concentrations crossing 800 ppm in later afternoons or mid-day following extended morning scheduled sessions. However, in the early morning, the computer lab had one instance where CO2 concentration crossed 1000 ppm. Architecture students utilise the lab at night-time, the room accumulated CO2 overnight. In one case, the concentration at 9AM before starting any scheduled session was 1142 ppm, after students used the space overnight, with the windows and doors closed, and the ventilation switched off. The lab remained above the 800-ppm threshold until 12:45PM.

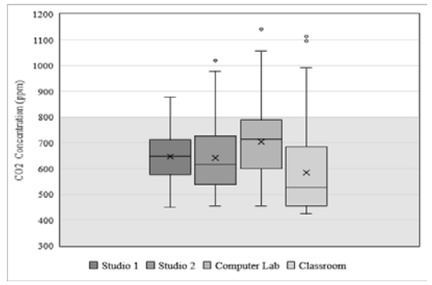


Figure 2:
CO2 measurements for the four spaces in reference to the 800 ppm reference level suggested by the UK Scientific Advisory Group for Emergencies (SAGE) [9,10]

Generally, the CO_2 concentration was below 800 ppm for 92.5% of the measurements taken in Studio 1, 87.4% of those taken in Studio 2, 77.8% of those taken in the computer lab, and 88.9% of the measurements taken in the classrooms. Overall, the computer lab had the highest average concentration of CO_2 and the most significant 800 ppm threshold violations.

Additionally, the computer laboratory had the largest and most severe occupancy limit violation, with more than 30 occupants in the space at one time observed on multiple occasions (the maximum allowed is 20). Other spaces were underutilised, with only the classroom exceeding its allowed occupancy of 22 by one user in one observation.

4.3 CO_2 Concentrations, Occupancy and Density

Table 3 presents the occupancy and density data. Figure 3 (A to D) shows the CO_2 concentration with the occupancy.

Table 3:
Occupancy and density in four spaces

	S. 1	S. 2	Comp	Class
Area (m^2)	141	93	61	86
Median Occupancy	6.5	12	9.5	12
Average space per occupant (m^2)	21.6	11.75	14.84	11.75

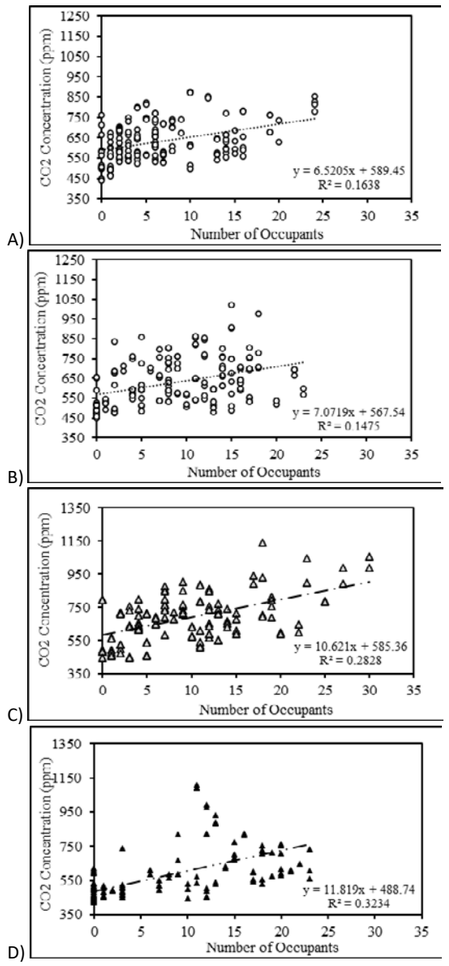
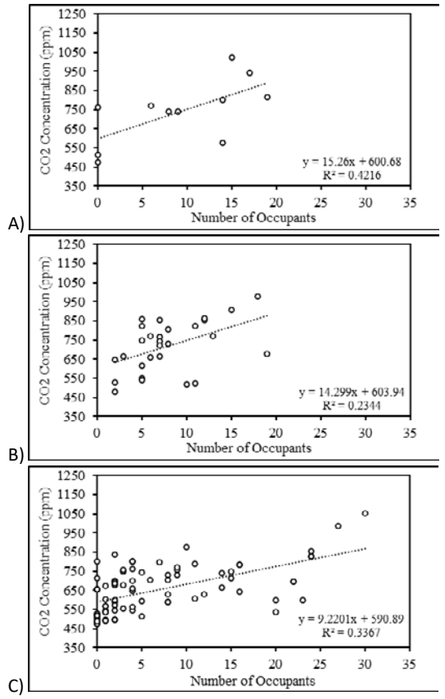


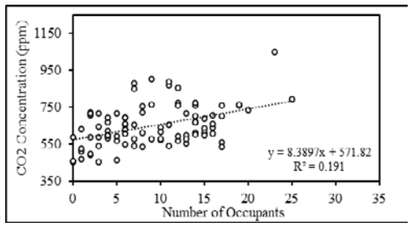
Figure 3:
CO_2 measurements for the four spaces In relation to occupancy. A) Studio 1, B) Studio 2, C) Computer lab, D) classroom.

The graphs in figure 3 have low coefficients of determination values mainly because they are an aggregate of the measurements that disregard time. In the case of CO_2 measurements, a time delay is expected in the concentration and occupancy. The graphs also ignore other factors, including whether the mechanical ventilation is functioning and if the doors and windows are closed or open. The study's dependence on discrete measurements also increased uncertainty. From Table 3 and Figure 3, we can see that the rooms with mechanical ventilation installed (namely the two studios and computer lab) had a lower CO_2 accumulation curve. The accumulation of CO_2 is negatively correlated with the space area (i.e., the larger the area, the lower the accumulation for the same occupancy).

4.3 The Effectiveness of Ventilation Sources

The data collection happened with no interference with the activities in the spaces, as well as user preferences, including their choice to open or close the windows, doors, and the HVAC system operation. Instead, the team observed the conditions of these parameters during the measurements. Figure 4 shows the aggregate effects of these parameters across the four spaces. Please note that only weak correlations were deduced from the data due to the reasons mentioned in section 4.2.





D)

Figure 4:
Aggregate CO_2 measurements of the four spaces in relation to occupancy, with varying ventilation conditions. A) Doors and windows closed and HVAC off, B) Doors and windows closed and HVAC on, C) Windows closed, Doors open and HVAC on, and D) Windows and doors open, and HVAC ON.

It is important to note that the classroom is excluded from the data presented in Figure 4 since it does not have an HVAC system installed. From Figure 4, we can see that the HVAC can reduce the accumulation of CO_2 in the spaces from 15.3 ppm per occupant to 14.3 ppm/occupant (about 7%). Opened doors further lower the rate to 9.2 ppm/occupant (an added 34% reduction), and opening the windows lowers the rate to 8.4 ppm/occupant (and added 6%). Overall, having the HVAC ON, and the doors and windows open reduces the accumulation of CO_2 per occupant by more than 45%.

The findings point to the fact that, without the ventilation or fresh air from the windows and doors in the spaces, CO_2 accumulation would be significant, even with the institution's proposed maximum occupancy. While mechanical ventilation helps mitigate the concentration slightly, the data shows that it was insufficient to inhibit the CO_2 concentration from passing the 800-ppm threshold proposed. This is explicitly clear during extended studio sessions.

4.4 Estimated Ventilation Rates

The decay curves of each space were extracted from the data: by isolating situations of large occupancy, followed by several hours of no occupancy. Specifically, for Studio 1, three decay situations were seen as appropriate, two for Studio 2, five for the computer lab, and four for the classroom. Normalised concentrations were calculated based on the methodology proposed in [12]. Multiple normalized curves were averaged to obtain a mean ACH value across the two weeks observed.

It is important to note that the conditions of the rooms were not controlled (i.e. HVAC, door, and window conditions were not changed or altered by the team). Thus, the ventilation rates calculated here represent the operational conditions of the spaces during the observation period with no intervention. Table 4 presents the estimates

Table 4:
Estimated ventilation rates in four spaces

	S. 1	S. 2	Comp	Class
Estimated ACH	0.591	1.144	0.736	0.935
R2	0.992	0.978	0.986	0.974
Max. Recorded Occupancy	24	23	30	24
l/s·person (95% confidence)	4.58-5.06	6.10-6.75	1.97-2.18	4.42-4.89

Except for Studio 2 and the classroom, the ventilation rates are below the ASHRAE minimum requirements of 5 l/s·person [8]. The overall air change rate in all the rooms is also below the 6 ACH proposed by the CDC [5].

5. CONCLUSION AND FUTURE RESEARCH

Motivated by the need to ensure safe and comfortable learning spaces after returning to campuses, this study examined how learning spaces in AUC compare to the health recommendations and best practices proposed to curb COVID-19 transmission. This study is the first of its kind undertaken post-COVID in Egypt. It broadens the ventilation-specific focus of previous work in this area by synchronously considering the space's safety, comfort, performance, and operational variables. The study focused on analysing the spaces with little or no intervention to capture their regular post-COVID operation.

Findings revealed that users' behaviour and lack of willingness to conform to guidelines, including maximum density allowances, resulted in the accumulation of CO_2, which could indicate an increased risk of transmission and infection. The observed density and classroom usage patterns also revealed gaps in policy enforcement. The analysis revealed that while the spaces were able to remain within the 800 ppm threshold set in the literature, untraditionally extended class sessions in the spaces resulted in a significant CO_2 accumulation that ventilation systems struggled to mitigate. Additionally, the use of the spaces outside regular operation hours resulted in similar accumulations.

In the spaces analysed, it was found that mechanical ventilation alone was not sufficient during close to full occupancy, with opened doors and windows reducing the average accumulation per occupant by close to 40%. The decay curves revealed that the ventilation rates in the four spaces are significantly below the recommended enhanced levels of 6 ACH for educational spaces and barely meet the minimum standard of 5 l/s·person. While there might be design and operation parameters to consider, the observations indicate that the ventilation gaps can be attributed to users' behaviour, including shutting down HVAC systems and closing doors and windows. Based on the findings, we offer four key recommendations:

- Revise mechanical ventilation performance in all occupied spaces, and ensure that HVAC equipment remains functional during occupancy.
- Ensure that mechanical ventilation schedules conform to actual usage – to ensure that after-hours and outside working hours used spaces remain well ventilated.
- Ensure that extended scheduled sessions in rooms have embedded breaks for ventilation and propose occupancy limits beyond which doors and windows must remain open as much as possible.
- Further, enforce guidelines and policy regarding maximum occupancy allowances.

We also recommend that the institution add CO_2 sensors in rooms for their health and safety monitoring for the post-COVID campus return.

Within a broader context, the findings can be applied across universities in Egypt to guide a return to university campuses that ensures that learning spaces are healthy, comfortable, and safe. Further research will expand the work explored here to a broad range of learning spaces. In addition, a study that will compare the performance of AUC learning spaces (cooling-dominated) to comparable spaces at UCL (UK- heating-dominated) is planned.

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SARS-CoV-2, ventilation strategies, thermal comfort and carbon implications for buildings

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ABSTRACT: The spread of SARS-CoV-2 since 2019 has rapidly become a global crisis with unprecedented records of deaths and hospitalizations in the last century. The infectious particles spread more easily indoors than outdoors and therefore built environment sector needs to find more effective engineering solutions to minimize the spread. Several health organisations and professional bodies suggest a layered approach to reduce infection rates which range from social distancing to improvements in ventilation strategies in buildings. Their approaches have widely been accepted and used worldwide even though with arguably low impact. Through a case study and by using dynamic simulations, this research studies the implications of recommended indoor ventilation requirements by COVID-19 protocols on existing office buildings in the UK. The findings highlight the related implications on thermal comfort and carbon emissions in three scenarios of building operation with natural ventilation and with mechanical ventilation (with and without heat recovery). This study shows a naturally ventilated building can maintain the required humidity level during the pandemic and the use of mechanical ventilation with no heat recovery is the least environmentally friendly solution among our scenarios.
KEYWORDS: SARS-Cov-2, Natural Ventilation, CO2 Emissions, Thermal Comfort

1. INTRODUCTION

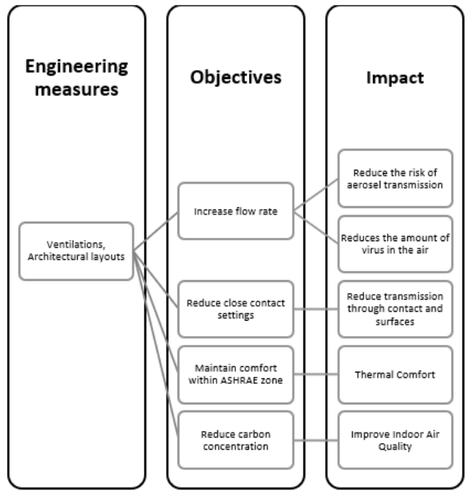
Climate change and global carbon emissions have been an overwhelming concern for decades. In the built environment, as one of the major contributors to global emissions, there has been significant research focus on energy efficiency in construction, occupants' comfort and ventilation systems (1). The result of such studies, findings and consequent developments have led to stricter building regulations on energy and ventilation strategies worldwide. For example, in the UK, approved document L and F provide specific construction standards for energy and ventilation systems. Furthermore, there has been a growing concern about indoor air quality and the impact of indoor pollution on users' health and well-being which has been strongly linked with relative humidity and indoor temperature (2).

Since the start of the 2019 global pandemic, significant changes have taken place worldwide to control the spread of the virus from lockdowns to social distancing and face coverings. The impacts of COVID-19 have been fully covered by the media and numerous studies looked at different ways to cure, prevent and control the spread of the virus. Meanwhile, arguably very limited research has so far looked at the impact of evolving COVID protocols on users' comfort and carbon emissions and quantified the impacts. Recently, (3) (4) (5) looked at COVID protocols implication on comfort levels and energy consumptions and reported challenges in balancing ventilation with comfort levels and reveal an urgent need for more investigations on how current protocols may impact comfort and carbon emissions.

Even though no study currently comprehensively quantifies the impact of ventilation and air flows on the SARS-CoV-2 transmission however the key role of aerosols in the pandemic is well documented (6). Natural and mechanical ventilation can dilute aerosols indoors, but this has implications for energy consumption, carbon emissions and users' comfort. Generally, the ventilation rate is the volume of air provided for a room over a certain duration, and some recommendations are based on second per person. According to CIBSE a value of 10 l/s/person is suitable for most commercial buildings (7). Approved documents from the UK government (8) suggests that COVID-19 transmission risk increases when the ventilation rate is below 5 l/s/person or when there is above 1500ppm CO2 concentration in the room. Further studies suggest colder and drier conditions are more habitable for the COVID-19 virus (9) and (8) concludes the humidity between 40% and 60% RH in the indoor environment is an optimized situation to reduce the risk.

To prevent the spread of the virus, besides hygienic and administrative protocols, some engineering methods are required to be adapted (10). As shown in Figure 1, engineering measures include appropriate ventilation as stated by CIBSE and general architectural layout settings. The objectives are to increase the flow rate and reduce contacts among users that could cause reducing the risk of transmission. Considering virus spread dynamics, (11) categorized ventilation strategies into three main groups of a) recirculating ventilation which includes ceiling fans and split air conditioning systems, b) mixing ventilation systems which include Air Handling Units (AHU) and Mechanical Ventilation with Heat Recovery (MVHR), c) displacement ventilation systems which include natural ventilation. Their study concluded ventilation systems based on centralised air distribution and ceiling level supplier recirculation is able to provide the optimum conditions for disease spread but only in high occupancy buildings even though natural ventilation is considered effective for all conditions.

Figure 1:
Engineering measures to prevent virus spread



2. METHODOLOGY

Following the guidelines by CIBSE and UK government, this research uses a case study, a four-storey office building with an open plan layout (each floor area is 183.3m^2) that complies with UK regulations in Part L1A to demonstrate the impact of maintaining the aforementioned ventilation rate and humidity for the overall comfort level and carbon emissions while the building is in operation. The wall construction includes (from outside) 3mm rainscreen cladding, 50 mm ventilated cavity, 180mm insulation with conductivity rate 0.025, 12mm cement-bonded particleboard, 50 mm unventilated cavity and 12.5mm plasterboard. The overall U-Value of the wall construction is 0.18 W/m^2k. The ground floor is cast concrete with timber flooring with a U-Value of 0.25 W/m^2k. We used Designbuilder for modelling and energy simulations. The software uses EnergyPlus as its calculation engine and numerous studies validated the software worldwide (12) (13). The case study is in London and the related weather files are used for simulations. The structure is a steel frame with low level of thermal mass and the infiltration rate is assumed at 0.5 ac/h. Figure 1 demonstrates the methodology used in this study.

Figure 2:
Research methodology

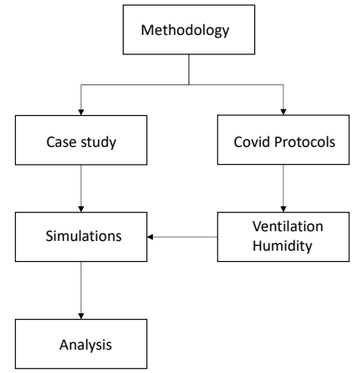
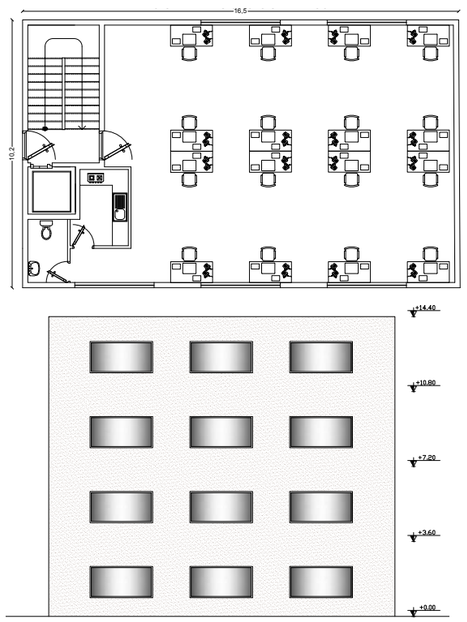


Figure 3:
Model layout (top) and south elevation (bottom).



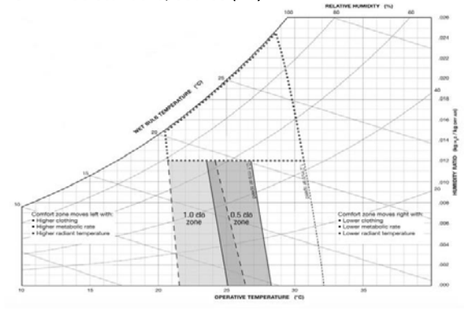
3. THERMAL COMFORT AND HUMIDITY

Understanding thermal comfort is important because of its relevance to energy and carbon emissions. Besides, the research shows people spend most of their time (90%) inside the buildings in developed countries (14). Despite the complicated nature of the thermal comfort subject, several studies have proposed a temperature range of 18-

26°C as likely to be within the human comfort zone (15). ASHRAE 55-standard in several versions identified thermal comfort as a subjective response and defined it as the 'state of mind that expresses satisfaction with existing environment' (16). ASHRAE-55 is based on the static heat balance approach, which includes four environmental variables (dry-bulb air temperature, mean radiant temperature, relative humidity and air velocity) and two human variables (activity and clothing level). For simplification and quantification purposes, this paper used this standard as a reasonable way to assess the thermal comfort/discomfort results. The overall discomfort hours simulated in this study are the overall hours that inside the model, comfort conditions are not met as depicted in Figure 4.

The adaptive ASHRAE standard is based on the differences between naturally ventilated and air-conditioned buildings. Generally, the range of comfortable temperatures in naturally ventilated buildings is greater than in air-conditioned ones (17) and higher humidity could lead to greater occupant sensitivity to temperature variations (18). Therefore, control of both temperature and humidity are equally important to maintain users' comfort. In terms of virus spread, (19) studied the impact of humidity and temperature on Severe Acute Respiratory Syndrome (SARS) which was first emerged in 2003. Their study shows the virus remains alive for over 5 days at temperatures of 22–25°C and relative humidity of 40–50% but higher temperatures and relative humidity of over 95% causes the virus inability to survive. In a similar vein, (20) suggests that daily lower temperature of 11–13°C is of higher risk for COVID-19 spread particularly in England compared to the ambient temperature of 22°C.

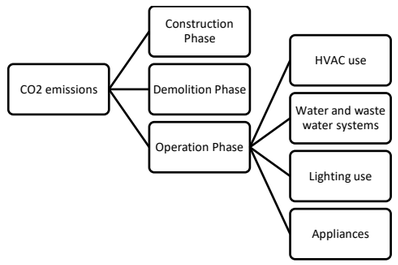
Figure 4:
ASHRAE 55 standard, source (16)



4. CARBON EMISSIONS

About 39% of the annual global CO2 are from buildings (21). The rate of emissions varies in different countries and despite all the research and global attention on carbon emissions, greenhouse gas emission or carbon footprint no data exist to explicitly categorise building types in terms of such emissions. Therefore, to what extent office buildings are responsible for such emissions are not known yet. The sources of CO2 emissions are shown in Figure 5 with a focus on the operational phase (as the scope of this study). This is a non-exhaustive list and CO2 emissions occur at the construction and demolition phase too. CO2 emissions are calculated in the software used by this study by multiplying fuel consumption by the kg CO2 per kWh conversion factor for that fuel.

Figure 5:
Co2 emissions in different building phases



5. RESULTS AND DISCUSSION

We examined the model in three scenarios that represent how an open-plan office building is most likely to be operated during the pandemic or post-pandemic. The first scenario is using natural ventilation with no humidification or dehumidification control (the most cost-effective strategy). A gas boiler with a COP of 0.85 is used for heating to calculate carbon emissions and a building occupancy rate of 0.11 (people/m2) is considered for simulations. This is a scheduled one in the simulation settings. The rate is explicitly defined for the working area zone with a maximum of 0.5 ac/h. The second and third scenario uses mechanical ventilation with humidification and dehumidification controls (constant supply) providing minimum fresh air (sum per person + per area) during the operations. The third scenario uses a heat recovery with a Dedicated Outdoor Air System (VOAS) as well as humidification and dehumidification controls.

Figure 6 shows the overall discomfort hours for the three scenarios and it shows the model with natural ventilation has the highest discomfort hours and the second scenario with mechanical ventilation has the minimum. The model with natural ventilation maintained the humidity between 40-60% the whole year without any need for mechanical controls. Figure 6 compares the relative humidity in the three scenarios. For SC2 and SC3 humidification control is necessary as without it the humidity level dropped below 40% as required by the protocols in January and very close to 40% in February (the simulated model uses the humidification controls).

For SC2 and SC3, mechanically-ventilated models, a very simple schedule was defined as a control unit that calculates the required air exchange rate and provides constant fresh flow for the model during the year. For SC1, the naturally-ventilated model, a feedback control strategy could certainly improve the operations as due to the dynamic of the emissions and the airing cycles, manual airing requires constant checks or rescheduling. This normally requires indoor CO2 monitoring to evaluate the ventilation efficiency.

Figure 6:
Monthly discomfort hours (based on ASHRAE-55 standard) for each scenario

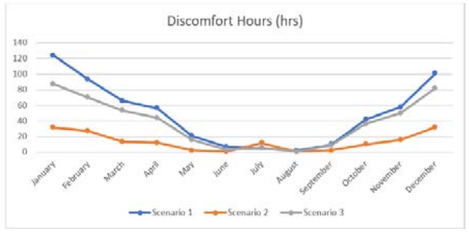


Figure 7:
The average percentage of humidity for each scenario

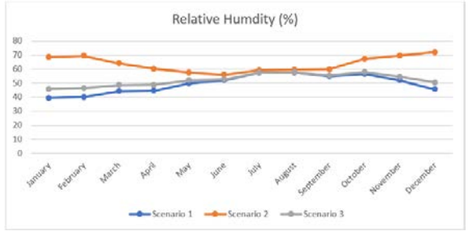


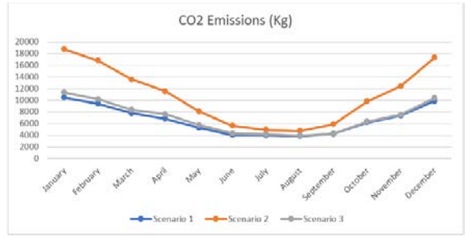
Figure 8 compares the total CO2 emissions for all the examined scenarios. As expected, the second scenario has the highest emission rates. This is only CO2 produced during the building operation and includes items as demonstrated in Figure 5. The highest emissions are related to the HVAC system as the winter period shows the highest rates. The formula/breakdown to calculate the CO2 emissions is Equation (1):

$$\text{Total Co2} = \text{Comv} + \text{Col} + \text{Coa} = (\text{Emv} + \text{EI} + \text{Ea}) \times \text{FF} + (\text{CH} \times 0.85) \times \text{FFH} \quad (1)$$

where Comv is the CO2 generated by mechanical ventilation, Col is the CO2 generated by lighting, Coa is the CO2 generated by building appliances, Emv is the amount of electricity used by mechanical ventilation, EI is the amount of electricity used by lighting, Ea is the amount of electricity used by appliances, FF is the carbon factor of electricity consumption which according to (22) is 0.30675 kgCO2e / kWh in the UK, CH is the central heating system with natural gas and FFH is the carbon factor for a heating system with gas equivalent to 7.89 kgCO2e/GJ.

Whilst the incorporation of mechanical ventilation seems necessary to maintain a higher level of thermal comfort but in terms of virus and humidity level, the model with natural ventilation can comply with the minimum level of humidity. The SC2 seems to be the least favourable option considering environmental issues and carbon emissions and any incorporation of mechanical ventilation is required to have heat recovery as well as humidification and dehumidification controls.

Figure 8:
Monthly Co2 emissions for each scenario



6. CONCLUSION

This study examines the implication of complying with current COVID protocols on comfort and carbon emissions from the operational phase of a case study in London. Table 1 summarises the findings in the three scenarios used for this research. An important empirical result of this study is the quantification of carbon emissions to maintain comfort and humidity level in office spaces.

Table 1:
Main scenarios and the implications

Main Scenarios	Implications
S1-Ventilation rate above 5 l/s/person with natural ventilation	• Relative humidity can be maintained above 40% without any controls. • Overall discomfort hours (based on ASHRAE-55, 2010) are highest in colder months like the other two scenarios.

	• CO2 emissions lowest compared to the other two scenarios
S2-Ventilation rate above 5 l/s/person with Mechanical supply	• Overall humidity level drops below 40% without humidification controls. • The overall discomfort hours is highest in cold months • SC2 has the highest CO2 emissions compared to the other two models
S3-Ventilation rate above 5 l/s/person Mechanical supply and exhaust ventilation with heat recovery	• CO2 emissions are close to scenario 1 • Relative humidity drops below 40% if no humidification control is used • Discomfort hours are minimum in the summer period and maximum in cold months like the other two scenarios

Further research is required to examine more building types in different locations in the UK and worldwide to measure the effectiveness of ventilation strategies on the spread of viruses and quantify the implications on comfort and carbon emissions. This could help to receive further critical support for public health and minimize the spread of SARS-CoV-2.

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A desktop review of the physical configuration of Australian Flexible Learning Environments

Within Primary School settings

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ABSTRACT: Flexible Learning Environments (FLEs) have become an integral factor of 21st century pedagogical practices, giving rise to a paradigm shift in the physical design of learning environments. Instead of a homogeneous layout typical of traditional classrooms, the physical configuration of FLEs' features multiple, dynamic and diverse range of learning settings, potentially used concurrently. This paper provides the findings from a desktop review of FLES from 39 recent schools located in New South Wales, Australia, that has mapped design similarities, established the variety of typologies and analysed the highest recurring top-10 typologies in terms of how they fare against high-performance benchmarks for healthy environments. The WELL Building Standard (WELL v2) was chosen as the analytical framework, for its holistic approach to design and performance of healthy environments. This paper aims to establish the gaps in current design guidelines and high-performance benchmarks, to identify opportunities for IEQ improvement. The existing guidelines are identified to be very performance-driven, and there is a lack of design-driven guidelines, to influence the indoor spatial-configuration, which in the context of FLEs has evolved to become a high-frequency variable that demands design attention. A combination of design and operational guidelines is essential for IEQ optimisation of FLEs.
KEYWORDS: Flexible Learning Environments, Indoor Environmental Quality, Typologies, WELL, Primary Schools

1. INTRODUCTION

There has been an increased realization of the need for flexibility in the design and arrangement of the physical space where learning occurs, to accommodate the new pedagogical demands (OECD, 2006). FLEs can be described as environments that constitute of spaces with permeable boundaries and reconfigurable and moveable elements, to enable dynamic learning using multiple purposeful settings (Neill & Etheridge, 2008). FLEs do not have a standardised spatial design, but are considered as an assemblage of spaces that are of sufficient size and flexibility (Reh, Rabenstein, & Fritzsche, 2011), to support diverse pedagogical activities. Through comprehensive research that linked 21st century pedagogical practices with architecture, FLEs have been identified to be comprised of a diverse range of learning spaces, such as student homebase, collaboration incubator, group learning, presentation space, teacher meeting space, wet areas, display space, breakout, individual pod and specialized focus lab (Fisher, 2007).

In comparison to traditional classrooms, FLEs are capable of simultaneously supporting a diverse range of learning activities, such as collaboration, discussion, feedback and reflection, guided, explicit, demonstration, experiential and independent learning (NSW-DOE, 2020). Traditional classrooms and FLEs are distinct in terms of functional attributes, interior design and choices afforded to students to be comfortable (Kariippanon, Cliff, Lancaster, Okely, & Parrish, 2018) (Refer: Table 1). In the FLE scenario, spatial design plays a crucial role in the management of pedagogical practices (Gremmen, van den Berg, Segers, & Cillessen, 2016), and physical configuration is fast becoming a key classroom resource for meeting learning outcomes (Attai et al., 2020).

The Indoor Environmental Quality (IEQ) performance within a FLE configuration, that is multi-functional and polycentric, is far more challenging than traditional classrooms. There have been some studies of the impact of heating, lighting and other physical factors on academic performance, but these focus on basic building attributes and do not address wider issues such as the relationship between classroom layout and educational practice (Earthman, 2004; Picus, Marion, Calvo, & Glenn, 2009). Indeed, a recent review of current literature has revealed several gaps and shortcomings, and a lack of empirical evidence on IEQ and student satisfaction, within FLEs (Vijapur, Candido, Göçer, & Wyver, 2021). This constitutes a significant challenge considering the extensive body of work from traditional classrooms showing the impact of IEQ on learning (Heschong, 1999), academic performance (Bakó-Biró, Clements-

Croome, Kochhar, Awbi, & Williams, 2012) and overall satisfaction (De Dear, Kim, Candido, & Deuble, 2015; Haddad, Osmond, & King, 2017).

Table 1:
Comparison of Traditional versus FLEs

	TRADITIONAL	FLEs
Learning modalities	Visual and Auditory	Visual; Auditory; Tactile and Kinesthetic
Technology	* Centralized Technology (such as smart boards) fixed or confined to specific areas * Used mainly by teachers	* Decentralized Technology (distributed throughout the space) that are mobile * Used by both students and teachers * Handheld digital devices
Learner	* Passive recipient Expected to be seated still, for prolonged time periods	* Active participant * Expected to move across a variety of learning activity settings
Pedagogy	* Didactic * Formal teaching	* Non-linear dialogic teaching * Collaborative and independent learning
Space	* Rigid layout within an enclosed room * One desk/seat per student * Single learning setting	* Organic space with permeable boundaries * No dedicated desk/seat for the students * Polycentric space, with distinct learning settings

In Australia, there is a significant growth in school infrastructure projects due to the population growth in many suburbs, and as part of this new infrastructure rollout, the design of learning spaces is changing at fast pace to accommodate the delivery of new-generation pedagogical practices. This paper provides a desktop review of a total of 39 recent primary school designs comprised of FLEs, with a view of mapping similarities and deriving typologies, and then analyzing how they fare against the recommendations from The WELL Building Standard Version 2 (WELL V2) (IWBI, 2020). WELL v2 was chosen as the framework of analysis as it is the world leading healthy building guidelines, and has a holistic approach relevant to the design and performance of healthy environments. This paper aims to identify key opportunities for design and performance improvement of these spaces.

2. METHODOLOGY

The desktop review was undertaken based on a comparative floorplan analysis of FLEs from a dataset of architectural drawings of 39 public Primary Schools located in NSW. The first step in this process was based on an approach of comparison and clustering of the FLEs' spatial layouts, to identify the highest recurring typologies that are currently operational in the NSW primary school sector, and map similarities in their spatial layout and design characteristics. The highest recurring typologies were then compared against selected features of WELL v2 concepts, namely, comfort, light, air, movement, and mind.

3. RESULTS

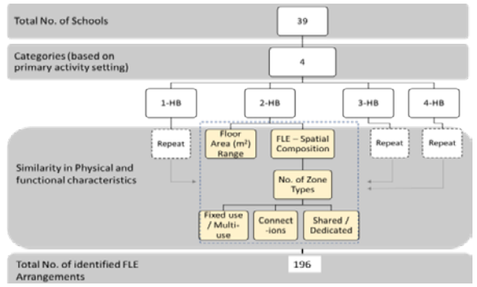
3.1 Similarity Mapping

Through an initial examination of the architectural drawings obtained for the similarity mapping review, a total of 196 types of FLE arrangements have been observed in the portfolio of 39 schools, to enable eight distinct learning modes recognized by the NSW curriculum. The next step involved grouping of the FLE designs, based on the functionality of the primary activity-settings, typically referred to as a Homebase, resulting in a broad classification of four types of settings (i.e. single, dual, triple or quad). It is to be noted that these 4 types were identified from the entire dataset, and not all these settings were present in every school.

Details of each variety (in terms of size and composition), ranging from Type 1-HB that can accommodate a single cohort of students, upto 2,3 or 4-HB that could accommodate up to 2,3 or 4 student cohorts, are presented below.

- Type 1-HB - was found to be in the range of 40-160m2 in floor-area, and is configured as a single multi-purpose space, or in connection to additional support spaces, that are either of fixed-use and multi-purpose spaces.
- Type 2-HB - was found to be in the range of 80-300m2 in floor-area and is configured as a single multi-purpose space (with the ability to be sub-divided into two spaces), either with or without connections to additional support spaces.
- Type 3-HB - was found to be in the range of 210-600m2 in floor-area and is configured as a single multi-purpose space (with the provision for sub-division via operable walls), either with or without connections to additional support spaces.
- Type 4-HB - was found to be in the range of 190-560m2 in floor-area and is configured as four individual spaces that can be combined into a single-space via operable partitions and has connections to additional support spaces.

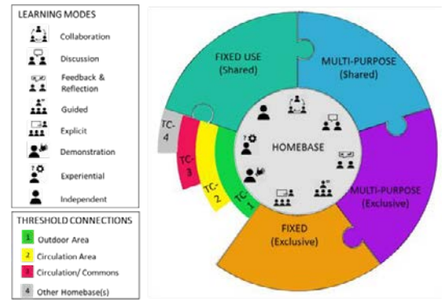
Figure 1:
Similarity mapping summary



The next step was to review the size (floor-area) and spatial composition (in terms of number of zones), and to identify other characteristics, in terms of fixed-use versus multipurpose, exclusive versus shared use, and the connections between the zones (in terms of physical access as well as visual and acoustic permeability). Overall, as summarized in Figure 1, the mapping process resulted in identifying 196 arrangements across the 39 schools.

An approach of binary coding was implemented, to map similarities, and the process resulted in grouping the 196 FLE arrangements into 58 typologies. From these 58 unique typologies, it is observed that the spatial configuration of FLEs could comprise of a stand-alone Homebase (i.e. a large open plan space that is multi-functional in character, and has moveable furniture elements to create spaces within spaces), or it could comprise of a Homebase with adjoining support spaces that are either multi-functional or of a fixed use, and are either for exclusive or shared usage. Overall, the internal partitions seem to be of varying characteristics, such as glazed-operable, opaque-operable, glazed-fixed, opaque-fixed or in some instances there is no physical barrier between spaces, rather the floor finish is varied to create the distinction between the zones. Another key observation is in terms of threshold connections (TC), for which a wide range of probabilities exist, comprising of links to internal and/or external spaces. These links could range from a simple connection to an adjacent 1) outdoor area, or 2) to a circulation area, or 3) to a circulation area containing learning-commons, or 4) to other Homebase(s). The way each of the FLE spatial arrangements are managed and utilized, is reliant on the school/teachers' pedagogical intent.

Figure 2:
Spatial configuration of FLEs



The highest recurring top-10 arrangements, of the mapped 58 FLE arrangements have been considered for further investigation, for the potential challenges and benefits, in terms of IEQ performance and sedentary behaviour reduction. The results indicate that the FLES mainly follow a cluster-composition, wherein the primary multi-functional settings are delivered to accommodate a single, dual, triple or quad amount of student cohorts, either with or without having additional support spaces. Having the multi-functional primary setting is an asset for being adaptable to meet the current and future pedagogical changes.

3.2 IEQ Performance

In terms of IEQ performance, FLEs are likely to be subject to significant challenges, in scenarios where they have insufficient acoustical separation, and they have limited opportunity to limit proximity of high and low-energy activity-settings (such as collaboration and independent learning). There is a likelihood of potential IEQ clashes that might arise within the top-10 recurring typologies that are identified through the similarity mapping, wherein the clash is likely to arise due to the proximity of the fixed-use versus multi-purpose space, and shared versus exclusive usage, and the characteristics of the internal partitions (in terms of operability, feasibility to be enclosed, transparency and acoustic separation).

The spatial volume of FLEs is a variable, as it relies on the opening and closing of the permeable boundaries. The occupant density is also non-uniform, as students are expected to be engaged in multiple learning activities, spread across the FLE, in dyads, groups and clusters. Despite the FLE being a heterogeneous space in terms of functionality, and having spatial volume and occupant density as variables, rather than constant as in traditional classrooms, the building services design, in terms of lighting and ventilation, seem to be provided in accordance with traditional guidelines in a linear

format, and do not seem to correspond with the FLEs' diverse and dynamic activity-settings.

For the top-10 FLE arrangements, it is observed that the common characteristic is the availability of a Homebase, comprising of moveable, light-weight furniture elements, to be able to reconfigure the space. Majority of the typologies have access to adjoining support spaces that are mostly designed for a single fixed usage, causing a risk to the usability of the space as it restricts the activity that could take place within. Another risk factor for the fixed use spaces is their characteristic of barrier-free direct connection with the Homebase, leading to high visual and acoustic permeability. Multi-purpose support spaces are also identified in four typologies, however majority of these are for shared usage. While there are significant benefits of having multi-purpose rooms, sharing them across multiple class-groups attracts the risk of acoustic and visual privacy and distraction issues. Every Homebase is designed to have access to the outdoor environment, for views and daylight availability. Windows for natural ventilation are also identified within each FLE, however, the ventilation effectiveness would need to be verified, because the space management might lead to the necessity for transitioning from single-sided to cross-ventilation, and vice-versa.

3.3 Comparison against WELL V2 concepts

The International WELL Building Institute's WELL Building Standard V2 (IWBI 2020) framework is a holistic instrument for advancing health and well-being of occupants within the built environment. The WELL v2 standard was chosen as the framework of analysis for its holistic approach relevant to the design and performance of healthy environments. The WELL framework is comprised of ten "concepts", which include Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind and Community. Each of these ten concepts contain "features" which are criteria that would assist in meeting the intent of the Concept. For the top-10 typologies that are identified in the similarity mapping, a comparison against WELL features has been conducted, specifically related to IEQ, sedentary behaviour, and connections to nature. The criteria of each feature are listed below in Table 2.

Table 2:
Selected criteria from WELL V2

Ref.	Title	Criteria
A07	Provide Operable Windows	For each floor, the openable window area is at least 4% of the net occupiable floor area.
L01_A	Light Exposure	Interior layout a. At least 30% of the regularly occupied area is within a 6m horizontal distance of envelope glazing in each floor and/or in each individual unit. OR b. Common spaces have unassigned seating and can accommodate at least 15% of regular occupants at any given time. At least 70% of all seating in the spaces is within a 5m horizontal distance of envelope glazing.
L01_B		Building design a. The envelope glazing area is no less than 7% of the regularly occupied floor area for each floor level or individual unit. OR b. The floor plate is no more than 65 ft between opposite walls that each have transparent envelope glazing, and there are no opaque obstructions higher than 3.2 ft within a 20 ft horizontal distance of the transparent envelope glazing.
L05_A	Daylight Design Strategies	Interior layout: 70% of all workstations are within 25ft (or 16ft) of transparent envelope glazing. Visible light transmittance (VLT) is greater than 40%
L05_B		Façade Design: Envelope glazing is no less than 25% (or 15%) of the regularly occupied floor area or individual unit. Visible light transmittance (VLT) is greater than 40%.
L05_C		Integrate solar shading to all vertical envelope glazing (either manual or automated control)
L09	Occupant Lighting Control	1: Lighting zones - All regularly occupied spaces contain lighting zones. Tier-1: One per 60 m2. One per 10 occupants Tier-2: One per 30 m2. One per 5 occupants
T08	Enhanced Operable Windows	1. Window design - Provide windows with multiple opening modes. Operable windows may be opened according to the following requirements: a. At least 70% of operable windows may be opened such that at least half of the opening is not more than 1.8m above the finished floor and opening is at least 0.3m in the smallest dimension. At least one such window is present in each room with operable windows.
S05	Sound reducing surfaces	Part 1: Implement sound reducing surfaces Minimum NRC/aw at ceilings - 0.90 for all available ceiling area Minimum NRC/aw at walls - 0.80 on at least 25% of two perpendicular walls
REDUCTION OF SEDENTARY BEHAVIOUR		
V09	Physical Activity Promotion	Offer physical activity incentives – For students. A program that aims to promote daily physical activity through at least one of the following: • Teaching strategies that incorporate movement and activity into the lesson. • Physical education. • Recess or similar physical activity breaks.
CONNECTIONS TO NATURE		
M02	Nature and place	Part 1: Provide connection to nature The project integrates the following throughout the space, including common circulation routes, shared seating areas and rooms: a. Natural materials, patterns, shapes, colours, images or sounds. b. At least one of the following: Plants (e.g., potted plants, plant walls); Water (e.g., fountain); Nature views
M09	Enhanced access to nature	Part 1: Provide Nature Access Indoors The project's floor plan is designed such that one of the following are met: a. At least 75% of all workstations and seating within shared areas and rooms, as applicable, have a direct line of sight to indoor plant(s), water feature(s) and/or nature view(s). OR
		b. All workstations and seating within shared areas (e.g., conference rooms, education spaces, common spaces), as applicable, are within 33 ft of indoor plant(s), water feature(s) or nature view(s).

A summary of the outcomes of the analysis is presented in Table 3. The WELL concepts support distinct health intents for improving occupant health and well-being. It is encouraging to see that most of the reviewed schools, are meeting the WELL design concepts in principle, of which the FLEs for single and dual cohorts have outperformed the larger deep-plan FLEs.

- AIR A07 - Windows are designed to meet the minimum requirement of 5% openable area, in accordance with NCC Section-F. Hence, exceed the WELL requirement. However, 20% of the typologies have fixed windows or insufficient amount of operable area.
- LIGHT L01A- Only 65% of the designs satisfied the WELL criteria of L01A. The remaining 35% did not satisfy the requirement, either due to the floor-plate being too deep, or due to common spaces being away from envelope glazing.
- LIGHT L01B – Around 52% seem to satisfy the WELL criteria, of having classrooms that have transparent glazing along opposite walls.
- LIGHT L05 – Majority of the designs seem to meet the criteria for daylighting, especially in terms of high visible light transmittance of external glazing and external shading for envelope glazing.
- SOUND S05 – The application of acoustic absorption did not seem to be uniform across the FLEs design. The performance characteristics of the installed sound-reducing surfaces could not be accurately verified, due to insufficient performance data.
- MOVEMENT V09 – Physical activity promotion has been considered to be 100% compliant, as the pedagogical model, lends itself to permitting students' to have non-sedentary routines. This approach is supported by the interior design features that provide for postural change (via variety of furniture) and also via multiple activity settings that the students could traverse between. However, on-site observations would be required to confirm the frequency of movement.
- MIND M02 and M09 – Around 75% of the designs satisfy the criteria, due to having connections to nature via external glazing.

Figure 3:
WELL-V2 Comparison Outcome (% Compliance)

WELL CONCEPT	WELL I.D.	STRATEGY	% Compliance
AIR	A07	Provide Operable Windows	80
LIGHT	L01_A	Light Exposure_A	65
	L01_B	Light Exposure_B	52
	L05_A	Daylight Design Strategies_A	78
	L05_B	Daylight Design Strategies_B	75
	L05_C	Daylight Design Strategies_C	80
THERMAL COMFORT	T08	Enhanced Operable Windows	80
SOUND	S05	Sound reducing surfaces	TBC*
MOVEMENT	V09	Physical activity promotion	100 *
MIND	M02	Nature and place	75
	M09	Enhanced access to nature	75

3. CONCLUSION

From the desktop review, it is identified that the spatial designs of FLES in NSW primary school settings have a wide range of variety and reiterate the findings from previous study (Vijapur et al., 2021) that they have neither a 'one-size-fits all approach', nor is the design restricted to creating simple opening or dissolving of boundaries between learning settings.

The top-10 highest recurring typologies are identified to be compliant with eleven of the WELL criteria, from seven out of eleven WELL concepts. While this outcome is encouraging, most of the compliant features are related to the building façade, and ignore the dynamics of spatial reconfigurability, occupant movement and

proximity of high and low energy activity settings, and therefore do not guarantee mitigation of potential internal IEQ clashes, specific to FLEs. Further field studies would need to be conducted to ascertain the actual performance of these spaces, the outcomes of which could be used to bridge the gaps in relevant design and benchmarking guidelines, to ensure delivery of health-promoting learning environments.

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Analysis of the effect of droplet dispersion (COVID-19 droplet surrogate) according to the use of air purifiers under cooling conditions in summer

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ABSTRACT: The world is in chaos due to the corona pandemic. Recently, indoor group infection has become a social problem. Droplet transmission with viruses from indoor airflow is the main source. This study analyzed the effect of the spread of droplets containing coronavirus when an air purifier is used in an air-conditioned classroom in summer. The experimental results are presented as the peak concentration that causes direct infection and the loss rate that can evaluate airborne infection.
As a result of the experiment, Peak concentration can be reduced by 42% or, conversely, can increase by 278% depending on the location. These results show that since air purifiers affect indoor airflow, the peak concentration can be raised or lowered depending on the situation.
On the other hand, the loss rate was found to reduce droplet nucleation by 39% and droplet reduction by 22% in turbo mode (500CMH). It is evaluated that it can significantly lower the level of airborne infection. Therefore, understanding the airflow associated with the use of air purifiers and using the air purifier appropriately will help prevent group infection by reducing the peak concentration and loss rate of droplets including the Corona 19 virus.
KEYWORDS: Droplet dispersion, Covid-19, Air purifier

1. INTRODUCTION

Coronavirus disease-2019 (COVID-19), which began in December 2019, has threatened the world. The World Health Organization (WHO) is making efforts around the world to prevent the spread of COVID-19, such as declaring a pandemic due to concerns about the spread of COVID-19. The highest possibility of transmission of COVID-19 is human-to-human transmission.[1-3] In particular, when coughing, sneezing, or even talking in an enclosed environment, the virus of an infected person is released into the air and spreads through aerosols and droplets.

Recently, many cases of Covid-19 cluster infection have been reported due to the operation of indoor air conditioners. According to a study by Lu et al., in January 2020, a cluster infection occurred in 9 people at a restaurant in Guangzhou, China, and it was determined that the main cause was the effect of air conditioning.[4] This was analyzed as the cause of the rapid diffusion of droplets throughout the space due to the rapid airflow when the air conditioner is operated. In summer, when the temperature and humidity are high, the operation of the air conditioner is essential. Therefore, it is necessary to prepare for the spread of droplets that spread covid-19 when operating the air conditioner.

The use of portable air purifiers is increasing worldwide. The main reasons for using air purifiers are different in each country. Korea and China have a lot of fine dust, so they use it to get clean air., Japan purchases it to prevent allergies caused by pollen. The United States purchases it to purify the air from dust from carpets and pets. For these reasons, the use of air purifiers has become common all over the world.

In addition to the common use of air purifiers, unexpected effects of air purifiers have been reported recently. It is said that air purifiers are effective in preventing COVID-19.[5] According to Zhao. B, using an air purifier in dentistry has a preventive effect in suppressing the spread of droplets through the mouth during the COVID-19 pandemic.[6] In addition, Chen, C et al. argued that the use of air purifiers in dental clinics is an effective way to reduce exposure to airborne droplets and aerosol particles. Mousavi, Ehsan S., et al. analyzed the effect of using an air purifier in a hospital room for COVID-19. When an air purifier was used in an isolated space, a 99% reduction effect was observed. And the optimal location of the air purifier was found to be near the patient's bed.

These reasons, the Centers for Disease Control and Prevention (CDC) recommended the use of a portable air purifier with a HEPA filter during the

pandemic. However, unlike the above cases, research has also been reported that the use of an air purifier can promote the spread of COVID-19. According to a study by Ham. S., it was argued that the cluster infection that occurred in a call center company was caused by the droplets of the infected person by the airflow of the air purifier.[7] Therefore, in this study, repeated experiments were conducted to examine the effect of the spread of droplets (including the Corona 19 virus) according to the use of an air purifier under the conditions of using air conditioners in summer.

2. Method

2.1 Droplet surrogate

Since the virus is transmitted through droplets, the size of the droplet containing the virus is more important than the size of the virus itself. According to the WHO, particles from human saliva with a size smaller than 5 μm were defined as droplet nuclei, and particles larger than 5 μm were defined as droplets. In this study, particles depicting droplets containing viruses were released and tested, and the particle size was analyzed by dividing the particle size into droplet (>5μm) and droplet nuclei(<5μm). In addition, the mass concentration of PM10, the evaluation method of Han. et al., was used to evaluate the overall effect of the virus. Since it is difficult to release human droplets in large amounts, a droplet surrogate material was used in the experiment. Experiments were conducted using paraffin liquid with an average diameter close to that of a droplet. In the case of paraffin liquid, special attention is required because it can cause respiratory problems, so it was tested in a strictly controlled place. In particular, it was kept unattended during the experiment.

2.2 Experimental setup

The experiment was conducted from July 27 to September 1, 2021 in a hot summer with an average outdoor temperature of 28 ± 3 ℃. It was held in a lecture hall at a university in Seoul, Korea. The room is 6 m wide, 8.75 m long and 2.8 m high. Fig. 1. shows the scene and equipment settings at the time of the experiment. Blower door depressurization test was performed to know the airtightness performance of the lecture hall. In this study, Retrotec 6100 (Retrotec, Everson, WA USA) was used. Blower door depressurization test was measured based on American Society for Testing and Materials (ASTM) E779:2010 and ISO9972:Europe (2016). The measurement result was 〖ACH〗_50 = 23. This is because old windows cause a lot of leakage. In addition, on the premise that the Electric Heat Pump (EHP) attached to the ceiling is operated in summer, the indoor temperature was set to 25℃, and it was operated in the weak wind speed mode. Measuring instruments were placed at the back (Point 1: P1), middle (point 2: P2), and front (point 3: P3) three places to measure the diffusion intensity according to location. There are two types of particle generator positions. A: When the infected student sits in the back seat, B: When the infected Presenter speaks in the front. The portable air purifier was placed in the back (a) or front (b) to conduct the experiment.

Figure 1:
Experimental setup, sampling location.

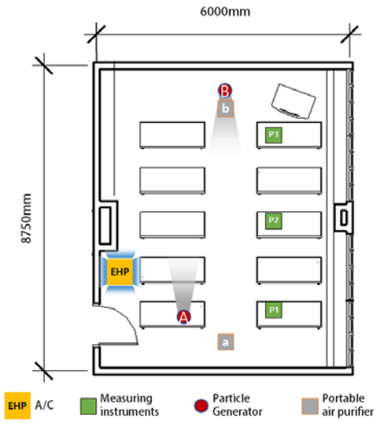


Fig. 2 shows the structure of the particle generator. The air is expelled from the air compressor. The air passes through the filter and silica gel and is discharged as dry pure air. During the release, the pressure was kept constant at 2 bar. During the repeated experiment, the same amount of paraffin oil was released by making the injection pressure and injection time the same.

Figure 2:
Structure of particle generator.

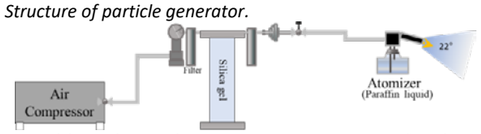


Table 1 shows the measuring equipment for the experiment. TSI-8530 and OPS3330 were used to measure the droplet concentration. TSI-8530 was used to measure particle mass concentration. It is mainly used to measure PM10 and PM2.5 and can measure with high accuracy. For particle number concentration, OPS 3330 was used. This enables accurate measurement of particle concentration and size-distribution using optical particle counting technology. TESTO-400 Identifies the (PMV) elements in the laboratory (temperature, humidity, air speed, radiation temperature). Portable air purifiers used low-cost products commonly used worldwide. This product has a particle CADR of up to 500 m³/h. Effectively, it has an effective area of 60 m². A HEPA filter was used for the filter.

Table 1
Laboratory measurement devices.

Device name images	Basic principle and condition
TSI-8530	TSI-8530 was used to measure particle mass concentration. It is mainly used to measure PM10 and PM2.5 and can measure with high accuracy.
OPS3330	For particle number concentration, OPS 3330 was used. This enables accurate measurement of particle concentration and size-distribution using optical particle counting technology.
TESTO 400	Identifies the PMV elements in the laboratory (temperature, humidity, air speed, radiation temperature)
Portable air purifier	This product has a particle CADR of up to 500 m³/h. Effectively, it has an effective area of 60 m². A HEPA filter was used.

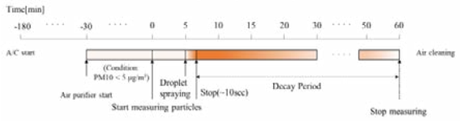
Table 2. summarizes the cases of the experiments conducted in this study. Experiments were conducted by dividing the experiment according to the droplet generation location, the air purifier location, and the air purifier flow rate into 10 cases. Each experiment was repeated 2-3 times. The location of each device is shown in Fig.1. Air purifier flow rate is about 109CMH (Cubic Meter per Hour) in low mode and 500CMH in Turbo mode. (i.e. low mode: 0.74 ACH (Air change per hour), Turbo mode: 3.4 ACH)

Table 2
Experimental cases.

Case	Particle generator location	Air purifier location	Air purifier flow rate Low mode(109CMH), Turbo mode(500CMH)
1	A	No	-
2	B	No	-
3	A	a	Low mode
4	A	a	Turbo mode
5	A	b	Low mode
6	A	b	Turbo mode
7	B	a	Low mode
8	B	a	Turbo mode
9	B	b	Low mode
10	B	b	Turbo mode

Fig. 3. shows the schedule of the particle dispersion experiment. 3 hours before measurement, operate EHP (A/C) to bring the average indoor temperature to 25±2 °C. The air purifier was operated for more than 30 minutes so that the initial concentration of each experiment was 5 μg/m³ or less based on PM10. The measurement was started, and the basal concentration was measured for 5 minutes, and then particles were diffused for 10 seconds. Measurement was terminated at the time point 1 hour after particle generation.

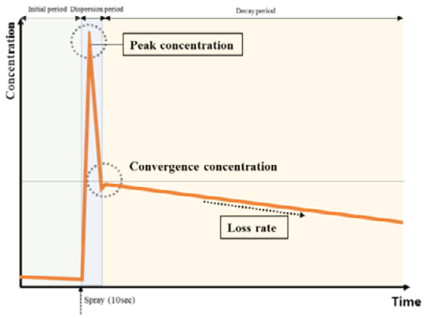
Figure 3:
Measurement schedule of droplet dispersion.



2.3 Particle dispersion analysis method.

The concentration of emitted particles in the particle dispersion experiment is shown in Fig.4 It shows the same trend. It forms an initial basal concentration and increases rapidly through dispersion immediately after particle generation. The instantaneous peak concentration of the initial droplet that occurs when a person sneezes or coughs contains a large amount of virus and is an important factor in direct droplet infection. Thereafter, the concentration decreases rapidly through deposition or removal of particles. A loss rate is calculated in a period in which the particle concentration stably decreases after a certain period of time (decay period). The reason that the loss rate is important is that it is a cause of aerosols infection because it is suspended in the air for a long time.

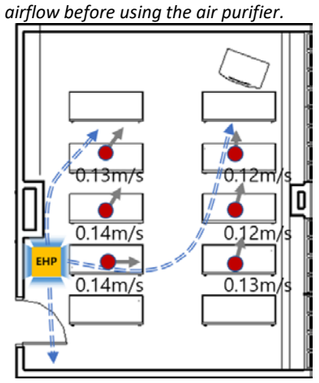
Figure 4:
Schematic diagram of droplet dispersion.



3. Results and Discussion

Before the experiment, the indoor airflow direction and wind speed were measured in 6 places using the indoor airflow Testo 400. Fig. 5 shows the airflow and wind speed in the room. The lecture hall was affected by EHP and infiltration. Thus, the overall airflow was directed forward and formed to the left, towards the window. In this study, droplet diffusion according to the use of an air purifier was tested on the premise of using A/C in summer. Data were logged at 30 second intervals.

Figure 5:
Classroom airflow before using the air purifier.



3.1 PM10 mass concentration difference according to particle generation location difference, No Air purifier (Case1 vs Case2)

In Fig. 6, Case 1 and Case 2 were compared to see how the concentration changed only depending on the location of particle generation in the state where the air purifier was not used.

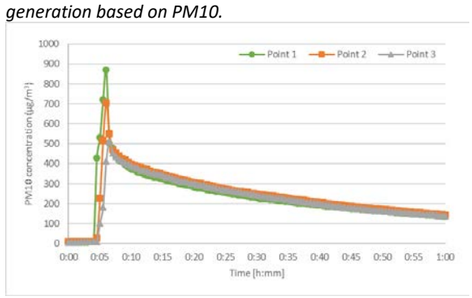
According to the location of Case 1 in Fig. 6, the peak concentration, Point 1: 871, Point 2: 707, Point 3: 515 μg/m^3, showed a clear difference.

The reason is that the airflow direction by EHP and the ejection direction of the particle generator are similar in Fig. 5., so it seems to have helped the initial diffusion. Therefore, Point 1, which is close to the location of A, appears to have the highest maximum concentration, and Point 3, which is the furthest away, appears to have the lowest peak concentration.

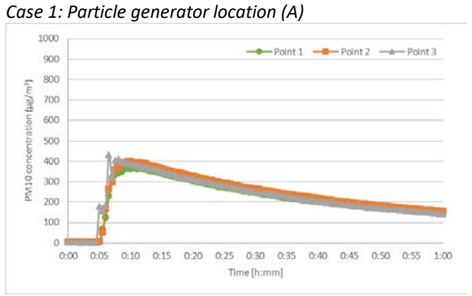
That is, when the moving direction of particle generation and the moving direction of the indoor airflow are the same, it is stratified according to the distance from the source and a high concentration is formed.

On the other hand, in Case 2, since the direction of the indoor airflow by EHP and the ejection direction of the particle generator are opposite, even if initially peak concentration particles are generated, they are propagated evenly in the mixed state and the difference in concentration by location does not appear clearly. This is a important finding as it shows that, in the spread of covid-19 virus, when the direction of propagation of droplets and the direction of indoor airflow are the same, high-concentration virus can be transmitted to a distant place.

Figure 6:
Differences according to the location of particle generation based on PM10.



Case 1: Particle generator location (A)



Case 2: Particle generator location (B)

3.2 Comparison of peak mass concentration.

In order to compare the degree of direct infection at high concentrations, the peak concentrations were compared.

Table 3. shows the increase rate of the peak concentration for each case, based on the peak concentrations of Case 1 and Case 2 where the particle generator positions are different.

Table 3
Comparison of PM10 average mass peak concentration by location.

Case	Setting (Particle generator location, Air purifier location, Air purifier mode)	Average peak concentration(μg/m³) Point 1 Base peak concentration (A)	Point 1 Average peak concentration (B)	Point 1 Rate of increase (A/B-1)*100	Point 2 Base peak concentration (A)	Point 2 Average peak concentration (B)	Point 2 Rate of increase (A/B-1)*100	Point 3 Base peak concentration (A)	Point 3 Average peak concentration (B)	Point 3 Rate of increase (A/B-1)*100
1(Base)	A--(No purifier)		871	0%		(A)	0%		(A)	0%
3	A,a,Low		905	4%		579	-18%		439	-15%
4	A,a,Turbo	871	990	14%	707	410	-42%	515	381	-26%
5	A,b,Low		1345	54%		956	35%		480	-7%
6	A,b,Turbo		1460	68%		1260	78%		886	72%
2(Base)	B--(No purifier)		368	0%		399	0%		432	0%
7	B,a,Low		394	7%		429	7%		670	55%
8	B,a,Turbo	368	397	8%	399	494	24%	432	1630	278%
9	B,b,Low		330	-11%		404	1%		621	44%
10	B,b,Turbo		353	-4%		381	-4%		360	-17%

3.2.1 Location of the infected student:(A)

1) When the position of the air purifier is at a (compare Cases 1, 3, and 4): At the position of Point 1, the peak concentration when using the air purifier increased by 4% in low mode and 14% in Turbo mode, whereas at Point 2 They decreased by 18% and 42%, respectively, and by 15% and 26% at Point 3, respectively. Point 2 and Point 3 show that the use of an air purifier can reduce the peak concentration. On the other hand, in the case of Point 1, since the air purifier operated in the direction of suppressing the progress direction of the particle generator, it is judged that the initial peak concentration of particles was concentrated and increased in the nearby Point 1.

2) When the position of the air purifier is at b (compare Cases 1, 5, and 6): In general, Point 1, Point 2, and Point 3 all showed higher peak concentrations than Case 1 without using an air purifier. It is judged that this is because the air purifier pulled the air in the direction that promotes the particle propagation direction of the particle generator. In Point3, when the air purifier was in low mode, there was a case where it actually decreased by 7%. This is judged to be the difference between the air purifier's pulling force and the instantaneous airflow effect.

3.2.2 Location of the infected Presenter: (B)

1) When the position of the air purifier is at a (compare Cases 2, 7, and 8): Point 1, Point 2, and Point 3 all showed higher peak concentrations than Case 2 without using the air purifier. It seems that the peak concentration all increased because the air purifier sucked in the direction of particle generation. In particular, in the case of Point3, 278% increased. This is a critical result. This is because if the air purifier pulls the airflow in turbo mode in a situation where the overall airflow in the room is directed towards the front of the room,

it can be seen that people near the infected presenter are 278% more likely to be infected.

2) When the position of the air purifier is at b (compare Case2, 9,10): Point 1, Point2, Point3 It seems that the peak concentration has decreased in general. This seems to be because the generated droplet surrogate was removed directly from a short distance. Nevertheless, in the case of Point 3, some peak concentrations were also increased in the low mode. This is considered to be caused by the temporary effect of airflow on the supply air of the air purifier more than the effect of the return air of the air purifier.

3.3 Comparison of loss rate: PM(0.3~10) number concentration.

Table 4. shows the loss rate according to the particle size of each case in a table in order to compare the loss rate of the droplet and the droplet nucleus. The average loss rate of PM 0.3-5 (droplet nuclei) throughout the experiment was 5.4, and the loss rate of PM5-10 (droplet) was 8.4. As a result of the experiment, the droplet showed a 54% higher loss rate than the droplet nucleus.

Table 4
Comparison of particle number concentration loss rate by case of PM0.3-5 and PM5-10.

Case	Loss rate (1/h) Point 1 Size:(0.3-5)μm	Point 1 Size:(5-10)μm	Point 2 Size:(0.3-5)μm	Point 2 Size:(5-10)μm	Point 3 Size:(0.3-5)μm	Point 3 Size:(5-10)μm
1	4.3	6.9	4.4	7.0	4.2	5.9
2	4.4	7.9	4.5	6.4	4.3	6.6
3	4.4	6.8	4.5	12.5	4.3	7.6
4	8.8	7.0	7.6	6.9	7.9	7.3
5	4.2	8.6	4.2	6.6	4.2	9.7
6	7.0	10.6	7.0	6.5	7.0	13.5
7	4.2	9.4	4.4	8.7	4.3	9.9
8	6.6	7.1	6.2	13.0	6.3	6.9
9	4.3	7.4	4.5	7.0	4.6	9.4

10	6.5	10.1	7.0	8.2	6.8	9.9
Average	**5.5**	**8.2**	**5.4**	**8.3**	**5.4**	**8.6**

Table 5. shows the loss rate by air purifier intensity. As a result of comparison, in the case of droplet nuclei in the air purifier low mode, the increase rate was almost 1% less effective. However, a 19% reduction effect was found to be relatively large in the droplet. In turbo mode, the effect was high in the case of droplet nucleus by 39% and in the case of droplet by 22%.

Table 5

Comparison of particle number concentration loss rate by air purifier intensity of PM0.3-5 and PM5-10.

	Droplet nuclei Size:(0.3-5)μm		Droplet Size:(5-10)μm	
	Loss rate(1/h)	Rate of increase (A/B-1)*100	Loss rate(1/h)	Rate of increase (A/B-1)*100
No purifier(A)	4.3	-	7.0	-
Purifier low mode(B)	4.34	-1.0%	8.6	-19%
Purifier turbo mode(B)	7.1	-39%	8.9	-22%

4. Conclusions

Studies that show that the use of air purifiers have a positive effect on the spread of COVID-19 and that it has a negative effect on the spread are tightly aligned. In this study, the effect of diffusion was evaluated by conducting a droplet dispersion experiment according to the use of an air purifier in summer using an air conditioner (EHP). As a result of the study, the peak concentration was analyzed to determine the degree of direct infection, and the loss rate was analyzed to determine the degree of infection in the aerosol.

In the peak concentration, the instantaneous peak concentration could be reduced by 42% depending on the location where the air purifier was used, and conversely, it also could be increased by 278%. This produces the complete opposite result depending on how the air purifier changes the airflow in the room.

On the other hand, the loss rate for evaluating aerosol infection was 39% for droplet nucleus and 22% for droplet in the air purifier turbo mode, showing high reduction efficiency.

However, in the low mode, it did not significantly affect the loss rate compared to the turbo mode. It is judged that the effect of infiltration was greater than the air volume of the air purifier because the airtightness of the classroom was weak. Even so, if it is an airtight thread, it will be effective in proportion to the air volume of purifier.

What can be known from this research experiment is that the direction of airflow has the greatest influence on viral infection indoors. This is because droplets containing the virus travel through the air stream and spread indoors.

The results of the study by Ehsan S. et al concluded that the optimal location of the air purifier is in an isolated space, near the infected person. Compared with the results of this study, the same result was derived that placing an air purifier near the source of lowering the peak concentration as a result.

Based on this evidence, we need to move away from the narrow thinking that the use of air purifiers or air conditioners spreads corona, and move toward maintaining safety from viruses by understanding the movement of airflow and using it effectively.

ACKNOWLEDGEMENTS

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Methodology to evaluate and educate on indoor air quality in Early Childhood Education Centers

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ABSTRACT: Several studies indicate that more than one in three children in Europe has bronchial asthma or allergies. The rate of respiratory diseases is progressively increasing and that there is also a clear relationship between school performance and indoor air quality. The increase in IAQ in children's schools produces a decrease in the demand for pediatric health care. The main objective of this project is to analyze the shelter capacity of children's schools against pollution phenomena, through the identification and evaluation of the key parameters in the environmental quality of children's schools. A primary purpose of the project is the transfer of the results to the education sector so that we all become aware of the problems caused by IAQ and be able to improve it.
The methodology proposed includes: the characterization of IAQ and outdoor air quality based on in situ measurement of the main environmental variables; the assessment of its shelter capacity, conducting surveys for teachers and students on environmental quality; and the execution of awareness activities that reinforce the participatory process in the project of the educational community. This method is innovative because it has been studied transversally between different disciplines to respond to the problem both technically and from awareness and social education.
KEYWORDS: Indoor Air quality, Outdoor air quality, Health, Educational Activities, Schools.

1. INTRODUCTION

Recent research concludes that outdoor air pollution causes about 3 million premature deaths in the world per year [1]. This fact directly affects the air breathed inside buildings, especially in the most polluted cities [2]. The APHEKOM project determines that European citizens are exposed to concentrations that exceed the recommendations of the World Health Organization (WHO), while establishing estimates that confirm that a reduction in air pollution in cities will generate significant economic benefits and monetary in Europe [3]. This situation occurs specifically in the large cities of Andalusia; For example, in the case of Seville, 33% of citizens are exposed to this pollution, exceeding the values established by Directive 2008/50 / EC and Royal Decree 102/2011, although if we take as limit values those established by According to the WHO recommendations, this consideration increases to 95% of citizens [4]. Studies on the behavior, effects and prediction of outdoor air pollutants [5] - [7] identify that the most common outdoor species in cities (NO2, PM <10, aerobiological particles - pollen and fungal spores— and O3) has a very direct relationship in the prevalence of asthma and also in its severity [8] - [12].

The pollutants found in indoor environments can have an equal or even greater impact on the health of children than the classic pollutants found outdoors, since the time spent indoors is usually greater than outdoors, encountering there is often a higher concentration of some of these pollutants indoors (endogenously produced) than outdoors [13]. It has been possible to identify a causal relationship between increased pollution (specifically PM2.5 and NOX) and the increase in cases of hospital admissions for children due to bronchiolitis, bronchitis and pneumonia for the city of Seville [14].

The main objective of this project is to present the methodology to analyze the refuge capacity against pollution phenomena in children's schools, through the identification and evaluation of the key parameters in the environmental quality of children's schools. After this analysis, carry out experiences that increase awareness on the part of children and the teaching team about the need to

control air pollution as a way of caring for the environment and, consequently, for the health of the human being.

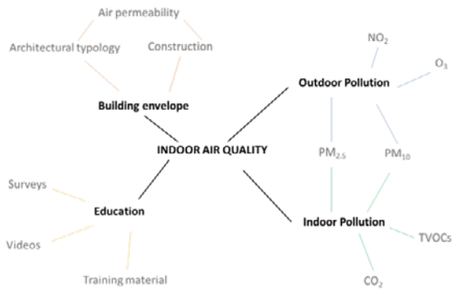
In this context, indoor air quality in schools has generated great public attention in recent years. There are studies that indicate that applying higher ventilation rates improves sick leave for both teachers [15]–[17] and students [18], [19], usually achieving significant reductions in the period of absence from school. This aspect not only results in a better state of health, but also has an influence on the process of maturation and cognitive development of minors [20], [21], as well as the fact that fewer days of illness for younger children has a positive impact on parental absenteeism in relation to caring for sick children [22]–[24]. These effects are currently poorly quantified, which means that estimates of the impact of social benefits of improving indoor environments are conservative in their expectations. It can also be established that there is a clear relationship between learning with thermal comfort, on the one hand, and indoor air quality and the degree of ventilation [25] on the other, as well as with the combination of both effects [26]. –[29].

2. METHODOLOGY

This project is based on 4 fundamental strategies (Figure 1):

- The typological, constructive and energetic characterization of Early Childhood Education Centers.
- The analysis of the main urban pollutants in the city.
- The analysis of the main internal pollutants in an Early Childhood Education Center.
- Development of learning material for the understanding of indoor air pollution for children.

Figure 1: Conceptual scheme.



2.2 Characterization of the study sample.

The choice of nursery schools that will be part of the sample will be carried out taking into account the air quality of the outside environment, including the distance to a busy road, industrial sources of emissions, etc., and the classification established by the draft European standard PNE-prEN 16798-3. The statistically most relevant and architecturally most significant children's schools within the study area and with locations with respect to different emission sources will be selected as case studies.

The morphological and dimensional characteristics, as well as the different constructive solutions of the buildings in the sample, will be analyzed, with the aim of identifying those factors with the capacity to influence behaviors in relation to the filtering capacity and emission of pollutants. The following tasks will be performed:

- Air permeability test of the envelope through the test described in UNEEN ISO 9972: 2019.
- Location of air leaks and thermal bridges using infrared thermography.
- Inspection and measurement of materials and thermal transmittance of enclosures and openings.
- Check list. Collection of information on possible sources of internal and external contamination and other information on the operation of the educational buildings.

2.3 Monitoring

Carrying out in situ measurement campaigns of environmental behavior through specific measurements and stable monitoring of the studied spaces. Three sampling locations were selected in each school (one sample per classroom) that are occupied during school hours. The classrooms selected for monitoring must be representative of the school building. The initial inspection should identify homogeneous blocks of classrooms.

Monitoring outdoor pollutant concentrations is important because children's exposure also occurs outside and from the transfer of environmental pollutants to indoor air. At least one outdoor air sample must be collected at each school for each pollutant. The sampling and measurement systems used will be for indoor and outdoor parameters:

- Indoor comfort parameters, datta loggers of temperature, humidity and air speed, continuous monitoring for 5 days a week for each of the seasons (autumn, winter, summer and spring).
- Indoor air quality conditions ($PM_{2.5}$, TVOCs and CO_2 concentration), continuous monitoring for 5 days a week for each of the seasons (autumn, winter, summer and spring).
- Indoor ozone measurement using identification patches, a daily sample for 5 days a week for each of the seasons (autumn, winter, summer and spring).
- Outdoor air quality conditions measurement (SO_2, $PM_{2.5}$, PM_{10} , ozone, and CO_2 concentration), using 3 daily measurements in different hourly ranges affected by urban traffic.

2.4 Development of learning material

A series of programmed activities have been developed to be carried out with students between 4-7 years old with the aim of raising awareness about the main sources and the health effects of air pollution emissions among the school community. Every day decisions can have an impact on the air we breathe and we all have a role to play and we can all be part of the solution.

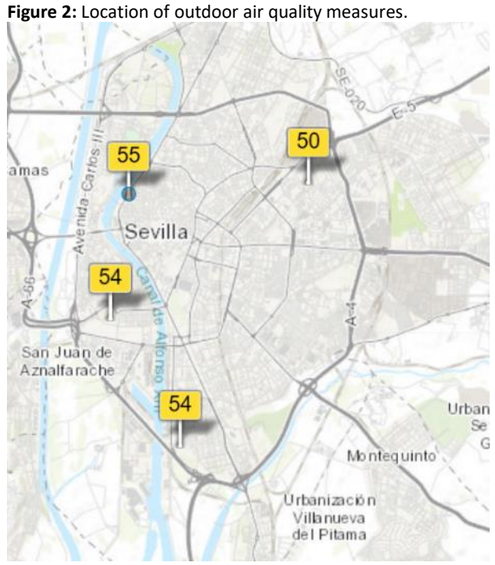
The activities consist of knowing what air is, what it is made of, studying the different contaminants present in the air and seeing how it affects living beings and the environment. They are also taught how to help improve air quality.

3. RESULTS

3.1 Urban pollutants identification

In the metropolitan area of Seville, measurements have been taken from 4 meteorological stations that provide data on air quality (Figure 2).

Figure 2: Location of outdoor air quality measures.



Measurements have been collected every 10 minutes of the different parameters in order to compare them with the indoor concentrations of pollutants in some of the Early Childhood Education Centers measured in Seville. Figure 3 shows a point measurement of the values of the station located in Los Bermejales, south of Seville.

Air quality is measured by the air quality index. Through a formula that assigns importance to the different contaminants. There are some colors to identify how polluted the air is. These colors range from blue, which indicates that the air quality is good, to purple, which indicates that the air quality is very poor. Figure 4 shows the hourly evolution of this index on March 20 and 21, 2022.

Figure 3: Pollutants concentrations.

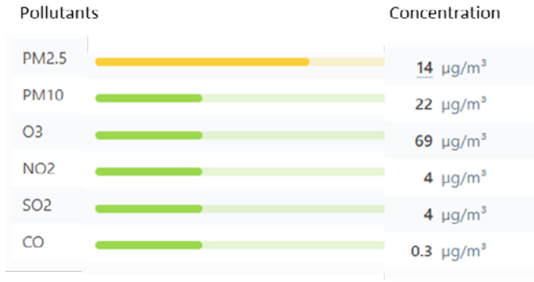
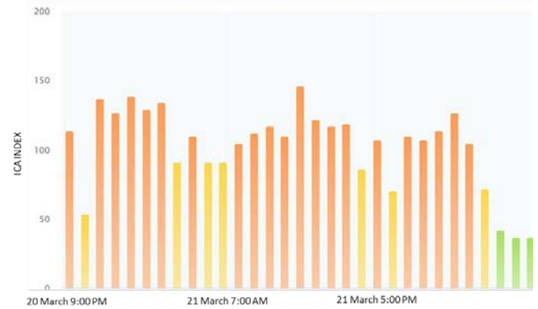


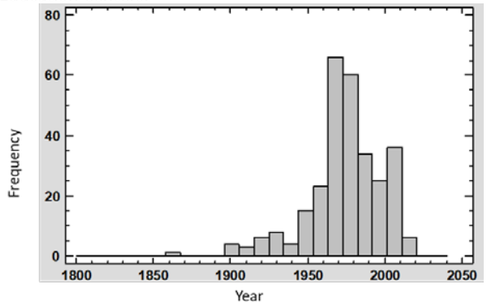
Figure 4: Air Quality Index.



3.2 Characterization of the study sample

In Seville there are 297 Early Childhood Education Centers. Figure 5 shows the years of construction, 63% of the total was built without any regulations and have more than 50 years.

Figure 5: Year of construction of Early Childhood Education Centers.



3.3 Monitoring

3.3.1 CO_2 Concentration.

Many indoor air quality (IAQ) studies adopt CO_2 concentration as an indicator of actual ventilation rates and as IAQ-index. It is generally accepted that CO_2 keeps 'bad company' and that levels above 1000 ppm are indicative of poor ventilation rates [30]—which corresponds to a ventilation rate of 8 l/s per person.

3.3.1 $PM_{2.5}$ Concentration.

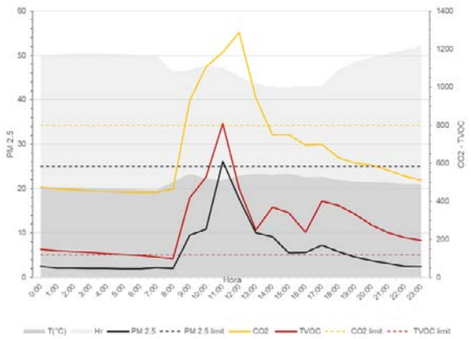
Airborne particulates are solid or liquid substances suspended in the air flow, and can include dust, fumes, smoke, microorganisms, mist, and fog. These particles can range widely in diameter, the most harmful in domestic environment are respirable suspended particulates (RSPs), especially the fine inhalable particle fraction, 2.5 µm or smaller—$PM_{2.5}$. The figures used as the control limit for the analysis proposed will be based on those established by the World Health Organization (WHO), which proposes an annual limit of the concentration of PM2.5 of 10 µg/m^3 and a daily limit of 25 µg/m^3.

3.3.2 TVOCs Concentration.

Accordingly, the concept of total volatile organic compound (TVOC) attempts to address this practical limitation by providing a simple measurement for the aggregate of all volatile organic compounds without making distinctions between individual chemicals. Typically, the concentrations of VOC detected indoors are higher than outdoors and have increased over the past decade, so that outdoor contribution may be considered negligible most of the time. Although there is no common regulation on the admissible TVOCs exposure inside homes, it is possible to establish some general thresholds from which inhabitants' sensitivity may arise (physiological responses and pathological processes can be identified in occupants). In the range of 120 to 1200 ppb, symptoms of irritation and discomfort can begin to appear in some occupants. Up to 10,000 ppb, these symptoms are generalized, taking different forms depending on the degree of sensitivity of the inhabitants and the species present, developing toxicity levels of up to 10,000 ppb.

Figure 6 shows the hourly evolution of the different parameters on an average day of the week in a classroom. In them it is seen how with the arrival of the students to the Center all the values increase. The drop in values coincides with the opening of windows in the classroom.

Figure 6: Indoor Air Quality Parameters.



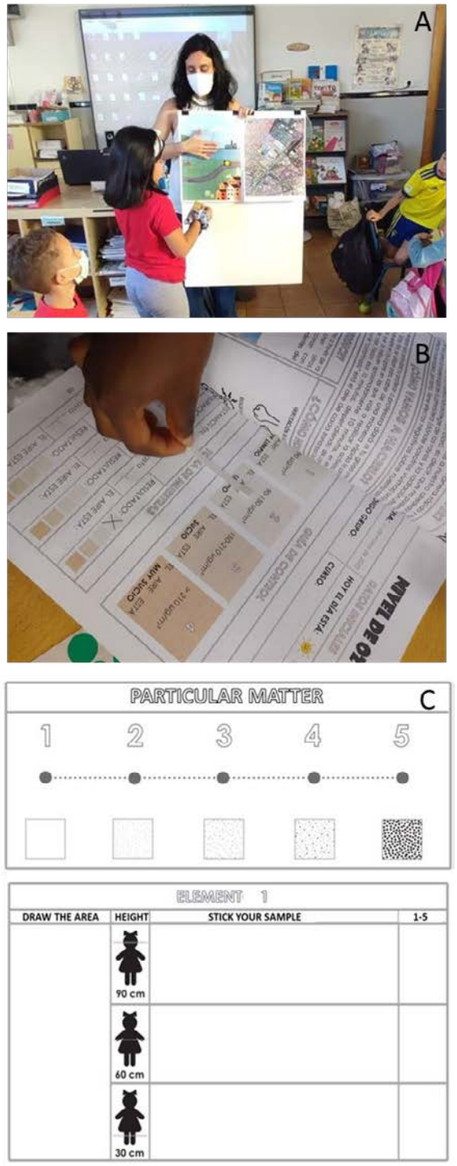
3.4 Learning about indoor/ outdoor air quality

100 students aged 6 and 7 have participated in learning sessions on indoor air quality. These conferences are part of some pilot experiences belonging to the research project UnCOVER.

This project focused on working with students in their early educational stages together with teaching teams seeks to identify the need to control and assess air pollution as a way of caring for the environment and consequently our health.

During these experiences, both informative and educational activities have been carried out in which the students have learned about the main types of pollutants in the air, their origin and their effects on our health and the environment. Activities have been carried out to locate sources of air pollution in a generic way and later locating them in their urban nucleus (Figure 7a), a series of activities have also been carried out to understand different pollutants such as the ozone level (Figure 7b) and the amount of particulate material (Figure 7c). The students have been highly motivated during the activities. In the satisfaction questionnaires that have been carried out on the activity, a total of 4.6 points out of 5 have been obtained. The educational team of the Center has also valued the activity very positively. It is a topic that is not currently included in the school curriculum and can improve it.

Figure 7: Classroom activities on air quality



4. CONCLUSION

An important aspect to highlight is that the focus of this work is perfectly framed within the Priority Regional Objective III (RPG3) of the Action Plan for the Environment and Children's Health for Europe (CEHAPE), to prevent and reduce respiratory diseases due to outdoor and indoor air pollution, which is an indicator of the relevance and timeliness of this research.

The study shows that the concentrations of indoor pollutants are above the values of outdoor pollutants.

Indoor Air Quality is a topic that is not currently included in the spanish school curriculum and can improve it. Different activities and stories can be downloaded free of charge from the Project's website UnCover to learn about indoor air quality in schools.

Future research and potential contribution of this research for architecture studies is a book on good construction and ventilation practices in educational buildings.

ACKNOWLEDGEMENTS

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Habitability in hot arid climate dwellings during COVID-19
Exploratory study

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ABSTRACT: The World Health Organization declared the SARS-CoV-2 virus impact as a pandemic in March of 2020. In Mexico, like many countries around the world, different health protocols were established for the general population. Among them, "Quédate en casa (Stay home)", which involved drastic changes to the use and livability of users' homes. The objective of this research was to determine the physical conditions of the dwelling and the activities within, particularly, but not limited to, the adaptations in habitation conditions due to confinement. Fieldwork was carried out through online surveys, which were applied in Mexicali, 293 effective records were obtained. The results showed that the amount of people and the available space in the house were adequate for home office and home school activities; additionally, the living conditions overall were found to be inadequate due to overcrowding, which did not allow the isolation of the infected. Even though this study was a first approach to characterize habitability conditions during the pandemic, it was possible to detect that most of the houses did meet the necessary conditions for prolonged confinement.
KEYWORDS: COVID-19, Dwellings, Habitability, Hot arid climate

1. INTRODUCTION

In March 2020, The World Health Organization (WHO) declared the SARS-CoV-2 virus impact as a pandemic [1]. In Mexico, as in many countries around the world, different health protocols were set for the general population. Among them, the program "*Lavarse las manos* (Wash your hands)", "*Sana Distancia* (Healthy distance)" and "*Quédate en casa* (Stay at home)". The latter involved drastic changes to the use and livability of users' homes.

The pandemic generated research in most disciplines, due to its psychological, economic, social, and cultural repercussions in addition to the impact on public health. From the discipline of architecture, several international and national studies were identified, such as those of the Torrojas Institute [2] in Spain, in Latin America [3], and particularly in Mexico [4] and the National Autonomous University of Mexico [5], yet in the city of Mexicali, there is only one investigation in progress, and it is part of the Transdisciplinary Network of Habitat and Sustainability Studies.

The objective of this article is to determine the physical conditions of the house, the activities of "home office" and "home school", and particularly the transformations that habitation conditions in the house had because of confinement, among others. This will allow the understanding of the extent of preparedness in the home for confinement requirements, as well as the actions when a resident of the house was infected with COVID-19.

2. METHOD

A mixed methods investigation was developed as a quantitative investigation with a non-experimental approach and a cross-sectional design through online surveys.

2.1 Case study

The city of Mexicali, Mexico, is located at 32°39’48” latitude North and 115°28’04” longitude West (Fig. 1) and an altitude of 3 meters above sea level.

Figure 1:
Location of Mexicali, Baja California, Mexico

Mexicali has a hot arid climate. Statistical data from 1981-2010 show a mean annual temperature of 23.7 °C. The climate of Mexicali presents a critical period due to high temperatures in the months of June, July, and August, with average high

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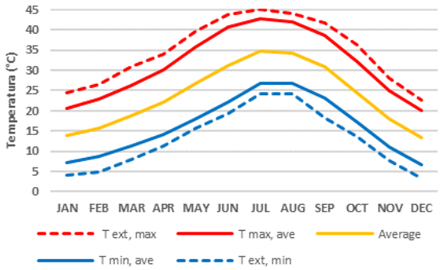
temperatures of 40.6 °C, 42.9 °C and 42 °C, with extreme high temperatures of 43.8 °C, 45 °C, and 44.2 °C, respectively. In addition, it presents a cold period in the months of January, February, and December with minimum mean temperatures of 7.1 °C, 8.8 °C and 6.8 °C and extreme minimums of 4.2 °C, 4.8 °C and 3.4 °C, respectively, as shown in Fig. 2.

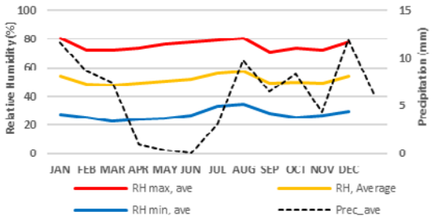
It should be noted that extreme maximum mean temperatures of up to 52 °C have been reached in the city on July 28, 1995 (National Meteorological System, 2010).

Figure 2:
Annual Mean Outdoor Dry Bulb Temperature, 1981-2010, Mexicali, Mexico.



Mexicali's climate is characterized as hot dry, with a mean annual relative humidity of 51%. The highest relative humidity in the warm season occurs in the months of June, July, and August, with average values of 52%, 56% and 57% with extreme values of 78, 79 and 81% respectively, which can be observed in Fig. 3.

Figure 3:
Annual Mean Relative Humidity and Rainfall, 1981-2010, Mexicali, Mexico.



The annual average precipitation is 6.11 mm, with greater presence of rainfall in winter, during the months of January (11.6 mm) and December (11.9 mm). In the warm period, there is sparse rainfall in the months of April to June and light precipitation in the months of August, September, and October, as can be seen in Fig. 3.

2.2 Field survey

A survey was conducted, with the design and implementation of a habitability questionnaire. To minimize the risks of contagion, the survey was applied through Survey Monkey, which was distributed by social media (Facebook) and by invitation sent by email with the support of students from the Faculty of Architecture and Design of the Autonomous University of Baja California.

The sample design was carried out with a confidence level of 95% and 5% error, which required a minimum of 384 records. Since the necessary number of records were not obtained, preliminary studies were conducted with the collected information, which allowed a glimpse of the phenomenon's behavior.

The application of the instrument was during Mexicali´s cold season -November 2020- and the seasonal transition during March-April 2021. Since it was distributed by digital means, it was necessary to perform data depuration, from which, 293 effective records were obtained. A descriptive statistical analysis was performed for data processing.

2.3. Questionnaire design

The questionnaire has 28 items, it consists of general data (city, subdivision), characteristics of the inhabitants (sex, age, number of inhabitants per dwelling), physical characteristics of the dwelling (type of dwelling, number of sleeping spaces and bathrooms, size of the spaces), habitability conditions, space usage, perception of COVID and services, among others. The design of the instrument was carried out by the Autonomous University of Coahuila [6].

3. RESULTS

Results show the climatic conditions of the case study and their impact on thermal comfort, it also indicates the inhabitants socioeconmic profile and its relation to the disease, the physical characteristics of the dwelling and a description of livability conditions performance (facilitated or worsened) according to the type of dwelling. Finally, it shows how the new necessary activities were faced during the period of confinement due to the pandemic.

3.1 Climatic conditions during the pandemic

Temperature oscillation patterns of outdoor environment in the period of the COVID-19 pandemic, are shown in Fig. 4.

Figure 4:
Outdoor temperature oscillation during COVID-19 pandemic, March 2020-June 2021, Mexicali, Mexico.

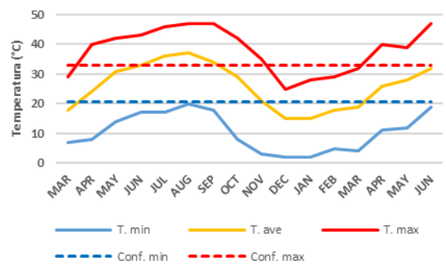


Figure 4: Outdoor temperature oscillation during COVID-19 pandemic, March 2020-June 2021, Mexicali, Mexico.

During the pandemic, according to Auliciem's comfort model, it was observed that in the critical hours between 14:00 and 16:00 h, which represent the mean maximum temperature, outdoor conditions are above the upper limit of the comfort zone, except in the period from December to March. With respect to the mean temperatures, which represent the time between 9:00 h and 10:00 h, the months of July to September fall outside of the comfort zone due to high temperatures, and the months below the comfort zone due to low temperatures are from December to March. Mean temperatures in April-June, and from October to November, are well within the comfort range.

Finally, the mean minimum temperatures, which represent the period between 4:00 and 6:00 h, are below the lower limit of the comfort zone. However, the critical cold period takes place from November to March.

The latter indicates that prevailing weather conditions during the pandemic showed unfavorable conditions for human thermal comfort. Since the inhabitants of the house were in confinement, the use of air conditioning equipment was essential to maintain comfortable conditions.

3.2 Dwelling inhabitants and COVID-19

According to the results of the exploratory study, it is observed that 83% of the sample are people from 15 to 30 years old, 14% from 31 to 50 years old and 3% are people from 50 years old and older.

In most of the cases (84%) the dwelling is shared with the family, only few cases are shown (3%) with a single inhabitant. Overall, it is estimated that in 54% of the dwellings there are 3 to 4 inhabitants, 31% are occupied by 5 to 7 people and 1% with more than eight persons (Fig. 5).

It is noted that, as shown in Table 1, around half of the respondents do not show an unfavorable health condition, either due to chronic illness, or that associated with age, in 47% if there is a condition of vulnerability associated with greater risk of contagion.

Figure 5:
Number of inhabitants per dwelling (percentage).

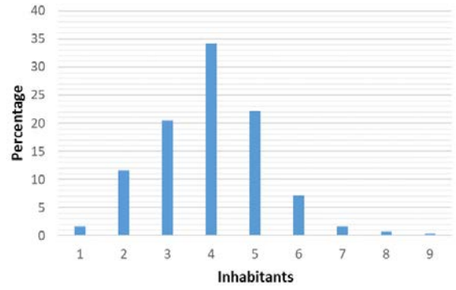
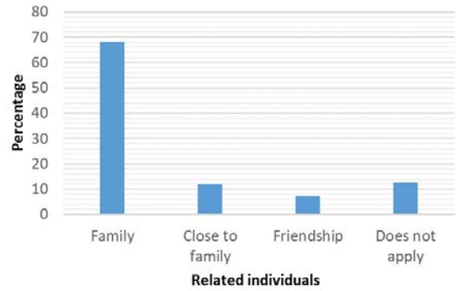


Table 1:
Inhabitant with special needs

Condition	Percentage
Disability	3
Advanced age (seniors)	14
Children below 15 years of age	25
Two or Three of these conditions	6
Does not apply / Not present	53
Total	100

During the pandemic, it is observed that for the most part the sampled population had an acquaintance or relative who became ill from COVID-19 (Fig. 6).

Figure 6:
Related individuals affected with COVID-19 (percentage).



3.3 Characteristics of the dwelling, the perception of environmental habitability and COVID-19

In the city of Mexicali, the predominant type of housing is single-family dwelling. In general, there are two main types of housing, those built by the inhabitant himself, or by contracting specialized architecture and/or engineering services or by direct contracting with masons (Model A); built mainly with brick, adobe, or concrete block walls; and wooden roofs, located in large lots that allow the inclusion of a garage, service patios and gardens; located in the popular neighborhoods of the city.

The other typology, Model B, are mass built housing or tract housing. The housing models are built mainly with concrete block walls and one way ribbed concrete slab, with expanded polystyrene insultation between reinforcements. Built in lots of approximately 6.00 meters wide, with housing surfaces that can range between 38m^2 to 65m^2. The reduced lot size typically allows a limited amount of exterior space, which is mostly designated for the garage, and leaves little space left for an outdoor garden or patio. Some examples of Models A and B are shown in Fig. 7. It is estimated that 58% of these dwellings are one level, 39% are two levels, while 3% live in an apartment (Fig. 8).

Figure 7:
Housing models A and B, Mexicali.

Model A Model B

Figure 8:
Single-family dwelling in one, two levels or apartment, Mexicali-Mexico.

In addition to having a living room-dining room-kitchen common area, Table 2 shows the number of sleeping spaces and bathrooms included in the home. With these data, it seems that the number of spaces does not represent a habitability problem, due to the availability of sleeping rooms and bathrooms, according to the number of inhabitants per dwelling.

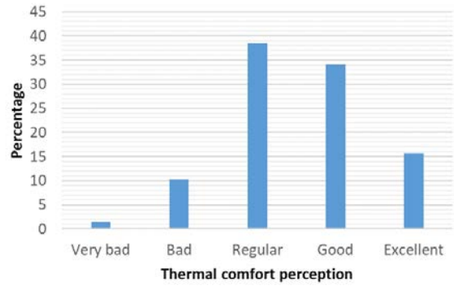
Table 2:
Bedrooms and bathrooms in Mexicali dwellings, during the pandemic

	Percentage		
Bedrooms	(%)	Bathrooms	(%)
1	3	1	39
2	38	2	42
3	46	3 or more	19
More than 3	13		
Total	100		100

The latter shows agreement with the fact that 80% consider that the size of the spaces in the home was sufficient, almost adequate, or adequate. However, 24% indicate that the degree of flexibility of the home to adapt it to another activity is very low and low, 35% specify regular flexibility and 40% indicate high and very high flexibility.

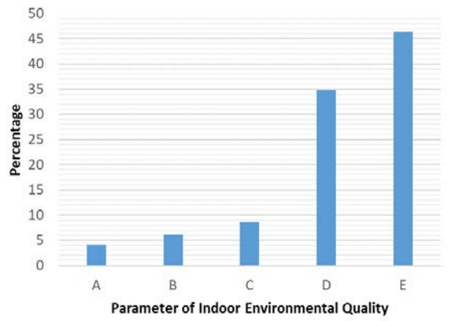
With respect to the habitability conditions of the dwellings, it is observed that most occupants registered a “Regular” or even “Good” thermal comfort level within the home (Fig. 9).

Figure 9:
Thermal comfort in dwelling, Mexicali, Mexico (percentage).



On the aspects from lowest to highest level of environmental comfort or satisfaction, the conditions of natural lighting, natural ventilation and comfortable temperature are presented in percentages between 4 and 9%, that is, there are few cases that present agreeable environmental quality during confinement (Fig. 10).

Figure 10:
Reported parameters of environmental quality, according to the inhabitant’s perception (percentage).



Notes: A (Good daylighting); B (Good natural ventilation), C (Agreeable temperature), D (Isolated from outdoor noise), E (Does not perceive bad odors).

The latter is linked to the type of housing, since in most of the windows the location is determined as a means of visual contact between indoor and outdoor, rather than by lighting effects and natural ventilation.

Regarding home ownership, it is observed that 87% have their own home (55% have already paid for it and 32% are paying for it), 11% live in a rented home and 2% in a borrowed home, which facilitates the feasibility of making required adaptations to the home.

3.4 COVID-19, confinement, and activities

Perception of COVID-19

The level of perception of risk in the face of COVID-19, 54% were worried and very worried, 42% between calm and very calm and 5% safe.

In Mexicali, in about half of the households (52%) it was easy to stay at home, in 45% it was difficult and very difficult, and in 3% it was extremely difficult.

Regarding the degree of tranquility that their home provides, 65% perceive it as high and very high, 20% as fair and 15% as low and very low.

COVID-19 afflicted inhabitant isolation

When asked about the isolation of inhabitants of the dwelling infected with the SARS CoV-2 virus, 48% remained isolated within the home, 6% did not isolate and 46% did not apply (did not present infected people in the home).

Activities and dwelling spaces

To work at home, 54% use the bedroom, 19% the dining room and 17% in the study room. Regarding the activities carried out in the home, and the use of the spaces, it is observed that 69% of the cases required some modification, such as rearranging or adapting a space for work activities at home or school activities at home (Fig. 11). In some cases, the private space, such as a bedroom, was adapted to a work area and/or to take online classes, in others, the dining area became the work area. Modifications were also made, when an occupant was found to be COVID-19 positive to allow isolation of the patient, even though bathroom areas were shared.

Figure 11:
Dining room table used as workspace, Mexicali, Mexico.

Source: González, K., 2021.

Regarding the space used most frequently during the pandemic, in 40% of the cases it was the living-dining room space, in 22% it was in the study room, in 28% it was marked as “other” and 9% used the kitchen. Regarding the “other” space, when prompted to specify, users indicated it was the bedroom. This implies that most of the population (99%) spent most of the time indoors during the pandemic and the use of the outdoor patio or garden was scarce (1%) (Table 3).

Table 3:
Activities during the “Quédate en casa (stay home)” campaign, Mexicali, Mexico.

Activities	Percentage
Domestic activity	28.8
Online work activity	59.6
Help child with homework	3.2
Sports	1.4
Arts and crafts	0.7
Family activity	1.1
Watch TV	1.4
Reading	0.7
Use of Electronic device	3.2
	100.0

4. CONCLUSION

Habitability conditions of houses in Mexicali, during confinement, presented two patterns, first, around half of the respondents indicated that the amount of people and the available space in the house were adequate for home office and home school activities, as well as for the isolation of a person sick with COVID-19. And second, where a third part of the sample, reported that living conditions were not adequate due to overcrowding, which did not allow the isolation of the infected, and hindered the reduction of contagion risks.

Overall, there was some degree of concern about the disease, however, the respondents perceived tranquility in their home. Even though this study was a first approach to the characterization of habitability conditions during the pandemic, it was possible to detect that most of the houses did meet the necessary conditions for prolonged confinement. However, it is recommended to delve into highly vulnerable socioeconomic sectors of urban populations for a broader understanding of the Mexican inhabitant’s experience during the COVID-19 pandemic.

ACKNOWLEDGEMENTS
The authors would like to thank Transdisciplinary Network of Habitat and Sustainability Studies and COVID 19 Paradigm in Architecture Research of Autonomous University of Coahuila.

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WILL CITIES SURVIVE?

Lighting and daylight control strategies using LabVIEW for optimizing visual comfort and energy savings

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ABSTRACT: This study presents control strategies based on the National Instrument Laboratory Virtual Instrument Engineering Workbench (NI LabVIEW) platform to reduce energy consumption as well as maintain visual comfort by controlling lighting fixtures and window blinds. A model prototype is presented equipped with motorized blinds and dimming lights controlled by NI LabVIEW, and light sensors for monitoring the indoor illuminance value. The results show that the model prototype performs well in maintaining uniformity of illuminance value. An annual simulation using Rhino/Grasshopper predicted that visual comfort can be well maintained by window blinds that rotate 45^0 (half-closed) without turning on one lamp, mostly during the daytime when the sky condition is clear; therefore, lighting energy consumption can be reduced by around 16%.
KEYWORDS: LabVIEW, energy efficiency, visual comfort, building automation, integrated control

1. INTRODUCTION

According to data on U.S. building sector energy consumption, buildings consumed about 39% of the total energy in the U.S., of which about 35% is accounted for by lighting (Brasington, 2019). Daylight utilization in buildings shows great potential for energy savings. To evaluate the performance of daylight utilization technologies, illuminance levels and uniformity need to be considered (Chiou & Lin, 2016). Optimum visual performance requires a certain level of uniformity across the working plane (Freewan & Al Dalala, 2020). Therefore, useful daylight illuminance (UDI) is mostly used for the simple evaluation of lighting design in architecture and visual discomfort (Galatioto & Beccali, 2016; Tabadkani et al., 2019). Based on occupants' behavior, visual comfort has mostly focused on working plane conditions (Galatioto & Beccali, 2016; Husin & Harith, 2012). Working plane illuminance levels between 500 and 2000 lux are sufficient for the visual task and for achieving visual comfort (Chaloeytoy et al., 2020).

Hirning et al. (2017) indicate that some sustainable buildings across 10 countries have some issues of visual discomfort from glare, causing building occupants to usually close window blinds. To cope with that problem, several control strategies are applied. Control strategies for controlling window blinds and lighting are essential to improve visual performance (Chan & Tzempelikos, 2013) and achieve energy savings from 30 to 50% (Konstantoglou & Tsangrassoulis, 2016). There are two control strategies for lights and blinds: independent and integrated. In an independent control strategy, the control systems control the lights and blinds separately using different sets of points and controllers, whereas in an integrated control strategy both lights and blinds are controlled using the same set point. Rule-based algorithms and co-simulation with EnergyPlus, BCVTB, and MATLAB are the common methods used in those control strategies (Mukherjee et al., 2010; Plörer et al., 2021). However, the programming languages used in those methods, such as C++, Python, or MATLAB, involves advanced programming skills to run them.

Instead of using those programming languages, this study presents control strategies based on the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) environment, a graphical programming environment widely used for measuring, monitoring, controlling, and recording operating conditions (Chinomi et al., 2017). LabVIEW is preferred because it supports thousands of hardware devices and recent technologies but keeps using common protocols and requires no programming skills (Hamed, 2012).

This study aims to maintain visual comfort by implementing an integrated control strategy to control the lighting fixtures and window blinds using LabVIEW, and to investigate the energy consumption reduction for lighting. A whole-year simulation is conducted to analyze the performance of the control system and annual energy saving.

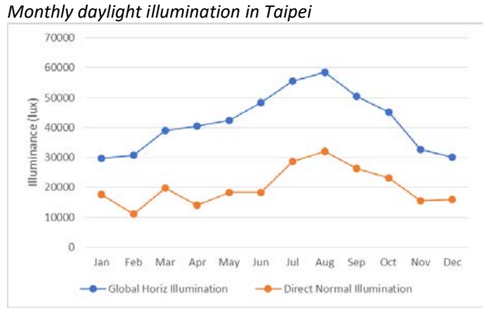
2. METHOD

This study applies an experiment method and a simulation method. An experiment using a model prototype was conducted to test and validate the algorithm building in LabVIEW while a simulation using building performance simulation software was used for simulating the indoor lighting performance and energy saving.

2.1 Daylight in Taiwan

Taipei, Taiwan, is selected as the location for this study. Located on 25°04'N 121°31'E, the hours of daylight/day in Taipei are between 10:35 hours (winter) and 13:39 hours (summer) while the annual hours of daylight are 12 hours (*Sunshine & Daylight Hours in Taipei, Taiwan*, n.d.). The average hourly global horizontal illumination is between 29,607 lux (winter) and 58,435 lux (summer); meanwhile, the average hourly direct normal illumination is between 11,128 lux (winter) and 32,066 lux (summer) (Fig. 1).

Figure 1:
Monthly daylight illumination in Taipei



Note: This figure is modified from the Taipei-Songshan weather data file.

To understand the daylight condition in a building, a simulation was conducted using Rhino/Grasshopper simulation software. Ladybug and Honeybee plugins were used to simulate the daylight and energy performance. A comparative study between Rhino/Grasshopper, DIVA, and Design Builder for analyzing illuminance level and energy consumption was conducted to validate the simulation model. The results showed that the indoor illuminance difference between Rhino/Grasshopper and Diva simulation is in the range of 10–20%, while the energy simulation difference between Rhino/Grasshopper and Design Builder is less than 10%.

A model with 8.2 m length x 3.6 m width x 2.8 m height (length:width was approximately 2 and length:height was approximately 3) and with a south-faced window was built in Rhino/Grasshopper simulation software (Fig. 2) to identify the daylight condition inside the building. The material reflectance of the ceiling, wall, floor, and surrounding ground was 0.8, 0.5, 0.2, and 0.8, respectively. Spatial daylight autonomy (SDA) and useful daylight illuminance (UDI) were simulated. The simulation results showed that there was a huge range of the illuminance level in the building, where the southern area near the window received abundant daylight and had a high illuminance level while the northern area did not receive any daylight. Figure 3 shows that the room was divided into three zones: high daylight zone (A), intermediate daylight zone (B), and low daylight zone (C). To solve that problem, a shading device was required to reduce the daylight for zone A while artificial lighting was required to provide enough lighting for zones B and C.

Figure 2:
Model built in Rhino/Grasshopper simulation software.

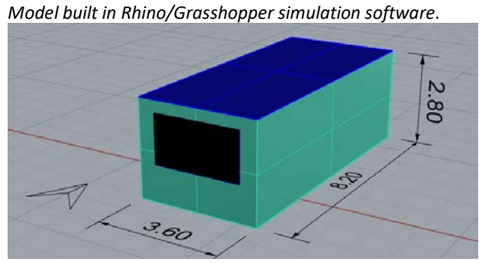
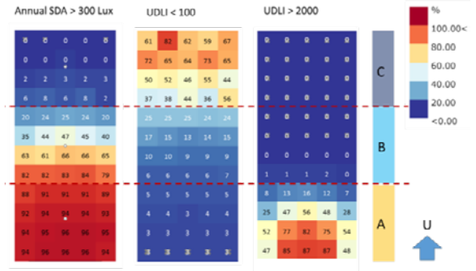


Figure 3:
Annual SDA and UDI simulation results.

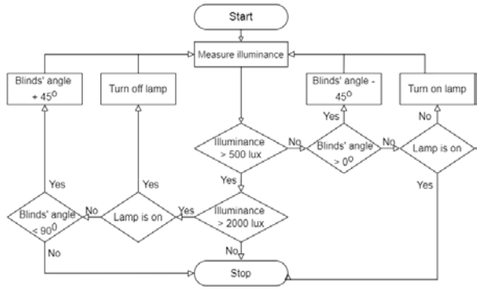


2.2 Control strategies algorithm

The light and blind control strategies are used to maintain indoor illuminance in the range of 500–2000 lux. Figure 4 shows the algorithm flow of the control strategies. As the initial condition, the lamp is turned off and the blind angle is set to 0^0 (blind opened). When the indoor illuminance is lower than 500 lux, if the blind angle is higher than 0^0, then it will reduce by 45^0 until it becomes 0^0 (blinds opened) and the lamp will turn on. When the indoor illuminance increase is higher than 2000 lux, the lamps will be examined first; if the lamp turns on, it will turn off. Later, the blind angle will gradually rotate 45^0 until the angle becomes 90^0 (blinds closed). The lamp and blinds remain steady in their current condition when indoor illuminance

is between 500 and 2000 lux. This process is repeated every minute.

Figure 4:
Algorithm flow of the control strategies.



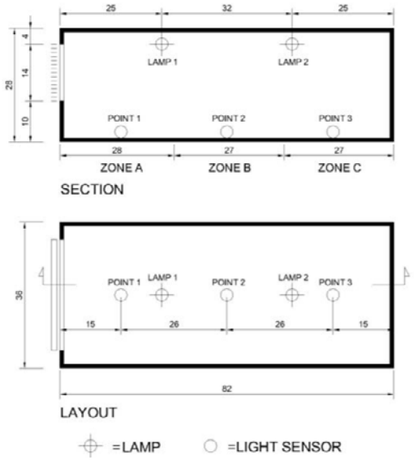
3. EXPERIMENTAL STUDY

3.1 Model prototype

A model with 82 cm length x 36 cm width x 28 cm height was built to analyze the illuminance level. The model had a window and was equipped with motorized blinds and light controlled by NI (National Instrument) LabVIEW. Several LED Fresnel lamps were placed outside the box and their lights were directed to the window to provide daylight. During the measurement, the LED Fresnel was brightened and dimmed gradually to change the light intensity penetrating the box (Fig. 5). Three illuminance sensors were presented inside the box in each zone for monitoring the indoor illuminance and an illuminance sensor was placed outside the box to monitor outdoor illuminance values. As using three lamps resulted in indoor illuminance exceeding 2000 lux, two lamps were used in the prototype, but only lamp 1 put between zone A and B was controlled by the control system because lamp 2 (put between zones B and C) needed to be turned on all the time to provide illuminance of more than 500 lux for zones B and C (Fig. 6).

Figure 5:
Model prototype equipped with motorized blind and lighting fixtures.

Figure 6:
Layout plan and section of the model



Note: The dimension is in cm.

3.2 Model prototype testing

The control strategies applied to the prototype indicate that it can maintain indoor illuminance values in a range of 500–2000 lux regardless of large changes to outdoor illuminance. Figure 8 shows the results of indoor and outdoor illuminance monitoring and Fig. 9 shows the blind angle and lamp condition for 120 minutes. Blind angle 90^0 indicates that the blinds are closed while 0^0 indicates the blinds are opened; 0 indicates that the lamp turns off and 1 indicates that it turns on.

During the experiment, the illuminance values of points 1 and 2 change because they are greatly affected by the outdoor condition (the LED Fresnel lamps), and lamp 1 controlled by NI LabVIEW; however, the illuminance values of point 3 do not change significantly because lamp 2 always turns on. In the beginning, the outdoor illuminance value is very low, which causes lamp 1 to turn on. As the outdoor illuminance value increases, at minute 20, the indoor illuminance value point 1 exceeds 2000 lux, resulting in lamp 1 being turned off at the next minute and the indoor illuminance values decreasing below 2000 lux. At minute 42, the illuminance values of point 2 exceed 2000 lux. Because lamp 1 is already turned off, the blinds rotate 45^0 at the next minute to reduce the indoor illuminance values.

Starting from minute 70, the LED Fresnel lamps were dimmed gradually to reduce the outdoor illuminance. From minute 43 to minute 95, the condition of the blinds and lamp do not change. But at minute 95, indoor illuminance values at points 1 and 2 are under 500 lux, causing the blinds' angle to change to 0^0 and illuminance points 1 and 2 to increase higher than 500 lux. As outdoor illuminance is reduced continuously, at minute 108, lamp 1 turns on because illuminance values of points 1 and 2 are lower than 500 lux. The condition of the blinds and lamp do not change until the end of the measurement (minute 120).

Figure 8:
Indoor and outdoor illuminance monitoring.

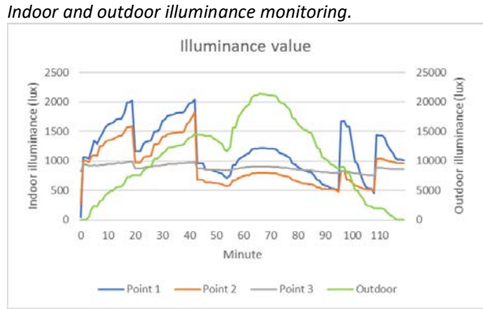
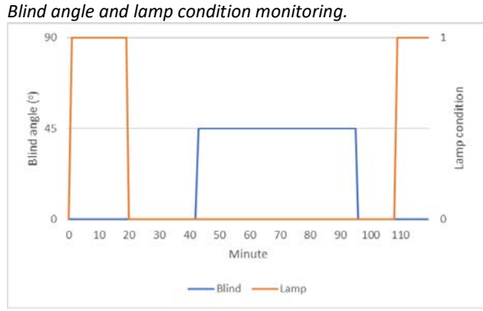


Figure 9:
Blind angle and lamp condition monitoring.



4. SIMULATION STUDY

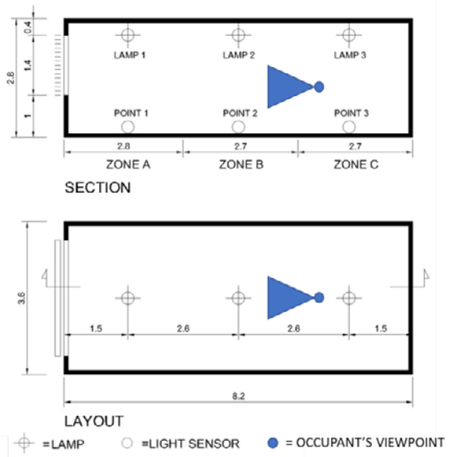
4.1 Simulation setting

The control system was implemented in the form of simulation in Rhino/Grasshopper software with Ladybug and Honeybee plugins to analyze the annual energy saving. A model with 8.2 m length x 3.6 m width x 2.8 m height was built in Rhino/Grasshopper simulation software. A window blind was installed on the south-facing window and three lamps were installed inside the model to provide uniform illuminance values when there is no daylight in the room; however, only lamp 1 in zone A was controlled because lamps 2 and 3 in zones B and C were needed to be turned on all the time to achieve the working plane illuminance levels between 500 and 2000 lux (Fig. 10).

In addition to indoor illuminance, glare analysis was conducted to evaluate visual comfort. DGP (daylight glare probability) and DGI (daylight glare index) are the common indices to analyze glare discomfort (Galatioto & Beccali, 2016). The glare analysis point of view was set 6 m from the window and at a height of 1.2 m (Fig. 10).

A typical day in spring, summer, and winter (March 21st, June 22nd, and December 21st) was simulated to represent the lighting condition for the shoulder (spring and fall), summer, and winter seasons in a year, respectively. The simulation was carried out using the weather data file of Taipei-Songshan under the clear sky condition. Based on the simulation, the window blind angle and lamp schedule for a year were obtained. Later, an annual energy simulation was conducted using the blind angle and lamp schedule.

Figure 10:
Layout plan and section of the model built in Rhino/Grasshopper simulation software.



Note: The dimension is in m.

4.2.1 Indoor visual comfort

The control system built in the LabVIEW platform was applied to the Rhino/Grasshopper simulation to control the window blind angle and lamp condition. Figure 11 shows the illuminance values of the simulation results. Because lamps 2 and 3 placed on zones B and C always turn on, the illuminance values of points 2 and 3 are in a range of 500–2000 lux; however, the illuminance value of point 1 changes based on the daylight and blinds and lamp 1 condition. In the shoulder season, the illuminance value of point 1 exceeds 2000 lux at 9:30, causing the blinds to rotate 45^0 (half-closed) at 9:31 to reduce the illuminance value. The blinds maintain that position until 16:20 and rotate to the initial condition at 16:21 because at 16:20 the illuminance value of point 1 is 488 lux, which is lower than the requirement. After return to the initial condition, the indoor illuminance value of point 1 raises to 870 lux at 16:21 but gradually decreases. At 16:57, it decreases to 463 lux, causing lamp 1 to turn on after 16:57. Figure 12 shows the blind angle and lamp 1 condition.

In the summer season, the indoor illuminance values of three measurement points are within the range of 500–2000 lux during the daytime, but after

16:30 the illuminance value of point 1 is lower than 500 lux, causing lamp 1 to turn on. Different from the other seasons, in winter the blinds rotate to 45^0 from 9:00 until 16:10 and rotate to 0^0 at 16:11 — longer than in other seasons— and the lamp turns on earlier, at 16:20. This condition can be explained in the summer season as the south-faced window façade receives less daylight compared to other facades but in the winter season receives more daylight than other façades; however, the time duration is shorter than other seasons.

Figure 11:
Indoor illuminance values during the shoulder, summer, and winter seasons.

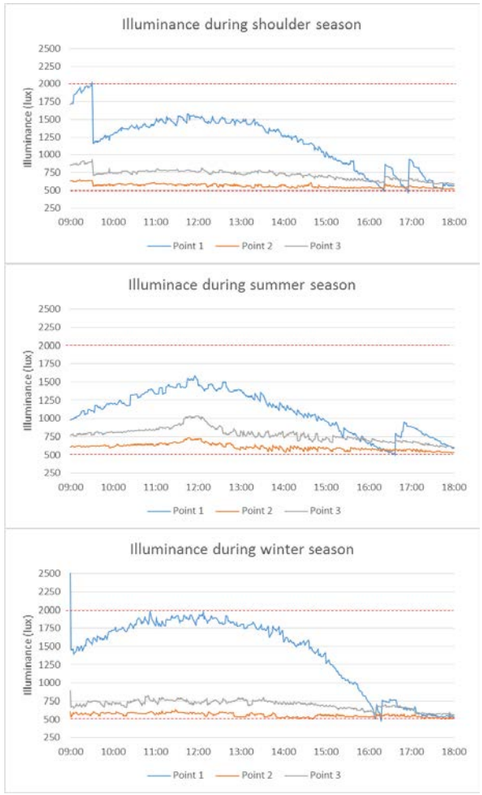
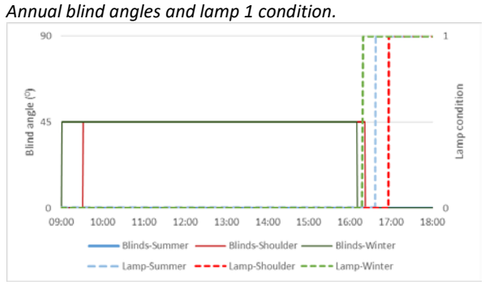


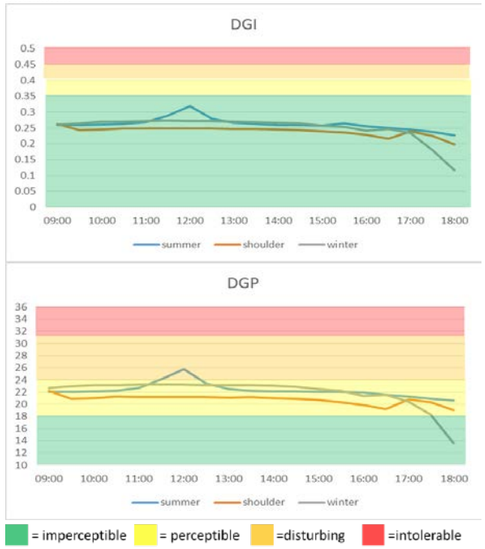
Figure 12:
Annual blind angles and lamp 1 condition.



The simulation results indicate that for almost the whole year, when the sky is clear, the blinds need to be half-closed (rotated to 45^0) in order to avoid excessive illuminance and visual discomfort. Because the illuminance value of point 1 is within the required range, lamp 1 does not need to be turned on mostly during the daytime.

Figure 13 shows the results of glare analysis for a typical day in the shoulder, summer, and winter seasons. Based on the values of DGP and DGI, the glare perceived is still able to be tolerated. All DGI values below 0.35, which indicates that the glare index is imperceptible while most DGP values are between 18 and 24, which indicates that the glare probability is perceptible and in the summer at noon the glare is disturbing.

Figure 13:
Glare analysis during the shoulder, summer, and winter seasons.



4.2.2 Energy savings

A simulation is conducted using the blinds and lamp schedule in Fig. 12 for analyzing energy consumption. The results are compared to the base case in which the simulation is conducted using a model without window blinds and all three lamps turn on from 9:00 to 18:00 for the whole year. An annual energy saving is presented in Table 1. Implementing the lighting control can reduce energy saving for lighting only by around 30% as the room depth is greater than the width, and only one lamp can be turned off during the daytime. By considering the energy consumption of the additional equipment for controlling the lights and blinds, the energy savings is about 16.19%.

Table 1: Annual energy savings prediction.

	Base Case	Model
Lighting (kWh/yr.m^2)	19.05	12.88
Equipment (kWh/yr.m^2)	-	3.09
Total (kWh/yr.m^2)	19.05	15.97
Savings (kWh/yr.m^2)	-	3.08
Savings (%)	-	16.19

5. CONCLUSION

This study presents lighting and daylight control strategies using LabVIEW to improve indoor visual comfort. The control strategies successfully maintain indoor illuminance between 500 and 2000 lux in various outdoor illuminance conditions. The simulation using the weather file of Taipei shows that shading devices are needed to control the indoor illuminance values and maintain visual comfort. In this case, venetian blinds rotated 45^0 need to be installed on the south-facing window. Only during the summer season, the venetian blinds do not need to be rotated 45^0. The simulation results show that applying the control strategies successfully maintains indoor illuminance within the comfort range and reduces glare discomfort.

The annual energy savings prediction indicates that control strategies implementation can potentially reduce energy consumption by 16.19%. Although the number is not great, implementing the control system is mostly able to achieve indoor visual comfort.

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Simulation-based assessment of human-centric lighting performance in tropical hospitals

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ABSTRACT: Recent research studies have been proven that in a healing environment, good quality of lighting is essential to create a comfortable environment for patients to rest and recuperate, which can enhance their circadian rhythm, leading to improvement in the health of patients and this reduces their vulnerability to develop serious complications which could affect the healing process. Therefore, this study aims to examine Human Centric Lighting (HCL) performance of a retrofitted tropical hospital ward via a spectral raytracing simulation tool—ALFA. The simulation results will serve as a solid basis for developing the HCL recipe for the ward in temporal and spatial approach.
KEYWORDS: Human Centric Lighting, Equivalent Melanopic Lux, M/P Ratio, Circadian Rhythm, Healthcare lighting

1. INTRODUCTION

Lighting plays a critical role in human health and daily functions as it impacts on the vision, performance of daily tasks, human biological rhythm and mood. With the discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) as a third class of photoreceptor, the concept of human-centric lighting (HCL) has become more important in the study of lightings as it attributes to both visual and non-visual effects of light (International Association of Lighting Designers [IALD] & LightingEurope, 2017) and this ensures that our internal body clock is synchronized via photoentrainment process (Foster, 2021). The objective of HCL is to enhance the health, well-being and comfort of the occupants in the living environment by synchronizing the internal body clock to natural light. Therefore, with HCL technology being implemented in hospital, patients can better recuperate as the circadian physiology is being considered which lead to improved quality of rest.

Daylighting is essential for patients' recuperation as research conducted by Strong (n.d.) shows that patients who are exposed to sufficient natural daylight could accelerate recovery, reducing the average length of stay, decrease depression during post-operation recovery and less pain will be experience.

Circadian rhythm refers to natural body cycle that occur on a 24-hour schedule to maintain and carry out important human functions throughout the day, such as the sleep-wake cycle, body temperature regulation and metabolism rhythm. Only in the recent decade, the team of scientists from the Johns Hopkins University had discovered a special type of photoreceptor in the retina called the ipRGCs, containing photopigment melanopsin, which is sensitive to blue light. When blue light enters the eyes, the melanopsin is stimulated, the signal is sent to the suprachiasmatic nucleus (SCN) in the brain to regulate the circadian system while the rest of the signal is sent to regulate the pupil dimension (Lledo, 2019).

In practice, the design of healthcare lightings is required to comply with local prescriptive code requirements and thus, lacking in human centric considerations. This could bring negative impact to the health and well-being of patients as the lightings could not fully support the needs of the healing patients. Therefore, with the aid of the lighting design simulation tools, this research aims to investigate the lighting conditions of a tropical hospital patient ward environment during day and night time to further explore the possibilities of smart lighting control strategies to be use for human centric lighting design performance, where the study efforts will serve as the solid basis for developing the HCL recipe for the patient ward in temporal and spatial approach and this could also contributes towards the well-being of hospital staffs and patients.

2. METHODOLOGY

A literature study on HCL metrics and simulation workflow described in this section focuses on simulation approach without actual measurements.

2.1 Human centric lighting measurement metrics

2.1.1 Equivalent Melanopic Lux

Equivalent Melanopic Lux (EML) is attributed to the response of ipRGCs to light, which is different from the conventional illuminance metric attributed to the cones in the eyes. The EML value is obtained by measuring 1.2m on the vertical plane to the eye level of the observer. Table 1 below shows a summary from the WELL Building Standard, specifying the recommended EML values for different locations as well as daylight exposure.

Table 1:
Recommended EML level in WELL Standard

Location	Recommended EML	Reference plane
Work areas	≥ 200 EML for more than 75% work desk (at least 4 hour per day for everyday in the year) ≥ 150 EML for electric lights	Vertical plane @ 1.2m above floor
Living Environments	Day time: ≥ 200 EML Night time: ≤ 50 EML	Wall facing @1.2m above floor Horizontal plane @ 0.76m above floor
Breakrooms	≥ 250 EML	Vertical plane @ 1.2m above floor
Learning Areas	≥ 125 EML for more than 75% desk 150 EML for electric light	Vertical plane @ 1.2m above floor
Healthy Sunlight Exposure		
Spatial daylight autonomy (sDA300, 50%) ≥ 55% of occupied area. 55% to achieve at least daylight of 300 lux annually		

2.1.2 Melanopic/Photopic Ratios

The Melanopic/Photopic (M/P) ratios is the comparison between melanopic potential measured at the eyes and the photopic vision (Miller & Irvin, 2020). M/P ratios describes the effectiveness of human response to light to trigger the ipRGCs and the non-visual functions in terms of alertness, sleep or relaxation. During daytime, the M/P ratios is high (> 0.9) due to high light intensity and blue enriched, suppressing melatonin hormone, creating alertness. During night time, the M/P ratios is low (< 0.35) as the light intensity reduces and is blue-depleted. Melatonin hormone is secreted from the body which promotes sleep.

2.1.3 Glare

Glare is a visual sensation where the luminance in the peripheral vision environment is greater than the luminance that the eyes can adapt. Glare exposure, regardless during the day or night, will reduce individual's visibility and cause discomfort. Glare is subjective as different people perceived it differently.

Daylight glare probability (DGP) is one glare metric that is use for daylighting glare analysis. DGP measures the vertical illuminance at human eyes to evaluate different level of discomfort glare as shown in Table 2.

Table 2:
DGP discomfort glare criteria

DGP range	Glare criterion
<0.35	Imperceptible
0.35 – 0.4	Perceptible
0.4 – 0.45	Disturb
>0.45	Intolerable

2.2 Case Study – Singapore General Hospital (SGH) Block 4 Ward 45

SGH being the largest tertiary hospital in Singapore, had undergone addition and alteration renovation work to Block 4 Ward 45, a general ward, to transform the ward to become more human centric with state-of-the-art medical facilities and high-end technology to provide better patient care.

In this research paper, simulation-based approach using Aftabsoft Radiance and ALFA applications was utilised to investigate the human-centric lighting performance under different conditions in SGH patient ward and their impact on health and well-being.

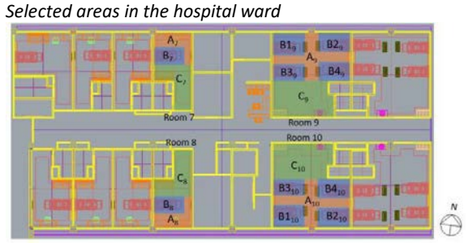
2.2.1 Artificial lightings used in SGH

Three main types of luminaires were used in the ward, namely tunable-white recessed panel, mood light and night light.

2.3 Modelling

In this research study, two 3D modelling software tools (i.e. Autodesk Revit and Rhinoceros 3D) were being used. Two single bedded rooms and two four-bedded rooms on the north and south orientation were selected for the study (Fig. 1).

Figure 1:
Selected areas in the hospital ward



2.4 Simulation parameters

In order to achieve accurate simulation results, the input parameters into the simulation model would have to be close to the actual environment. The key parameters were the location and time of the day, sky conditions and surface finishing materials. Table 3 below shows a summary of the simulation parameters settings.

Table 3:
Settings of simulation parameters

Location	Latitude	Longitude	Elevation
Singapore	1.29°N	103.85°E	23m
Date		21st September	
Time	1pm	5pm	8.30pm & 10pm
Sky condition	Clear and overcast	Clear and overcast	Clear
Lighting condition	Daylight and artificial light	Daylight and artificial light	Artificial light only
Ground Spectrum		Uniform	
Albedo		0.15	

2.4.1 Location and time of the day

The latitude and longitude of SGH building site is 1.29 N and 103.85 W respectively. The building is orientated in north-south facing direction, with a 7-degree anticlockwise off the north orientation. In this simulation, the date was set to September 21 on the equinox period. For daylighting simulation, due to varying amount of light at different time period, the time of study was chosen at 1pm, where the amount of daylight is the highest and 5pm in the evening to compare the difference in the amount of daylight penetration into the ward. For artificial lighting simulation, the time was chosen at 1pm and 5pm in the day as well as 8.30pm and 10pm at night to determine the difference in light exposure by the patients.

2.4.2 Sky condition

Sky condition is another important parameter for daylighting simulation. The CIE clear sky and overcast sky models were selected for daylighting analysis as they showed two extreme conditions in terms of sky luminance distribution (Igawa, Nakamura, & Matsuura, 1999).

2.4.3 Materials for surface finishes

A site visit to the hospital was conducted and visual observation was made to inspect the ward design. The walls have two different colours, grey and white. The colours of the vinyl floor and grid ceiling tile are beige and white respectively. A reflectance measurement test was conducted in a patient ward room using a luminance meter and a 18% reflectivity digital grey card. After the measurements had been taken and some simple calculation was performed, the reflectance value of these surfaces would be obtained. The reflectance values for the set of surfaces (white wall, grey wall, floor, and ceiling) are 56.5%, 46.3%, 40.8%, 64.3%. These reflectance values were input into the simulation.

2.5 Simulation workflow

The simulations for daylighting glare and circadian lighting were conducted to understand the effectiveness of HCL design for the hospital ward. The workflow for the simulations will be described in detail.

2.5.1 Daylighting glare simulation workflow

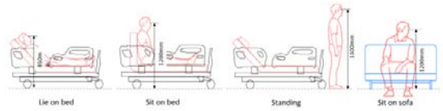
Aftabsoft Radiance simulation software was used to perform daylighting glare simulation. Before conducting glare simulation, the measurement points would have to be defined as they depicted the perspective view of a camera placed in the view direction. The height of all measuring points was set at 1.7m from the ground. The perspective view of the camera was able to generate the 3D view images of the room interior in Revit, which would then be automatically converted to high dynamic range (HDR) images by the software and the model will be exported into Radiance for simulation. After some adjustment to the settings in Radiance, field of view (FoV) images were generated and the glare results would be obtained after running the simulation.

2.5.2 Circadian lighting simulation workflow

ALFA, a radiance-based plug-in tool, was used to perform circadian lighting analysis. When the hospital ward model was exported into Rhinoceros 3D, the model lost all its material properties, retaining only the dimensions and shapes. The studied spaces were further divided into smaller zones (Fig. 1) to conduct circadian lighting analysis within the zones. The single-bedded rooms were divided into 3 zones, namely A, B and C. Zone A is closest to the window, Zone B is the bed area and Zone C is the circulation corridor leading to the toilet and the door. Similarly for 4-bedded rooms, the spaces were divided into 6 zones, namely A, B1, B2, B3, B4 and C. Zone A is the circulation corridor around the bed area. Zones B1, B2, B3 and B4 are the bed areas and Zone C is the inner corridor around the toilet and wash basin area. The numbers in subscript refers to the respective room.

Upon defining the zones in the rooms, some of the settings would need to be configured before simulation. Firstly, the location, time and sky condition settings. Following, mapped the materials to different surfaces in the Rhino model in ALFA based on the default ALFA library. After assigning the materials, the grids containing sensor points were defined in the model to perform simulation. In the hospital ward, there are several patients' behaviour, ranging from lying on the bed, sitting either on their bed or sofa reading, watching tv or having a meal to standing. The height of each respective position measured to the eye level was 850mm, 1200mm and 1600mm (Fig. 2). The height of the sensor points will be set accordingly to simulate the different positions in the ward.

Figure 2:
Position of patients in the ward



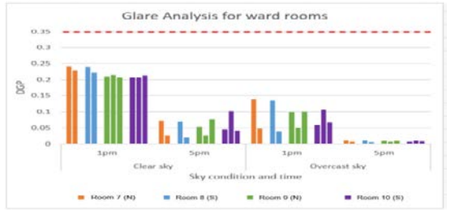
3. RESULTS AND DISCUSSION

The simulation results of these four wards will be benchmarked against WELL Building Standard for Lighting and warrant certain conclusions regarding HCL performance.

3.1 Daylighting Glare Simulation Results

The glare simulation results revealed that there was no daylight glare issue in the patient ward during daytime as the DGP values are lower than the benchmark of 0.35, making it imperceptible for the human eyes (Fig. 3). The DGP level is higher during clear sky than overcast sky due to the cloud cover obscuring the sun in overcast sky, reducing direct luminance. As ward rooms are oriented in north-south direction, there will be lesser direct sunlight which results in lesser glare issues.

Figure 3:
Daylight glare simulation results



3.2 Circadian Entrainment Simulation results

The simulation results of circadian entrainment presented three different offset heights (850mm, 1200mm and 1600mm) for EML values and M/P ratios obtained from ALFA simulation during the day and night time under the five different sky conditions: Clear sky (1pm & 5pm), Overcast sky (1pm & 5pm), Clear sky with electric lightings (1pm & 5pm), Overcast sky with electric lightings (1pm & 5pm) and night time with electric lightings only (8.30pm & 10pm). All the ward rooms are installed with human centric lightings where the colour temperature is tuned accordingly at different time of the day. As ALFA is a software with limitation of importing actual spectral power distribution (SPD) into the software, the chosen SPD is not the actual SPD. During daytime, it was hypothesized that all the artificial lightings in the ward are turn off and the only source of light is daylighting (5000K). Only during the evening time at 5pm, the ward room downlights (4000K) are turn on as the sky gets dark. The ward room lights are turned on from 5pm to 10pm. During night time at 10pm, the downlights are turn off for patients to rest while the night lights (3000K) are switch on until the next day for safe night time movement.

3.2.1 Equivalent Melanopic Lux (EML) Results

The EML simulation was conducted to assess the melanopic lux perceived by the patients' eyes in different wardroom during the day and night. The results from the simulations will compare the same type of wardroom at different simulation conditions and all the results will be benchmark against WELL standard. The EML results of patients lying on the bed (sensor offset height: 850mm) is shown in Fig 4. to 5. The red dashed line represents the WELL standard at 200 EML.

Figure 4:
EML results for single bedded ward (Daylight)

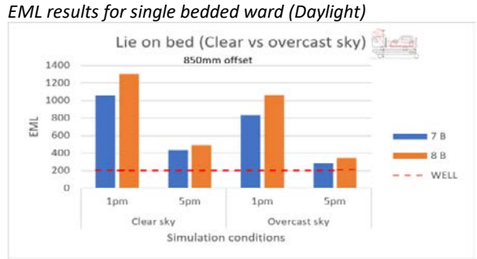
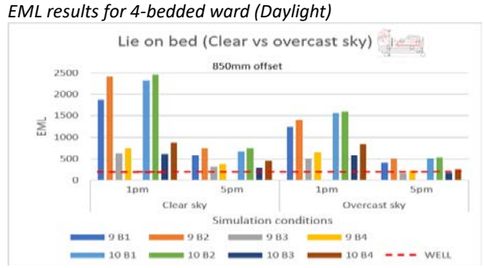


Figure 5:
EML results for 4-bedded ward (Daylight)



The wards facing the south orientation have higher EML levels as compared to north orientation. Most of the bed zones can meet 200 EML threshold but there are certain zones that did not meet the requirement. As shown in Fig. 5, at 5pm overcast sky setting, zones $B3_9$ and $B3_{10}$ fell below standard by 14.5% and 9.5% respectively.

Comparison between daylight and daylight with artificial lightings shows the EML level increases significantly when artificial lights are turn on, where all the bed zones are able to meet the WELL standard (Fig. 6 to 7). This is because artificial lightings can stimulate biological effects to suppress hormone melatonin, keeping the patients awake during the daytime.

Figure 6:
EML results for single bedded ward (Daylight with electrical lighting)

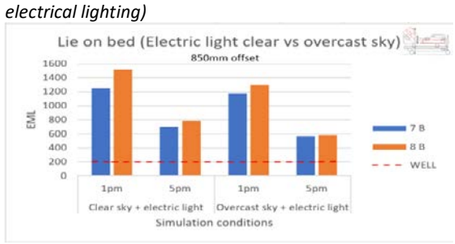


Figure 7:
EML results for 4-bedded ward (Daylight with electrical lighting)

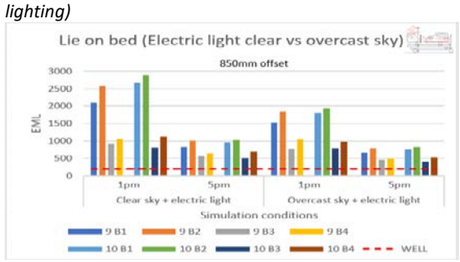


Fig. 8 shows the results for EML simulation when artificial downlights are turn on and the patient is lying down on bed. The red dashed line represents WELL standard at 50 EML. According to the WELL standard, the wardroom has to maintain EML level below 50, hence the bed zones did not meet the requirement. As shown in night light scenario (Fig. 9) with the working plane set at ground (0mm), the bed zones can meet the requirement as it is below 50 EML.

Figure 8:
EML results for single and 4-bedded ward—night time

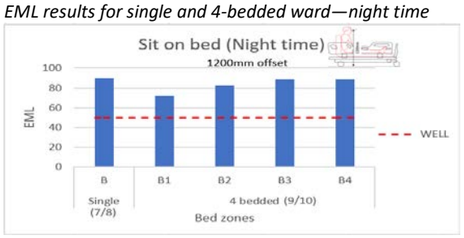
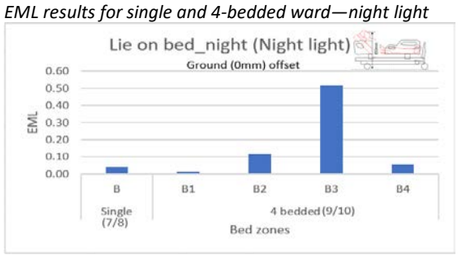


Figure 9:
EML results for single and 4-bedded ward—night light



3.2.2 Melanopic/Photopic (M/P) Ratio Results

The results of M/P ratio show the circadian efficacy of a light source during day and night time. The simulation parameters have the following thresholds being set: i) Blue Enriched, alerting (M/P > 0.9); ii) Blue Depleted, calming (M/P < 0.35); iii) Neither (0.35 < M/P <0.9). The results will be compared against the maximum threshold of 0.9 and minimum threshold of 0.35, denoted by blue and orange dashed lines respectively.

The results of M/P ratio simulation during daytime for single and four-bedded wards are shown in Fig. 10 and 11.

Figure 10:
M/P ratio results for single bedded ward

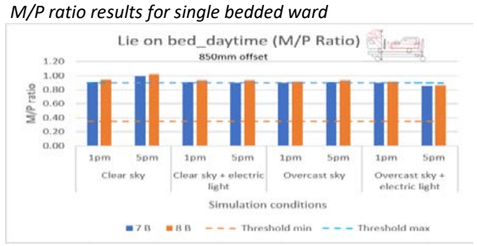
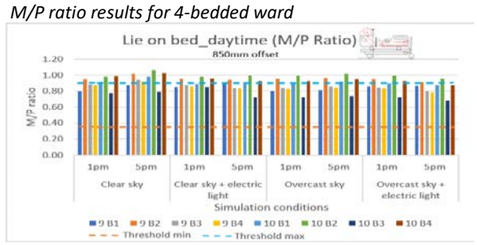


Figure 11:
M/P ratio results for 4-bedded ward



Based on the outcome results, there is no correlations with the simulation conditions. Using Fig. 10 and Fig. 11 as examples, during clear sky condition, high amount of blue light is expected at 1pm comparing to evening 5pm, where blue light is depleting. The results shows that the M/P ratio is higher at 5pm as compared to 1pm when it is expected to be low, closer to 0.35 or even less. The M/P ratio is expected be the lowest at 5pm overcast sky condition, however, the simulation results shown is almost similar to 1pm clear sky conditions. As seen in 4-bedded ward room, location of bed zone B4 is further away from the window as compared to bed zone B2 closer to the windows, the results show there is as much daylight as zone B2. Such strange phenomenon occurs in the rest of the results, regardless of patients' position in the zones. The reason may be due to the unrealistic spectral sky model used in ALFA software, where the SPD of the sky definition contains constant high blue component for daylight. This causes the expected and simulation outcomes to be largely different.

Fig. 12 to 13 shows the results for M/P ratio of artificial downlights during night time when patients are lying on bed (sensor offset: 850mm) and with night light condition (sensor offset: 0mm) respectively. As shown in both figures, the bed zones are below the lower threshold limit of 0.35, indicated as calming. The colour temperature of the artificial downlight is 3000K with SPD chosen to be more orange. During night time, melatonin hormone is secreted by the pineal gland in the brain to promote sleep. To avoid circadian disruption in patients, blue light is depleted at night so as to facilitate sleep for patients, which explains the low M/P ratio falling below lower threshold limit.

Figure 12:
M/P ratio simulation for single and 4-bedded ward downlight condition (850mm offset)

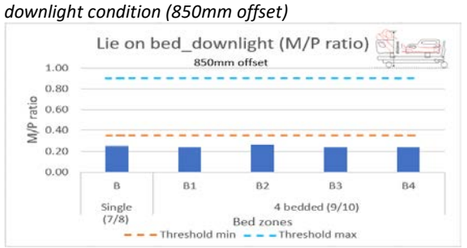
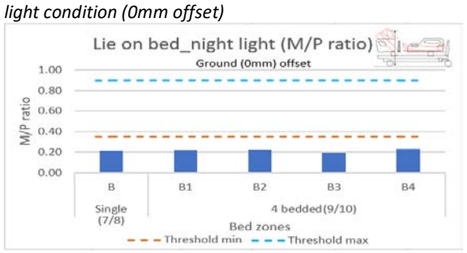


Figure 13:
M/P ratio simulation for single and 4-bedded ward night light condition (0mm offset)



4. CONCLUSION

This study is conducted to examine the effect of HCL on patients living in the hospital ward over the course of a day. The study only focuses on using simulation approach to produce results and generate data to reach the research objective. The results obtained from simulations and discussions lead to the following conclusions. Firstly, regardless of measurement positions in the hospital ward, the DGP is below the minimum requirement of 0.35 which is denoted as imperceptible. Therefore, patients resting on their bed will not feel any discomfort glare as large glare sources are located at the window area which is protected using external shading device, where only sufficient amount of direct sunlight can enter the ward room. Secondly, the ward rooms are well lit during the daytime. The results show that at 1pm, when the sky is clear and luminous intensity is high, daylight illumination can fulfil EML requirement in WELL standard. However, at 5pm, when dusk sets in, the illuminance level is low and artificial lightings have to be turned on to increase the EML to maintain it above the minimum WELL requirement. Similarly, for overcast sky condition scenario, simulation results show that daylight is sufficient at 1pm but insufficient at 5pm, hence artificial lighting need to be used to supplement the space. Thirdly, the due to limitation of software used in this case study, the artificial lightings are assumed to be in 100% operating mode which cause the EML to be higher than the minimum stated circadian requirement. In addition, SPD in the ALFA software has a different definition which causes inaccuracy in results. For example, the sun position is unclear during overcast sky condition simulation which lead to inaccurate and less variation in the M/P ratio results. Lastly, to provide a more concrete evidence and justification on benefits of HCL in hospital, the simulation should be done on a quarterly basis instead of single day analysis. This can provide a variety of results for analysis and better improve the hospital healing environment.

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Analysis of summer sky types using CIE standard sky model for the location of Gurugram, India

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ABSTRACT: Daylighting is recognized as a significant approach for designing energy-efficient buildings. It can be apprised from the literature review that researchers in the past have attempted to propose methodologies for defining suitable measured CIE sky types for some tropical countries, but a similar type of comprehensive study for Indian tropical climate was attempted 3 decades back. This paper aims to determine the representative CIE standard general sky model(s) for the summer months of 2020 & 2021 for the location of Gurugram, India. For the collection of luminance distribution data, the EKO Sky Scanner MS-321LR instrument has been set up. The sensor with a viewing angle of 11 degrees captures the hemisphere in 145 sequential steps. The data is recorded for the sky dome every 10min for 8 hours between 1000 hours to 1800 hours i.e., for 49 scans in a day. The adequacy of the proposed sky model is assessed using the root mean square errors (RMSE) method. For the analysed sample set of summer months, it is perceived that the clear sky condition pertains for almost 60% of the measured time. Therefore, the researchers, academicians, and industry experts may consider clear sky conditions while computing their daylight analysis for the summer months for accurate daylight analysis results.
KEYWORDS: Daylighting, sky model, illuminance, CIE, Sky scanner

1. INTRODUCTION

Daylighting is a key component in designing energy-efficient buildings. The appropriate combination of daylighting, electric lighting controls and fenestration design and size can result in significant energy savings by reducing 20-30% electric lighting loads and associated cooling loads (Riya Malhotra, 2021). It is further associated with enhanced occupant visual comfort, productivity, health, and well-being. The foremost step for illuminating a building's interior is to acquire information on daylight availability. At any point, the amount of daylight illuminance inside a building is influenced by the luminance levels and patterns of the sky in the direction of views of the surface, the quantity and character of daylight and the nature of building apertures it penetrates (Danny H. W. Li, 2002) (Mardaljevic, 2013) (Nancy Ruck, 2001).The availability of methodical climatic information is vital for indicating the sky luminance distribution to evaluate indoor daylight illuminance, wherein the climate-based daylight modelling encompasses outdoor climatic conditions that change continuously (Munoz C, 2014). It is observed from the literature review that researchers in the past have attempted to propose methodologies and have identified suitable CIE sky types for some tropical countries, but a similar type of comprehensive study with real time measured data for Indian tropical climate is rarely found. Currently, most of the applications work with simplified sky luminance models. Various research teams worldwide had carried out studies to determine the luminous efficacy constants. For instance, Perez presented a model known as the "all-weather model" for luminance distribution from routine irradiance measurements, the mean instantaneous sky luminance angular distribution patterns for all sky conditions from overcast to clear, through partly cloudy, skies (R. Perez, 1993). Igawa proposed sky radiance and luminance distribution models for all-sky conditions, from clear to overcast (Norio Igawa, 2001). Bartzokas adopted Kittler's standard sky luminance distribution (SSLD) method to define the typical daylight conditions for Central Europe and the Mediterranean with special attention to partly cloudy sky conditions (A. Bartzokas, 2003). Kittler's proposed SSLD method defines the fifteen sky types of relative luminance distributions; five overcast, five clear and five transitional skies that are modelled by the combination of gradation and indicatrix functions (Richard Kittler, 1998). The developed model is adopted as a CIE standard for sky luminance prediction by the International Commission on Illumination as per ISO 15469:2004 standards (CIE International Commission on Illumination, 2004) (Refer to Table-1).

The CIE model is currently the most comprehensive sky model, covering 15 typologies that depict a wide variety of sky circumstances from substantially overcast to cloudless weather. Some of the elements that affect sky luminance distributions are the solar position, atmospheric turbidity, air pollution, cloud amount, type, and pattern, which can impact unpredictable sunlight and skylight (Stanislav Darula, 2004) and can only be determined from sky measurement data. The CIE model predicts the sky luminance better than the Perez model in the Indian tropical condition if one knows the correct CIE sky type (Nabeel Ahmed Khan, 2020). Currently, the most widely utilized sky conditions for computer-based daylight simulations are CIE overcast and clear sky conditions. It's critical to see if a sky model can be created that closely resembles the properties of the real sky and gives building professionals more accurate daylight predictions. A sky scanner can be used to analyse the diffuse sky's radiation contribution, which is an important parameter for daylight software modelling, light pollution research, building automation, and design. It is generally recommended that illuminance data be collected over a lengthy period of time to determine trends in occurrences and eliminate any abnormalities.

Sky luminance is affected by several difficult-to-specify meteorological, seasonal, and geometric factors (Mardaljevic, Daylight Simulation: Validation, SKy Models and Daylight Coefficients, 2000). The goal of this study is to determine the CIE standard general sky model(s) for the summer months of 2020 and 2021 in Gurugram, India.

2. METHODOLGY

For this study, EKO Sky Scanner MS-321LR (Refer to Figure-2) is set up at the Mahindra-TERI Centre of Excellence (MT CoE) lab for the collection of luminance distribution data located at 28.4595° N, 77.0266° E Gurugram, India. The sensor with a viewing angle of 11 degrees captures the hemisphere in 145 sequential steps (Refer to Figure-1). The data is recorded for the sky dome every 10min for 8 hours between 1000 hours and 1800 hours, i.e., 49 scans a day. A combination of 2/3rd of measured data and 1/3rd of extrapolated and interpolated data is used to analyse the CIE standard sky type for the summer months (March-September) of 2020 and 2021.

Table 1:
CIE 15 sky types as per ISO 15469:2004

Sky type	Gradation Group	Indicatrix Group	Description of luminance
1	I	1	Overcast with a steep gradation and azimuthal uniform
2	I	2	Overcast with a steep gradation and slight brightening toward the sun
3	II	1	Overcast moderately gradated, azimuthal uniformity
4	II	2	Overcast moderately gradated and slightly brightening toward the sun
5	III	1	Overcast or cloudy with overall uniformity
6	III	2	Partly cloudy with a uniform gradation and slight brightening toward the sun
7	III	3	Partly cloudy with a brighter circumsolar effect and uniform gradation
8	III	4	Partly cloudy, rather uniform with a clear solar corona
9	IV	2	Partly cloudy with a shaded sun position
10	IV	3	Partly cloudy with brighter circumsolar effect
11	IV	4	White – blue sky with a clear solar corona
12	V	4	Very clear / unturbid with a clear solar corona
13	V	5	Cloudless polluted with a broader solar corona
14	VI	5	Cloudless turbid with a broader solar corona
15	VI	6	White – blue sky, turbid with a wide solar corona effect

Figure 1:
Sky dome showing 145 patches

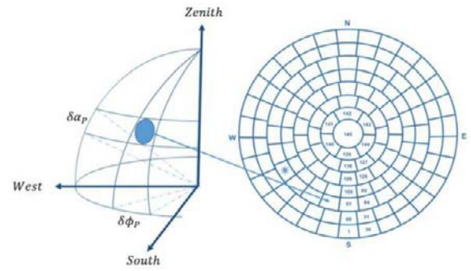


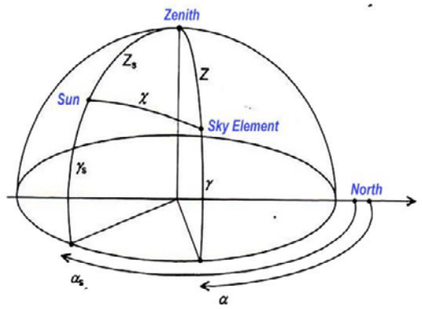
Figure 2:
Sky Scanner installed at the location

2.1 Analysis

A set of luminance distributions that can be utilized to harmonise observed sky brightness patterns is determined as the CIE standard general sky. Further, the concise and effective statistical distribution of the CIE General Sky types with the most desirable sky brightness patterns that transpire on the site location can be used to identify the site's daylight climate. The luminance distributions of various sky standards were modelled using Equations 1–8 and compared to the scanned sky luminance data to establish the set of standard skies (CIE International Commission on Illumination, 2004). The CIE sky model requires the measured value of Zenith luminance (kcd/m2), Zenith angle (Z), and the azimuth difference between the element and the sun, |α-αs| to determine the position of any sky element. If Z_s is the zenith angle of the sun, the angular distance between the element and the sun is given by,

$$\chi = \arccos(\cos Zs.\cos Z + \sin Zs.\sin Z.\cos|\alpha - \alpha s|) \quad (1)$$

Figure 3:
Angles defining the sun and the position of the sky element



Alternatively, the angle of elevation, γ, may be used instead of the zenith angle, Z, to define the position of an element. (Refer Figure-3)

$$Z = \frac{\pi}{2} - \gamma \quad (2)$$

Similarly, the zenith angle of the sun may be obtained from the solar elevation by,

$$Z = \frac{\pi}{2} - \gamma s \quad (3)$$

The ratio of the luminance, L*a*, of an arbitrary sky element to the zenith luminance, L*z*, is

$$\frac{La}{Lz} = \frac{f(\chi).\varphi(Z)}{f(Zs).\varphi(0)} \quad (4)$$

The ratio of the luminance gradation function, ϕ, relates the luminance of a sky element to its zenith angle:

$$\varphi(Z) = 1 + a.\exp\left(\frac{b}{\cos Z}\right), \text{ when } 0 \le Z \le \frac{\pi}{2} \quad (5)$$

$$\varphi\left(\frac{\pi}{2}\right) = 1, \quad \text{at the horizon}$$

Equation 4 requires the value at the Zenith;

$$\varphi(0) = 1 + a.exp\ b \quad (6)$$

The function f is a scattering indicatrix that relates the relative luminance of a sky element to its angular distance from the sun:

$$f(\chi) = 1 + c.\left[\exp(d\chi) - \exp\left(d\frac{\pi}{2}\right)\right] + e.cos^2\chi \quad (7)$$

Its value at the Zenith is,

$$f(Zs) = 1 + c.\left[\exp(dZs) - \exp\left(d\frac{\pi}{2}\right)\right] + e.cos^2 Zs \quad (8)$$

Where,

a, b	-Luminance gradation parameters;
α	-Azimuthal of sky element (Clockwise from north) [rad];
α_s	-Azimuth of the sun (Clockwise from north) [rad];
C, d, e	-Scattering indicatrix parameters;
x	-Shortest angular distance between a sky element and the sun [rad];
y	-Angle of elevation of a sky element above the horizon [rad];
y_s	-Angle of elevation of the sun above the horizon [rad];
φ(Z)	-Gradation function of the sky element;
φ(0°)	-Gradation function for Zenith;
f(χ)	-Indicatrix function of the sky element;
$f(Z_s)$	-Indicatrix function for Zenith;
L_a	-Luminance of a sky element [cd/m2];
L_z	-Zenith luminance [cd/m2];
Z	-Angular distance between a sky element and the zenith [rad];
Z_s	-Angular distance between the sun and zenith [rad].

The performance of each standard sky luminance model was evaluated using the root-mean-square error (RMSE) after the measured luminance was normalised with regard to horizontal illuminance and solar elevation.

The modelled sky brightness should be first standardised to horizontal diffuse illuminance by multiplying all luminance values by the normalisation ratio (NR) as follows:

$$NR = \frac{\Sigma Lmea\ cos\alpha.sin\alpha.d\alpha.d\varphi}{\Sigma lpred\ cos\alpha.sin\alpha.d\alpha.d\varphi}$$

Where L_{mea} is the measured sky point luminance (cd/m2); L_{pred} is the predicted sky point luminance in relative form (dimensionless).

The following formula is used to determine the root mean square error:

$$\text{RMSE} = \sqrt{\frac{1}{N}\Sigma\left(\frac{L_{pred} - L_{mea}}{L_{mea}}\right)^2}$$

N is the number of readings (dimensionless) [N=145 for 145 patches].

The procedures mentioned in the above equations are repeated for every measured luminance scan by an in-house excel based calculator tool where the inferred CIE General sky is the one with the lowest RMSE in each scan. Thereafter, the frequency of the 15 CIE General Standard Skies is detected and the RMSE may be computed. The daily and monthly data for the summer months of 2020 and 2021 were analysed using the same methodology. The cumulation of each sky type for 49 scans per day i.e. 5978 scans from March to September, was computed as percentage occurrences.

3. OBSERVATIONS AND RESULTS

A comparative analysis for the summer months 2020 and 2021 (Refer Figure-4 to Figure-10) analysed through RMSE expresses that CIE standard general sky type 14 described as 'Cloudless turbid with a broader solar corona' is the most occurred sky type with 40% average sky type occurrence (Refer Table-2 and Figure-12).

Table 2:
%Occurrence of Sky-type 14 during summer months 2021 & 2021

Month	2020	2021
MAR	53%	48%
APR	49%	51%
MAY	41%	34%
JUN	36%	39%
JUL	25%	29%
AUG	26%	33%
SEP	54%	35%

Although, it was observed that sky type 9 described as 'Partly cloudy with a shaded sun position' is the predominant sky type for July and August with a 25% average sky type occurrence for the summer months (Refer to Table-3 and Figure-8, 9 & 12) which justifies the monsoon months in India.

Table 3:
%Occurrence of Sky-type 9 during summer months 2021 & 2021

Month	2020	2021
MAR	7%	11%
APR	26%	27%
MAY	24%	23%
JUN	20%	15%
JUL	40%	38%
AUG	43%	33%
SEP	16%	33%

The adequacy of the proposed sky model is assessed using the root mean square errors (RMSE) method in representing the actual sky conditions. The monthly RMSE analysis of the summer months of 2020 and 2021 is showcased in Figures 4 to 10.

Figure 4:
March CIE sky Type RMSE Analysis

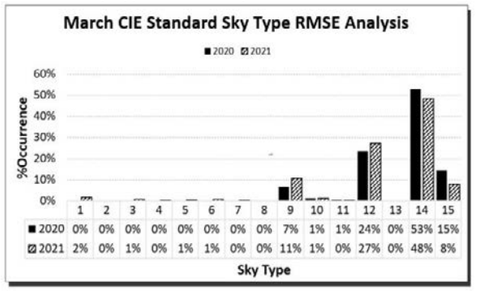


Figure 5:
April CIE sky Type RMSE Analysis

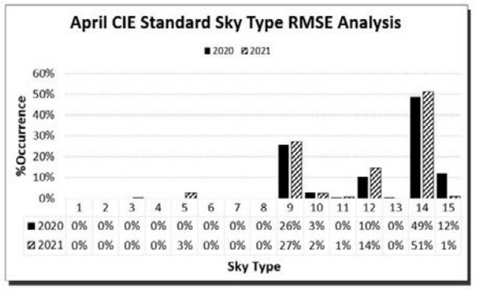


Figure 6:
May CIE sky Type RMSE Analysis

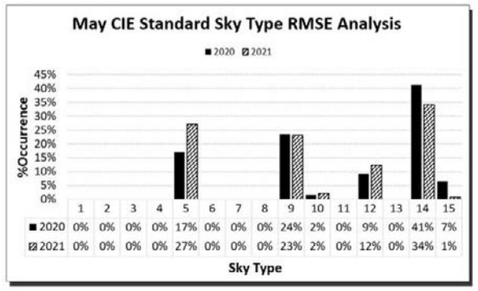


Figure 7:
June CIE sky Type RMSE Analysis

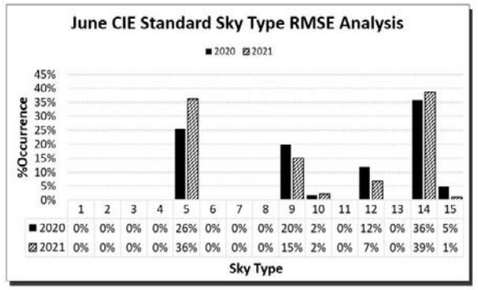


Figure 8:
July CIE sky Type RMSE Analysis

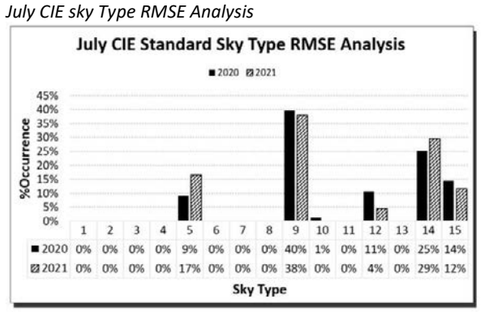


Figure 9:
August CIE sky Type RMSE Analysis

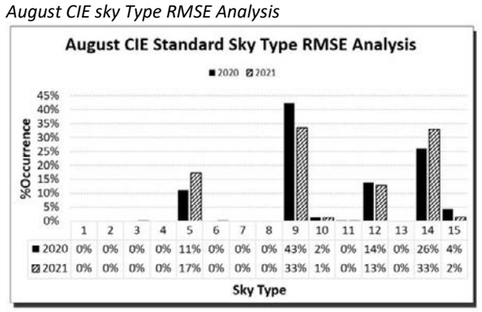
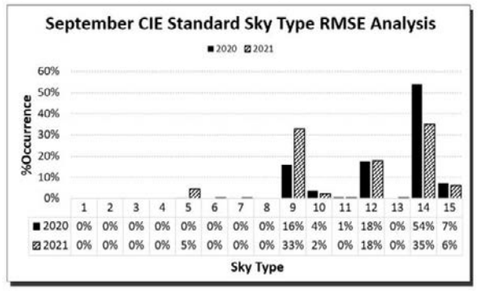


Figure 10:
September CIE sky Type RMSE Analysis



A 6% increase with a 15% weighted average in the occurrence of sky type 5 described as 'Overcast or cloudy with overall uniformity' is observed from April in the year 2021 compared to a 9% weighted average in 2020 (Refer Figure-5). Similarly, a 5% decrease in the occurrence of sky type 15 described as 'White – blue sky, turbid with a wide solar corona effect' was observed for the subsequent year. A slight increase of 1% was observed for sky type 9 and a decrease of 1% for sky type 14. Whereas, a consistent trend was observed for sky type 10 described as 'Partly cloudy with brighter circumsolar effect' and sky type 12 described as 'Very clear/unturbid with a clear solar corona' with a weighted average of 2% and 12% respectively during the summer months 2020 and 2021 (Refer Table-4 and Figure-11).

Table 4:
Percentage Average, Percentage weighted average Sky-type occurrence during summer months 2020 & 2021

Sky Type	%Average	%Weighted Average 2020	%Weighted Average 2021
1	0.14	0.03	0.26
2	0.00	0.00	0.00
3	0.09	0.03	0.14
4	0.01	0.01	0.01
5	12.04	9.04	15.03
6	0.08	0.03	0.12
7	0.03	0.00	0.06
8	0.00	0.00	0.00
9	25.36	24.88	25.83
10	1.82	1.98	1.66
11	0.24	0.29	0.20
12	13.88	13.98	13.78
13	0.05	0.06	0.05
14	39.51	40.49	38.54
15	6.75	9.18	4.32

Figure 11:
Weighted average sky type occurrence: Summer Months 2020 & 2021

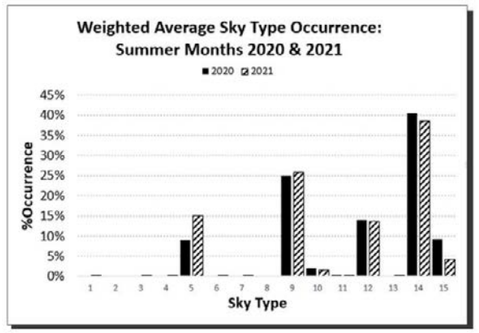
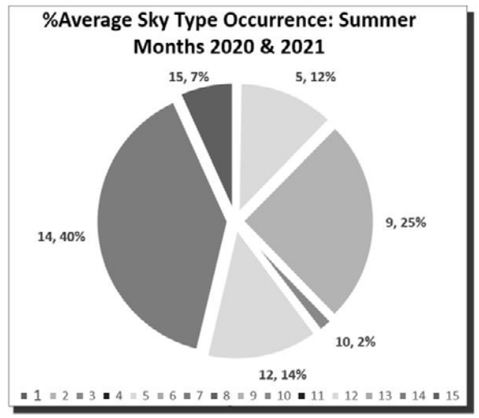


Figure 12:
%Average Sky Type Occurrence July-Aug-Sep 2020 & 2021



4. CONCLUSION

The sky luminance distribution data is measured from a sky scanner installed at Gurugram, India, and is analysed using the CIE standard root mean square errors (RMSE) method. For the summer months of 2020 & 2021, it is perceived that clear sky condition pertains for almost 60% of the measured time. However, it was observed that %Average sky type occurrence for July to September showcases sky type 9 i.e. nearly equal to the %Average occurrence of sky type 14 from the summer months of 2020 and 2021 (Refer to Figure-11 & 12). Therefore, for daylight analysis, the researchers, academicians, and industry experts may consider clear sky conditions while computing their daylight analysis for the summer months.

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An integrated approach for performance evaluation of perforated screens

Daylight sufficiency, solar gains, glare, thermal comfort, and energy use as key factors

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ABSTRACT: This work investigates the importance of Perforated Screens (PS) design for fully glazed façades in terms of five main domains. Several PS designs were evaluated based on annual performance simulations and specific performance metrics: daylit and overlit areas, solar gains, daylight glare probability (DGP), spatial thermal comfort, and total annual energy (TAE) use. The Analysis of Means (ANOM) was applied to find the statistically significant values to select the optimal PS design variables. Specifically, it was used to test whether the PS design results' means differ from the overall grand mean. In the end, the optimal designs were those with a 40-50% perforation ratio, medium-sized holes, medium and thick screens, and moderate separation from the glazing. Compared to a case study with no PS, the optimal designs got significant improvements. First, 48% of the workplane was enhanced from overlit to daylit. Then, 40% of views with disturbing glare during more than 5% of time were avoided, mainly in the back of the space. Besides, the mean radiant temperature in the zone was decreased by 2.47°C and 6.52°C during summer and winter, respectively. Finally, TAE was also reduced by 41% and solar gains by 32%.
KEYWORDS: Daylit area, Solar Gains, Daylight Glare Probability, Spatial Thermal Comfort, Total Annual Energy

1. INTRODUCTION

Solar screens can take many different designs with different purposes, ranging from aesthetic criteria to assessing daylight and solar protection for buildings. On the one hand, daylight should be enhanced indoors since it helps to create a visually stimulating and productive environment for building occupants while contributes to reducing energy consumption from artificial lighting and active thermal conditioning systems [1–3]. On the other hand, solar gains must be controlled to contribute to space heating or to save energy demand for cooling [4,5].

Apart from these goals, the assessment of discomfort glare in buildings is also a crucial parameter to verify for an accurate and conscious daylighting design [6]. Nevertheless, glare is rarely examined simultaneously with the previous two factors. Generally, glare must be minimized to a certain level to avoid discomfort or loss in visual performance and visibility [7]. Keeping the balance between the maximization of daylight harvesting and risk management of potential discomfort is the most ambitious challenge for designers [8].

Furthermore, it has been seen that thermal comfort has a significant role in how people perceive a building, behave in the built environment, and the amount of energy they consume daily [9]. Therefore, thermal comfort was also considered in this work, according to the climate conditions, to achieve both user comfort along with reducing energy consumption.

1.1 Objective

This work investigates the relation concerning daylight provision, solar gains, annual glare, thermal comfort, and energy use through an 'early-design framework' where each study domain interrelates with all the others. The aim is to optimize the architectural design of Perforated Screens (PS), shading systems widely used as second skins in fully glazed façades, to provide balanced solutions for building occupants. The investigation here reported attempts to be a first insight into the overall performance of PS, taking into account the five main domains (issues that are generally investigated independently of each other).

2. METHODOLOGY

2.1 Case study

The study consisted of annual simulations of an office room located in Seville, Spain. The room measures 7 m × 7 m × 3 m (refer to Fig. 1). It has a PS in front of the fully glazed South façade for which 18 different designs varying the perforation ratio, number and distribution of holes, screen thickness, and glass-to-PS distance were considered (refer to Fig. 2).

Figure 1:
Plan and section views of the case study.

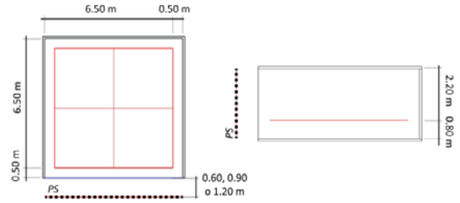
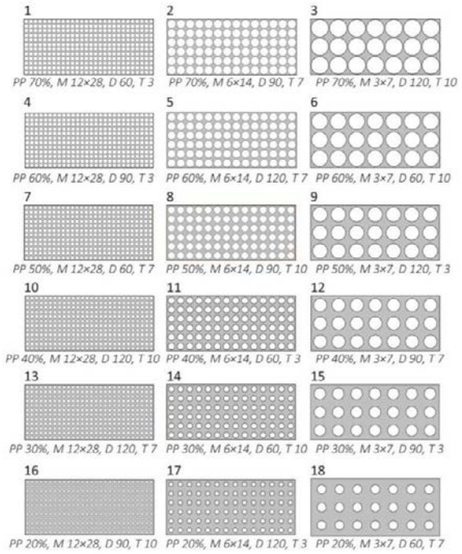


Figure 2:
Sample of 18 representative PS, selected for the statistical analysis. PP: Perforation Percentage; M: Matrix; D: glass-to-PS distance (cm); T: PS thickness (cm).



The purpose of the sample was to offer representative examples of a wide variety of PS designs. The statistical selection was based on the orthogonal method that allows complete and balanced comparisons among the different factors (here, design variables) through an orthogonal array (here, L18(61)(33)). Thus, 18 PS can represent a total of 162 PS, which would be the result of all possible combinations of the design variables: seven perforation percentages (PP), three matrices (M), three distances (D), and three thicknesses (T). Then, estimations, trends, and the significance of the factors can be derived from the orthogonal method. For more detailed information about using OAs, please refer to a more extensive documentation in [10].

The design variables were defined as follows:

- PP is the ratio of the total surface of the holes to the opaque surface. It is assumed to be from 20% to 70%, divided into 6 steps of 10%.
- M is the distribution of the holes (vertical × horizontal) on the opaque screen. M is arranged with 12×28=336 holes, 6×14=84 holes, or 3×7=21 holes.
- D is the distance between the inside surface of the screen and the outside surface of the glazing system. It is set at 60 cm, 90 cm, or 120 cm. These distances are founded on the widths of the glazing-screen cavity most commonly built for cleaning purposes or as hallways and balconies.
- T refers to the PS thickness for which 3 cm, 7 cm, or 10 cm were tested. These dimensions are based on the materials most commonly used in manufacturing (e.g. composite resins, ceramic, or brick).

2.2 Simulation setup

The assessment of daylight in buildings has evolved towards Climate-Based Daylighting Modelling (CBDM), considering annual dynamic daylight conditions (both sunlight and skylight). In this investigation, the EPW file for Seville was used to run the simulations with ClimateStudio.

Daylight Availability (DAv) is a CBDM metric that divides the space area into several parts [11]: the daylit area and the over-lit area are used in this study to account for the sufficiency of daylight and the potential risk of excessive sunlight penetration, respectively. The daylit area is the portion of the workplane that receives useful illuminances within the range between 300 lux to 3000 lux during at least 50% of the working hours. The overlit area is the portion of the workplane measured when daylight illuminances exceed 3000 lux for at least 5% of the occupied hours. These metrics were calculated over the workplane at 0.80 m above the floor, with sensors spacing 0.25 m apart. Reflectances of walls, ceiling, floor, and PS were set at 50%, 70%, 20%, and 80%, respectively. A 78.1% visual transmittance was considered for the glazed façade. The lighting power density is 10.6 W/m2 and the lighting control system corresponds to a manual on/off switch that mimics the behaviour of users that are likely to turn off lights at levels of around 250 lux.

Furthermore, Daylight Glare Probability (DGP) is used to evaluate glare from daylight and is considered part of the main CBDM metrics for assessing daylight quality. DGP is based on the analysis of glare and the vertical illuminance at the

eye's level [12]. Values under 20% are not validated; under 35% glare are not perceptible; between 35% and 40% are perceptible but not disturbing whereas between 40% and 45% are disturbing. In this work, DGP is used on an annual basis to assess the percentage of views with disturbing glare for more than 5% of the time. For DGP evaluation, critical view positions at 1.20 m above the floor were evaluated through Radiance with rotating angular fisheye cameras.

Then, solar gains or 'windows total transmitted solar radiation energy' is also accounted for PS performance evaluation. Solar gains refer to the short-wave solar radiation transmission through external fenestrations. Moreover, the 'Spatial Thermal Comfort (STC)' that accounts for distributions of the Predicted Mean Vote (PMV) across the floor area of the zone thermal model was also studied. PMV is based on a simple steady-state physiological model that predicts the mean comfort vote on the ASHRAE scale of a group of building occupants from a value derived from the four physical variables of radiant temperature, air temperature, humidity, and air movement, along with the insulation of their assumed clothing level and their metabolic rate. A comfortable environment is deemed to be one in which PMV is -1, 0, or 1 on the ASHRAE scale [13]. The relations between the boundaries of the PMV index are still under investigation – it has been shown a greater degree of thermal adaptation to local climate through a combination of physiological, behavioural, and psychological circumstances [14].

Finally, the Total Annual Energy (TAE), as the zone ideal loads (kWh/m2) for the year is also calculated in this work. TAE considers the energy use for lighting, plus cooling and heating. The EnergyPlus software option of using 'an ideal loads air system' is used for calculations. The occupancy and equipment loads are 0.1 people/m2 and 12W/m2, respectively. The heating and cooling setpoint temperatures are set to 21°C and 25°C, respectively. Besides, a 45% minimum relative humidity and a 50% maximum relative humidity are established in simulations. Lastly, the fresh air is fixed at 12.5 L/s/person and the sensible heat recovery is set at 0.64. Infiltrations are not considered. A clear double-glazing of 6 mm, separated by a 13 mm air gap, with 0.703 SHGC, and 2.785 W/m2 U-value was considered.

The fitness functions for the balanced solutions were: contributing with >50% of the workplane as daylit area, <40% of the workplane as over-lit area, and <90 kWh/m2 of solar gains (based on previous publications [10]); <30% views with disturbing glare >5% of time, and 50% of the occupied time within the desired thermal comfort range (as analogous of the daylight criteria); and <120kWh/m2-year for TAE (following the Passive House Institute certification criteria for low-energy projects). Table 1 summarizes the metrics considered in this study and the related fitness functions.

Table 1:
Performance metrics considered for PS evaluation.

Metric	Description	Fitness Function
Daylit area	% wp with 300-3000 lux, during >50% time	>50%
Overlit area	% wp with >3000 lux, during >5% time	<40%
Solar gains	kWh/m² for zone	<90 kWh/m²
DGP	% views with disturbing glare >5% time	<30%
STC	%wp of PMV	>50% PMV -1 to 1
TAE	kWh/m² for zone	<120 kWh/m²

Note: wp means workplane.

Then, statistical analyses will be run to find correlations among the different metrics. More specifically, the Analysis of Means (ANOM) will be used to find the statistically significant values to select the optimal PS design variables. The ANOM is a statistical inferencing procedure and visualization tool to analyse means from experiments. In this work, the ANOM is used to test whether the PS design results' means differ from the overall mean (also called grand mean or mean of means).

3. RESULTS

Table 2 presents the simulation results for the metrics obtained from the PS vs those from a reference case with no PS (Ref) that is included for further comparison. As observed, significant improvements were achieved when using PS. For some cases, the daylit area increased from 12% to 69%, and the overlit area reduced from 88% to 1%; the TAE reduced from 268 kWh/m2 to 94 kWh/m2, solar gains from 292 kWh/m2 to 41 kWh/m2, and the glare from 70% to 0%.

These results provide important insights into the PS performance. As stated in the literature review, PS can improve the interior environment. Therefore, PS design is important to be considered, particularly during the early stages of the projects when the decisions are made. In this regard, the ANOM can guide the selection of specific design variables to improve the PS performance. In Fig. 3, the dotted line shows the grand mean that can be used as a benchmark of the overall PS performance. Thus, the design variables over that line could be referred to as the optimal for the daylit area whereas those under that line as the optimal for the overlit area, daylight glare, solar gains, and TAE.

From the above, it can be inferred that the optimal PS configurations are those with a 40-50% perforation ratio, medium-sized holes, medium and thick screens, and moderate separation from the glazing. From these variables, M and T showed slighter differences. PS with >60% perforation ratios were the worst suited since they reduced the daylit area and considerably maximized the overlit area, daylight glare, solar gains, and TAE.

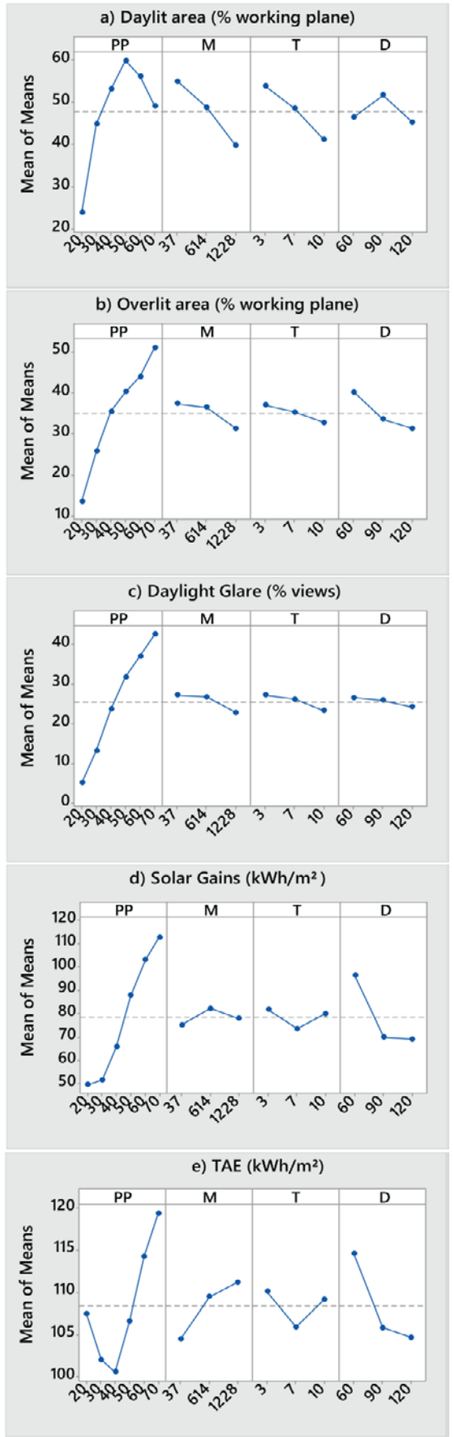
Table *2:*
Simulation results for the PS options: Annual mean values.

PS	Daylit	Overlit	Solar Gains	TAE	Glare
	% wp	% wp	kWh/m²	kWh/m²	% views
1	47	53	129	132	41
2	50	50	111	119	44
3	51	49	98	108	42
4	56	44	101	112	38
5	60	40	89	105	36
6	52	48	120	125	38
7	57	43	93	109	31
8	60	40	86	107	31
9	63	37	85	104	33
10	38	28	62	98	16
11	57	43	94	112	28
12	64	36	41	92	27
13	30	18	41	106	11
14	36	30	74	107	13
15	69	30	41	94	16
16	11	1	41	111	0
17	30	15	41	108	8
18	30	24	67	104	8
Ref	12	88	292	268	70

Regarding STC, no significant differences were found among the PS that achieved a grand mean PMV of ~1.91 over the plane and throughout the year. Instead, the reference case with no PS achieved a PMV of 2.0. To better understand the differences related to thermal comfort, the mean radiant temperature was also accounted for two specific times: June 21st at 14 h and December 21st at 14 h. Table 3 summarizes the simulation results for the spatial thermal comfort: PMV and MRT during summer and winter.

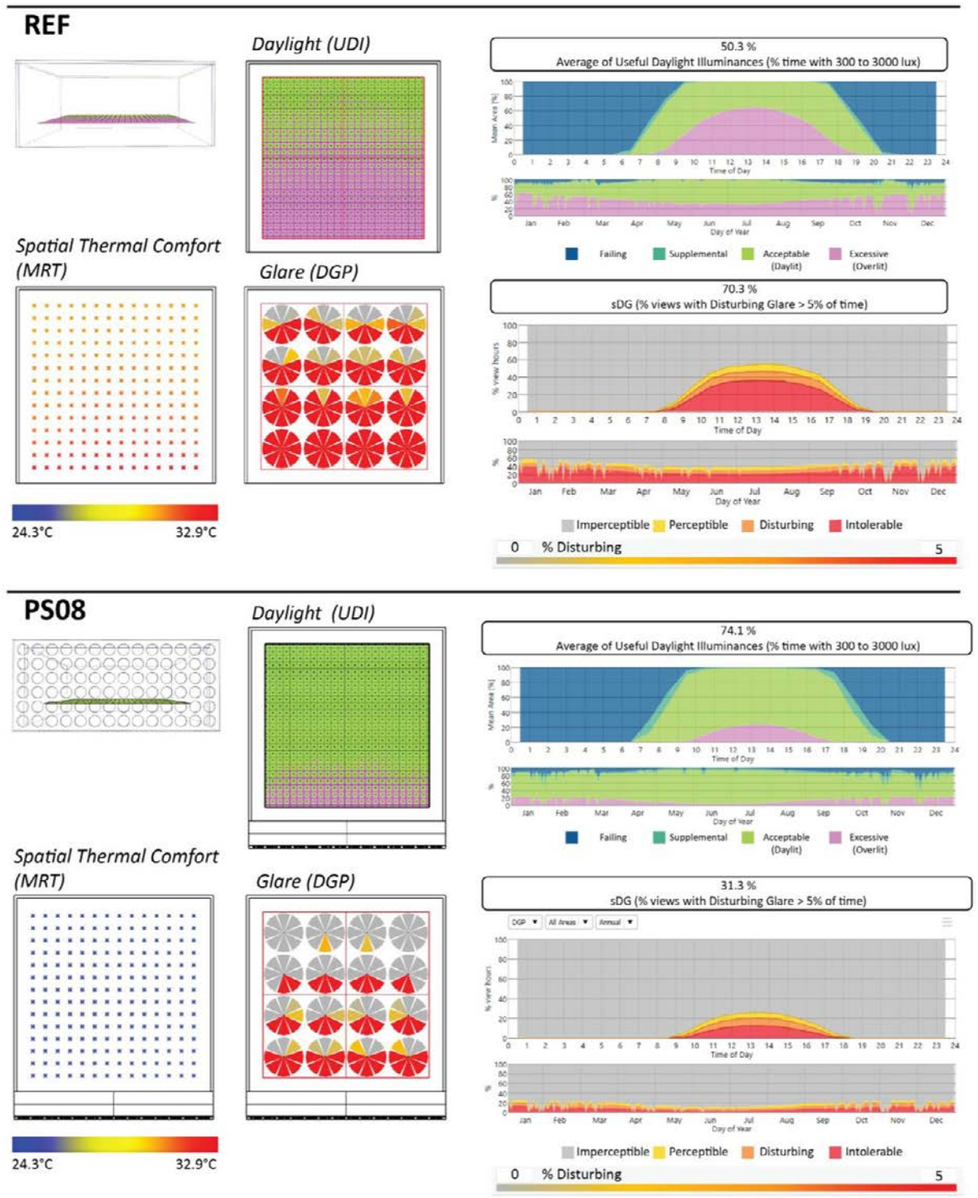
As observed, the differences between summer and winter were more relevant than the differences among the PS options. For example, the grand PMV mean was 2.25 during summer but 1.98 during winter. The related grand MRT means were 26.42°C and 24.54°C. When contrasting these results against the case study with no PS, significant reductions of the MRT were achieved: 2.47°C and 6.52°C, during summer and winter. These results provide support for prior studies that pointed out the importance of shadings to enhance daylighting and visual comfort.

Figure 3:
ANOM: Main effects plot for data means.



This method can be used to guide the selection of optimal design variables for PS. Thus, a balance among the design objectives (daylight, thermal, and visual comfort) can be evaluated during the design process. To better understand the improvements of the optimal screens, PS08 was selected to compare the results between using and not using PS (Fig. 4).

Figure 4:
Comparison of the annual results for daylight, thermal and visual comfort: Ref vs PS08. Available in colour online.



PS08 is characterized by PP50% and D90cm, which were the optimal values for daylighting design (refer to Fig. 3a). It can be seen from Fig. 4 that PS08 reached important increments of the daylit area and reductions of the overlit area: 48% of the workplane was improved from overlit to daylit, throughout the year. Besides, it was a clear reduction of the glare problems over the workplane, mainly in the back of the space. Overall, 40% of views with disturbing glare during more than 5% of time were avoided. Regarding the TAE and solar gains, the optimal PS got reductions of 41% and 32%, respectively.

Table 3:
Spatial thermal comfort: Mean value over the workplane.

PS	annual	June 21st, 14 h		Dec 21st, 14 h	
		PMV	MRT	PMV	MRT
1	1.914	2.241	26.28	1.989	24.56
2	1.916	2.234	26.16	1.990	24.58
3	1.913	2.246	26.37	1.989	24.53
4	1.913	2.250	26.43	1.989	24.55
5	1.914	2.240	26.27	1.990	24.56
6	1.913	2.261	26.44	1.989	24.54
7	1.915	2.238	26.23	1.990	24.57
8	1.915	2.240	26.26	1.990	24.56
9	1.913	2.252	26.48	1.988	24.51
10	1.914	2.250	26.44	1.989	24.55
11	1.914	2.240	26.27	1.988	24.50
12	1.915	2.249	26.42	1.990	24.56
13	1.906	2.245	26.33	1.983	24.35
14	1.915	2.270	26.53	1.990	24.57
15	1.915	2.239	26.26	1.990	24.57
16	1.914	2.288	26.84	1.989	24.55
17	1.914	2.287	26.83	1.990	24.56
18	1.915	2.278	26.65	1.990	24.56
Ref	2.005	2.342	28.89	2.251	31.06
grand mean	1.914	2.253	26.42	1.989	24.54

4. CONCLUSION

PS can greatly influence the overall performance of buildings. Proper design criteria should be developed to achieving not only daylight sufficiency, solar control, and energy efficiency but also to provide visual and thermal comfort. The building design process must consider the interrelation of the five domains to contribute significantly throughout the entire life cycle of the buildings and, ultimately, to the construction of cities and buildings in a green and sustainable way.

The results here presented are linked to the case study. However, the methodology could be applied to other case studies including not only new development but also retrofit processes. The advantage of using the method is the rapid comparison among different design options of PS, particularly during the early stages of the projects. This would allow the selection of the optimized trade-off solution between the different goals.

This type of analysis is becoming increasingly relevant, as building façade design evolves towards adaptive and efficient systems. Seasonal and daytime variability should be fully addressed in future works to set adaptive key factors to design dynamic building envelopes. Design methods that account for daylight, thermal, and visual performance are necessary for a holistic assessment of indoor comfort.

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Adaptation of Internal Venetian Blind for Office Spaces

A Passive Strategy for Sustainable Daylight Design

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ABSTRACT: The absence of efficient shading elements in glass faceted high-rise office buildings result in excessive daylight penetration inside causing glare, irregular illumination distribution, solar heat gain, and visual and thermal discomfort. Internal venetian blinds reflect light efficiently and ensure homogeneity of daylight illuminance by adjusting louver angles while allowing a view of the outdoors. This research aims to identify the characteristics of internal blinds to enhance the interior luminous environment of office spaces in high-rise buildings with glazed envelopes. Different parameters of venetian blinds are studied, e.g., slat geometry, the configuration of slats and the distance between slats for south, east and west orientations. Climate-based dynamic daylight annual simulation is done using the DAYSIM simulation program. The results suggest that for three orientations, internal venetian blinds with "inverted V" louver geometry having a 45º vertex angle are feasible for enabling effective indoor illuminance. Regarding separation distance, 160mm is suitable for south orientation whereas 70mm provides the best performance among the studied options for east and west orientations. This research proposes feasible configurations for internal venetian blinds which are appropriate for high-rise buildings with glazed façades for three orientations (south, east and west) to ensure sustainable interior design.

KEYWORDS: Daylight, Simulation, Internal venetian blind, Glazed façade, Office spaces.

1. INTRODUCTION

The dense urban environment in Dhaka has shifted the commercial buildings with deep office plans having less access to daylight [1]. Modern envelope technologies encourage the adoption of large transparent facades for commercial buildings [2]. Admittance of daylight inside a space depends on the natural determinants e.g., orientation, altitude of the sky, daylight quality, and other factors such as glazing type, aperture size and shading devices [3]. Glazed envelopes, allow an immense amount of daylight to penetrate causing visual and thermal discomfort and glare. The portion closer to the window receives excessive daylight, whereas most office spaces have to depend on artificial lighting [4]. Internal shading elements reduce glare, provide better illumination distribution, and increase daylighting penetration into the active workspaces. This opens up limitless possibilities for external façade design to designers and reduces the construction costs as well [5]. Dhaka has a composite climatic condition, so both overcast and clear sky conditions persist throughout the year. Internal venetian blinds are adjustable and moveable so they can respond to dynamic weather conditions [4]. They act as a passive means to enhance daylighting quality and become more energy efficient. It is necessary to develop effective configurations of internal venetian blinds for different orientations that would balance glare controls, respond to seasonal variation in natural light, and be used efficiently with the building envelopes [6].

2. INTERNAL VENETIAN BLIND

Internal venetian blinds significantly impact incident light and have a distinctive ability to adjust their slat angles to allow the view outside, provide glare protection, and ensure effective daylighting inside office spaces. The blinds' screen usually consists of separate moveable slats arranged equally and spaced [5]. Some design parameters of blind configurations affect the performance: slat depth 'L'; distance between two consecutive slats 'd'; and the angle of slat inclination with the horizontal plane and normal 'Θ' (Figure 1) [4].

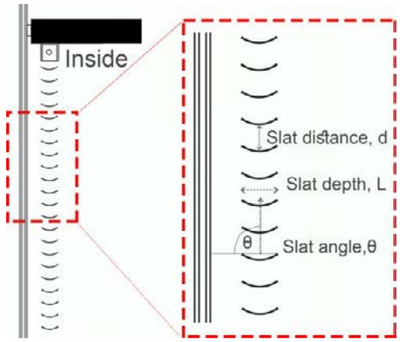


Figure 1: Schematic of internal venetian blind configuration (after, Nicoletti. et.al, 2020)

A study was carried out to figure out the performance of blind geometry types and tilt angles in terms of view and interior illuminance [7]. A study was conducted to find out the impact of venetian blind control system on energy consumption reduction while at the same time ensuring visual comfort to users [8]. Another comparative study shows that internal venetian blinds provide better indoor illumination levels in comparison to roller blinds [9]. Blind performance is linked to human factors such as users' satisfaction, view and ease of usage. A pilot study was conducted in office spaces examining the effects of the manual, semi-automatic and automatic blind systems in correspondence to user satisfaction levels. The result shows that almost 85% of people felt daylighting level within a comfortable range using the manual system and did not have any complaints regarding dimness, shadow, and brightness, or lighting distribution [10]. In a study of two types of internal blinds (vertical and horizontal) for office spaces, it is found that horizontal internal venetian blind performs better in correspondence to the luminance environment [11]. However, few studies focused on the performance of blind parameters in different orientations in the context of Dhaka are available. As a result, this study intends to analyze the performance of three blind parameters: slat geometry, separation distance and angle of slat inclination, for three critical orientations (south, east and west) inside a glass faceted office building located in Dhaka.

3. METHODOLOGY

In the climatic context of Dhaka, the North façade does not need any kind of shading element [4], so the study focused on the daylighting performance of South, East and West orientations.

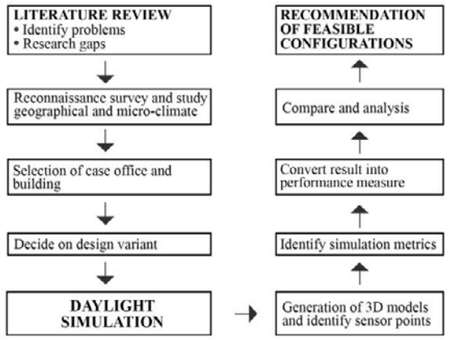


Figure 2: Flow diagram of the research process

A detailed field investigation was carried out to study the selected case office space. Appropriate simulation tools are selected to create the physical model based on the data as they are found during the field investigation. The overall methodology that is followed during this research is shown in Figure 2. Four commercial office buildings were primarily surveyed to find out the most suitable one for simulation analysis. To ensure a comfortable luminous environment, it is crucial to study human factors i.e., employees' respondence to the visual environment and post-occupancy study. As a result, the surveyed buildings were selected based on operational years for more than 6 years. Other criteria considered while selecting the case building and site are the following [12].

- The site is located within the urban context.
- The commercial office building represents open plan office layout design in Dhaka.
- The building façade had glazing on at least three sides, preferably south, east and west.
- The building façade had plain curtain walls, i.e., without any ornamental elements or shading devices.
- The commercial building is built according to the building construction regulations of the concerned authorities of Dhaka.
- The internal layout had the potential to allow ample penetration and distribution of daylight.
- The commercial office buildings fall under the category of high-rise buildings i.e., 10 stories or above.

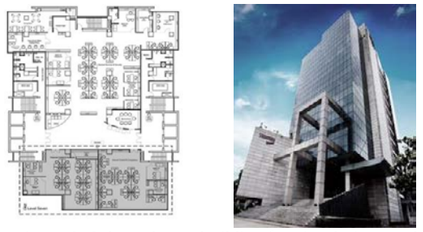


Figure 3: Selected case building for simulation study

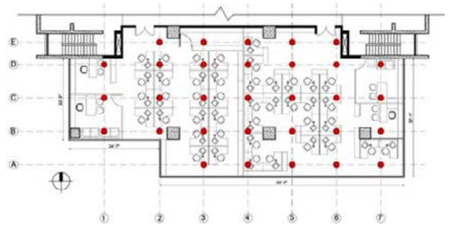
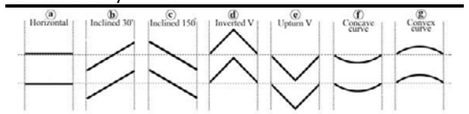
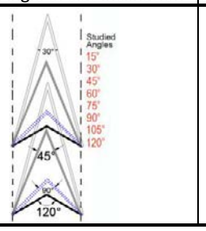
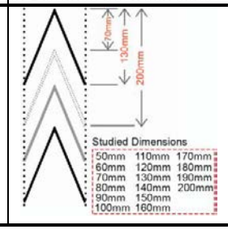


Figure 4: Location of core sensor points

Surveyed office buildings were checked against the above-mentioned selection criteria. The case building in Figure 3 satisfies all the criteria which a13-storiedoried commercial office building with a glazed façade on the south, east and west

orientations. The seventh floor of the building was selected for simulation study which represents the typical office layout of the rest of the floors (Figure 3). An active portion of the floor is selected for daylight simulation which is the main working zone and remains active throughout the office hours (10:00 AM– 5:00 PM). According to the LEED v4 (2010) requirements and methods, for spaces greater than 14 square meters, measurements of a maximum 3000mm square grid are recommended. The case space measures 289 square meters (3107sft), which is divided into 2700mm x 3600mm grids. The axis lines and core sensor points are placed at certain locations so that they pass through the desks and important locations. The study intends to evaluate the overall illuminance level inside the office space, so the sensor points are considered core sensor points. Five gridlines are set in XX' axes which represent the east-west direction and seven in YY' axes which represent the north-south direction. A total of 31 core sensor points is created and the work plane height is set at 750mm above floor finish (Figure 4).

Table 1: Studied blind parameters for each stage of the simulation procedure

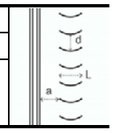
1. Geometry of Slat	
	
2. Angle of slat inclination	3. Distance between slats
	

This research focuses on three different parameters for venetian blinds for three different orientations (Table 1). The simulation output for the parameters is then compared with the output when there is no blind installed. During the simulation, it is considered that the blind configurations are static and completely open. The following slat characteristics are considered during the simulation study.

- Slats have a negligible thickness
- Slats are opaque
- Slat surface is smooth and without any irregularities
- Edge effects are negligible

The commonly available width and separation distance of a blind is 100mm [12], so for the 3D model interface, 100mm is selected for slat width. The specifications for the blind configuration used for the simulation study are shown in Table 2.

Table 2: Constant parameters for blind configurations used in the simulation

Blind Specification			
Blind Width	L	100mm	
Distance between slats	d	100mm	
Separation distance between distance and glass facade	a	25mm	
Blind material	Aluminium (reflectance:0.92)		

The 3D model was created using ECOTECT software and the material parameters are kept similar to what they were found during the field survey. The floor height was considered 3.35m, which is the floor-to-ceiling height of the office space. The parameters for the material finish used in the 3D model are as follows.

- **Ceiling:** White painted plaster (reflectance: 0.6)
- **Internal wall:** White painted brickwork (reflectance 0.6)
- **Floor:** Off-White porcelain tile finishes (reflectance: 0.5).
- **Glazing:** Double glazed with aluminium frame (reflectance: 0.78, U value: 2.35W/m2K).

The simulation procedure is carried out using DAYSIM software, considering minimum illuminance as 300 lux on office work plane height [13]. The dynamic daylight metrics help to commute time series for illuminance, which are used to find the annual dynamic daylight performance metrics. The simulation outputs are evaluated based on annual dynamic daylight performance metrics i.e., Daylight Autonomy (DA%), maximum Daylight Autonomy (DA_{max}%) and Useful Daylight Illuminance ($UDI_{<100}$%, $UDI_{100\text{-}2000}$% and $UDI_{>2000}$%). The performance metrics use the same annual illuminance profiles which are based on US Department of Energy weather files (2008) for Dhaka. The average illumination value for each performance metric is calculated and presented in a table to get the annual output. Rating points are assigned depending on their performance. The highest point (for example 8 points) means the best performance, whereas, the lowest point (1 point) indicates the worst performance among the studied options (Table 1). The score of each performance metric is finally summed up to get the score for ranking; the higher the score, the higher the rank.

4. SIMULATION ANALYSIS AND RESULT

The simulation outputs from the design variant in each stage are compared with the condition with no blind.

4.1 Simulation output and analysis for slat geometry

The first stage of dynamic simulation analysis involved the evaluation of slat geometries (Table 1) for three critical orientations.

Table 3: Dynamic simulation output with rating points and ranking of different slat geometries

Orientations	Slat geometry	Value & Rating points (RP)	DA (%)	DA_{max} (%)	$UDI_{<100}$ (%)	$UDI_{100\text{-}2000}$ (%)	$UDI_{>2000}$ (%)	Total RP	Ranks
South	No Blind	Value	91.4	30.8	3.8	54.5	41.7	17	7th
		RP	*7*	*1*	*7*	*1*	*1*		
	Horizontal	Value	90.1	22.8	4.5	60.3	35.2	19	5th
		RP	*6*	*3*	*4*	*3*	*3*		
	Inclined 30^0	Value	84.7	16.1	5.3	67.5	27.2	25	2nd
		RP	*2*	*7*	*2*	*7*	*7*		
	Inclined 150^0	Value	90.1	27.2	4.2	57.2	*38.6*	18	6th
		RP	*6*	*2*	*6*	*2*	*2*		
	Inverted 'V'	Value	82.9	15.5	5.5	69.4	*25.1*	26	1st
		RP	*1*	*8*	*1*	*8*	*8*		
	Upturn 'V'	Value	85.3	17.4	5.1	67	*27.9*	24	3rd
		RP	*3*	*6*	*3*	*6*	*6*		
	Concave curve	Value	88.8	22	4.2	61.3	*34.5*	23	4th
		RP	*5*	*4*	*6*	*4*	*4*		
	Convex Curve	Value	88.6	20.2	4.4	63.3	*32.3*	24	3rd
		RP	*4*	*5*	*5*	*5*	*5*		
East	No Blind	Value	91.4	30.8	3.8	54.5	41.7	13	8th
		RP	*6*	*1*	*4*	*1*	*1*		
	Horizontal	Value	90.8	28.3	3.9	56.8	39.2	16	6th
		RP	*4*	*3*	*3*	*3*	*3*		
	Inclined 30^0	Value	90.1	26.9	4.1	58.8	37.2	20	3rd
		RP	*1*	*6*	*1*	*6*	*6*		
	Inclined 150^0	Value	90.9	29.4	3.9	55.7	*40.3*	14	7th
		RP	*5*	*2*	*3*	*2*	*2*		
	Inverted 'V'	Value	90.1	26.4	4.1	59.3	*36.6*	25	1st
		RP	*1*	*7*	*1*	*8*	*8*		
	Upturn 'V'	Value	90.1	26.9	4.1	58.9	*37.1*	22	2nd
		RP	*1*	*6*	*1*	*7*	*7*		
	Concave curve	Value	90.7	27.9	3.9	57.3	*38.5*	18	5th
		RP	*3*	*4*	*3*	*4*	*4*		
	Convex Curve	Value	90.5	27.6	4.0	57.8	*38*	19	4th
		RP	*2*	*5*	*2*	*5*	*5*		
West	No Blind	Value	91.4	30.8	3.8	54.5	41.7	13	8th
		RP	*6*	*1*	*4*	*1*	*1*		
	Horizontal	Value	90.7	27.8	3.9	56.5	39.6	17	5th
		RP	*4*	*3*	*3*	*4*	*3*		
	Inclined 30^0	Value	90.9	29.3	3.9	55.4	40.7	14	7th
		RP	*5*	*2*	*3*	*2*	*2*		
	Inclined 150^0	Value	89.9	25	4.1	58.8	*37.1*	24	2nd
		RP	*1*	*8*	*1*	*7*	*7*		
	Inverted 'V'	Value	89.9	25.5	4.1	58.9	*37*	25	1st
		RP	*1*	*7*	*1*	*8*	*8*		
	Upturn 'V'	Value	90	25.9	4.1	58.4	*37.5*	21	3rd
		RP	*2*	*6*	*1*	*6*	*6*		
	Concave curve	Value	90.6	27.3	4	56.3	*39.2*	16	6th
		RP	*3*	*4*	*2*	*3*	*4*		
	Convex Curve	Value	90.6	27.2	4	56.9	*39.1*	20	4th
		RP	*3*	*5*	*2*	*5*	*5*		

In the case of south orientation, the base case with no blind scored the highest mean DA% value (91.4%), while, the inverted V slat scored the lowest point with DA mean of 82.9% (Table 3). Inverted V slats performed better with the lowest mean (15.5%) for DA_{max}% whereas; slats inclined at 150^o showed the highest value (27.2%). The condition without blinds showed the highest DA_{max} mean percentage (30.8%), which indicates that the installation of an internal venetian blind is essential for the studied space. Mean $UDI_{<100}$% for the base case is found to be the lowest (3.8%), hence scoring the highest rating of 7 points. On average, inverted V has the highest percentage (69.4%) of $UDI_{100\text{-}2000}$% and scored 8 rating points. In regards to $UDI_{>2000}$ % metrics, inverted V with a percentage of 25.1% scored the highest rating of 8 points.

The simulation procedure for east and west orientations used the same procedure as they are used for the south orientation. The comparison and analysis of the performance metrics (Table 3) revealed that the blind configuration with an inverted V slat scored the maximum number of points for three orientations, hence it is ranked in the first position.

4.2 Simulation output and analysis for slat inclination

The geometry from the first stage is evaluated by varying the vertex angles (Table 1) for three orientations in the 2nd stage of daylight simulation.

The mean simulation output for south orientation (Table 4) shows that the mean DA% is the highest (87.2%) for vertex angle 120^o among the studied options. In terms of mean DA_{max}%, the number gradually rises from vertex angle 15^o onwards to 120^o angle. The highest percentage is observed for $V120^o$ (19.7%), which is rated 1 point. Concerning $UDI_{<100}$ % metrics, $V120^o$ scored the highest rating points (8 points) with a mean $UDI_{<100}$ of 4.6%. With regards to performance metrics $UDI_{100\text{-}2000}$ %, the highest rating point (7 points) is assigned to 45^o vertex angle with a mean percentage of 75.3%. At last, for the $UDI_{>2000}$% metric, the lowest mean percentage is observed for vertex angles 15^o and 30^o, which is 15.4%. $V120^o$ has the highest $UDI_{>2000}$% which led them to a rating point of 1. Based on the rating points, the 45^o vertex angle is ranked in the first position.

Similarly, the mean percentages of all metrics for east and west orientations show that $V45^O$ scored the highest points and ranked 1st position based on their performance. On the other hand, 120^o vertex angle is ranked the last position with the lowest rating point for both orientations. As a result, for three orientations, inverted V slat geometry with vertex angle 45^o is considered most feasible than any other studied angle.

Table 4: Dynamic simulation output with rating points and ranking of the angle of slat inclination

Orientations	Inverted V vertex angle	Value & rating points (RP)	DA (%)	DA_{max} (%)	$UDI_{<100}$ (%)	$UDI_{100-2000}$ (%)	$UDI_{>2000}$ (%)	Total RP	Ranks
South	V15°	Value	61.9	10	9.6	75	15.4	21	4th
		RP	*1*	*7*	*1*	*5*	*7*		
	V30°	Value	61.9	10	9.4	75.2	15.4	23	2nd
		RP	*1*	*7*	*2*	*6*	*7*		
	V45°	Value	64.1	10.2	9.1	75.3	15.6	24	1st
		RP	*2*	*6*	*3*	*7*	*6*		
	V60°	Value	69.5	10.7	7.7	75	*17.3*	22	3rd
		RP	*3*	*5*	*4*	*5*	*5*		
	V75°	Value	76.4	11.6	6.6	73.6	*19.8*	21	4th
		RP	*4*	*4*	*5*	*4*	*4*		
	V90°	Value	83.1	14.7	5.5	69.9	*24.6*	20	5th
		RP	*5*	*3*	*6*	*3*	*3*		
	V105°	Value	84.3	17.2	5.1	66.8	*28.1*	19	6th
		RP	*6*	*2*	*7*	*2*	*2*		
	V120°	Value	87.2	19.1	4.6	64.9	*30.5*	18	7th
		RP	*7*	*1*	*8*	*1*	*1*		
East	V15°	Value	88.5	24.7	4.5	61.5	34.1	20	3rd
		RP	*1*	*6*	*1*	*6*	*6*		
	V30°	Value	88.5	24.7	4.5	61.6	33.9	22	2nd
		RP	*1*	*6*	*1*	*7*	*7*		
	V45°	Value	88.8	24.7	4.5	61.6	33.9	23	1st
		RP	*2*	*6*	*1*	*7*	*7*		
	V60°	Value	89.1	25	4.3	61.1	*34.6*	20	3rd
		RP	*3*	*5*	*2*	*5*	*5*		
	V75°	Value	89.6	25.3	4.2	60.7	*35.1*	19	4th
		RP	*4*	*4*	*3*	*4*	*4*		
	V90°	Value	89.9	25.7	4.2	60	*35.8*	17	5th
		RP	*5*	*3*	*3*	*3*	*3*		
	V105°	Value	90.3	26.6	4	58.8	*37*	16	6th
		RP	*6*	*2*	*4*	*2*	*2*		
	V120°	Value	90.3	27	4	58.3	*37.7*	13	7th
		RP	*6*	*1*	*4*	*1*	*1*		
West	V15°	Value	88.3	23.1	4.4	62	33.6	20	4th
		RP	*1*	*6*	*1*	*6*	*6*		
	V30°	Value	88.3	23.1	4.4	62.1	33.5	22	2nd
		RP	*1*	*6*	*1*	*7*	*7*		
	V45°	Value	88.4	23	4.4	62.4	33.2	27	1st
		RP	*3*	*7*	*1*	*8*	*8*		
	V60°	Value	88.7	23.5	4.3	61.5	34.1	21	3rd
		RP	*4*	*5*	*2*	*5*	*5*		
	V75°	Value	89.2	23.9	4.3	60.5	35.3	19	5th
		RP	*5*	*4*	*2*	*4*	*4*		
	V90°	Value	89.8	25.1	4.2	59.3	36.5	18	6th
		RP	*6*	*3*	*3*	*3*	*3*		
	V105°	Value	90	26	4.1	58.3	37.7	17	7th
		RP	*7*	*2*	*4*	*2*	*2*		
	V120°	Value	90.3	26.1	4.1	57.8	38.2	15	8th
		RP	*8*	*1*	*4*	*1*	*1*		

4.3 Simulation output and analysis for the distance between slats

Sixteen dimensions for separation distance are studied starting from 50mm to 200mm with an interval of 10mm (Table 1).

The analysis for south orientation (Table 5) shows that, in terms of mean DA%, a gap of 200mm is assigned 16 rating points. Concerning mean DA_{max}%, 200mm scored the lowest rating point (1 point) with a mean of 14.4%. On the other hand, mean $UDI_{<100}$ % is found to be highest (9.9%) for 50mm. In regards to $UDI_{100-2000}$%, 160mm gained the highest value (75.8%), hence rated 12 rating points. At last, $UDI_{>2000}$% shows the highest percentage (23.3%) for 200mm. 160mm separation distance is ranked first with the highest rating point (46 points). So, for south orientation, inverted V slats with 45° vertex angle and a gap of 160mm are proved to be most feasible.

Table 5: Dynamic simulation output with rating points and ranking of the separation distance for south orientation

Distance between slats	Value & rating points (RP)	DA (%)	DA_{max} (%)	$UDI_{<100}$ (%)	$UDI_{100-2000}$ (%)	$UDI_{>2000}$ (%)	Total RP	Ranks
50mm	Value	60.9	10	9.9	74.8	15.3	**32**	**11th**
	RP	*1*	*13*	*1*	*4*	*13*		
60mm	Value	61.3	10	9.8	74.9	15.3	**35**	**10th**
	RP	*2*	*13*	*2*	*5*	*13*		
70mm	Value	62	10.1	9.7	74.9	15.3	**37**	**8th**
	RP	*4*	*12*	*3*	*5*	*13*		
80mm	Value	61.6	10.1	9.3	75.2	15.4	**39**	**7th**
	RP	*3*	*12*	*5*	*7*	*12*		
90mm	Value	62.9	10.1	9.5	74.9	15.6	**37**	**8th**
	RP	*5*	*12*	*4*	*5*	*11*		
100mm	Value	64.1	10.2	9.2	75.2	15.6	**41**	**6th**
	RP	*6*	*11*	*6*	*7*	*11*		
110mm	Value	64.9	10.3	8.8	75.4	15.8	**43**	**4th**
	RP	*7*	*10*	*8*	*8*	*10*		
120mm	Value	65.2	10.4	8.9	75.1	16	**39**	**7th**
	RP	*8*	*9*	*7*	*6*	*9*		
130mm	Value	67.3	10.6	8.3	75.4	16.3	**42**	**5th**
	RP	*9*	*8*	*9*	*8*	*8*		
140mm	Value	68.4	10.7	8	75.6	16.4	**44**	**3rd**
	RP	*10*	*7*	*10*	*10*	*7*		
150mm	Value	70.7	10.8	7.5	75.7	16.9	***45***	**2nd**
	RP	*11*	*6*	*11*	*11*	*6*		
160mm	Value	73.1	10.9	7	75.8	17.2	**46**	**1st**
	RP	*12*	*5*	*12*	*12*	*5*		
170mm	Value	75.2	11.1	6.6	75.5	17.9	**43**	**4th**
	RP	*13*	*4*	*13*	*9*	*4*		
180mm	Value	76.8	11.4	6.4	74.6	19	**37**	**8th**
	RP	*14*	*3*	*14*	*3*	*3*		
190mm	Value	78.6	11.7	6	73.7	20.3	**36**	**9th**
	RP	*15*	*2*	*15*	*2*	*2*		
200mm	Value	80.6	14.4	5.8	70.8	23.3	**35**	**10th**
	RP	*16*	*1*	*16*	*1*	*1*		

The simulation procedure for east and west orientations used the same procedure as they are used for the south orientation. In terms of total rating points, 70mm scored the highest points (32points), hence, it is ranked first for east orientation. On the other hand, the cumulative rating points for west orientation are highest (38 points) for 70mm separation distance. Hence, 70mm is ranked first for west orientation.

In summary, the analysis and comparison of the vertex angles identified that an internal venetian blind with inverted V slat geometry having a 45° vertex angle is feasible for the south, east and west orientations. A separation distance of 160mm between slats in south orientation and a gap of 70mm in east and west orientations is needed for effective daylight performance inside an office space (Figure 5).

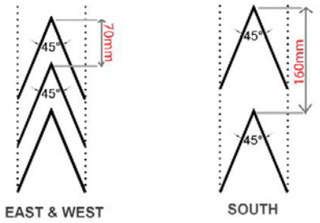


Figure 5: Identified blind configurations for south, east and west orientations

5. CONCLUSION AND RECOMMENDATION

The selection of effective internal shading elements based on orientations is fundamental to ensuring sustainability inside an office space. This research intends to study the parameters of internal venetian blinds for three critical orientations inside glass faceted office buildings in the context of Dhaka. Results from the simulation concluded that inverted V slat with 45° vertex is appropriate for the three orientations. In terms of separation distance, 70mm is most feasible for east and west, while 160mm is most suitable for south orientation. This research identified a few recommendations for active workspaces inside offices to improve the overall luminous environment by the installation of internal venetian blinds which are as follows.

- Slat separation distance impacts the overall daylight condition inside office spaces more.
- Glare can be minimized by installing an internal venetian blind with inverted V slat geometry.
- Reduction of vertex angle for inverted V slat geometry, reduces glare percentage.
- Factors such as outside view and human collaboration are needed to be within comfortable range to ensure blinds' effectiveness.

A post-occupancy evaluation can be done to evaluate the effectiveness of the studied blind configurations and find out whether the occupants are using them effectively. Simulation analysis with spatial illumination metrics can be carried out to extend the dynamic metrics and get an overview of the 3-dimensional aspect for blind parameters. Further studies can be carried out in correspondence to view and vary the operating schedule/system. In addition, studies on human collaboration in real-time settings can be carried out to determine users' satisfaction levels.

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Energy efficiency strategies for a Netzero energy building in southern Brazil

Analysis, diagnosis and retrofit proposal

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ABSTRACT: Reducing energy demand projected for 2030 is one of the topics addressed in SDG7 of the 2030 Agenda. In this context, buildings are big energy consumers, and the use of energy efficiency and renewable energies will allow balancing the demand and energy generation. Netzero Energy Buildings (NZEB) or self-sufficient energy buildings combine these two concepts so that buildings reduce their demand and start to generate their energy. The objective of this study is to evaluate energy efficiency strategies to turn a university building into a NZEB. The object of study is a building located in Passo Fundo, in the south of Brazil, composed of laboratories and classrooms. The building artificial lighting, air conditioning, and thermal comfort conditions were evaluated through simulations and in-loco surveys. Afterward, the retrofit of the lighting systems was proposed, with a reduction of 53.91% in lighting power. The air conditioning retrofit allows a reduction of 36.78% in the system power, totalling a reduction of 18.02% in the current consumption of the building. These active strategies will allow reducing the capacity of the photovoltaic system so that the building becomes an NZEB, in addition to improvements in internal environments regarding lighting and thermal comfort.
KEYWORDS: Retrofit, Energy efficiency, Thermal comfort, SDG7

1. INTRODUCTION

Issues related to energy efficiency are subject to the 2030 Agenda and the Sustainable Development Goals through SDG7. Electricity is one of the key elements for the transition from fossil fuels matrix to renewable and clean energy matrix, reducing greenhouse gas emissions and contributing to the mitigation of climate change in this process.

The issue of energy access, whether fuel, electricity, or other sources, also has an aspect of social equity, in which resources are available regardless of the income levels of populations [1]. But it will be necessary to reduce consumption to generation projections support increase in demand for electricity forecasted until 2050.

In this context, buildings are among the principal electricity consumers, especially in the residential and industrial sectors [2]. In this scenario, the concept of Netzero Energy Buildings aims to reduce the energy consumption of buildings through energy efficiency strategies and compensate consumption by renewable energy sources [3] a recent theme in Brazil, introduced by GBC Brazil Zero Energy certification.

In Brazil, buildings are responsible for 52% of electricity consumption, with dwellings using 46% of electricity in their total consumption and commercial buildings corresponding to 92% [4]. In 2016, there was a study by INPE (National Institute for Space Research) demonstrating the climate vulnerability in the energy sector concerning hydroelectric production in the northern and central regions of Brazil. In addition, other vulnerabilities have also been identified, such as the temperature rise that reduces the energy transmission capacity, the air density that will impact the performance and electric field, and the winds that could damage the facilities [5]. In this sense, it is necessary to invest in energy efficiency and renewable energy to ensure energy supply resilience.

Energy efficiency strategies are techniques to reduce a building's consumption, increasing the ratio between energy produced and consumed in the building use phase, reducing maintenance and operation costs, resulting in an increased systems reliability [6]. The financial savings generated by reducing consumption is an aspect that encourages the search for alternative energy sources and energy efficiency strategies [7]. However, energy efficiency alone will not support the increase in demand, and buildings need to contribute in addition to reducing demand.

In this way, the building renovation under the netzero or self-sufficiency strategy constitutes a holistic approach, considering the building life cycle, as well as the environmental impact, in addition to the renewable energy incorporation, while the deep renovation or retrofit has an approach focused on reducing energy consumption [8]. In this context, the building is considered as an energy generator, incorporating aspects that go beyond traditional design [9]. The requirements for a zero-energy building are: to significantly reduce consumption during the operation phase; achieve an energy balance based on sources without greenhouse gas emissions, and the building not emitting these gases and finally being economically viable [3].

As living laboratories, universities can be used to validate the strategies that constitute a Netzero Energy Building - NZEB, to later be replicated for other types of buildings and for cities. The objective of this study is to analyze the technical and economic feasibility of energy efficiency strategies, as a part of a project to make a university building in southern Brazil into a NZEB, being used as a concrete living laboratory to evaluate strategies replicable to other buildings.

2. MATERIAL AND METHODS

The study was developed in Passo Fundo, a medium-sized city, with an estimated population of 206,103 inhabitants [10], in the north of Rio Grande do Sul state, in Southern Brazil, located at 28º15’ S, 52º24" W.

The object of assessment is the L1 building of the University of Passo Fundo - UPF, currently used by undergraduate courses in Food Engineering, Chemical Engineering, and the Postgraduate Program in Food Science and Technology, also housing the CEPA – Food Research Centre. The building used since 2000 is the first in Campus to receive photovoltaic solar panels in its structure, arising the possibility of being converted into a Netzero energy building. Figure 1 shows a top view of the L1 building:

***Figure 1**: L1 Building top view*

2.1 Characterization method

The characterization of the building adapts the application in the Analysis and Diagnosis of Eco-efficiency research at the University of Passo Fundo [11,12]. This method is based on the Energy Audits of the Universitat Politècnica de Catalunya - UPC, combining static information, such as building characteristics, systems, and internal space, and dynamic data, such as energy consumption, user behaviour, and environmental variables.

2.2 Thermal conditions evaluation

Infrared thermographic measurements were carried out to defining environmental comfort strategies, such as shading devices. Thermal comfort analyses had already been performed based on ASHRAE Standard 55 [13]. Two laboratories with distinct solar orientation and a classroom were selected to carry out measurements. After data collection, the images were processed in the Testo IRSoft® software.

2.3 Artificial and natural lighting evaluation

The artificial lighting system was identified in loco, collecting data regarding the type and number of lighting fixtures, lamps, absence/presence of reactors, as their distribution in the spaces. Illuminance was measured by a digital luxmeter; minimum illuminance values are selected based on the level of accuracy, age of users, and reflectance of work surfaces defined by the NHO11 [14]. Night classrooms and laboratories should have an average of 500 lux, while bathrooms can have 200 lux for general lighting, 100 lux for circulation areas, and other environments should consider 300 lux.

2.4 Retrofit proposals

The building was modelled on Autodesk Revit educational version, a BIM (Building Information Modelling) software, due to interoperability with analysis software, through IFC (Industry Foundation Classes) and DWG files.

To evaluate the proposals for the artificial lighting system, the DIALUX® was used, modelling the current system, to assess the theoretical lighting capacity of the existing system and model the retrofit scenarios. The Velux Daylight Visualizer® software is used to assess natural lighting simulations. After the simulations are defined consumption reduction strategies.

3. RESULTS

Next, the results of the analyzes carried out in-loco will be presented, as well as the proposals for retrofitting the building.

3.1 Retrofit proposals

The thermal performance evaluation has already been carried out [11, 12], in this sense, to demonstrate the need for shading devices, thermographic images were taken. The images were taken on a sunny autumn day (May), a cloudy winter day (June), a cloudy spring day (September), and a sunny summer day (December). Figure 2 to 5 shows the thermographic measurements:

***Figure 2**: Thermographic view of the north facade in summer*

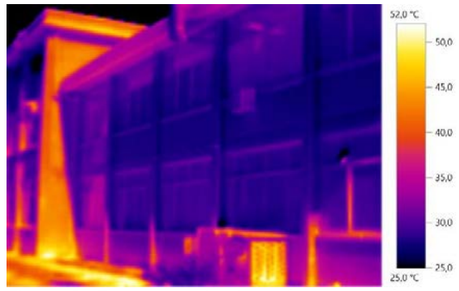


***Figure 3**: Thermographic view of the west facade in summer*

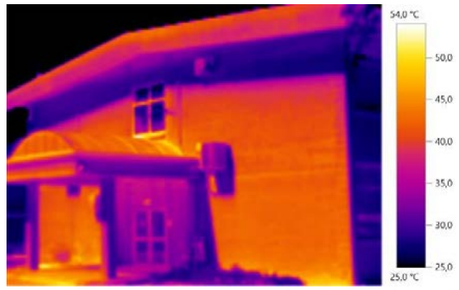
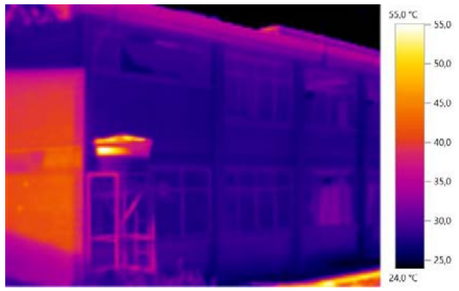


***Figure 4**: Thermographic view of the south facade in summer*

The building requires improvements regarding thermal comfort. Brises-Soleil, eaves, and thermal insulation are resources to reduce the building thermal load in a way that complements the solar orientation and natural ventilation, taking advantage of the climate to maximize internal comfort [15].

In north facade windows, shading devices should be considered in order to reduce thermal loads, preferably without harming the natural lighting levels of the environments. On the east and west facades, strategies to increase thermal transmittance (increasing the time for the absorbed external heat to be transferred to the internal environment) such as external coatings or vegetation to reduce the thermal load. The use of air conditioning should be considered in rooms facing south to compensate for possible thermal losses during cold periods, noting that air conditioners also contribute to the control of humidity and indoor air quality.

***Figure 5**: Thermographic view of the south facade in summer*



The shape of the building also influences the energy performance, as compact shapes reduce the facade surface, therefore, they reduce the areas of thermal losses and gains, so that rectangular and elongated shapes present greater thermal variation in relation to buildings with a cubic shape [15]. In the L1 building, the rectangular shape provides the thermal gain of the north facade at the expense of the heat loss of the south rooms, being also influenced by the vegetation barrier near the north facade. The vegetation produces thermal load reduction only in part of the building, justifying the adoption of other complementary devices.

3.2 Lighting Retrofit

The building partially meets the lighting requirements, requiring the retrofit of the installed systems. As for natural lighting, some of the environments allow use in conjunction with the artificial system but are insufficient to fully achieve demand in the building's work areas, requiring supplemental artificial lighting, in addition to changing the activation direction of existing luminaires. Figure 6 shows a lighting system view:

***Figure 6**: View of a theoretical classroom*

As for artificial lighting, the on-site verification indicated values below those required by the NHO11. The verified indices are due to the reduction in the useful life of the lamps, which also reduces the luminous flux and illuminance in the work area.

Therefore, it is recommended to replace existing fluorescent lamps with LED models and adjustments to the luminaires. In addition to the benefits related to the reduction of energy consumption, the retrofit of the lighting system will also imply psychological benefits for the building users, through the adequacy of the illuminance in the task areas, by the uniformity of the color temperature, and excessive contrast adjustments, reducing the possibility of visual fatigue. The neutral white temperature lamps and high CRI (Color Reproduction Index) will allow better visualization of colors, an essential requirement for practical classes and laboratory activities related to food.

The replacement of fluorescent lamps with LED lamps, with longer life, lower power, similar luminous flux, and the removal of the ballasts can reduce the installed load of the system and improve the conditions of visual comfort in the environments. The savings obtained by the retrofit were 53.91% concerning the installed load of the lighting system, 54.4% about LPD – Lighting Power Density and 4.2% to the current total consumption of the building. Observing that the building is mostly composed of laboratories, therefore, equipment such as ovens and refrigerators are responsible for most of the consumption. In addition, the building is not being used to its full capacity due to the restrictions of the 2019 pandemic.

Reducing the Lighting Power Density to 5.74 W/m² would allow for an A rating (most efficient) by INI-C [16], which establishes the value of 8.7W/m² as the parameter for greater efficiency. The potential for reduction by retrofit is presented in Table 1.

***Table 1**: Lighting retrofit summary*

ARTIFICIAL LIGHTING SYSTEM RETROFIT			
	Lamp/power	Total power	Consumption (2.080 hours/year)
Existing System	Fluorescent 32W+Reactor	42,11kW	87.588,8 kWh/year
Retrofit Proposal	18W LED	19,40kW	40.352 kWh/year
Reduction on lighting consumption			**53,91%**
Annual avoided energy			**667,28kWh/year**
Total consumption reduction			**4,2%**
Lighting Power Density - LPD reduction (in W/m²)			**12,60> 5,74 (54,4%)**

About previous studies, the study carried out in the V2 building on the same campus used a building with a similar built area (3,670.92m²), with the same use (educational) and a similar number of lamps and installed luminaires (1,134 lamps), obtaining a 41.16% reduction in lighting system consumption [17], however, the retrofit impact is greater on total consumption, since V2 has fewer laboratories and high consumption equipment than in the L1 building.

The study carried out in schools in South Africa found that lighting was responsible for 31% to 57% of energy costs, with an average of 40%. The daily savings ranged from 80 to 190kWh and energy saved was from 14,710 to 38,030kWh/year [18]. In the study carried out at the Universidade Federal Fluminense – UFF - in Rio de Janeiro [19], the illuminance of the rooms was also in in disagreement with the regulations and through the retrofit it would be possible to reduce the consumption of classrooms by 50.2% and 54.4%, with improved illuminance and the power density reduced by more than 50%m, remaining below 6W/m².

Therefore, even within the same typology (educational), the definition of the uses of a building directly implies the possibilities of reducing electricity consumption, even if some characteristics are similar, even in two buildings on the same campus.

3.3 Air conditioning Retrofit

The assessment shows that the air conditioning system can also be retrofitted, by replacing existing appliances with inverter technology models, helping to reduce the building's consumption while maintaining the air conditioning capacity.

The presence of users increases the thermal loads of the building, influencing the results of degrees/hour of heating [20]. In this sense, as the L1 building is not being used in its entirety due to pandemic restrictions, energy consumption is below usual. Location may also interfere with the building's systems. A school building in Spain where heating is responsible for 62% of energy consumption while lighting corresponds to 12% [21] is different to hot climates, like in Egypt, where energy towards indoor comfort is for cooling rooms [7]. In Brazil, cooling energy consumption predominate. Therefore, the building climate also demands different strategies for energy supply, as factors such as the facades and windows solar orientation will influence comfort conditions, even in the same city.

The retrofit proposal considered the installation of air conditioners in theoretical classrooms and laboratories, in addition to the replacement of

existing equipment. Table 2 presents the reduction potential for the retrofit of the air conditioning system:

***Table 2**: Air conditioning summary*

AIR-CONDITIONING SYSTEM RETROFIT			
	Model	Total power	Consumption
Existent	No inverter	202,60kW	72.936kWh/year
Retrofit	Inverter	128,06kW	46.104kWh/year
Reduction on system consumption			**36,78%**
Annual avoided energy (current consumption) in kWh/year			**2.190,63 kWh/year**
Reduction on building total consumption			**13,81%**

Several studies have obtained energy savings through the retrofit of air conditioning systems. Simulating the use of VRF-type (variable refrigerant flow) air conditioners would allow consumption reductions of 11.7% to 17.8% depending on the system used [22]. A setpoint (standard operating temperature) from 24ºC to 25ºC can lead to an average reduction of 16.4% in air conditioning consumption [23]. Lower internal loads induce a lower energy demand, and the reduction of cooling by 1ºC can represent a 30% reduction in air conditioning consumption [24]. Therefore, the performance of the envelope directly influences air conditioning consumption.

3.4 Ecoefficiency improvements

The joint application of the lighting and air conditioning retrofit will allow a reduction of approximately 18.02% in the load and the current total consumption of the building, from 15,861.60 kWh per year to 13,003.68 kWh consumed per year. In addition, the building's consumption profile would be maintained even with the equipment increasing its share of total consumption, reducing the installed load from 539,660W to 442,425W. Table 3 presents the current and post-retrofit eco-efficiency indicators.

***Table 3**: Building eco-efficiency indicators*

ECO-EFFICIENCY INDICATORS			
Indicator	Existent	Retrofit	Reduction
kWh/year	15.861,60	13.003,68	**18,02%**
kWh/m²/year	4,12	3,38	
kWh/user/year	8,73	7,16	
LPD W/m²	12,60	5,74	**45%**

A large part of energy consumption is due to the equipment and laboratories that predominate in the configuration of the building, unlike other buildings on the campus in which theoretical classrooms constitute most of the buildings. Therefore, high reduction rates would depend on more efficient equipment use in laboratories. The building's eco-efficiency indicators will be modified from the active strategies

Therefore, the adoption of energy efficiency measures can reduce consumption, also reducing the costs of implementing the renewable energy generation system. In the L1 building, there is already a photovoltaic system operating, with 6.76 kWp. The retrofit demand reduction would reduce the system power required to achieve self-sufficiency from 10.8kWp to 9kWp.

The current survey showed that the building does not achieve the desired energy efficiency parameters, either for its envelope or its lighting and air conditioning systems. The lighting system retrofit will allow a reduction of 53,91% in lighting consumption, in addition to providing benefits to user's health and productivity through illuminance indices improvement. The retrofit of the air conditioning system will allow a 36.78% reduction in the consumption of this system, even considering the placement of more air conditioning systems in laboratories and classrooms, reducing total consumption by 18,02%.

4. CONCLUSION

The L1 building significant energy consumption, resulting from the building's shape and use characteristics, offers the possibility of evaluating different consumption reduction strategies that can be replicated for existing and new constructions.

Together, the two strategies will allow a reduction in total consumption of 18,02%. In addition to these, the adoption of solar protection devices in some windows, use of natural lighting, automation, and guidance on consumption habits can generate even bigger savings. Furthermore, the adoption of these strategies reduces the size of the renewable energy system to make the building self-sufficient in energy, also reducing implementation and operation costs, contributing to convert the L1 Building into a Netzero Energy Building and replicate these strategies to other building typologies.

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Generative design for an urban morphology based on solar access strategy

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ABSTRACT: This paper proposes a generative design approach based on a resilient and equitable morphology that integrates the resources of the immediate context. It deals with a method for determining the location and urban morphology according to a passive solar access strategy.
We propose the shading restriction to limit the constructions' shade inside the plot during a shading cut-off time. The generative design makes it possible to generate a digital model of the different density solutions by varying the access solar duration. It allows to define an urban morphology resilient both to urban densification and better use of the useful resources of the context.
We present a model of solar neighbourhood approach to optimize solar resources at the urban block level. We discuss the results of its experimentation on three neighbouring plots in Tunis. The results are encouraging to renew the morphological urban rules and to propose a passive urban strategy adapted to climate changes.
KEYWORDS: Resilient urban morphology, Solar access, Passive strategy, Generative design.

1. PROBLEMATIC AND APPROACH

The current health crisis deeply changes the way of thinking on urban forms, just like the epidemics of the 19th century which paved the way to hygienic urban planning. Chappel (2021) highlights the relationship of urban density with the spread of the epidemic. Covid-19 forces us to revise our distances from others and restrict our exchanges in a well thought out framework. It probably signals a return to the health approach (Dhaher, 2020). Several studies propose a rediscovery of the sanitary precepts of post-covid urban planning(Cohen, 2020; Gangloff & Morteau, 2021; Lévy, 2021). Covid-19 calls into question urban regulations and its standardized arrangements.

We notice that the prospect rule, as currently formulated, limits the solar access in winter, and curbs urban densification (Raboudi & al., 2012; Raboudi & Ben Saci, 2013). We might ask how can we take advantage of the digital advancement of generative design to generate a digital model of buildings morphology according to the prospect respecting the useful period of solar access. We propose to think of an urban morphology strategy that optimizes solar resources at the urban block level.

The solar right is appeared at the end of the 1970s. The concept of the solar envelope described by Knowles between 1968 and 1971 (Knowles, 1974, 1980) proposed a morphological concept that guarantees this right and allows solar access to a building without shading its neighbouring buildings. The concept has undergone a great effort of formalization and digital development (Koubaa Turki & al., 2020).

We propose here a new application of this concept: the restrictive solar envelope which is determined by the buildings' location according to the shading restriction inside the plot (Koubaa Turki & al., 2018). In fact, it is defined by the shading cut-off time and the restrictive shadow fence.

The aim of this paper is to define the morphology of neighbouring buildings based on local resources: plot forms, solar access and shade limits.

2. RESTRICTIVE SOLAR ENVELOPE

The restrictive solar envelope is an envelope derived from the solar envelope. This volume preserves solar access according to spatio-temporal constraints. The restrictive solar envelope is determined by optimizing the layout of the buildings. It is defined by the shading cut-off time and the restrictive shadow fences. The shading cut-off time corresponds to the maximum capture period of desirable direct solar irradiance during winter. The restrictive shadow fence is defined by shading restriction inside the plot.

2.1. Method for delimiting the shading cut-off time

We define ,for a given place, the shading cut-off time (denoted To) by calculating the sum of the direct solar irradiation (denoted Rdh) received per hour and m² of vertical surface in winter (21 December to 21 March) by different orientations of facades with a rotation's step of 22.5° (Table1).

We are interested in a solar neighbourhood approach to maximize the capture of direct solar irradiance in winter. We refer to the Pareto(1967) principle to define the retained time period that allows capture of at least 80% of the total irradiance for about 20% of day's hours.

Table1.
Direct irradiance (kw/m²) in winter for different orientations of facades in Tunis.

Hour	∑Rdh	% Rdh
07:00	0	0
08:00	10	0.9
09:00	101	8.1
10:00	148	11.8
11:00	171	13.7
12:00	186	14.9
13:00	190	15.1
14:00	187	14.9
15:00	160	12.8
16:00	86	6.9
17:00	14	1.1
18:00	0	0
[10:00, 15:00]	1042	83.2%

We then observe that, from 7:00 to 9:00, and from 16:00 to 18:00, direct solar irradiation is negligible compared to the total irradiation. The cumulative percentage of irradiation from 10:00 to 15:00 is 83.2% compared to the total sum of the irradiance received in winter. Based on the Pareto principle, the time period retained allows capture of at least 80% of the total irradiance. This led to fixing the shading cut-off time To = [10:00, 15:00]. This duration corresponds to 25% of the day's hours.

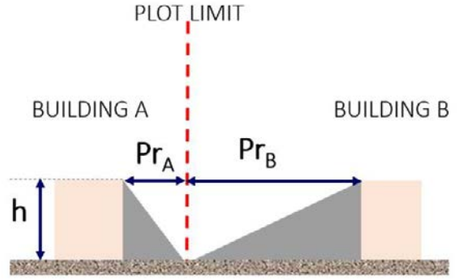
2.2. Determining the location and restrictive shadow fences

In this research, we propose to define the restrictive shadow fence by studying the extent of the shade between the neighbouring plots of an urban block according to the solar access. It allows to restrict the shade inside the plot during the cut-off time. In addition, it makes it possible to deduce the location of the buildings so as to guarantee that the shade is restricted in the interior of the plot during the desired solar access slot.

We develop the shading restriction prospect, denoted Pr, which is the minimum distance that guarantees the shade restriction in the plot during the shading cut-off time.

We take an example of two buildings A and B situated in two neighbouring plots (Figure 1). Their shades are restricted to the plot limits during To.

Figure 1.
Illustration of shading restriction initialization from shading restriction prospect.



The shading restriction prospect varies according to the date, the orientation and the height of the facade such as:

$$Pr = h * \cos \beta / \tan \alpha \text{ (meter)} \quad (1)$$

Where: *Pr* - the shading restriction prospect (m);
h - the height of the facade (m);
α - the angle of the solar height (degree). α expresses time;
β - the angle between the normal of the facade and the projection of the solar vector on the ground (degree). β expresses the orientation of the facade.

We retain the maximum value of the shading restriction prospect during the shading cut-off time. This value guarantees that the building does not cast shade in winter outside the boundary of the plot during the desired solar access slot.

3. EXPERIMENTATION AND RESULTS

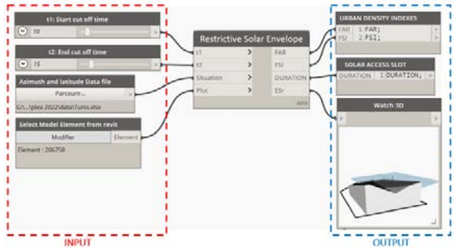
We present an application example on an urban block of three plots located in Lac of Tunis (Figure2).

Figure 2.
Satellite photo of the urban block composed of three plots A, B and C located at the Lac district of Tunis (latitude 36°50'31.22"N, longitude 10°16'48.75"E).

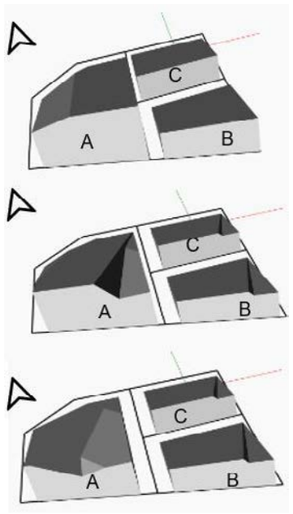
We propose an algorithm written on Dynamo for the generation of the restrictive solar envelope (Figure 3). The program makes it possible to detect

the boundaries of plots imported from Revit, to calculate the shading restriction prospect, and to determine the location of the building and generate the restrictive solar envelope for each hourly variation of the cut-off time. It calculates the floor space index (FSI) and the floor area ratio (FAR) for the resulting building forms of each plot in the urban block.

Figure 3.
Restrictive Solar Envelope components (a). Examples of 3D Solutions generated (b).



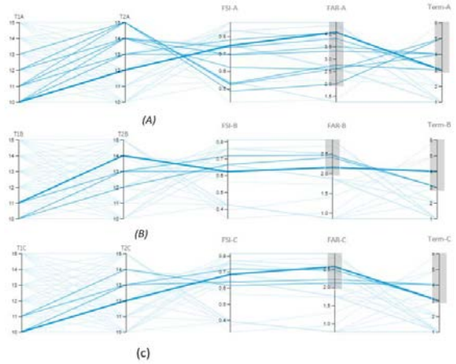
(a)



(b)

The cross product of solutions makes it possible to obtain 9261 morphological variants of buildings in this urban block. We add filters for: (1) the FAR equals at least 1.75 which is the value recommended by the actual regulation in Tunis and (2) the duration equals at least 3 hours that represent 50% of the cut-off time (Figure 4).

Figure 4.
Parameters diagrams of solutions obtained for each plot (A, B, C) corresponding to the various urban density of shading cut-off time.



We examine the results by two studies where the goals are to (1) maximize the FAR and (2) maximize the duration.

Firstly, we propose to study the best solution that maximizes the FAR corresponding to a minimum shading cut-off time of three hours for all plots (Table2).

Table 2.
Results for a maximum FAR and a minimum 3 hours duration of cut-off time for the three plots.

	Plot A	Plot B	Plot C
FSI	0.748	0.718	0.685
FAR	4,048	2.461	2,564
Duration	3	3	3
Cut-off time	[10:00,12:00]	[11:00,13:00]	[10:00,12:00]

For the same shading cut-off time [10:00,12:00] the geometry of plot A allows it to gain 63.33% in FAR compared to plot C. Besides, Plot B can reach a maximum FAR of 2,461 for [11:00,13:00], 64,48% less than the FAR of plot A.

Secondly, we propose the goal of having a maximum duration of cut-off time for the three plots (Table3). Plot A can guarantee five hours of solar access with a FAR of 2.576. Besides, for the two plots B and C, the maximum duration is four hours, FAR are respectively 2.149 and 2.215.

Table3.
Results for a maximum duration of shading cut-off time on the three plots.

	Plot A	Plot B	Plot C
FSI	0.620	0.625	0.636
FAR	2,576	2,149	2,215
Duration	5	4	4
Cut-off time	[10:00,14:00]	[10:00,13:00]	[10:00,13:00]

We notice that plot A has an additional hour of solar access and a gain of 20% of FAR compared to plots B and 16% to C. For the same four hours of shading cut-out time [10:00,13:00], the FAR of plot A would be 3,491which represents a respective gain of 62% and 57% relative to B and C.

4. DISCUSSION AND CONCLUSION

This paper proposes a resilient approach to optimize urban density and solar access by studying optimum duration and FAR ratio. It proposes a method for determining the urban morphology by controlling the restriction shading at the boundary of the plot and the solar access time slot. The variation of the period of the shading cut-off time makes it possible to manipulate the urban density while guaranteeing solar access over a useful solar access time slot.

The aim of this approach is to exploit the morphological potential of each plot. The position, shape and size of the plot impact the FAR and the duration of solar access.

The experimentation is done in a three urban blocks in Tunis. The comparison of the results obtained with the current indexes of the urban regulation of Tunis (FSI=0.5 and FAR=1.75) shows a clear improvement by using this model.

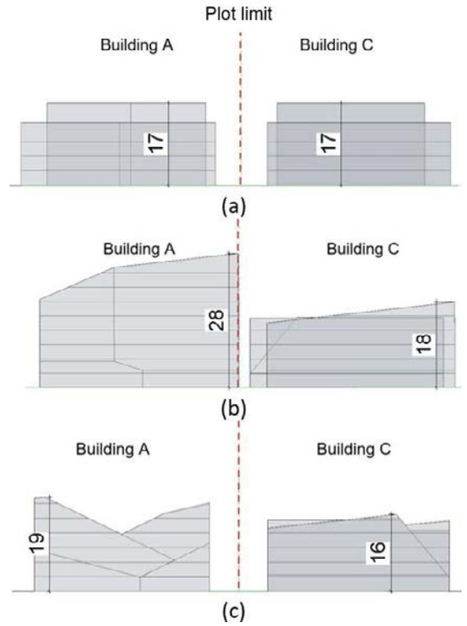
The first study improves the FSI up to 49.6% for plot A; 43.6% for plot B and 37% for plot C. Besides, the FAR is improved to 131% for plot A; 40.6% for plot B and 46.5% for plot C.

The second study improves the FSI up to 24% for plot A; 25% for plot B and 27% for plot C. Besides, the FAR is improved to 47% for plot A; 23% for plot B and 26% for plot C.

Reducing the shading restriction time to 3 hours (50% of the time slot guaranteeing 83% solar irradiation) has a greater impact on the FSI and the FAR than seeking to increase the duration of cut-off time.

We also notice that this approach improves the maximum height indicated by the urban regulation. It can increase until 28m for study 1 and until 19m for study 2 (Figure 5) compared to 17m as indicated by the actual urban regulation. The model allows to build higher buildings with restrictive shadow approach. This strategy optimizes the distribution of shade between neighbouring buildings in winter.

Figure 5.
Height of buildings in North Elevation:(a) actual regulation, (b) the first study for maximum FAR and (c) the second study for maximum duration of restring shadow in plot.



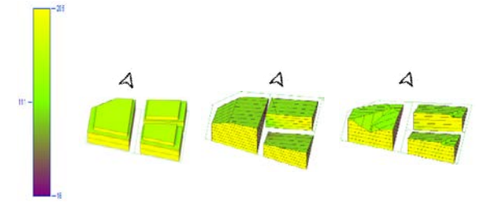
The experimentation would be interesting to check the results in several block configuration and lot of diverse sizes and orientation, in order to cover the scope of the conclusions arrived in the present work.

Studying the maximum of FAR and duration allows to obtain the best solutions of each plot. The multi-objective approach would be necessary in this case.

We calculate the winter solar energy at the shadow cut-off time received on envelope for each study. We compare them to the results of the envelope resulting from urban regulations (Table 4).

Table 4.
Solar energy received on the envelope in Winter at the shadow cut-off time (kWh/m²).

Plot	Actual Regulation	Max FAR Study 1	Max FAR Study 2
A	79	104	108
B	79	102	106
C	88	98	107
A+B+C	92	101	110

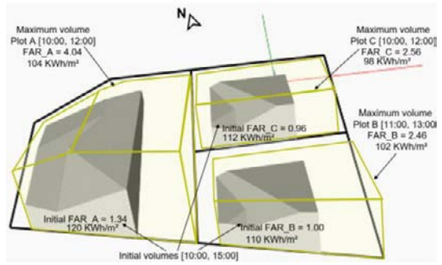


We compare received energy on actual regulation volume and max FAR volume for study 1 and 2. The solar energy received on the restrictive solar envelope of plot A increases to 24% for study 1 and to 27% for study 2. For plot B, the solar energy received on the restrictive solar envelope increases to 22% for study 1 and to 25% for study 2. For plot C, the solar energy received on the restrictive solar envelope increases to 10% for study 1 and to 18% for study 2. For the three plots, the improvement is 9% for study 1 and 8% for study 2.

The model improves the solar resource on the envelope and specially for study 2. This is a consequence of the fact that the forms of this study restrict the shade for 4 hours while it is 3 hours for study 1. The results can be put into perspective by hour to make them comparable. The solar resource can be considered as a parameter to select the better urban morphology.

We compare the restrictive solar envelope volume for the initial condition [10:00, 15:00] and for max FAR volume (Figure 6).

Figure 6.
Comparison the restrictive solar envelope volume for the initial condition [10:00, 15:00] and for max FAR volume.



Comparing to the initial volume with a cut-off time of (10:00, 15:00], the FAR of the three plots increases about 60%. Besides, The received energy decreases for 13%, 7% and 12% respectively for plot A, B and C.

The building location determined by shadow restriction can be further enhanced by a shadow mutualisation approach. Each building accepts the shade of its neighbour and gains in buildable area and building height. The shadow fences can be extended until the feet of the neighbouring buildings. This increases the height of the buildings. These neighbouring buildings share part or all of the shade.

It is possible to optimize urban densification and solar access to the needs of each region. The model of the neighbourhood solar approach can be adapted to different optimization situations of solar resources at the urban block level.

This research is limited to studying a single aspect of sustainable urban planning: solar access. The model can expand by involving more environmental parameters such as thermal comfort, lighting, ventilation, etc.

In tracing the boundary of the building on the road side, the model favours the alignment prospect rule to allow the user to include aesthetic or functional choices (parking space, security) etc. The model can be extended to include other urban constraints such as visibility, function, etc.

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Practice and evaluation of sponge city strategies for flash flooding mitigation in Mediterranean coastal cities

A case study of El Poblenou, Barcelona

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ABSTRACT: With global climate change, storms and floods have affected many cities around the world, and coastal cities are under greater threat. The Urban drainage systems have developed for a long time, and "Sponge city" is a new generation of sustainable and flexible urban drainage systems based on the LID concept to adapt to environmental changes and respond to natural disasters, which has shown significate effects in flooding mitigation in many practices. In this study, we selected El Poblenou of Barcelona as study area, constructed an urban inundation model based on topographic and precipitation data, simulated and visualized urban flood events in two scenarios of sponge city strategies. The result shows that the sponge city strategy can effectively reduce the surface runoff and flood area, and the Scenario with the high infiltration capacity significantly mitigates the urban flooding risk.
KEYWORDS: Sponge City, Urban Flash Flood, Stormwater Management, Inundation mitigation

1. INTRODUCTION

Climate change caused by global warming is already a global problem.

Since 1850, each of the last three decades has been successively warmer on the Earth's surface than any previous decade. And the period from 1983 to 2012 was most likely the warmest 30-year period of the past 800 years in the Northern Hemisphere (IPCC 2012, IPCC 2014)

Global warming directly causes sea level rise, climate change and atmospheric circulation, and causes extreme weather events like torrential rains, floods, heat waves and etc.

Due to frequent human activities, coastal areas are more susceptible to extreme weather events. Urban flooding caused by excessive rain has become one of the biggest climate problems in many coastal cities, so we urgently need to manage rainwater measures to mitigate urban flooding risks.

The "sponge city" is considered to be a new generation of sustainable and highly flexible urban drainage system based on the LID concept, which can adapt to environmental changes and deal with urban rainwater problems such as floods in extreme climates.

"Sponge city" is a new generation of sustainable and flexible urban drainage systems based on the LID concept to adapt to environmental changes and respond to natural disasters, which means that the city can be like a sponge that absorbs rainwater, which is then naturally filtered and purified by the ground and stored in urban aquifers. The collected rainwater can be easily extracted and reused for irrigation and domestic use. (MOHURD, 2014)

Since the concept of "Sponge City" was proposed at the "Low Carbon Forum 2012", many scholars have carried out research and practical work on "Sponge City".

Unlike gray infrastructure in traditional LID concepts, "Sponge City" aims to establish a multi-scale green infrastructure through an ecological approach to comprehensively solve the urban water problem (Yu et al., 2015).

The main technical measures to realize the sponge city include the rainwater retention system, the rainwater reuse system, the rainwater harvesting system, and the rainwater infiltration system (Shi et al., 2016). Due to the complexity of these water circulation systems, many academics use hydrological models to quantitatively predict, analyse and simulate sponge cities (Cai, 2016). Randall et al. use the SWMM hydrological model to assess the potential to achieve rainfall capture targets over a long period of time in Beijing (Randall et al., 2019). And Wang builds a sponge city flood prediction and simulation system that combines hydrological data, topographic data, GIS data, and real-time and interactive hydrodynamic models in a three-dimensional environment to simulate flood events in the pilot sponge city.

Due to the special climate of the Mediterranean regions, they are regularly affected by high precipitation events that often lead to devastating flash floods (Beaulant et al., 2011). Between 1950 and October 2009, EM-DAT (2009) reported 395 severe storm and flood events in 19 Mediterranean countries. In addition, the western Mediterranean region is threatened by the Cold drop phenomenon every autumn, which often causes torrential rains from the Spanish Mediterranean coast and even catastrophic floods. Therefore, it is very important to practice the strategies of flooding mitigation in the Mediterranean region.

2. STUDY AREA AND DATA

The study area is El Poblenou, which is an extensive neighbourhood of Barcelona (Sant Martí district) that borders the Mediterranean Sea to the south, Sant Adrià del Besòs to the east, Parc de la Ciutadella in Ciutat Vella to the west, and Sant Andreu to the north. It has a land area of 1.577 km^2 and a population of more than 30,000 habitants.

2.1 Land information

Figure 1:
Land Cover of El Poblenou.

Topography plays a major role in determining the accuracy of flood inundation areas, so DEM resolution and vertical accuracy are related to the accuracy of flood inundation maps (Siddharth et al., 2015). The horizontal resolution and the vertical accuracy associated with LiDAR data are significantly better compared to the old DEMs derived from contour surveys, cartography, photogrammetry, interferometry and radar imaging (Aguilar et al., 2010). In order to obtain a surface elevation map with high resolution and accuracy, we processed the LIDARCAT2 point cloud data of ICGC (Cartographic and Geological Institute of Catalonia) to obtain a surface elevation map with a resolution of 1m. In this process, we need to first classify the LIDAR point cloud data, remove the interference points including vegetation, obtain the ground surface and building surface point data, and then extract values into the topographic map to obtain the surface elevation model.

Copernicus' Urban Atlas provides land cover and land use data, we can identify land types and obtain CN values through TR-55 manual (US Soil Conservation Service, 1986), as shown in Figure 1.

2.2 Rainfall information

In the territorial group formed by the basins of the metropolitan area, the flows have been obtained for the return periods of 1, 10, 25, 50, 100 and 500 years. There are two types of rainfall used in the territories of the metropolitan area (Table 1):

Table 1:
Rain design

Rain Type A (Zone Delta Llobregat)				Rain Type B (General zone)			
T	I_s, max	I_1	P_d	T	I_s, max	I_1	P_d
1	114	32	65	1	99	28	60
10	210	59	135	10	183	52	120
25	242	68	170	25	210	59	150
50	262	74	190	50	228	64	170
100	281	79	215	100	244	69	200
500	319	90	285	500	277	78	255

In this study, we will simulate the rainfall-runoff model with the one-hour precipitation of a 100-year heavy rainstorm. The amount of precipitation is 69mm.

According to the design of sanitation network, the drainage speed is about 20mm per hour, and the total drainage water is about 30,000 m^3.

3. METHODOLOGY

In this paper, we will evaluate the effect of sponge city strategies in urban flooding mitigation by constructing an urban inundation model. This model consists of a terrain model and a rainfall-runoff model.

3.1 Terrain model

The terrain model can be obtained from topographic maps, surface elevation maps, and land cover maps. The terrain model should be able to fully display the three-dimensional land information of the study area, including land cover type, elevation, etc.

3.2 Rainfall-runoff model

The rainfall model can be expressed by the water balance equation, as shown in Equation (1):

$$\mathbf{Q_r = Q_p - Q_f - Q_d - Q_e} \quad (1)$$

where Q_r – amount of surface runoff;
Q_p – total precipitacion volume;
Q_f – amount of infiltration;
Q_d – amount of drainage water;
Q_e – amount of evaporation;

Due to the short duration of the storm we studied, evaporation (Q_e) may be negligible in this paper. Therefore, the equation can be written as equation (2):

$$\mathbf{Q_r = Q_p - Q_f - Q_d} \quad (2)$$

In this model we mainly study the increase of infiltration and the decrease of surface runoff. The amount of infiltration mainly depends on the infiltration capacity of the soil in the study area. The Soil Conservation Service curve number (SCS-CN) method proposed by the US Soil Conservation Service (1986) has been considered as a broad and practical tool in many studies (Jiao et al., 2017), so we can query the CN values according to the land information obtained in the terrain model to calculate the estimated infiltration, as shown in Equation (3):

$$\mathbf{R} = \begin{cases} \frac{(P-\lambda \cdot Sr)^2}{[P+(1-\lambda)\cdot Sr]} & \text{when } \mathbf{P \geq \lambda \cdot Sr} \\ 0 & \text{when } \mathbf{P < \lambda \cdot Sr} \end{cases} \quad (3)$$

where R – direct runoff;
P – amount of precipitation (mm);
λ – initial abstraction coefficients, sets as 0.05 (D´Asaro and Grillone, 2012);
Sr – maximum soil moisture retention, Sr=25400/CN-254, the CN is the curve number according to TR-55 manual (US Soil Conservation Service, 1986);

Then, we can calculate the amount of infiltration by Equation (4):

$$\mathbf{Q_P - Q_f = Q_r + Q_d = \sum_{n=1}^{N} A_n R_n} \quad (4)$$

where A_n – land area of the nth type land;
R_n – direct runoff caused by nth type land;

After obtaining the surface runoff, we can estimate the flooding area and inundation height through ArcGIS 3D Analyst Tools.

3.3 Sponge city scenarios

There are multiple approaches to water treatment in the framework of the Sponge City strategy, including lamination, interception, filtration, infiltration, retention and storage, drain.

Therefore, it is possible to establish the following table for the sponge city strategies applicable to the City of Barcelona: (Medi Ambient i Serveis Urbans-Ecologia Urbana, 2017)

Table 2:
Sponge city strategies applicable to the City of Barcelona

	Volume reduction increase Cost increase →		
Retention		Water cisterns	Rain garden
Filtration	Vegetated strips	Green covers	
Infiltration		Permeable pavement	
Treatment	Vegetated ditches	Bioretention strips	Wetlands

The practice of sponge city strategies can effectively improve the infiltration capacity of land, but it also requires certain economic cost support.

In this paper, we simulate two scenarios of sponge city strategies (Table 3).

Table 3:
Sponge city scenarios

	Scenario 1 (Low cost)	Scenario 2 (High Mitigation)
Building roof	Extensive green roof	Intensive green roof
Walking trail	Rain garden	Pervious concrete
Parking	Car Park (permeable pavement)	Street Parking (permeable asphalt)
Open space	Permeable pavement	Wetland Park

In Scenario 1, we use the more economical sponge city strategies, while in Scenario 2, we use the sponge city strategies that can increase infiltration capacity more efficiently but at a higher cost. We will simulate urban flood events in these two scenarios and compare them with the current condition, so that different zonas can choose the better sponge city strategy scenario according to their own situation.

4. PRACTICE AND ANALYSIS OF SPONGE CITY STRATEGIES

4.1 Specific Plan

We will propose the specific plan of the sponge city strategies from four aspects: Building roof, Walking trail, Parking, and Open space. Different strategies mean different flooding mitigation effects and capital investment. Usually, the appropriate plan will be selected according to the actual situation of the region. (Figure 2)

Figure 2:
Plan of Sponge City Strategies.

Building Roof: green roofs feature a plant finish in the thickness of the soil or substrate, designed for environmental benefits. It can also be called a green roof, green roof or garden roof, and the vegetation cover can be full or partial. It does not refer to roofs with potted plants, but to building techniques used on roofs to improve habitat or save energy consumption, i.e. technologies that achieve ecological functions. Green roofs are a great example of multifunctional urban design.

Due to the difficulty of obtaining consent from private owners to retrofit roofs, this study selected commercial and public buildings to build green roofs.

There are two types of green roofs, extensive green roofs are extensively treated and require very low maintenance once the vegetation has been consolidated. The Intensive green roof, on the other hand, has an intensive or semi-intensive plant finish that requires normal maintenance

Walking Trail: El Poblenou has two main walking streets and a coastal promenade. The use of rain gardens on the sidewalks can effectively absorb rainwater and become part of the landscape. It is planned to build a rain garden of 1 to 1.5 meters wide on both sides of the sidewalk, which is estimated to be 10% of the total sidewalk area. Another more effective way is to use the pervious concrete, but the cost is relatively high.

Parking: Most of the open-air public parking lots in El Poblenou are in poor condition, and it is planned to use permeable pavement in the car park, a common choice is turf stone paver filled with grass. I also noticed that on-street parking occupies most of the road, and the original impervious pavement can be replaced with permeable asphalt, which is estimated to be 20% of the total road area.

Open Space: For parks and public spaces, we plan to increase permeable paving and plant cover. In addition, the introduction of the wetland park into the coastal park of El Poblenou can effectively improve the urban landscape and adjust the urban microclimate while providing water storage functions.

4.2 Scenarios of sponge city strategies

As we can see in the Table 4, all two scenarios show their flooding mitigation effects from the proposed strategies. In Scenario 1, the flooding volume is 53387.87 m^3, around 8% less than the current condition, and the flooding area is reduced by 12%. Scenario 2 shows slightly better flooding mitigation than Scenario 1, the flooding volume produced by Scenario 2 is 48723.20 m^3, and the flooding area is 61514 m^2, which means the influence of precipitation flood decreases by around 25%.

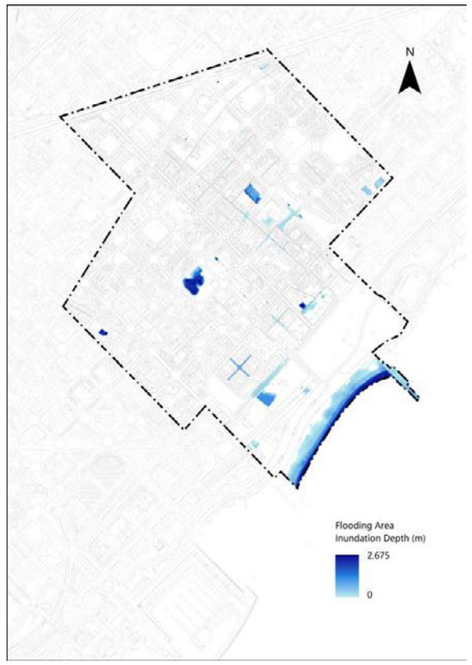
Table 4:
Sponge city scenarios

	Infiltration Volume (m^3)	Runoff Volume (m^3)	Flooding Area (m^2)	Maximum Inundation Depth (m)
Current condition	20225.33	57899.77	80400	2.675
Scenario 1 (Low cost)	24737.24	53387.87	71248	2.615
Scenario 2 (High Mitigation)	29401.91	48723.20	61514	2.545

Using Arcgis 3D Analyst Tools to simulate urban flash floods and present inundation maps in accordance with proposed scenarios (Figure 3,4,5). We can see in the Flooding maps that the sponge city strategies have a significant effect in flooding mitigation, greatly reducing the flood area. Scenario

2 can reduce most of the accumulation water on the streets.

Figure 3:
Flooding map (Current condition).



5. CONCLUSIONS

Storms and floods have affected many cities around the world, not just coastal cities, but coastal cities are clearly under greater threat. Urban drainage systems have developed for a long time, and sponge city is the latest generation of sustainable and flexible urban drainage systems. Today, we have a lot of technology to obtain high-precision urban and weather data, and many tools to help process these data. Quantifying and visualizing flood assessments can provide a more intuitive view of the urban flooding mitigation effect of strategies. Through the comparison between the current condition and the two scenarios, it can be seen that the sponge city strategy can effectively reduce the surface runoff and flood area, and the Scenario 2 with the high infiltration capacity significantly mitigates the urban flooding risk.

Figure 4:
Flooding map (Scenario 1).

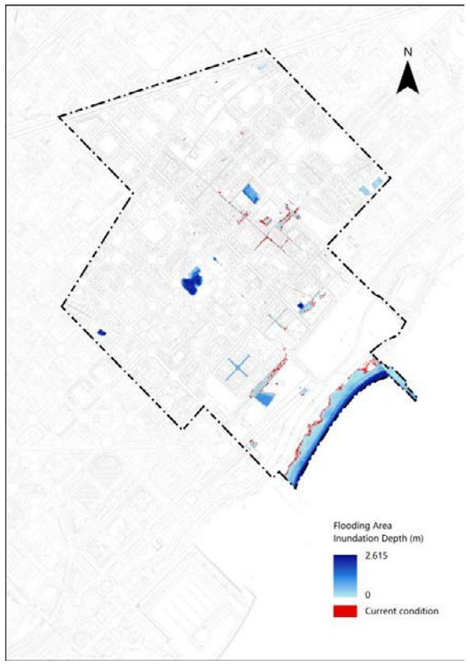
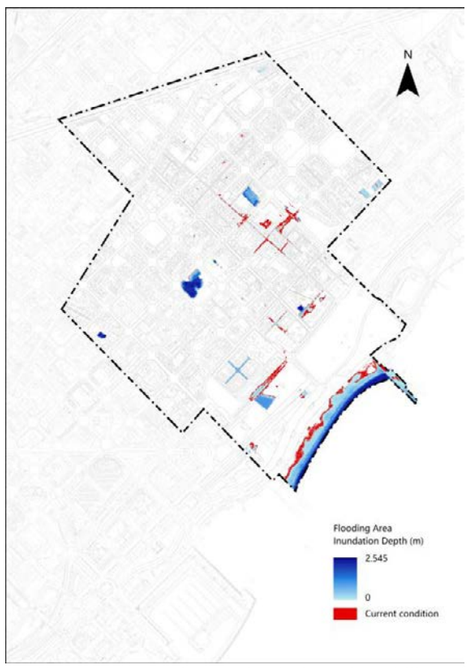


Figure 5:
Flooding map (Scenario 2).



However, we also noticed that the ability of infiltration of soil is limited, and the sponge city strategy will have a certain upper limit on the mitigation of surface runoff. It still cannot completely eliminate surface accumulation water, and the proposal with infiltration capacity means more capital cost. Therefore, we should choose the appropriate proposal and coordinate with other drainage strategies to obtain the maximum benefit.

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Sustainability index
A tool to assess the performance of Indian smart cities

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ABSTRACT: Achieving productive and healthy life is the key to sustainability. To achieve sustainability and resilient planning, India has launched a smart city program for 100 cities. This paper aims at assessing the 10 smart cities on the performance criteria across seven themes and supporting twenty sub-indicators. It calculates the performance on three scales- good, average, and poor at the ward and city levels. The scores are presented as per the indicators. In Indian cities, physical infrastructure such as sanitation and water gets higher priority. The lifestyle theme performed better than other themes, and the economy performed poorly indicating major intervention here as economics play an integral part in any sustainability framework. The sustainability indices inform that Kochi and Bhubaneshwar perform best and worst amongst the selected cities scoring 235 and 160 respectively out of a maximum 300. Most of the cities' performance is average and above-average indicating a capacity and capability of performing better post smart city development. This study will equip the stakeholders to identify the adequacy and lacunas for future planning and policy-making.
KEYWORDS: Performance, Smart City, Sustainability index, Sustainable Development Goals (SDG)

1. INTRODUCTION

The Sustainable Development Goals (SDGs) promote shared responsibility, where all people can live productive, vibrant, and peaceful lives on a healthy planet (UN, 2019). The Urban Agenda 2030 for sustainable development acknowledges cities to have a key role in achieving SDG targets. The study, therefore, focuses upon SDG goal 11 -sustainable cities and society- and assesses the sustainability of existing cities. United Nations provides a framework for global and national sustainability, however, it understands the context-specificity and allows adoption of its national targets (Gong & Lyu, 2017). Accounting for the National level data may provide benchmarking for nations to account for their sustainability yardstick.

Urban planning in India is driven by various programs launched by the government of India (Praharaj et al., 2018). The recent urban planning interventions consist of the smart city project. It aims to upgrade the existing cities and provide a sustainable urban environment that improves the urban quality of life and built more inclusive, sustainable, and resilient societies (MUDP, 2015). The smart city mission launched in 2015 thus includes various strategies like redevelopment, retrofitting, greenfield development, etc (Smith et al., 2019). It plans to use smart solutions for infrastructure and sustainable development. The government has chosen 100 cities for this project across the nation.

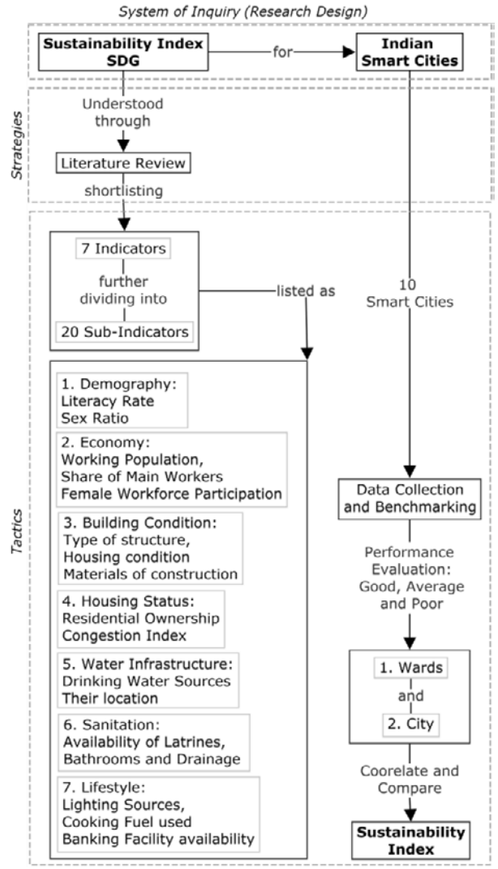
Despite periodic initiatives and programs, India fails to develop a national strategy for a sustainable future. The major reason for failure is assumed to be a lack of focus in measuring the outcomes (GoI, 2012). Researchers claim that evaluation is the first step toward sustainable development (Yigitcanlar et al., 2015). Prior to the application of such a strategy, it is necessary to review and rate the existing conditions of cities on a similar scale. Indian cities are characterized by poor infrastructure, slum formation, high population growth, uneven migration, low education level, traffic issues, and so on (Ghosh & Kansal, 2014). Although global initiatives provide frameworks, they do not address typical context-specific Indian city issues. Also, sustainability implies a state of development that considers a set of conditions and tries to improve for long-term social, economic, and environmental benefits. There have been attempts in the past by governmental agencies to develop frameworks in India. Some failed on comprehensive urban performance assessment (MUDP, 2009), or adaptability within the planning process (BIS, 2016), or unsuitable in the current scenario (Praharaj et al., 2018), or unavailability of required data. Hence, the study tries to develop a sustainability index for Indian cities to assess their level of sustainability that acknowledges these drawbacks. The sustainability index is formulated to address SDG goal 11. Sustainability assessment of chosen smart cities can help to evaluate the current status of urban sustainability and may guide improvements in the required sectors.

The remainder of the paper is divided into various sections. Section 2 presents the methodology of the study, and section 3 introduces the smart cities and states the importance of indicators in the study. Section 4 presents the data that includes indicator benchmarking, normalization, and indexing. It demonstrates and presents sustainability index and city score calculations. Section 5 discusses and concludes the study.

2. METHODOLOGY

The methodology tries to identify typical issues that drive sustainability in identified 10 Indian cities. Figure 1 represents the methodology.

Figure 1:
Methodology



The indexing method involves the following steps
Indicator selection- The indicators are categorized under seven themes- Demography, Economic, Building Condition, Housing status, Water infrastructure, Sanitation, and Lifestyle. They are further subdivided into 20 sub-indicators. Each sub-indicator is studied for its contribution to sustainability.
Data collection- The data is extracted from the Census reports, Urban and Regional Development Plans Formulation and Implementation Guidelines, city development plans, and other official reports. Spatial maps are generated by the authors at the wards and city levels.
Benchmarking of the indicator score is done as per the available literature. They are further normalized at three levels of sustainability based on their performance scores as good, average, and poor. The indicators are assigned weights using experts' opinion surveys and linear aggregation provided sustainability indices.

3. STUDY AREA AND STUDY INDICATORS

This study considers 10 Indian cities from the first phase smart city project to cover various regions in India (Figure 2, Table 1). The study is conducted both at wards and city levels.

Figure 2:
Ten Indian Smart Cities

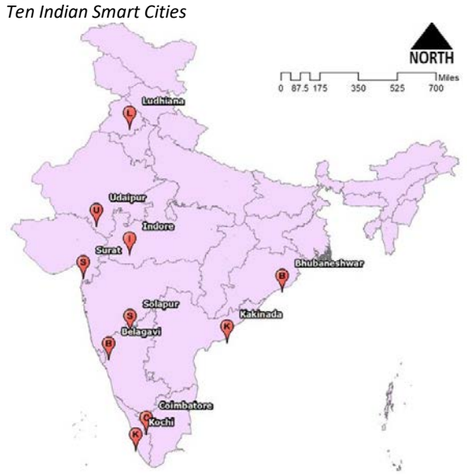


Table 1:
Characteristics of Selected cities

CITY, STATE	Population (Census 2011)	Wards	Characteristics
Surat, Gujarat	44,67,797	101	Textile Hub, Diamond Hub
Indore, Madhya Pradesh	19,64,086	75	Education Hub, Business capital of the state
Ludhiana, Punjab	16,18,879	75	Industrial Centre, Manufacturing and Commercial Hub
Coimbatore, Tamil Nadu	10,50,721	72	Textile Hub and Multiple Engineering units
Solapur, Maharashtra	9,51,558	98	Industrial City and Textile Hub
Bhubaneshwar, Odisha	8,37,737	81	Capital city, Planned City, Strong Cultural Identity
Kochi, Kerala	6,01,574	71	Port City, Commercial Capital

			of the state
Belagavi, Karnataka	4,88,292	60	Strong Culture and Heritage
Udaipur, Rajasthan	4,51,735	55	Tourist City, Strong Trade & Commerce
Kakinada, Andhra Pradesh	4,43,028	70	Port city, Exports Sea and Agricultural Produce

3.1 Indicators and their contribution to Sustainability

Dynamics in developed and developing countries differ a lot, and so do the sustainability issues in urbanization (Kamble & Bahadure, 2019). Therefore, the criteria applied for measuring the performances of cities in developed countries should be according to conditions pertaining to the developing countries (Plessis, 2001). Hence the indicators are to be consciously and sensitively picked up. Frameworks help to break down complex structures into simple indicators and provide ease of assessment. Such a system is quite relevant in Indian cities where finding data remains an issue (Kamble & Bahadure, 2021a). Therefore, each indicator is also sub-divided into sub-indicators.

Demography (literacy (LR), sex ratio (SR))- India is the second-most populous country in the world. The relative per capita availability determines demography as a vital sustainability determinant. Certain aspects that seem to be viable, may become unsustainable considering the demographics. In India, literacy and sex ratio are the influencing factors of demography. Literacy empowers people, the community, and women for their economic growth (Robinson-Pant, 2008). India ranks 112th in the world for gender inequality, whereas the sex ratio shows favour to a male child (Panda et al., 2016).

Economy (working pop (WP), main workers (MW), female workforce (FW))- Economic indicators have been used in planning policies since the 1960s (Taylor, 1981) as economics is an integral part of any sustainability framework (Gong & Lyu, 2017). Chandrasekhar et al., (2006) identify that India can take benefit of demographic dividends and work towards economic goals. Economic indicators can measure economic potential substantially and further guidance for future planning. In India, female workforce participation is very low as compared to the world average (Panda et al., 2016). Hence it is important to quantify it as a performance factor for calculating employment equity.

Building condition (structure type (ST), house condition (HC), const. material (CR-Room, CW-Wall, CF-Floor))- Indicators that quantify building conditions are perfect to acknowledge the local conditions in various parts of the cities (Bhattacharya et al., 2016). Housing condition is one of the influencing factors for residential satisfaction (Ibem & Aduwo, 2013). Migrants with low income and lack of housing facilities in the core city often land up in peripheral slum housing which contributes to haphazard housing conditions (Ghosh & Kansal, 2014). Thus accounting for the house condition enables to measure the performance of an urban area for future change. Careful assessment of building conditions can track issues in time and helps in strengthening urban sustainability (Hemphill et al., 2004).

Housing status (ownership status (OS), congestion index (CI))- Several programs like 'Housing for all mission', 'Rajiv Gandhi Awas Yojana', 'Pradhan Mantri Awas Yojana', and 'Basic services for urban poor' were initiated in past to provide shelter to Indian citizens (Praharaj et al., 2018). However, ownership status can acknowledge the actual conditions and measure the performance. Ownership of housing also contributes to the retention of indigenous people in the old city and contributes to social sustainability (Chen & Yang, 2018). The statistics highlight that 30% of the urban population in India live in poor quality, overcrowded accommodation (NIUA, 2011). Therefore, the congestion index is another important factor that can comment on the liveability and quality of spaces within cities. The Congestion index is calculated through Equation (1)

$$\text{Congestion index (CI)} = \text{Avg. Household size of ward} / \text{Avg. rooms number} \quad (1)$$

Water infrastructure (drinking water (DW), source location (SL))- Water is a basic requirement and also indicative of health and cleanliness in the residents along with a good quality of life (Panda, Chakraborty, & Misra, 2016). Although a very essential indicator, 40% of urban Indian households do not have access to piped water supply (NIUA, 2011). Also, the ill capacity of municipalities to provide pure water is evident by looking at the increase in water purifiers and bottle industries in the recent past (GoI, 2011). Hence, the location of the water source becomes an important indicator apart from having one. Planning commission 2008 (Ghosh & Kansal, 2014) acknowledges water availability, quality, and coverage as the major issues in water infrastructure in India.

Sanitation (latrine (LA), bath (BA), and drainage (DR))- A safe sanitary disposal facility is an important factor for health care. Sewerage and sanitation facilities are highly correlated to infant mortality in slums. Therefore, a vital indicator of attention in India when considering a smart city. McKinsey, (2010) report identified local service delivery to be the weakest link in Indian sustainability goal achievement. Hence measuring sanitation facilities is an important performance indicator for Indian cities.

Lifestyle (lighting (LS), cooking (CF), banking (BF))- Electric lighting conditions in Indian cities have shown a rising trend in the past decade (Panda et al., 2016), and could contribute to good quality of life in residents. Another alarming issue in Indian urban areas is the high pricing of gas cylinders. This aggravates the situation and leads to the use of inefficient, high polluting fuels with low nutrition and health security (Ghosh & Kansal, 2014). Keeping this in mind, accounting for the fuel for cooking is essential. Lifestyle is also linked to savings and managing accounts. Since a large population lives in slums and has migrated with less economic security, access to banking facility accounting is a concern for economic sustainability.

4. DATA PROCESSING AND ANALYSIS

4.1 Benchmarking, Normalization, and Weights

With a lack of uniformity in data, benchmarking of indicators is difficult in the Indian context (Kamble & Bahadure, 2021b). Benchmarking assures indicator performance assessment and further normalization makes indicators comparable. Table 2 represents the benchmarking as per performance. Further, they are normalized as Good, Average, and Poor with an index of 3, 2, and 1 respectively. The indicator domains have been awarded weights as per the expert opinion surveys.

Table 2:
Indicator Benchmarking

Indicators	Weights	Indicator	Good (3)	Average (2)	Poor (1)
Demography	0.15	LR	> 90%	75-90	< 75 %
		SR	> 980	950-980	< 950
Economic	0.12	WP	> 50%	35-50%	< 35%
		MW	> 95%	80-95%	< 80%
		FW	> 50%	35-50%	< 35%
Building Condition	0.15	ST	> 90% Permanent	75-90% Semi-Permanent	< 75 % Total Temporary
		HC	> 90% Good	75-90% Livable	< 75% Dilapidated
		CR	>90% Concrete	75-90% Handmade Tiles, Machine made Tiles, Burnt Brick , Stone, Slate, Metal, Asbestos sheets	< 75 % Thatch, Bamboo, Wood, Mud, Plastic
		CW	>90% Burnt brick, Concrete	75-90% Mud, Unburnt brick, Wood, Stone, Metal, Asbestos sheets	< 75 % Stone not packed with mortar, Thatch, Bamboo,
		CF	>90% Stone, Cement, Mosaic tile	75-90% Wood/ Bamboo, Burnt Brick	< 75 % Mud
Housing status	0.15	OS	Owned > 75%	Rented	Any others
		CI	> 0.6	0.4-0.6	<0.4
Water Infrastructure	0.18	DS	> 90% Tap water from treated source	75-90% Tap water from Untreated source, Well, Hand pump, Tube well	<75% Spring, River, Canal, Tank, Pond, Lake
		DL	> 90% Within premises	75-90% Near premises	<75% Away
Sanitation	0.17	LA	> 90% Within premises	75-90% Near premises	<75% Away
		BR	> 90% Bathroom	75-90% Enclosure without roof	<75% No bathroom
		DR	> 90% Closed drainage	75-90% Open drainage	<75% No drainage
Lifestyle	0.08	LS	> 90% Electricity, Solar	75-90% Kerosene, Other oil	<75% No lighting
		CF	> 90% LPG/PNG	75-90% Kerosene, Electricity, Biogas	<75% Fire-wood, Crop residue, Cow dung, Coal, Charcoal
		BF	>65 %	35-64%	< 35%

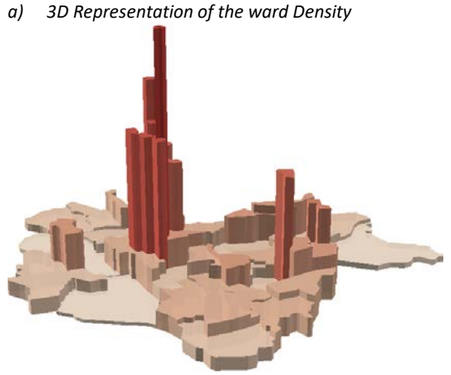
4.2 Assessing the Existing Status of the cities

The cities are subdivided into wards for administrative purposes. The data is collected at the ward level for each city. The demography data is taken as per the latest Census of 2011. The existing status of each ward is computed first in actual numbers for the identified indicators. They are then categorized as per the benchmarking (good, average, and poor), refer to table 2. The city's performance is computed on three scales by categorizing the wards as per their performances and presented in percentages. The total number of wards falling under each indicator category scores informs the performance of each ward.

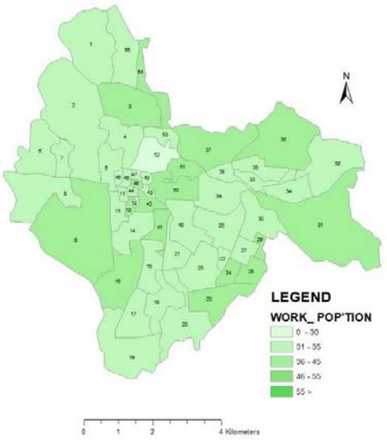
The data processing of the Udaipur city is represented as a case example. Figure 3 (a to d) represents the data processing of the 55 wards of the city. It can be observed that the city's performance is good for certain indicators like lifestyle and structure type while for female workforce participation and sanitation it performs poorly. Overall performance of the city is Average.

***Figure 3**: Udaipur City Data*

a) 3D Representation of the ward Density



b) Working Population as per Wards

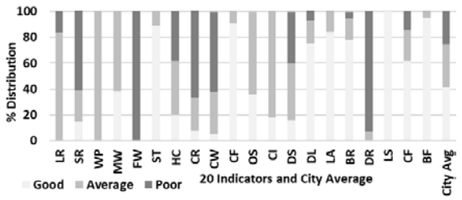


c) Indicator score as per ward

Ward	LR	SR	WP	MW	FW	ST	HC	CR	CW	CF	OS	CI	DS	DL	LA	BR	DR	LS	CF	BF
1	83	967	34	92	24	89	70	59	83	88	83	4.4	77	73	76	74	35	94	66	67
2	84	901	37	96	24	99	86	78	75	100	74	0.9	87	95	99	98	55	99	94	94
3	73	904	37	88	23	97	88	72	81	97	72	1.0	55	97	99	98	72	100	97	95
4	81	906	36	90	22	97	83	62	73	97	65	1.3	74	94	96	94	62	97	90	89
5	84	954	36	91	22	98	67	37	35	88	77	1.8	84	95	99	98	83	100	93	82
6	80	1013	36	92	22	96	67	52	58	95	77	2.5	89	89	96	88	16	99	71	66
7	86	912	38	91	22	89	73	62	68	89	79	4.7	51	65	76	72	21	92	68	68
8	87	945	37	97	22	96	73	60	73	92	80	1.8	59	83	89	84	68	96	73	80
9	88	954	36	97	22	99	90	36	39	99	70	0.5	90	98	99	97	34	100	90	75
10	90	1038	30	98	21	95	92	31	68	96	74	0.4	99	99	100	98	53	99	97	94
11	77	892	38	91	21	98	54	45	69	99	69	1.7	92	88	99	97	19	100	93	89
12	73	941	38	91	21	93	64	9	23	97	61	1.0	69	91	97	94	23	98	87	80
13	85	946	33	97	21	98	88	68	58	99	64	0.8	93	98	99	100	87	100	91	81
14	85	948	37	94	21	93	70	46	78	94	68	1.4	96	93	96	93	46	100	74	64
15	83	1011	33	95	21	98	94	92	74	100	69	0.5	79	100	100	100	81	100	99	98
16	71	935	34	84	21	83	44	42	39	89	76	9.6	66	42	80	71	4	98	48	39
17	85	939	35	97	20	97	78	84	62	99	75	1.3	64	94	96	96	52	100	92	91
18	87	956	36	97	20	99	85	70	83	100	81	0.7	75	97	98	95	42	99	93	96
19	81	904	35	93	20	98	77	80	77	98	76	0.6	80	90	95	95	74	99	91	86
20	81	917	35	93	20	98	86	75	75	98	74	0.6	70	93	93	95	22	99	86	85
21	80	954	34	97	20	90	68	69	66	95	59	1.3	71	87	91	87	23	99	76	69
22	86	965	33	96	20	98	85	79	78	98	71	0.7	67	96	98	97	21	99	94	93
23	82	1015	36	94	20	87	78	65	48	88	79	4.7	60	73	82	80	18	97	77	66
24	80	896	37	86	19	99	83	78	45	98	74	0.5	95	99	100	100	57	100	98	94
25	85	920	34	98	19	99	75	65	82	97	62	0.3	85	99	98	96	51	100	95	90
26	85	954	34	98	19	97	74	92	87	99	81	0.9	73	97	99	98	51	99	96	96
27	82	908	34	95	19	99	84	58	74	98	74	0.3	81	100	100	100	77	100	97	96
28	80	906	34	97	18	96	80	62	89	95	74	2.4	75	91	91	91	51	97	87	85
29	84	1006	34	96	18	98	74	73	37	100	82	0.5	84	100	100	100	37	100	98	94
30	85	958	36	97	18	99	90	92	96	99	75	0.3	66	95	97	97	46	100	95	94
31	82	1010	33	96	18	95	66	65	68	96	59	4.4	85	80	82	78	30	97	70	71
32	73	948	33	88	18	95	69	77	86	97	72	4.1	91	94	93	96	32	98	93	88
33	71	933	33	93	18	98	68	76	89	98	68	1.4	84	91	95	94	30	99	79	74
34	73	893	35	97	18	97	94	91	94	99	71	0.7	80	98	100	99	54	100	94	98
35	86	945	33	89	18	98	83	59	65	99	75	1.0	86	97	97	95	32	99	90	83
36	79	981	34	95	18	98	81	88	98	100	66	0.8	92	95	98	95	29	97	89	92
37	80	962	34	95	18	98	86	86	88	98	84	0.8	82	94	96	95	26	100	95	93
38	81	956	35	92	18	97	77	36	50	98	71	1.1	92	93	89	91	41	99	83	78
39	76	957	31	97	17	98	75	78	82	97	77	0.9	40	93	92	91	52	99	91	93
40	88	922	33	98	17	98	86	77	69	98	68	1.6	78	84	99	98	17	100	95	92
41	86	937	34	96	17	83	75	49	56	91	62	7.5	64	83	86	84	45	97	74	80
42	70	868	36	92	16	98	64	67	61	99	72	2.3	84	98	99	96	73	100	97	87
43	73	902	33	92	16	97	62	39	75	99	70	2.9	75	95	99	98	44	100	98	87
44	79	917	34	94	16	93	68	13	50	99	80	1.7	78	88	93	87	67	99	85	80
45	82	943	32	93	15	97	61	38	54	94	67	1.9	88	97	99	96	47	100	95	78
46	82	956	33	95	15	90	63	17	56	96	67	3.7	90	84	92	82	50	100	81	62
47	85	691	33	95	14	97	67	62	74	99	82	1.9	69	90	99	97	23	100	93	81
48	78	950	32	97	14	94	55	22	60	100	73	2.1	79	93	92	91	8	99	96	74
49	85	995	31	95	14	98	52	60	51	99	71	1.2	50	92	94	92	63	99	90	80
50	76	937	33	94	14	99	66	63	79	99	82	0.9	79	90	94	98	41	99	94	91
51	84	942	35	97	14	99	89	77	85	99	78	0.6	72	98	98	99	37	100	98	95
52	76	942	32	93	13	98	90	70	82	98	66	0.4	80	99	100	99	49	100	96	97
53	72	788	39	95	13	99	90	81	88	99	81	0.7	88	99	99	98	60	100	85	82
54	81	911	32	93	12	94	77	68	78	95	73	2.8	79	92	84	85	49	99	78	90
55	75	937	31	93	10	99	80	74	71	99	75	0.8	59	98	98	98	60	100	95	97

Note: FP is per 1000 male, CI is as per Equation (1) & other indicators are representated in %

d) Performance percentage of total wards and city



4.3 Sustainability Index of the cities

To calculate the sustainability index (SI), indicator weights are obtained using expert opinion. Opinions are statistically analyzed and provide weights to individual indicators. SI of each city and performance scale (Good, Average, and Poor) is calculated using Equation (2). Further, City Score (CS) is calculated using Equation (3)

$$SI_{ps} = \frac{\sum_{k,ps}\left(\sum a_{ps} \times b_k\right) X\, 100}{\sum SI} \quad (2)$$

where SI=Sustainability index;
ps=performance scale;
k=indicator;
a=indicator category (demography, economy, …);
b=indicator weights.

$$CS = (SI_G \times 3) + (SI_A \times 2) + (SI_P \times 1) \quad (3)$$

where CS=city score;
SI_G=Sustainability index for the good performance scale;
SI_A=SI for average performance scale;
SI_P=SI for poor performance scale.

4.4 Results

The results show that out of the selected cities, Kochi has the highest SI_G and lowest SI_P, resulting in the highest CS. Also, Bhubaneshwar has the highest SI_P and lowest SI_G, resulting in the least CS.

Refereeing to the indicator scores (Table 3), most of the cities have poor demography. Also, all the cities have an average score for the economic indicator. This is due to a high workforce with low literacy and being involved in the informal sector. Only 4 cities have above-average building conditions, which is relatable to the housing status that has only 2 cities performing above average. The physical infrastructure which includes water infrastructure and sanitation shows a fair performance of all the identified cities. Bhubaneshwar shows a poor score for physical infrastructure across cities. Lifestyle scores high (good and very good) in lifestyle, showing that people are more concerned with personal equipment and gadgets.

Table 3:

City Scores and Sustainability Index

Cities → Indicators↓	Surat	Indore	Ludhiana	Coimbatore	Solapur	Bhubneshwa	Kochi	Belgaum	Udaipur	Kakinada
Demography	147	143	135	233	193	157	256	224	169	220
Economic	193	178	175	185	190	163	179	176	179	174
Building Condition	236	197	222	194	164	160	210	185	209	170
Housing status	178	197	200	142	166	163	269	198	226	161
Water Infrastructure	236	141	252	227	207	153	256	223	222	217
Sanitation	257	238	260	226	173	154	253	248	221	216
Lifestyle	210	258	221	220	178	178	265	218	281	210
City Score	216	194	215	204	179	160	235	208	213	202
Score Reference	300-250 very good		250-200 good		200-150 average		150-100 poor		100-below very poor	

4. DISCUSSION AND CONCLUSION

The current study tries to measure scores of identified potential smart cities and bring them on a comparative scale to assess them for sustainability. The weights obtained from the experts show that physical infrastructure such as sanitation and water has been given the highest priority. Panda et al., (2016) report that the sewerage network in India is quite low than the global average. According to Praharaj et al., (2018), any study measuring performance in Indian cities should take into account the water infrastructure.

Kochi, the city with the highest CS, shows that it has the highest SI_G in demography, housing status, and water infrastructure amongst studied cities. The second-highest scorer city, Surat has the highest SI_G in the economy, building condition, and sanitation. However, CS is a cumulative score, that is influenced by indicator weights, and various sub-indicators. Hence, although CS can rank cities, individual indicator and sub-indicator scores should be considered for upgrading the city infrastructure and resulting in overall high SI.

The study supports the smart city mission which tries to improve the quality of life by enabling infrastructure and local area development through smart technology. The development of a sustainability index 1) Measure and quantify the lacunas within a city; 2) Bring Indian cities on a similar scale for assessment at a national level; 3) Monitor the sustainability progress of cities; and 4) Supports the assessment of the SDG index. This method can set a benchmark for city performance and provide relative quantities for smart city development projects. The smart city initiative focuses on the provision of quality of life. The city score suggests that currently, the cities lie in the average performing zone. Therefore, the cities have the potential to improve scores to good and very good post smart city interventions.

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Rhodanian neighborhoods in transition

Towards an integrative strategy facilitating decision-making for new sustainable fluvio-neighborhoods

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ABSTRACT: In the changing history of city-river relationships, cities are today questioning strategies for "reconciliation". Thus, rather degraded sites like riverside brownfields represent an important potential for the creation of new sustainable fluvio-neighborhoods. This research project focuses on the Rhone, and aims at developing an integrative strategy facilitating decision-making for rhodanian neighborhoods in transition. This paper presents the methodology of the research, which is composed of three work packages: 1-a research by design approach, 2-a decision-making support, and 3- interactions with stakeholders. Thanks to the "research by design" approach, several project-based visions developed on 4 selected study sites along the Rhone form the material for the elaboration of the decision-making support. The latter consists of two separate but correlated elements: a sustainability profiler, and an analysis framework for the new city-river balance. It is enriched by inputs from different stakeholders.
KEYWORDS: Rhone, Sustainable neighborhoods, Research by design, City-river balance, Integrative strategy

1. INTRODUCTION

Over the centuries, cities have developed changing relationships with their waters. After a clear sidelining of rivers in cities, today is an opportune time to question the potential for "reconciliation" of these relationships. In fact, current inward densification objectives of urban areas combined with flood protection strategies are generating a wide field of exploration for the future evolution of urban riverbanks. In this perspective, rather degraded sites like riverside brownfields represent a significant potential for the creation of new sustainable fluvio-neighborhoods.

This research project focuses on the Rhone, an emblematic territory for the reconquest of urban riverbanks. The current shape of the Rhone is the result of a long series of developments, exploitations, and appropriations over time [1]. It shows a discontinuous density between its metropolitan centers and the intermediate regions, more neglected [2]. In light of the climatic emergency, this territory lives a decisive time in its evolution, where the matter of planning strategies on fluvial sites intensifies. In this context, many landscape, urban, and architectural issues are questioning the project approach to be adopted for the development of fluvial neighborhoods. The regeneration process of these sites going hand in hand with the accentuation of their specific city-river dynamics, the ambition of the research is thus to develop sharp knowledge in the understanding of the issues related to the neighborhoods in transition along the Rhone.

Focusing on this challenge, the ongoing research presented in this paper aims at developing an *integrative strategy* facilitating decision-making for sustainable fluvio-neighborhoods. The paper gives an overview of this objective through the description of the methodological research approach as well as its expected general and specific outputs.

2. RESEARCH METHODOLOGY

The development of the *integrative strategy* focuses on the emerging issues raised by fluvio-neighborhoods in transition. In this sense, the proposed *integrative strategy* is expected to enrich the perception of these sites by offering guidance to the stakeholders involved in this type of projects, contributing thus to the decision-making process.

The methodological work packages taken for the development of the *integrative strategy* are: 1- The research by design approach, through the development of project-based visions and the definition of the components of the city-river balance; 2- The conception of a decision-making support, through the establishment of sustainability profiles and the implementation of an analysis framework; 3- The interactive exchanges with the involved stakeholders, through a series of interviews with various experts and working sessions on the study sites.

These three work packages are not only strongly interconnected but become also the parts of the *integrative strategy*.

2.1 Research by design

The development of project-based visions and the definition of the components of the city-river balance constitute the "research by design" approach. The projectual process becomes a concrete research tool that lies between theoretical and operational issues. Thanks to the knowledge emerging at the same time from developing design projects and studying current practices as well as the state of the art, the approach constitutes a powerful tool for architectural research [3].

2.1.1 Project-based visions

The relationships to the river are not uniform depending on cities [2], and several parameters must be taken into account when looking at fluvial sites : the establishment (position to the river, distance to the urban center) ; the physical environment (size of the site, density, urban morphology, building typologies); usage (type and rate of activity, number of users, cultural elements); the city-river interaction (type and nature of the link with the river, public and green spaces, ecosystems, risks). With that in mind, 4 distinct study sites are selected along the Rhone (Fig. 1): Sion and Geneva in Switzerland, respectively Givors and Avignon in France. Each site is located in a different Rhone hydraulic regime (excluding the Delta), and is expected to become a new urban polarity.

Figure 1: Rhone basin, 4 study sites and hydraulic regimes of the river

The 4 study sites present similar characteristics. They all show a strong link to the Rhone, through genuine landscape qualities, as well as the presence of a major mobility infrastructure in the direct vicinity: a motorway bridge in Sion and Givors, a railway bridge in Geneva, and a major touristic road in Avignon. In addition, the high potential of the riverbanks allows to imagine new uses and resilient developments. (Fig. 2). Moreover, the study sites are destined to be regenerated into mixed-use neighborhoods, with a flagship program that is adapted to the specificities and needs of each location. Sion focuses on the theme of education with a new campus, Geneva deals with the creative economy with cultural activities, Givors lends itself to the establishment of a research center in the field of energy, and Avignon will house a cultural center dedicated to the performing arts.

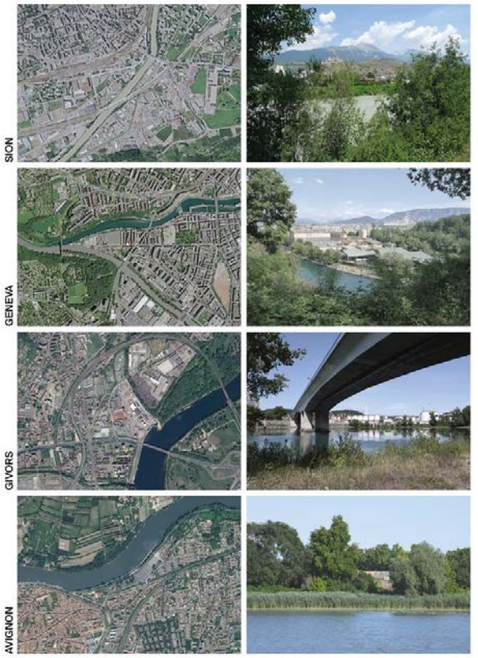

Figure 2: Current situations (orthophotos) and river landscape views of the 4 study sites

The research project is then combined with an annual architectural studio intended to undergraduate students. For each of the 4 selected sites, between 8 and 10 projects are developed. Students work taking an iterative approach on multiple scales: from the urban project to the construction detail. In groups, they analyze, explore, and experiment with sustainable architectural strategies. A total of about 50 projects is expected. At the end of each studio, a variety of projects presenting the best qualities in terms of interactions between the site and the river are selected and deepened during intensive workshops to generate project-based visions. They become the "raw material" for the progressing and testing of the decision-making support.

On each of the 4 rhodanian study sites, 3 project variants are developed in addition to the current situation, for a total of 12 visions per site. Three prospective attitudes categorize the project-based visions: "Weave", "Orient" and "Deploy" relate to the specific contribution of the new neighborhood to the spatial relationships between the actual urban fabric of the city and the landscape area of the river.

Weave: the prospective attitude weaves sequenced links with the river's landscape space. It translates into an urban form and an urban structure that are part of a logic of extension of the existing built fabric of the city (Fig. 3).

Figure 3: Site plans of "Weave" for the 4 study sites (from top to bottom: Sion, Geneva, Givors, Avignon)

Orient: the prospective attitude orients and opens up the built fabric of the existing city towards the river. It results in an urban form that alternates between concentrated built spaces and unbuilt public spaces (Fig. 4).

Figure 4: Site plans of "Orient" for the 4 study sites (from top to bottom: Sion, Geneva, Givors, Avignon)

Deploy: the prospective attitude deploys a river frontage that is permeable to the built fabric of the existing city. It translates into a large-scale urban form that enters in dialogue with the larger landscape while offering a vast public space at the water's edge (Fig. 5).

Figure 5: Site plans of "Deploy" for the 4 study sites (from top to bottom: Sion, Geneva, Givors, Avignon)

The three prospective attitudes not only give rise to several urban morphologies but also generate diverse public spaces in connection to the river. In the perspective of a convivial city open to transformation [4], the potential of sustainable rhodanian neighborhoods is therefore particularly rich and qualitative.

2.1.2 Components of the new city-river balance

At the neighborhood level, the concept of new city-river balance involves a transition from current practices to resilient practices [5]. Through a review of the literature and the analysis of a large series of current practices, the various elements constituting the city-river relationship are specified [6].

The first step is to understand the rhodanian territory as a set of resources and fragilities linked to the river. These "Rhodanian Intensities" are broken down into six points: Urbanization and flood risk; Energy and transport; Agriculture, ecosystem and landscape; Tourism, leisure and recreation; Governance and management; Heritage and culture of the river.

The "Rhodanian Intensities" are then derived into 6 components, understood as resilient urban attitudes in the framework of the ecological transition: Positivizing the risk; Energy transition; Environmental dynamics; Living environments; Shared processes; River agilities.

These components are the basis on which the various dimensions of the analysis framework of the new city-river balance are developed, in order to feed the decision-making support (Fig. 6).

2.2 Decision-making support

Multi-criteria evaluative approaches, as a means of establishing a common project goal, are at the heart of an informed decision-making process and an overall quality approach [7]. At the neighborhood scale, there is a strong need for "tailor-made" evaluative methods [8] structured around environmental, socio-cultural, and economic sustainability indicators. To complete this requirement, indicators related to the city-river dynamics are also needed. As mentioned above, fluvial sites present similar issues in terms of planning but different particularities. Hence, the decision-making support is conceived to compare project-based visions independently by sites.

The elaboration of the method includes: The determination of a list of indicators (quantitative and qualitative) to be evaluated in order to tend towards a multidimensional representation of the issues characterizing sustainable fluvial neighborhoods; The establishment of the evaluation framework, i.e. the definition of "measurable" values to indicate the degree of satisfaction with respect to each indicator considered; The testing and optimization of the method, applying it to project-based visions as well as to the current situation; The elaboration of the graphic representation of the comparative evaluation results, in order to communicate with various audiences.

For more precision and adaptability, the proposed decision-making support consists of two separate but correlated elements: a tool for establishing sustainability profiles, and an analysis framework for the new city-river balance (Fig. 6).

2.2.1 Sustainability profiler

The sustainability profiler is based on the NEBIUS methodology (Neighborhood-scale Evaluation to Benchmark the Integration of Urban Sustainability) [9–11], which facilitates the evaluation of key aspects of sustainable neighborhoods. This tool, at the same time precise and straightforward, addresses equally the standard three sustainability pillars (environmental, sociocultural and economic) adapted to the built environment [12]. In addition, its robustness also allows for specific adaptations without losing consistency.

The criteria leading to the sustainability profiles for each project-based vision are as follows: Density and Mix; Energy performance, Lifestyles, Ecology and Economic efficiency.

2.2.2 Analysis framework

The analysis framework relies on the concepts of nature-based solutions and resilient city.

According to IUCN, nature-based solutions are “actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” [13]. Given that urban environments have an important role to play in sustainability transitions [15] in the face of climate change phenomena, resilient cities aim at transforming vulnerability into dynamic adaptation [14]. Therefore the planning of nature-based solutions in cities involves several principles [16] in order to guarantee “inclusivity, livability and resilience” [17].

In this context, the analysis framework for new city-river balance intend to address the challenges specifically related to the rhodanian urban communities. Indeed, the need for place-specific scenarios and their assessment in terms of potential impact [18] seems particularly adapted to the neighborhood scale.

The analysis framework for the new city-river balance is structured by 6 components, each one declined in 3 dimensions referring as much to spatial scales (Region, City, Neighborhood) as to specific impacts (Coherence, Contribution, Quality). The components (described in chapter 2.1.2) therefore lead to 18 dimensions: Risk management, Risk culture, Porosity – Energy strategy, River mobility, Carbon neutrality – Active river, Fertile meshings, River-urban biodiversity – River resources, River urban life, River experience – Integrated water management, Flurbanization, Co-construction – Heritages, River usages, Urban aquosity.

This system of quantitative and qualitative dimensions allows a multi-criteria comparison of city-river balance scenarios through sustainable fluvio-neighborhoods.

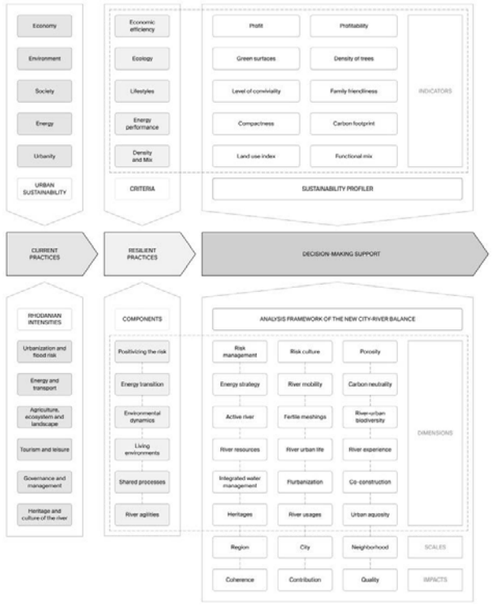

Figure 6: Decision-making support

2.3 Interactions with stakeholders

In order to guarantee the multidisciplinary approach inherent to the concept of sustainability [19], stakeholders active in urban river territories and coming from a variety of professional backgrounds (architects, urban planners, hydrologists, engineers, geographers, sociologists, politicians, economists, representatives of the study sites, etc.) are intensively solicited throughout the research project. Building on the strong links between the assessment device and the process leading to it [20], stakeholders involvement is inseparable from the decision-making support tool.

First, targeted interviews intend to determine the elements that can define city-river dynamics. It allows increasing the understanding of the territory under development, the issues related to the city-river relationship as well as the related principles of sustainability.

Second, on-site working sessions are organized to enrich the research activity on the Rhone territory and to promote the exchange of knowledge. They aim particularly at: Establishing an interdisciplinary dialogue; Linking the different stakeholders of the Rhone urban area; Bring out the specificities of each Rhone study site; Defining sustainable city-river dynamics; Confronting the project-based visions with the perception of the concerned stakeholders; Testing and optimizing the decision-making support.

3. RESEARCH EXPECTED OUTPUTS

Beyond the development of theoretical knowledge on the nature of the "Rhodanie Urbaine", this research project is expected to provide an *integrative strategy* for fluvio-neighborhoods in transition. This *integrative strategy* will accompany decision-makers in the planning of new sustainable fluvio-neighborhoods by offering not only an unprecedented decision-making support but also guidance to elaborate project-based visions for specific sites along the Rhone and to implement long-term interactions with stakeholders.

In terms of communication and dissemination, the research project is presented in detail on a dedicated website [21].

4. CONCLUSION

This work examines the challenges raised by the management and steering of the evolution of fluvial sites engaged within the context of sustainability transitions. Throughout a multidimensional research project along the Rhone as a vector of multiple urban uses, an *integrative strategy* of decision-making support for sustainable fluvio-neighborhoods is developed.

Thanks to the notion of integrated design, which aims to exploring unprecedented links between the methodological rigor of research and the inventiveness potential of the project, the “research by design” approach constitutes a real knowledge tool for architectural and urban issues. The project-based visions facilitate the exploration of the different existing and potential city-river dynamics generating the future rhodanian neighborhoods. Although the research is specific to the Rhone, the structure of the decision-making support makes it adaptable to other economic, social and territorial river contexts, such as for instance river cities of Latin America.

The research is currently progressing with the deepening and evaluation of the project-based visions in Givors and Avignon, which will be followed by the on-site working sessions with stakeholders.

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Urban greening for achieving a sustainable urban environment for a tropical city

Nagpur through geospatial approach

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ABSTRACT: During COVID 19 pandemic people were confined to their homes which resulted in CO2 emissions reductions. Despite this reduction, there is a global temperature rise, "UN Emission Gap Report 2020" has revealed. Environmental studies show that urban greening through green infrastructure can make cities resilient against temperature rise and promote sustainable urban development. The study aims to explore the geospatial approach for urban greening to achieve a sustainable environment in a tropical city, Nagpur, as part of the urban planning thesis presented in 2020-2021. The study involves the identification of greening interventions & green cover in climatically diverse cities, strategic integration of greening into the current planning framework via model development for prioritizing an area as per its greening requirement by using overlay analysis geospatial technique in Arc GIS 10.6. The study shows that greening is an efficacious response for sustainable urban development in tropical climates. Geospatial techniques can analyse the greening data spatially and statistically and prioritize a location for greening hence, facilitating the rational endeavour of a decision-maker.
KEYWORDS: urban greening, geospatial techniques tropical.

1. INTRODUCTION

1.1 Climate Change and COVID 19 Economy Recovery

Globally witnessed urbanization often leads to a rise in atmospheric temperature. Carbon dioxide (CO2) levels and other greenhouse gases in the atmosphere rose to new records in 2019, making it the second warmest year on record. *(UN, 2020) (1)* Last year COVID 19 pandemic confined people in their homes due to restrictions that resulted in carbon emissions reductions. But this positive environmental outcome was temporary as global economies have begun to recover from the pandemic. These emissions are expected to return to higher levels introducing climate change-induced survival challenges. Economic restoration with the downfall of COVID-19 cases offers us fresh opportunities to launch recovery plans. Saving lives and livelihoods requires urgent action to address both the pandemic and climate change challenges. Therefore these plans can be fused with climate change resilient strategies as a diversion towards a sustainable economy that works for both people and environment. The sustainable development goal no. 13 is to take urgent action to combat climate change and its impacts. *(UNEP, 2020)(2)*

1.2 Urban greening to combat climate change in tropical regions

At present India is witnessing rapid urbanization and its tropical regions that are facing climate change in terms of a shift in weather patterns, rise in sea level, and extreme weather events. Among many changes in weather patterns, one is rise in regional temperature that results in heat stress over outdoor spaces. Researchers believe that urban greening can help in reducing heat stress over a region with tropical climate by offering cool places. Urban greening (UG) can be understood as "public landscaping and urban forestry projects that create mutually beneficial relationships between city dwellers and their environments". *(Albro, Episode 51: Urban Greening with Sandra Albro (Holden Forests & Gardens), 2020)(3)*. In short, it is making urban spaces green. Some common forms of UG are parks, gardens, recreational places, aquatic fronts, spaces near heritage sites, and transport corridors.

2. LITERATURE STUDY

2.1 Cited benefits of urban greening

Many studies have shown that the greening of grey surfaces through a vegetated cover can deliver multiple benefits as they shift blue water (runoff) to green water through evapotranspiration, and store and gradually release rainwater. *(S.Pullin, 2010)(4)* Some studies shows temperature reduction of 1.5 to 4 deg. C by 10 hectares to 100 hectares of greening respectively. Removing 7% to 24% PM10 pollutant from air and carbon sequestration of 25 ton/hectare, 13 ton/hectare, 0.5 ton/hectare and 0.7 ton/ hectare by wildland, residential, commercial and transport corridor greening respectively. *(Nature, 1995)(5)*

2.2 Concepts of urban greening

2.2.1. Green Infrastructure

A strategically planned network of natural and semi-natural areas with other environmental features was designed and managed to deliver a wide range of ecosystem services. *(Commision, 2020)(6)* Urban greening in the form of green infrastructure is seen in Acra (Hot & semi-arid climate), Alexandria (Subtropical desert climate), Bristol (Warm & temperate climate), Bydgoszcz (Cold & temperate climate), Csomor (Warm & temperate climate), Chennai (Tropical Savanah climate), Glulianova (Warm & temperate climate), Budapest (Humid Subtropical climate) due to loss of vegetation, unutilized parks, lack of standards, poor land management, excessive thermal heat, lack of funding structure and neglected green space respectively as the issues before UG. *(Union, 2007)(7)*

2. 2.2 Ecosystem Based Adaptations (EBA)

It refers to the sustainable use of biodiversity and ecosystem services in an overall adaptation strategy. It helps in adaptations to adverse effects of climate change in a cost-effective way, generate social, economic, cultural co-benefits and contribute to biodiversity conservation. Urban greening in the form of ecosystem-based adaptations are seen in Dresden (Warm & temperate climate), Dodoma (Tropical wet & dry climate), Sanok (Cold & temperate climate), Singapore (Tropical rainforest climate), Vizag (Tropical wet & dry climate) due to low public participation, urban flooding, poor governance, rapid urbanization, and thermal heat respectively as the issues before UG. *(Union, 2007)*

2.2.3 Nature bases solutions (NBS)

Actions, which are inspired, supported by, or copied from nature to help societies address a variety of social, economic and environmental challenges in sustainable ways. Urban greening in the form of ecosystem based adaptations were seen in Doncaster (Warm and temperate climate), Kathmandu (Warm & temperate climate), Maidstone (Warm & temperate climate) due to poor land management, biodiversity loss and neglected green space respectively as the issues before UG. *(Union, 2007*)

2.3 Ideal Green cover

The practical implementation of greening requires the knowledge about existing and target green cover. But, there are currently no internationally recognized standards to evaluate a green space, however a WHO (Europe Regional office) report suggests urban policy-makers and practitioners to ensure access to 0.5 to 1 Hectare of green space within 300m from urban resident's home. *(WHO, 2017)(8)* These recommendations were referred from English Nature's research report which suggests minimum green space area of 1 hectare/1000 population (equivalent to 10 m2/ resident). *(Nature, Accessible Natural Green Space: Standards in Towns and Cities, 2006)(9)* In India, the URDPFI guidelines recommends, 10-12 sq.m per person green space. *(MoUD, 2015)(10)*

Ideal green cover (existing/proposed) should comply with these standards with contextual adjustments inclined towards the benefits offered by urban greening like outdoor temperature and pollution reduction.

By knowing urban greening's impact on climate and reducing pollution and eventually the quality of life, worldwide cities with their quality of life index (QoLI) ranking and green cover are listed below (Table 1).Here QoLI (higher is better) is an estimation of overall quality of life by using an empirical formula which takes into account [Purchasing power index (PPI), safety index (SI), health care index (HI), climate index (CI)] - Higher is better &, [pollution index (PI), house price to income ratio (HIR), cost of living index (CLI), traffic commute time index (TI)] – lower is better. *(numbeo, 2021)* Formula:

QoLI= 100 + {(PPI/2.5) – (HIR * 1) – (CLI/10) + (SI/2) + (HI/2.5) – (TI/2) – [(PI*2)/3] + (CI/3)}.

Table 1: *Cities with their per capita green cover*

City (QoLI Rank)	QoLI	PI | CI	Climate	Avg. Temp	Population	/capita GC
Ahmedabad (190)	113	71|49	LS	27.1	5.57	9.38
Amsterdam (66)	166	30|87	W&T	10.7	0.81	508.09
Austin (9)	188	26|82	W&T	20.4	1.94	276.70
Bangalore (191)	113	83|89	T	22.9	10.6	2.01
Barcelona (139)	139	53|95	W&T	15.5	1.62	8.81
Brussels (126)	143	62|83	W&T	10.7	1.16	738.44
Chennai (208)	105	74|53	T	27.9	9.99	0.81
Delhi (245)	74	90|58	LS	24.6	27.6	6.61
Dublin (145)	137	39|85	W&T	9.4	0.56	35.84
Edinburgh (31)	177	27|84	W&T	8.3	0.52	156.24
Helsinki (30)	177	13|62	C&T	6.4	0.65	115.62
Hyderabad (189)	144	75|73	LS	25.9	8.70	0.93
Kolkata (224)	89	78|60	T	26	21.0	7.14
Lisbon (108)	152	35|98	W&T	16.7	2.04	183.53
London (161)	128	58|88	W&T	10.8	13.67	436.03
Los Angeles (154)	131	66|95	W&T	17.6	13.15	90.19
Melbourne (37)	175	25|94	W&T	14.4	4.96	152.17
Milan (185)	117	67|88	W&T	13	0.30	93.18
Montreal (93)	156	33|52	C&T	7.1	1.75	3130.3
Mumbai (241)	75	82|71	T	26.4	21.7	9.36
New York (144)	137	57|79	W&T	11.9	19.28	658.36
Noida (220)	94	92|58	LS	24.6	0.63	16.49
Sydney (29)	177	26|97	W&T	18	4.92	224.94
Tokyo (101)	155	43|85	W&T	15.2	9.7	163.82

Here, LS - Local steppe, W & T - Warm & Temperate, T - Tropical, C & T - Cold & Temperate, Avg. Temp. is in deg. C , population is in millions, GC- Green cover and per capita green cover is in sq.m.

3. MATERIAL & METHODS

3.1 Study Area

The study site is Nagpur city because it is one of the rapidly developing central India's metro cities

that ranks third in the list of the urban centers in the state of Maharashtra. Nagpur enjoys the privilege of being a hub of the health care industry in the state, the tiger capital of the country, well connected to other major metro cities of the country, etc. As per the 2011 census, its population is 2.4 million and stretches over 225.08 sq. Km. *(CRISIL, 2015)(11)* The city experiences a tropical savannah climate (Aw in Köppen climate classification. *(Merkel, 2021)(12)* The average annual rainfall is 1161.54 mm, where summer temperature escalates up to 48 C, the highest among all tropical cities in India. Once considered the greenest city in India, today Nagpur is experiencing green degradation due to rapid urbanization. The Nagpur development plan highlights a deficiency in recreational areas such as parks and playgrounds that has the potential to be urban green spaces. Hence, in such a scenario of urbanization with a degrading environment, a sustainable planning approach through urban greening is necessary. Nagpur Municipal Corporation (NMC), the city's urban local body has divided it into ten administrative zones (Figure 1).

3.2 Data sources

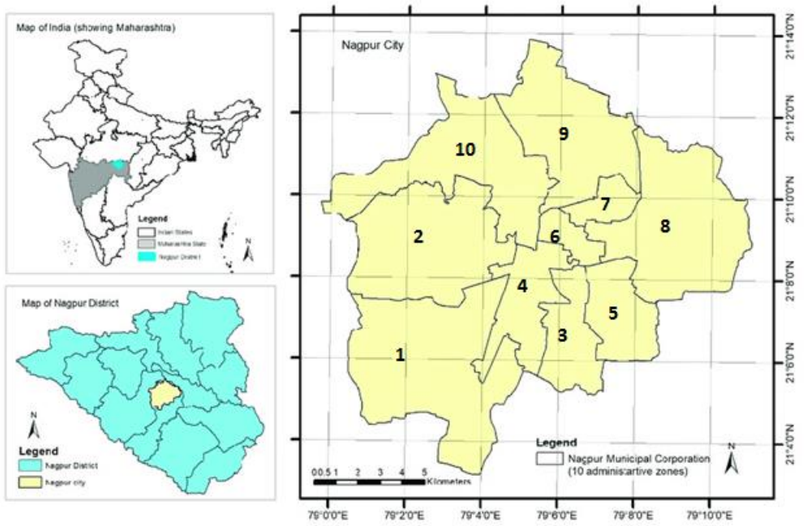
The data includes various map types related to UGS, administrative boundary data, census data. For generating multiple maps types, high-resolution google earth imagery was used as the base map. The satellite imagery obtained from the USGS platform

3.3 Methodology

The adopted methodology is aimed towards guiding urbanplanning and decision-making process to identify potential spaces for urban greening. The method involves data collection required for spatial analysis based on multiple greening parameters. The parameters like urban green space area & number deficiency, urban green space disparity, green cover per person, number of air & noise pollution areas, number of trees, average land surface temperature, average normalized difference vegetation index, population, and preferred location for watershed are analyzed. Arc GIS 10.6 was used to represent the parametric results. The below section explains in detail the methodology adopted for deriving data for each parameter. Urban green spaces were classified as per the following standards recommended by URDPFI & Urban Greening Guidelines, 2014 given in table 2. *(MoUD, 2015)(10)*

Table 2*: Standards used to study UGS*

Type of Urban Green Space	Population	UGS No.	Required Area (insq.m)
Tot Lots	2500	1	125 – 2000
Neighborhood Park	15,000	1	10,000
Community Park	1,00,000	1	50,000
Residential Playground	5000	1	5000
Neighborhood Playground	15,000	1	15,000



allowe ne urban used t rocessing zone boundaries and tree data was obtained from Nagpur Municipal Corporation (NMC). Population data was obtained from the census 2011 data.

of satellite imagery into UGS category map by manually digitizing UGS within an administrative boundary. The UGS were categorized into tot lots, neighborhood parks, community parks, residential unit playgrounds, neighborhood unit playgrounds & urban forests as per URDPFI & urban greening guidelines. With the help of area details extracted from the digitized UGS area data and URDPFI standards, the zone's UGS area deficiency was calculated using the following equations *(moud, 2015) (MoHUA, 2014)*,

SRA = (P x RA) / RP (1)

Step 2: DA = SRA – EA (2)

Step 3: DA% = (EA / SRA) x 100 (3)

Where, SRA: Standard Recommended UGS Area, P: Population RA: Recommended Area per unit UGS, RP: Recommended Population per unit UGS, DA: Deficiency in Area, EA: Existing UGS Area.

3.3.2 Average normalized difference vegetation index (ANDVI)

Normalized Difference Vegetation Index (NDVI) helps to identify vegetation density on an area of land. The low value (0.1 & below) of NDVI corresponds to sand, barren areas, rocks, or snow. The average NDVI of all zones was determined to know the quality of UGS using Arc GIS (Figure 2).

3.3.3 Number of trees (TN)

Considering the positive impact of trees on the environment, vector data related to tree holding of a zone was created in ArcGIS 10.6 as a remark of existing UGS.

residential unit playgrounds, neighborhood unit playgrounds & urban forest as per URDPFI & urban greening guidelines (Figure 2) Using digitized UGS quantity data and standards, zone's UGS number deficiency was calculated using the following equations. *(MoUD, 2015)(10) (MoHUA, 2014)(13)*

SRN = (P x RN) / RP (4)

DN = SRN – EN (5)

DN% = (EN / SRN) x 100 (6)

Where, SRN: Standard Recommended UGS Number, P: Population RN: Recommended Number per unit UGS, RP: Recommended Population per unit UGS, DN: Deficiency in Number, EN: Existing UGS Number.

3.3.5 Average land surface temperature (ALST)

Average LSTs of all the zones were calculated using Landsat 8 data in ArcGIS (Figure 2). Using temperature gap in LST at Regional Meteorological Centre (RMC) and its outdoor temperature (To), (42.5°C–41°C=1.5°C), TO of zones were calculated. Zones were prioritized as per high thermal condition, which creates difficulty in achieving a comfortable temperature (Tc) (from Humphrey's equation: Tc=12.1+(0.53*To). *(Arvind Krishan, 2001)(14)*

3.3.6 Pollution sensitive areas (PL)

Locations with high air and noise pollution identified by NMC officials, were mapped as an attribute of the zone in ArcGIS 10.6. Zones holding such locations were prioritized for urban greening.

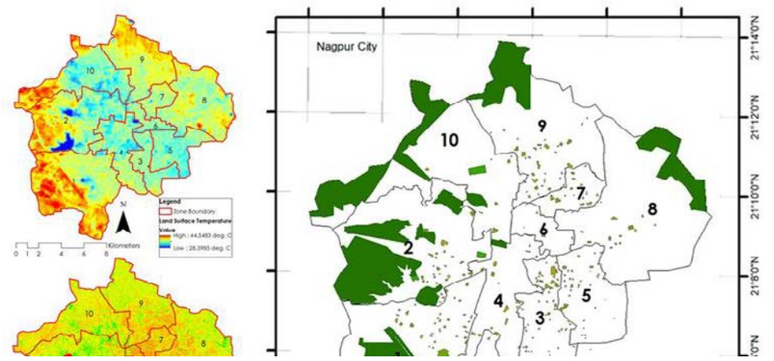


Figure 2: *Map of Nagpur city (1.Map showing location & number of UGS, 2. LST map showing surface temperature, 3. NDVI map showing condition of UGS) (Girhe, 2021)*

3.3.4 Urb

To det sparity, the deficiency, sa a grid, and quantity map ed in ArcGIS administrative boundary and categorizing them into tot lots, neighborhood parks, community parks, 10.6. Based on the number of UGS required to make

zones with unevenly distributed UGS as evenly distributed UGS zones, the priorities were decided.

3.3.8 Green cover per person (GCPP)

The green cover per person was determined by extracting UGS area details of the respective zones from the UGS category map in ArcGIS 10.6 and dividing it from the zone population. *(India, 2021)(15)* It was calculated in terms of sq.m per person.

3.3.9 Zone population (ZP)

To determine the amount of greening required, vector data related to the population of a zone was created in Arc GIS 10.6 as a remark of existing pressure over the UGS. Zones with a high population were prioritized for urban greening. *(India, 2021)(15)*

3.3.10 Water Shed Preference (WSP)

The location of low-lying areas with the potential to be watersheds was mapped as an attribute of the zone Arc GIS 10.6. Zones holding such locations were prioritized for urban greening.

4. ANALYSIS

4.1 Urban green space area & number deficiency

Among all 10 zones, zone 7 has the highest UGS area deficiency. The reason behind it is land dominated by commercial land use. Due to the presence of large functional UGS, zone 1 & 2 has the least deficiency in UGS area. Zone 6 & 10 have the highest UGS number deficiency due to a lack of dedicated UGS. Zone 2 & 3 has the least UGS number deficiency due to the presence many functional and dedicated UGS.

4.2 Urban green space disparity & Green cover per person

All the zones have non-uniformly distributed UGS. Zones 2, 3, 4 & 9 would require less additional UGS to make them zones with uniformly distributed UGS. Zone 1 has the highest green cover per person (3.95 sq.m per person) and zone 7 has the lowest green cover per person (0.08 sq.m per person).

4.3 Pollution sensitive areas & Number of trees

Sensitive areas appear more in the central region of the city. Zone 2 holds the highest number of air and noise pollution areas and zone 8 holds the least number of air and noise pollution areas. Zone 1 has above 60,000 trees. Zone 2 & 10 has 40,000 to 60,000 trees respectively.

4.4 Average land surface temperature & Average normalized difference vegetation Index

Zone 1, 2, 10, 9 & 8 experiences high thermal condition. Significantly large patches of green cover are present in zone 1, 2, 4 & 10. Zone 3, 5, 8 & 9 are dotted with green spaces. Zone 6 & 7 have a significantly less green cover. Zone 2 & 4 has a dense green cover. Significantly more green cover is present on the east side of the city. Large patches of barren/ vacant land in zone 1,2,8,9 & 10.

4.5 Zone population & Watershed preference

Zone 8 has more population than other zones. Zone 2 is likely to hold more water.

5. RESULTS

All 10 zones were awarded ranks for their performance in their urban greening parameter (Table 3). These ranks helped in the identification of priority zone for greening by the weighted overlay geospatial technique (Figure 4).Weighs/ influence percentage would be set as per the decision maker's best judgment governed by the context of urban greening. Example for using weighted overlay geospatial technique with influence % as AD:10%, ND:10%, UGSD:5%, GCPP:20%, PL:5%, TN:5%, ALST:15%, ANDVI:15%, ZP:10% & WSP:5%.

Ranking Equation: Priority Zone for Urban Greening

Zone Weightage = 0.1 * AD + 0.1 * ND + 0.05 * GD + 0.2 * AG + 0.05 * TZ + 0.05 * SZ + 0.15 * ALST + 0.15 * ANDVI + 0.1 * ZP + 0.05 * WS

Result: Zone 8 & 9 preferable for immediate urban greening (mentioned in Figure 3).

6. CONCLUSION

The adopted methodology and ranking equation in the study stood beneficial in identifying the geospatial technique's potential to aid sustainable planning in a tropical city. It was noted that greening has become a key component in planning because of its multiple benefits. Identified per capita green cover in worldwide cities signifies a strong relation between their quality of life and green cover. Thus, urban greening through green infrastructure can make cities resilient against temperature rise and promote sustainable urban development. Hence, strategic model for Nagpur city was prepared by using geospatial techniques via Arc GIS 10.6 and remote sensing imagery from USGS (geographic data portal). It is essential to visualize green issues at big scale, contextually & parametrically. Geospatial techniques help in generating comprehensive visualization to aid the rational endeavor of a planner. The urban local body can use this model to frame greening initiatives & management practices.

Table 3: *Parametric performance of the zones*

Zone	AD	ND	UGSD	GCPP	PL	TN	ALST	ANDVI	ZP	WSP
1	0.1%(2nd)	19% (3rd)	0.47 (6th)	3.94 (1st)	8 (8th)	608634 (1st)	38.77 (10th	0.13 (4th)	239171 (6th)	9 (8th)
2	0% (1st)	0% (1st)	0.4 (4th)	4.67 (2nd)	10(10th	421776 (3rd)	36.52 (5th)	0.12 (1st)	159458 (1st)	10(10th
3	58% (4th)	5% (2nd)	0.34 (1st)	1.51 (3rd)	8 (9th)	112130 (5th)	35.52 (3rd)	0.17 (3rd)	248715 (7th)	6 (9th)
4	55% (3rd)	11% (4th)	0.31(2nd)	1.5 (4th)	6 (5th)	110255 (6th)	35.65 (6th)	0.13(2nd)	238851 (5th)	7 (7th)
5	57% (5th)	49% (6th)	0.45 (5th)	0.92 (7th)	3 (3rd)	64511 (8th)	35.29 (1st)	0.14 (5th)	199742 (4th)	3 (3rd)
6	58% (8th)	95%(10th	0.48 (9th)	0.07 (9th)	2 (2nd)	30966 (10th)	37 (7th)	0.17(10th)	285495 (9rd)	1 (2nd)
7	54%(10th	71% (7th)	0.47 (8th)	0.61(10th)	5(4th)	40304 (9th)	35.52 (2nd)	0.16 (9th)	189182 (2nd)	2 (4th)
8	63% (7th)	79% (8th)	0.49 (7th)	0.4 (8th)	1 (1st)	189098 (4th)	36.33(4th)	0.15 (8th)	368678(10th)	5 (1st)
9	64% (6th)	46% (5th)	0.37 (3rd)	0.78 (5th)	5 (6th)	107955 (7th)	37.84 (9th)	0.159(7nd)	196779 (3rd)	4 (5th)
10	62% (9th)	90% (9th)	0.48(10th)	0.1 (6th)	6 (7th)	458209 (2nd)	37.18 (8th)	0.159 (6th)	285385 (8th)	8 (6th)

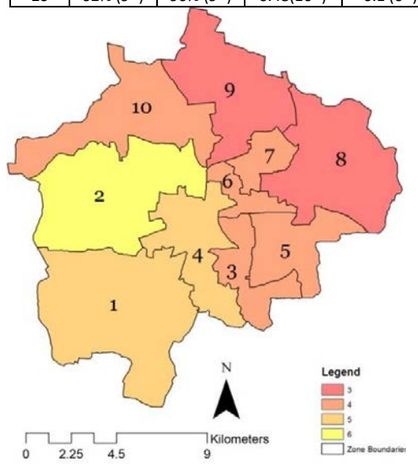


Figure 3: *Weighted overlay map: Result of ranking equation (Girhe, 2021)*

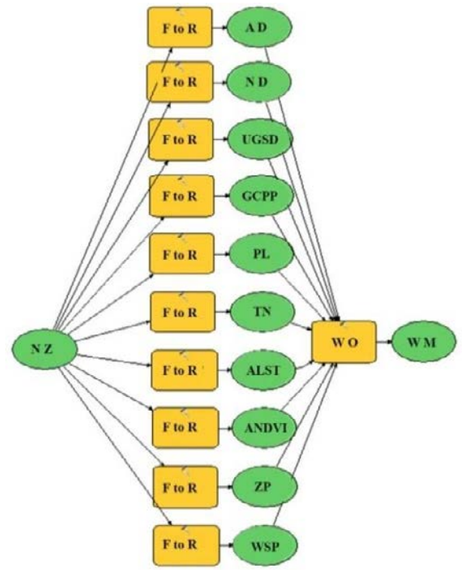


Figure 4: *Weighted Overlay Arc GIS Model (N Z: Nagpur zones, F to R: Feature to Raster, W O: Weighted overlay & W M : Weighted map)*

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Courtyard with ventilation as climate resilient solution

Evaluating the new houses against traditional Sultanate of Oman

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ABSTRACT: In the last few years, the design of the courtyard has gained attention by the designers for its microclimatic advantages of the indoor spaces. Though it has now been widely accepted and used to design buildings all over the world, there is still little knowledge when it comes to the thermal performance features of the courtyard - especially in extremely hot and humid locations like the Sultanate of Oman. This paper evaluates to what extent inner courtyard design affects the internal thermal environment, such as, indoor air temperature and air velocities of the houses in the Sultanate of Oman during extreme arid conditions. It also evaluates the optimised design model considering the standard specifications for plots across dwellings of Oman. By comparing the environmental performance of houses with and without courtyards, this paper investigate how courtyards could be useful solutions for new dwellings during extreme conditions. The paper suggests that designers should consider the size, location, and orientation during the initial phase of courtyard design to make them climate resilient. The study results also showed a considerable improvement in the thermal performance of the indoor areas of the house with an indoor courtyard compared to the ones without a courtyard.

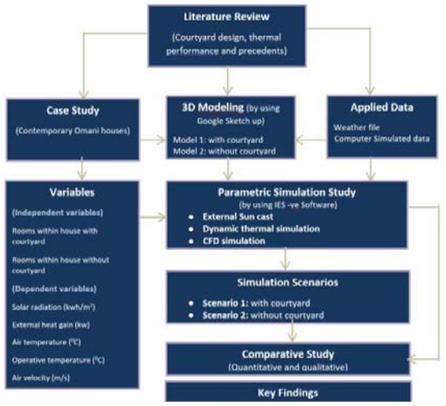
1. INTRODUCTION

A courtyard is one of the oldest design features that has its root in hot and dry regions. The shape, size, and dimensions of the courtyard have an impact on the shadow falling on the building's footprint. A recent article suggested a range of data-driven assessment methods to anticipate warm temperature in conventional yards that are viable to all extreme climatic conditions [1]. Apart from protecting dwellers, the purpose of the courtyard can vary, such as cultural, e.g., gatherings, cooling, and religious factors [2]. A traditional 'Sultanate of Oman' was taken as a case study area under one of the recent articles that stressed the importance of domestic yard in Islamic cultures and explained how inner courtyards contributes as a cooling system and climate moderator impacting thermal comfort in Omani dwellings [2]. Another article highlighted the various factors of the surfaces of the building that supports the inner courtyard that acts as a cooling element by reducing the humidity and moderating the thermal environment in countries having hot and arid climate [3]. However, limited research has demonstrated the effectiveness of a courtyard building in enhancing the indoor thermal environment of the overall houses in a hot arid climate. Therefore, this paper addresses this research gap.

2. METHODOLOGY

This paper presents the performance of courtyard designs through quantitative simulation techniques (figure 1). The computer-aided study was utilised to evaluate the effect of courtyard on indoor thermal environment of various parts of the dwelling units at the initial design stage.

Figure 1:
Overall methodology



The computer-aided data considered materials and specific climatic conditions based on extreme weather conditions and dwelling requirements in the Sultanate of Oman. The performance of the courtyard design is assessed using simulation software – Integral Environmental Solution - Virtual Environment (IESVE). Sun cast analysis was used to assess the solar shading performance as an established method [4]. Computational Fluid Dynamics (CFD) was used to compare the performance of two Scenarios.

2.1 Data Validation and Conceptual Model

Since this research was conducted during Covid19 lockdowns, it was not possible to collect primary field data from the selected case studies. Simulated data were validated in two phases. Firstly, IESVE weather data (Figure 2) was validated against the meteorological data from a weather station located approximately 40km away from the site. Secondly, the primary field data of a recent study [5] was utilised to test the conceptual simulated model for the validation process. Both cases, 15% deviations of mean dry-bulb temperature were found.

Figure 2:
IESVE air temperature data for validation

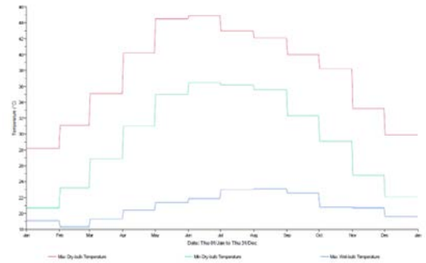
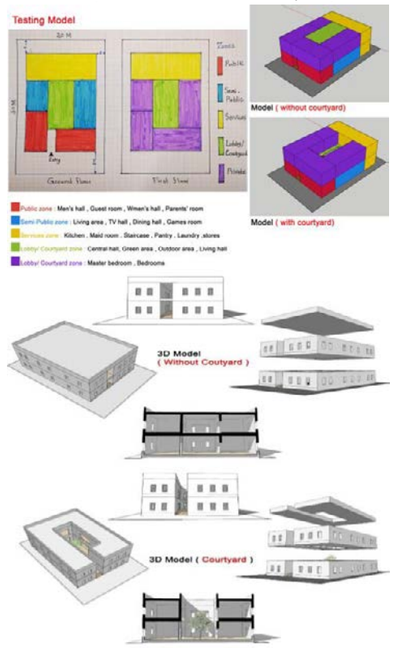


Figure 3:
3D model of the testing model house considered for simulation (with and without a courtyard)



Conceptual models (figure 3) were based on common functional layouts and orientation of vernacular houses and new residential plot sizes.

2.2 Simulation Tool and Design Parameters

The dynamic building simulation tool, IESVE, translates complex-building physics principles and detailed dynamic thermal calculations into actionable insights. It also provides the design professionals with a variety of variables in the simulation analysis of buildings. A courtyard was used as independent variable. Please refer to Appendix for the materials specifications used for the simulation. A summary of the variables is shown in Table 1.

Table 1:
Independent and dependent variable parameters used in IES-VE modelling

Orientation of dwelling	Living room (East side), Bedroom (Westside), Dining room (South westside)
Independent variables	Rooms within a house with and without courtyard
Dependent variables	Solar radiation (KWh/m²), External heat gain (KW), Air temperature (°C), Operative temperature (°C), Air velocity (m/s)
Internal gain	A model house with 10 people was considered to calculate the internal gain Maximum sensible gain – 90 W/P Maximum latent gain - 60 W/P
Plot area	20m x 30m – permissible area for house
Materials and Technology	Opaque roof, Glazed external window, Opaque external wall Specifications of the materials are detailed in the Appendix section of this report.
Solar gain	Peak summertime – ranges from 26.06 kWh/m² to 230.89 kWh/m² Peak wintertime – ranges from 15.48 kWh/m² to 143.47 kWh/m²
Wind rose	Peak summertime – wind blows from the NW 12.5% of the time at Muscat Peak wintertime - wind blows from the NE >18% of the time at Muscat

2.3 CFD Simulations and Comparative Study

'MicroFlo' (CFD) App of IES software was used to compare the air flow pattern in the three units of the building based on natural ventilation. It was used to predict convective heat transmission at the outer surfaces of the dwelling units and the inner areas of the units towards the courtyard. Comparative analysis was developed in terms of location of dwelling units affecting the thermal comfort of a given area of hot and arid climatic regions. Data were also analysed based on design targets adopted in a previous study [5].

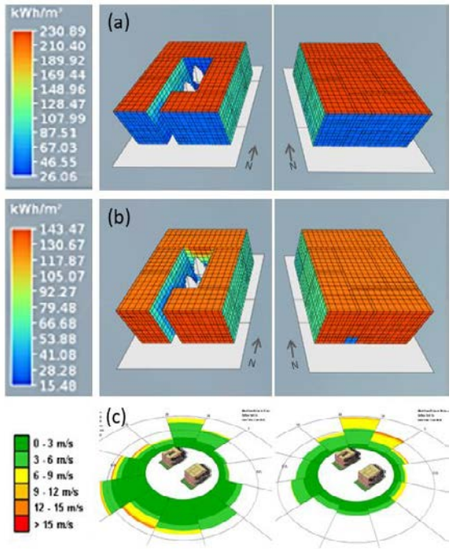
3. ANALYSIS AND RESULTS

3.1 External Sun Cast

The figure 4 evaluates the incident solar radiation of air movement simulations considering inner courtyard and without courtyard scenarios during peak summer (January) and peak winter (June) conditions in Muscat, Oman. Maximum direct solar gain can reduce during peak summer by

placing the windows to the south and including the overhangs. The size of the glass becomes very important to balance the load on the cooling components to ensure only sufficient solar gain will allow that serves the lighting purpose during the peak cooling times. This will enable the sunlight to generate less heat but the lighting that provides efficiently. Meaning, along with sufficient lighting, the energy demand for cooling can be reduced. Airflow rates are maximum within the courtyard area during the daytime. Additionally, in terms of incident solar radiations within the courtyard area, the ground remains in the shade the whole year. In retrospect, wind flow enters the courtyard at every hour of the day.

Figure 4:
Incident solar radiations during (a) summer and (a) winter, (c) External wind pattern in winter and summer



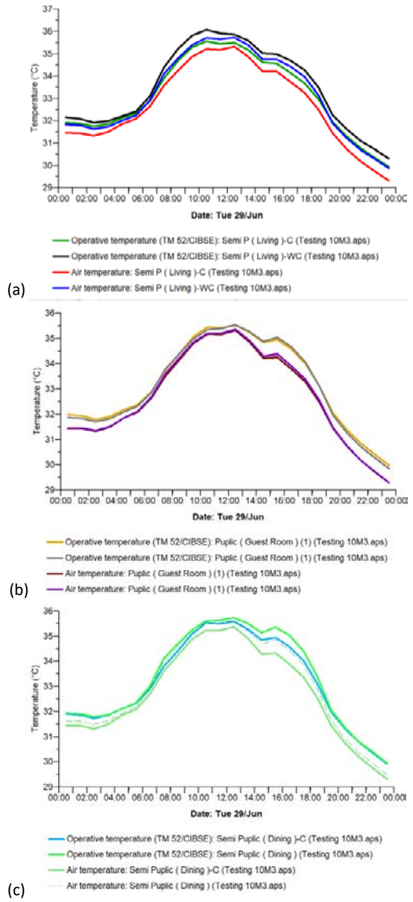
3.2 Air and Operative Temperature

Though Apache dynamic simulation was conducted for the whole year, indoor temperatures (dry-bulb and operative temperature) was assessed every hour of a day (29th June, peak summer) in all the 3 dwelling units (i.e., living room, bedroom, and dining room) and depicted in figure 5. Figure 5 shows that air temperature is slightly cooler in the rooms with courtyards compared to that without courtyards. It also means effective ventilation can provide additional thermal comfort to users of these residential spaces.

3.3 Effective Ventilation through CFD simulation

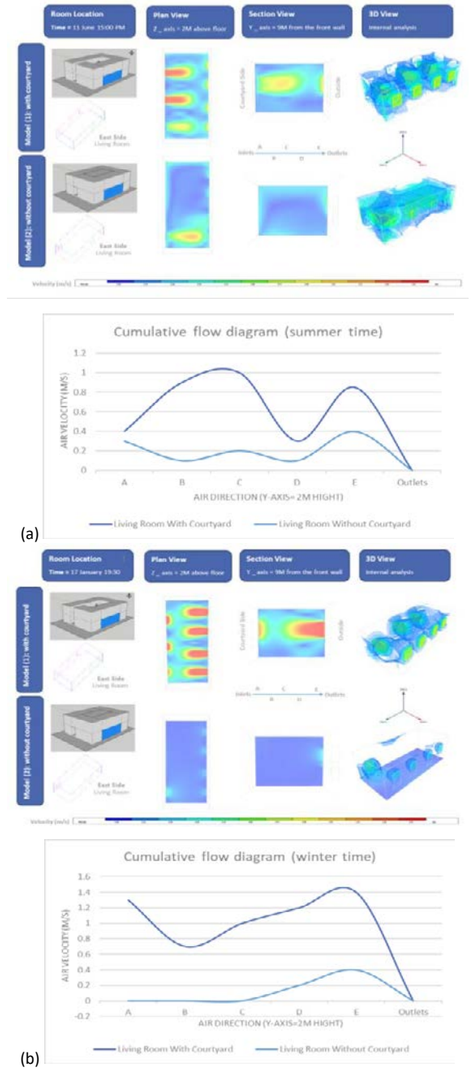
Numerical calculations were conducted using the MicroFlo to simulate airflow and heat transmission procedures. This considered the level of 2m over the ground surface. The factors affecting the wind velocity and thermal environment are the geometry of the courtyard, the orientation of the dwelling units, and the materials used. Figures 6-8 are the results from the CFD simulation during summer and winter of the living rooms, bedrooms and dining rooms.

Figure 5:
Air temperature and operative temperature of (a) living (b) bed, and (c) dining rooms (with and without courtyard)



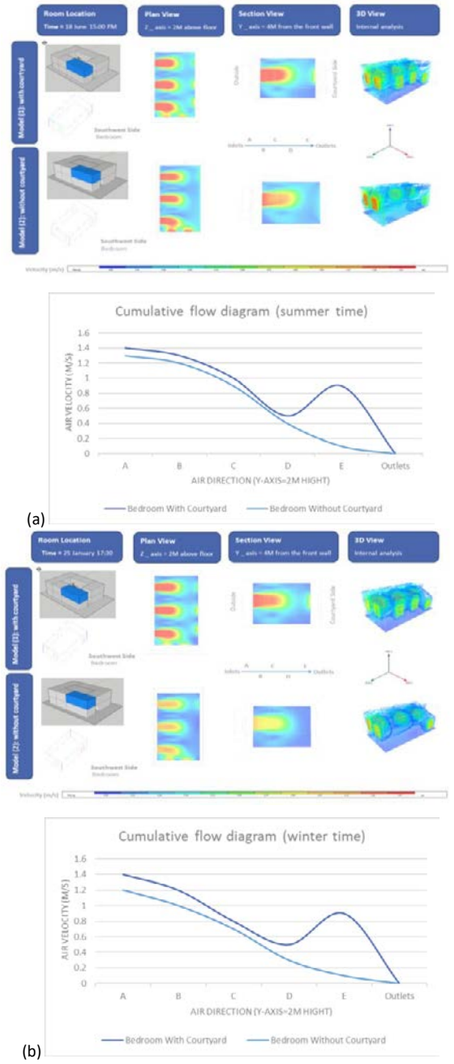
Temperature can be reduced by having good ventilation that helps to get cool air and to improve the wind velocity. Different dwelling units located in different directions were compared by measuring the wind velocity within the courtyard area and by assessing the performance of natural ventilation. The figures 5-8 show the air velocities and temperature of specific rooms adjacent to the dimension of the sites (East, West, and South-west) during peak summer and wintertime. It indicates a prominent decrease in temperatures achieved by the central courtyards. The living room on the east side experiences good airflow during the peak summertime, thereby reducing the surface temperatures.

Figure 6:
Air velocity and cumulative flow diagram during peak (a) summer and (b) winter in Living room



Wind flow is considerably high from outside during peak winter rather than within the courtyard, thereby reducing the cooling of the living room faced on the east side. Whereas the house without courtyard experiences more wind from all sides.

Figure 7:
Air velocity and cumulative flow diagram during peak (a) summer and (b) winter in Bedroom

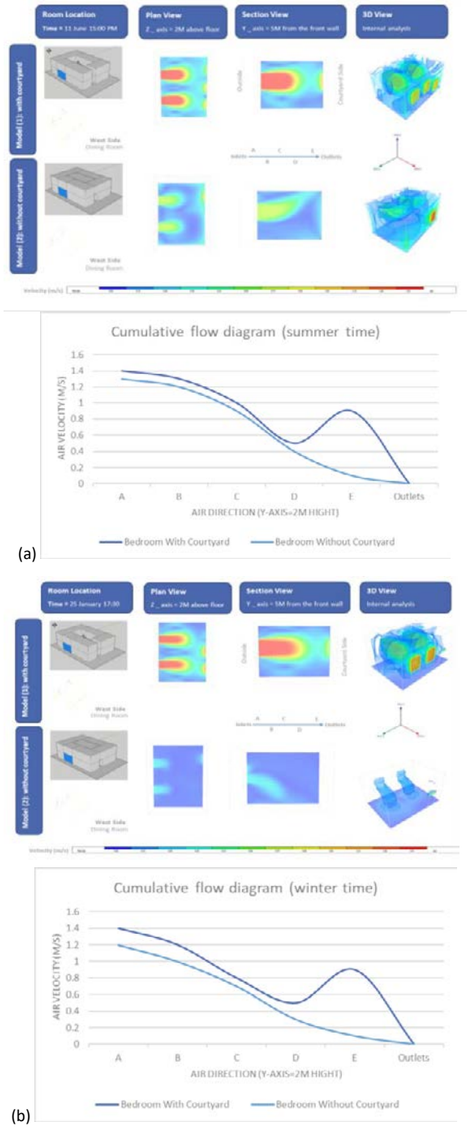


The bedroom on the southwest side experiences maximum airflow during peak summer. With courtyard design at the inner house, helps to reduce the surface temperature within the bedroom making it cool from inside.

During the peak summertime, there seems to be a good flow of wind on the west side as well within the courtyard that in turn cools the inner surface of the house. Whereas the house without courtyard design experiences average wind flow from outside that makes the wall temperature low. On the west side of the house, the outside experience good

airflow rather than the courtyard side keeping the inner house warm during peak winter.

Figure 8:
Air velocity and cumulative flow diagram during peak (a) summer and (b) winter in Dining room



4. KEY FINDINGS

The simulations listed in the above sections showed the location of the courtyard plays a vital role in maximizing the flow of wind and increasing the shading aspect within the dwelling unit during daytime. The high wall structures helps in increasing the thermal comfort as it provides shading through the daytime, thereby reducing the direct solar radiation. Furthermore, reducing the size of the courtyards and their surroundings wall structures and increasing the shaded areas not only reduces the solar gain in the courtyard surfaces but also restricts the ventilation during summer. Gardening and planting trees within the courtyard area decrease the wind velocity and increase relative humidity. This enhances thermal performance during certain hours of daytime. A few findings are illustrated in Table 2.

Table 2:
Summary of the Key findings

Study	Key findings
External Sun-cast	• High wall structure help in increasing the thermal comfort as it provides shading through the daytime, thereby reducing the direct solar radiation • Wind velocity is typically low within the courtyard, but it is higher if the surrounding plots are vacant while the envelope of the courtyard have some perforation or windward openings • Compared to the exposed area, the surface shaded by the building performs better in terms of air temperature. This indicates that shading can be an important strategy for achieving a desirable thermal environment.
Dynamic Thermal	• Courtyards elongated in North-South orientation with the increased number of floors reduces solar radiation • Incorrect orientation against wind and solar gain may lead to reduced thermal performance. Likewise, proper directions and open-to-sky courtyards can enhance thermal performance.
CFD	• Thermal comfort is maximized within the shaded area of the courtyard than the exposed surface of the courtyard. Hence, courtyard design and proper orientation play a vital role in increasing thermal performance. • Temperature can be reduced by having good ventilation that helps to get cool air and to improve the wind velocity.

5. CONCLUSION

The latest developments in the Sultanate of Oman have led to huge energy consumption, and significant electrical energy was generated to serve the residential sectors. Air conditioners, concrete structures have added to the rapid modernization of the country since the 1970s. Modern lifestyles have increasingly contributed to maximising energy consumption. In contradiction, vernacular architecture sets an example for providing both climatic, economic, and cultural solutions, that are more suitable for enhancing the comfortable atmosphere by making use of only natural materials and renewable sources of energy. By designing inner courtyard spaces in contemporary Omani houses gives substantial prospects for energy savings along with having traditional passive cooling techniques.

This paper examined the impact of design factors to achieve inner thermal comfort in relative humid regions. This paper evaluated the aspects such as shape, size, orientation, shading structures to improve thermal performance. Based on the simulations conducted, it reveals that the appropriate direction of the courtyard, size, and shape of the courtyard to increase the shading features will enhance the air velocities and potentially improve the thermal performance of the inner courtyard and its surrounding surfaces.

Traditional building with an inner courtyard which was well-thought-out as one of the significant cooling techniques is now being considered to be the most popular design criteria in modern architecture. Furthermore, while designing a courtyard, several physical aspects affect the natural ventilation. Even slight variations in the physical aspects of the courtyard like size or orientation will stimulate the pattern of wind flow and effectiveness of natural ventilation.

Orientation of the inner courtyard plays a vital role in improving the thermal performance within the dwelling units. During summer, dwelling units oriented towards the north provides improved thermal comfort due to air velocity and shading feature. Whereas during winter, dwelling units oriented 30 degrees towards the east enhances the solar gain in the surrounding surfaces. In addition, gardening and planting of trees prove to provide a better thermal atmosphere as compared to roofing techniques used in modern architecture. However, the thermal behaviour of any dwelling unit is affected by providing a gap between the courtyard roof and its opening. Research can further extend to evaluate the material of the walls and roof shading, size, and shape of the courtyard, and a number of openings and windows considered can enhance the thermal performance and reduce energy consumption considering the future scope of courtyard design in extreme hot air climate.

ACKNOWLEDGEMENTS

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APPENDIX

Materials specifications (roof and windows) and permissible area (source: IESVE construction profile)

(a) Specifications for Opaque roof

(b) Specifications for Glazed external window

(c) Specifications for Opaque external wall

(d) 3D visualization of the permissible area for house

Spatial mapping approach to target the local deployment of distributed energy resources in the UK

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ABSTRACT: Energy systems in most countries distribute electricity over centralized networks using primarily carbon intensive fossil fuels. For energy system to become decarbonised and decentralised to meet climate targets, large-scale application of distributed energy resources (DERs) that provide low carbon heating and electricity will be necessary. This paper uses a domestic energy mapping approach to baseline energy use and target appropriate dwellings for the application of DERs (heat pumps, rooftop solar, batteries) in five existing neighbourhoods (each comprising 200-450 dwellings) located in five council districts in Oxfordshire (UK). The dwellings are assessed using a bottom-up energy model called DECoRuM combined with a GIS-based approach to spatially map results. The results show that rooftop solar installation potential ranges widely depending on neighbourhood; between 1%-9% of dwellings can take up installations of 4kWp size and above, with an average size of 2.1 kWp, resulting in average energy reductions ranging from 69%-77%. The proposed approach can enable local authorities, community energy project developers and district network operators to extract local spatial intelligence rapidly and accurately for large-scale deployment of distributed energy resources. This can avoid expensive reinforcement of the local electricity networks.
KEYWORDS: Geographic Information System, Mapping, Distributed Energy Resources, Renewables, Community energy

1. INTRODUCTION

The conventional power systems in most countries primarily use diesel, coal, and natural gas–based generation units for producing electricity for distribution over their centralised networks. These conventional generation sources emit significant greenhouse gas (GHG) emissions, contributing to climate change [1]. However, several countries are successfully progressing in their effort to reduce GHGs from the energy supply network. This is an important first step as increasing capacity of conventional power systems on a centralized grid cannot sufficiently meet increasing global energy demand nor reduce GHG emissions [1].

To meet the UK government's net zero GHG emissions target by 2050 [2], the national energy supply network has been improved significantly. In 2020 the UK supplied more electricity via renewable energy sources (RESs) than fossil fuels [3]. Despite this type of progress there is concern that the centralized energy system structure has constantly proven to be vulnerable to the impacts of a changing climate and extreme weather events in many places. Examples include the 2017 hurricane Maria in Puerto Rico [4], annual heatwaves in Los Angeles causing blackouts [5], and the winter 2021 snow storm Uri in Texas [6].

In the UK the domestic sector has been lagging all other sectors in reducing emissions [2]. Furthermore, there has been an increase in the number of people working from home. This number has nearly quadrupled in the last 20 years [7]. Notably, this statistic was printed before the COVID-19 lockdown and the resulting cultural shift that is expected to occur as a result of employees and employers becoming accustomed to staff working from home [8].

During the pandemic in 2020, total global electricity and gas demand levels were lower; however, residential electricity consumption increased in many countries. Where the USA saw an almost 30% increase in residential electricity consumption, the UK reported an increase of 2% in total residential energy consumption, despite a warmer than average year [9]. According to the UK Office for National Statistics (ONS) [10] 24% of businesses in the UK intend to use increased homeworking going forward. This means that more energy is expected to be used during the day at home instead of in the office. One positive outcome from this would be a higher rate of self-consumption (SC) in domestic scale renewable energy, e.g., photovoltaics, especially if coupled with a heat pump.

From a technological standpoint, in order to meet the net zero target in the residential sector, the Committee on Climate Change [7] recommends that from 2025 no new homes should be connected to the gas grid. Instead, these homes should use low-carbon systems like heat pumps or be connected to community heat networks. As the recommendations for meeting the low carbon targets include a significant shift from gas to electrification of heat and transport, several future scenarios forecast an increase in peak demand.

To help offset this demand there will need to be a large increase in low carbon generation which tends to be variable and intermittent, Balancing the system, especially in the summer will also be a challenge, wherein a projected 30 GW of solar connected to the distribution network would mean the difference of almost 20 GW transmission demand depending on whether it is a cloudy or sunny day.

Batteries help balance grid consumption. In a recent previous project [11], a high electricity consuming gas-heated household utilised the battery to charge after hours in a time-of-use-tariff (TOU) arrangement. The household displaced 25% of their total electricity use by doing this. This contributed to a reduction in peak demand and saved the household an estimated £105 in one year. If the dwelling used a heat pump for heating, the savings are estimated to have been higher.

A solution to these problems is decentralisation of energy using renewables, energy storage, demand side response (DSR), smart networks, and increased interconnection [12]. A decentralised system relies on distributed generation or distributed energy resources (DERs), energy storage and demand response.

- The primary component to energy decentralization is distributed generation.
- Second, energy storage allows for more efficient use of generated energy and is important for flattening the curve of RES intermittency.
- Third, demand response, through smart grid technology helps facilitate grid management.

As an example, in Australia, where 16% of all RES generation is from rooftop solar installations, a Decentralised Energy Exchange (deX) has been set up. The deX signals to households when there is a power demand surge giving them the ability to auction excess self-generated or battery-stored power back to the grid at market-determined prices [13].

The technology has yet to reach the point of allowing intelligent autonomous user control over the buying and selling of their energy on a decentralised network [14] and avoiding cybersecurity risks whilst opening multiple multi-directional pathways for energy exchange [15]. However, for the grid to be decarbonised and decentralised, there is a need for large-scale area-based deployment of DERs.

Geospatial energy mapping is emerging as a useful approach for targeting suitable areas for application of energy saving measures, given their ability to provide rapid and accurate spatial intelligence. This paper uses a domestic energy mapping approach (DECoRuM - Domestic Energy, Carbon counting and carbon Reduction Model) to baseline energy use and rapidly target appropriate homes for the application of DERs (e.g., heat pumps, rooftop solar, batteries) in five existing neighbourhoods in Oxfordshire, England.

2. CASE STUDY AND METHODS

The case study neighbourhoods are in five district councils in Oxfordshire England. These district councils are Oxford, Bicester, Didcot, Abingdon, and Charlbury. The neighbourhoods comprise between 200 to 450 dwellings and were assessed using a bottom-up energy model called DECoRuM (Domestic Energy, Carbon counting and carbon Reduction Model) combined with a GIS-based approach to spatially map and visualise the results.

2.1 Identification of focal neighbourhoods

The first step was to identify areas of interest in the five council districts of Oxfordshire. The selection of each area was a combined effort between local interest and data-driven nudging from the authors (researchers) on the project.

The data-driven suggestions for area selection were informed by a research interest in choosing areas with:

- high fuel poverty (as this is a high priority for retrofit in the UK),
- high energy consumption,
- other socio-economic factors like vulnerable householders, and
- an attempt to cover a wide variety of dwelling types.

The process involved assessing publicly-available datasets including the UK Government's sub-national energy [16] and fuel poverty [17] data at lower layer super output area (LSOA) (areas of approximately 400-800 dwellings). As an example, Table 1 shows key characteristics of the selected neighbourhoods.

The local engagement involved providing maps of recommended areas of study to local low carbon community groups. The community groups in turn, approved or made requests for other areas to be evaluated.

Table 1:
Characteristics of dwellings [16, 18, 19].

	Dwellings	Mean Area	Dominate type	Mean EPC
ABINGDON	349	84 m²	1950-65 Semi-detached	61 (D)
BICESTER	440	83 m²	1950-65 Terraced	65 (D)
CHARLBURY	211	101 m²	1960-76 Semi-detached	61 (D)
DIDCOT	320	67 m²	1950-65 Semi-detached	53 (D)
ROSEHILL	431	97 m²	1930-49 Terraced	63 (D)

2.2 Creation of the baseline and the retrofit model

A full description of the development, assumptions and limitations of the model (DECoRuM) are detailed in [20, 21]. Data for calculations include actual dwelling characteristics (e.g., floor area, built age, area of glazing, area of exposed fabric, etc.) gathered from historic (Digimap) and current maps (OS MasterMap and Google street view). Fabric, system and energy related data were gathered from EPCs [19] and literature describing home characteristics based on age and typology (e.g. Tabula/Episcope [22]).

Statistics on retrofit progress in England [23] was also applied to the model baseline. This included:

- 68% of cavity wall dwellings were estimated to have cavity wall insulation by 2013,
- 80% of all dwellings and 91% of housing association homes were estimated to have more than half of windows double-glazed by 2013, and
- 56% of dwellings had 150mm or more of loft insulation by 2013.

In the energy models of the dwellings, three carbon reduction measures were applied to create the electrification retrofit package. These were heat pumps, rooftop photovoltaic, and batteries. No additional fabric or passive reduction improvements were added to the retrofit package.

Dwellings were modelled with heat pumps as the UK Government is planning to install 600,000 heat pumps per year by 2028 to move from the gas network to electricity. The dwellings were modelled with air source heat pump (ASHP): coefficient of performance (COP) = 2.6. In addition, all dwellings were assessed for rooftop solar suitability. The model considers roof area, orientation of the roof and obstacles on the roof identified via aerial imagery. Based on the empirical data from two studies [24, 25] (one located in a neighbourhood next to Rosehill and another in York, England) by the authors, the average self-consumption (SC) of PV in 78 dwellings was found to be 50%. This SC was applied to the model.

Finally, the impact of batteries was calculated using findings from the same empirical research. From these, an additional SC of 34% was gained by using a 13.5 kWh Tesla Powerwall II battery in each dwelling.

3. RESULTS

3.1 Baseline consumption results

Rosehill and Charlbury had the highest mean consumption. The lowest mean and smallest range in consumption results were in Didcot. Throughout all neighbourhoods most dwellings were in the 2,000 – 4,000 kgCO_2 range for the baseline. Didcot had the most dwellings below this range and Rosehill had the most above this range. Table 2 shows the mean results for the baseline model in the five neighborhoods: a total of 1751 dwellings.

Table 2:
Modelled baseline energy and emissions results

	Mean energy consumption	Mean CO_2 emissions
ABINGDON	16,331	3,234
BICESTER	15,781	3,373
CHARLBURY	17,857	3,598
DIDCOT	14,354	2,868
ROSEHILL	17,919	3,643

Currently there are only a total of 35 dwellings with PV installed in all mapped areas (2%); Bicester with the most (n=14, 3%). This indicates a significant potential for distributed renewable energy.

3.2 Retrofit results

Following the full electrification retrofit package modelling of the entire selection of 1751 dwellings, the mean total annual energy reduction potential was found to be 74%. Table 3 shows the mean results for the individual neighborhoods.

Table 3:
Modelled retrofit energy and emissions results

	Mean energy consumption	Reduction %	Mean CO_2 emissions
ABINGDON	3,864	75%	863
BICESTER	4,279	69%	964
CHARLBURY	3,865	77%	919
DIDCOT	3,491	74%	780
ROSEHILL	4,099	76%	942

Overall photovoltaic installation modelling results across all dwellings showed the potential to install a mean of 2.1 kWp with a max. of 14.1 kWp. Table 4 distributes the results between the most common dwelling type and age for each neighbourhood. Potential PV installations were the largest in Charlbury and smallest in Didcot which respectively had the largest (101 m²) and smallest (67 m²) mean dwelling areas.

Table 4:
PV potential and mean reduction results for the dominate dwelling types in each neighbourhood. D = detached, SD = semi-detached, Ter = terraced.

	Percent of total	Mean PV (kWp)	Mean reduction
ABINGDON			
1950 - 1965 SD	58%	2.0	75%
1950 - 1965 Ter.	39%	2.1	72%
1950-1965 D	3%	2.2	76%
BICESTER			
1950-65 Ter.	57%	1.7	67%
1950-65 SD	12%	2.1	66%
1950-65 D	10%	3.5	70%
CHARLBURY			
1966 - 1976 SD	55%	2.8	79%
1967 - 1976 D	29%	2.9	75%
1968 - 1976 Ter.	16%	2.6	72%
DIDCOT			
1950 - 1965 SD	94%	1.6	74%
1950-1965 D	3%	2.3	79%
1950 - 1965 Ter.	3%	1.1	75%
ROSEHILL			
1930 - 1949 Ter.	48%	1.8	73%
1930 - 1949 SD	26%	1.9	74%
1950-1965 SD	13%	2.9	74%

Bicester had the largest range in PV potential. This can be seen in figure 1 where the left side of the map shows a section of predominate detached dwellings and their larger PV potential.

Figure 1:
Rooftop PV potential in Bicester; Map© Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence).

The right side of the map shows the predominance of terraced dwellings with the majority smaller array size in PV potential.

Rosehill had a fairly well integrated distribution of reduction potential throughout the neighbourhood. The boundary boxes in figure 2 show potential areas to begin retrofit where energy consumption reduction is forecasted to be higher.

Figure 2:
Energy consumption reduction potential in select area of Rosehill; Map© Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence).

4. DISCUSSION

The mapping process and spatial maps presented in this paper make energy use visible by highlighting groups of dwellings by their PV array size or energy consumption reduction potential. Benefits include use as a communication tool for planning and where to allocate funding, and a visual source for tracking retrofit progress and change.

From the analysis, there was a 74% reduction in total energy consumption. As can be expected, this approach will not bring the residential retrofit sector to net zero; however, the reductions are noteworthy. Where contribution to the net zero target is the goal, these measures would ideally be combined with deep / whole-house retrofits (e.g. inclusive of insulation, air tightness) to achieve greater reductions. In addition, local community

buildings like schools and/or dedicated energy centres may be required to provide more renewable and storage solutions to create a localised DER micro-grid.

Overall, across all dwellings there were higher reductions in detached dwellings. This is generally because they are larger dwellings in which space heating is reduced and on which there is larger roof space for PV installation. In fact, area to reduction correlation through all dwellings is positive though the correlation coefficient is moderately weak (r=0.4).

As would be expected, smaller PV arrays provided greater SC ratios. This was also seen empirically in the ERIC (Energy Resources for Integrated Communities) project [24] where dwellings with 1.5 kWp, 2.25 kWp and 2.5 kWp resulted in total electricity consumption correlation to SC of r = 0.61, r = 0.47 and r = 0.31 respectively. Therefore, though it is tempting to question the value of the impact of such small PV systems, smaller PV arrays were more efficiently used in these dwellings. In addition, batteries help use more of the generated electricity, further increasing the cost efficiency of the PV.

Morrissey *et al.* [26] demonstrated through a survey in northwest England that the willingness to pay (WTP) for uninterrupted power was high. WTP was high to avoid outages during peak times, higher to avoid outages on weekends and holidays, and highest to avoid interruption in heating in winter. Furthermore, households with only electric heating had the highest WTP. The authors suggest increasing efficiency of the electricity system through targeting power quality to customers based on their household characteristics and willingness to pay. This, however, could lead to inequity and deepening fuel poverty. Alternatively, avoiding outages through decentralisation would be a better way to utilise WTP.

The pandemic has expanded fuel poverty as work changes and lockdowns have increased time at home driving up energy consumption and energy costs [27]. Energy generation and storage can reduce the pressure assuming the upfront costs are appropriately subsidised or affordable. With batteries, fuel poor dwellings can benefit from Economy 7 tariff or a dynamic pricing tariff. As mentioned in the introduction, one live dwelling saved an estimated £105 by charging overnight. Even without PV, TOU tariffs would be effective money saving and peak load shifting option.

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Spatial mapping approach to target the local deployment of distributed energy resources in the UK

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ABSTRACT: Energy systems in most countries distribute electricity over centralized networks using primarily carbon intensive fossil fuels. For energy system to become decarbonised and decentralised to meet climate targets, large-scale application of distributed energy resources (DERs) that provide low carbon heating and electricity will be necessary. This paper uses a domestic energy mapping approach to baseline energy use and target appropriate dwellings for the application of DERs (heat pumps, rooftop solar, batteries) in five existing neighbourhoods (each comprising 200-450 dwellings) located in five council districts in Oxfordshire (UK). The dwellings are assessed using a bottom-up energy model called DECoRuM combined with a GIS-based approach to spatially map results. The results show that rooftop solar installation potential ranges widely depending on neighbourhood; between 1%-9% of dwellings can take up installations of 4kWp size and above, with an average size of 2.1 kWp, resulting in average energy reductions ranging from 69%-77%. The proposed approach can enable local authorities, community energy project developers and district network operators to extract local spatial intelligence rapidly and accurately for large-scale deployment of distributed energy resources. This can avoid expensive reinforcement of the local electricity networks.
KEYWORDS: Geographic Information System, Mapping, Distributed Energy Resources, Renewables, Community energy

1. INTRODUCTION

The conventional power systems in most countries primarily use diesel, coal, and natural gas–based generation units for producing electricity for distribution over their centralised networks. These conventional generation sources emit significant greenhouse gas (GHG) emissions, contributing to climate change [1]. However, several countries are successfully progressing in their effort to reduce GHGs from the energy supply network. This is an important first step as increasing capacity of conventional power systems on a centralized grid cannot sufficiently meet increasing global energy demand nor reduce GHG emissions [1].

To meet the UK government's net zero GHG emissions target by 2050 [2], the national energy supply network has been improved significantly. In 2020 the UK supplied more electricity via renewable energy sources (RESs) than fossil fuels [3]. Despite this type of progress there is concern that the centralized energy system structure has constantly proven to be vulnerable to the impacts of a changing climate and extreme weather events in many places. Examples include the 2017 hurricane Maria in Puerto Rico [4], annual heatwaves in Los Angeles causing blackouts [5], and the winter 2021 snow storm Uri in Texas [6].

In the UK the domestic sector has been lagging all other sectors in reducing emissions [2]. Furthermore, there has been an increase in the number of people working from home. This number has nearly quadrupled in the last 20 years [7]. Notably, this statistic was printed before the COVID-19 lockdown and the resulting cultural shift that is expected to occur as a result of employees and employers becoming accustomed to staff working from home [8].

During the pandemic in 2020, total global electricity and gas demand levels were lower; however, residential electricity consumption increased in many countries. Where the USA saw an almost 30% increase in residential electricity consumption, the UK reported an increase of 2% in total residential energy consumption, despite a warmer than average year [9]. According to the UK Office for National Statistics (ONS) [10] 24% of businesses in the UK intend to use increased homeworking going forward. This means that more energy is expected to be used during the day at home instead of in the office. One positive outcome from this would be a higher rate of self-consumption (SC) in domestic scale renewable energy, e.g., photovoltaics, especially if coupled with a heat pump.

From a technological standpoint, in order to meet the net zero target in the residential sector, the Committee on Climate Change [7] recommends that from 2025 no new homes should be connected to the gas grid. Instead, these homes should use low-carbon systems like heat pumps or be connected to community heat networks. As the recommendations for meeting the low carbon targets include a significant shift from gas to electrification of heat and transport, several future scenarios forecast an increase in peak demand.

To help offset this demand there will need to be a large increase in low carbon generation which tends to be variable and intermittent, Balancing the system, especially in the summer will also be a challenge, wherein a projected 30 GW of solar connected to the distribution network would mean the difference of almost 20 GW transmission demand depending on whether it is a cloudy or sunny day.

Batteries help balance grid consumption. In a recent previous project [11], a high electricity consuming gas-heated household utilised the battery to charge after hours in a time-of-use-tariff (TOU) arrangement. The household displaced 25% of their total electricity use by doing this. This contributed to a reduction in peak demand and saved the household an estimated £105 in one year. If the dwelling used a heat pump for heating, the savings are estimated to have been higher.

A solution to these problems is decentralisation of energy using renewables, energy storage, demand side response (DSR), smart networks, and increased interconnection [12]. A decentralised system relies on distributed generation or distributed energy resources (DERs), energy storage and demand response.

- The primary component to energy decentralization is distributed generation.
- Second, energy storage allows for more efficient use of generated energy and is important for flattening the curve of RES intermittency.
- Third, demand response, through smart grid technology helps facilitate grid management.

As an example, in Australia, where 16% of all RES generation is from rooftop solar installations, a Decentralised Energy Exchange (deX) has been set up. The deX signals to households when there is a power demand surge giving them the ability to auction excess self-generated or battery-stored power back to the grid at market-determined prices [13].

The technology has yet to reach the point of allowing intelligent autonomous user control over the buying and selling of their energy on a decentralised network [14] and avoiding cybersecurity risks whilst opening multiple multi-directional pathways for energy exchange [15]. However, for the grid to be decarbonised and decentralised, there is a need for large-scale area-based deployment of DERs.

Geospatial energy mapping is emerging as a useful approach for targeting suitable areas for application of energy saving measures, given their ability to provide rapid and accurate spatial intelligence. This paper uses a domestic energy mapping approach (DECoRuM - Domestic Energy, Carbon counting and carbon Reduction Model) to baseline energy use and rapidly target appropriate homes for the application of DERs (e.g., heat pumps, rooftop solar, batteries) in five existing neighbourhoods in Oxfordshire, England.

2. CASE STUDY AND METHODS

The case study neighbourhoods are in five district councils in Oxfordshire England. These district councils are Oxford, Bicester, Didcot, Abingdon, and Charlbury. The neighbourhoods comprise between 200 to 450 dwellings and were assessed using a bottom-up energy model called DECoRuM (Domestic Energy, Carbon counting and carbon Reduction Model) combined with a GIS-based approach to spatially map and visualise the results.

2.1 Identification of focal neighbourhoods

The first step was to identify areas of interest in the five council districts of Oxfordshire. The selection of each area was a combined effort between local interest and data-driven nudging from the authors (researchers) on the project.

The data-driven suggestions for area selection were informed by a research interest in choosing areas with:

- high fuel poverty (as this is a high priority for retrofit in the UK),
- high energy consumption,
- other socio-economic factors like vulnerable householders, and
- an attempt to cover a wide variety of dwelling types.

The process involved assessing publicly-available datasets including the UK Government's sub-national energy [16] and fuel poverty [17] data at lower layer super output area (LSOA) (areas of approximately 400-800 dwellings). As an example, Table 1 shows key characteristics of the selected neighbourhoods.

The local engagement involved providing maps of recommended areas of study to local low carbon community groups. The community groups in turn, approved or made requests for other areas to be evaluated.

Table 1:
Characteristics of dwellings [16, 18, 19].

	Dwellings	Mean Area	Dominate type	Mean EPC
ABINGDON	349	84 m²	1950-65 Semi-detached	61 (D)
BICESTER	440	83 m²	1950-65 Terraced	65 (D)
CHARLBURY	211	101 m²	1960-76 Semi-detached	61 (D)
DIDCOT	320	67 m²	1950-65 Semi-detached	53 (D)
ROSEHILL	431	97 m²	1930-49 Terraced	63 (D)

2.2 Creation of the baseline and the retrofit model

A full description of the development, assumptions and limitations of the model (DECoRuM) are detailed in [20, 21]. Data for calculations include actual dwelling characteristics (e.g., floor area, built age, area of glazing, area of exposed fabric, etc.) gathered from historic (Digimap) and current maps (OS MasterMap and Google street view). Fabric, system and energy related data were gathered from EPCs [19] and literature describing home characteristics based on age and typology (e.g. Tabula/Episcope [22]).

Statistics on retrofit progress in England [23] was also applied to the model baseline. This included:

- 68% of cavity wall dwellings were estimated to have cavity wall insulation by 2013,
- 80% of all dwellings and 91% of housing association homes were estimated to have more than half of windows double-glazed by 2013, and
- 56% of dwellings had 150mm or more of loft insulation by 2013.

In the energy models of the dwellings, three carbon reduction measures were applied to create the electrification retrofit package. These were heat pumps, rooftop photovoltaic, and batteries. No additional fabric or passive reduction improvements were added to the retrofit package.

Dwellings were modelled with heat pumps as the UK Government is planning to install 600,000 heat pumps per year by 2028 to move from the gas network to electricity. The dwellings were modelled with air source heat pump (ASHP): coefficient of performance (COP) = 2.6. In addition, all dwellings were assessed for rooftop solar suitability. The model considers roof area, orientation of the roof and obstacles on the roof identified via aerial imagery. Based on the empirical data from two studies [24, 25] (one located in a neighbourhood next to Rosehill and another in York, England) by the authors, the average self-consumption (SC) of PV in 78 dwellings was found to be 50%. This SC was applied to the model.

Finally, the impact of batteries was calculated using findings from the same empirical research. From these, an additional SC of 34% was gained by using a 13.5 kWh Tesla Powerwall II battery in each dwelling.

3. RESULTS

3.1 Baseline consumption results

Rosehill and Charlbury had the highest mean consumption. The lowest mean and smallest range in consumption results were in Didcot. Throughout all neighbourhoods most dwellings were in the 2,000 – 4,000 kgCO_2 range for the baseline. Didcot had the most dwellings below this range and Rosehill had the most above this range. Table 2 shows the mean results for the baseline model in the five neighborhoods: a total of 1751 dwellings.

Table 2:
Modelled baseline energy and emissions results

	Mean energy consumption	Mean CO_2 emissions
ABINGDON	16,331	3,234
BICESTER	15,781	3,373
CHARLBURY	17,857	3,598
DIDCOT	14,354	2,868
ROSEHILL	17,919	3,643

Currently there are only a total of 35 dwellings with PV installed in all mapped areas (2%); Bicester with the most (n=14, 3%). This indicates a significant potential for distributed renewable energy.

3.2 Retrofit results

Following the full electrification retrofit package modelling of the entire selection of 1751 dwellings, the mean total annual energy reduction potential was found to be 74%. Table 3 shows the mean results for the individual neighborhoods.

Table 3:
Modelled retrofit energy and emissions results

	Mean energy consumption	Reduction %	Mean CO_2 emissions
ABINGDON	3,864	75%	863
BICESTER	4,279	69%	964
CHARLBURY	3,865	77%	919
DIDCOT	3,491	74%	780
ROSEHILL	4,099	76%	942

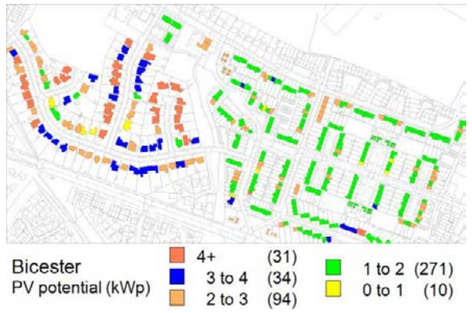
Overall photovoltaic installation modelling results across all dwellings showed the potential to install a mean of 2.1 kWp with a max. of 14.1 kWp. Table 4 distributes the results between the most common dwelling type and age for each neighbourhood. Potential PV installations were the largest in Charlbury and smallest in Didcot which respectively had the largest (101 m²) and smallest (67 m²) mean dwelling areas.

Table 4:
PV potential and mean reduction results for the dominate dwelling types in each neighbourhood. D = detached, SD = semi-detached, Ter = terraced.

	Percent of total	Mean PV (kWp)	Mean reduction
ABINGDON			
1950 - 1965 SD	58%	2.0	75%
1950 - 1965 Ter.	39%	2.1	72%
1950-1965 D	3%	2.2	76%
BICESTER			
1950-65 Ter.	57%	1.7	67%
1950-65 SD	12%	2.1	66%
1950-65 D	10%	3.5	70%
CHARLBURY			
1966 - 1976 SD	55%	2.8	79%
1967 - 1976 D	29%	2.9	75%
1968 - 1976 Ter.	16%	2.6	72%
DIDCOT			
1950 - 1965 SD	94%	1.6	74%
1950-1965 D	3%	2.3	79%
1950 - 1965 Ter.	3%	1.1	75%
ROSEHILL			
1930 - 1949 Ter.	48%	1.8	73%
1930 - 1949 SD	26%	1.9	74%
1950-1965 SD	13%	2.9	74%

Bicester had the largest range in PV potential. This can be seen in figure 1 where the left side of the map shows a section of predominate detached dwellings and their larger PV potential.

Figure 1:
Rooftop PV potential in Bicester; Map© Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence).



The right side of the map shows the predominance of terraced dwellings with the majority smaller array size in PV potential.

Rosehill had a fairly well integrated distribution of reduction potential throughout the neighbourhood. The boundary boxes in figure 2 show potential areas to begin retrofit where energy consumption reduction is forecasted to be higher.

Figure 2:
Energy consumption reduction potential in select area of Rosehill; Map© Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence).

4. DISCUSSION

The mapping process and spatial maps presented in this paper make energy use visible by highlighting groups of dwellings by their PV array size or energy consumption reduction potential. Benefits include use as a communication tool for planning and where to allocate funding, and a visual source for tracking retrofit progress and change.

From the analysis, there was a 74% reduction in total energy consumption. As can be expected, this approach will not bring the residential retrofit sector to net zero; however, the reductions are noteworthy. Where contribution to the net zero target is the goal, these measures would ideally be combined with deep / whole-house retrofits (e.g. inclusive of insulation, air tightness) to achieve greater reductions. In addition, local community

buildings like schools and/or dedicated energy centres may be required to provide more renewable and storage solutions to create a localised DER micro-grid.

Overall, across all dwellings there were higher reductions in detached dwellings. This is generally because they are larger dwellings in which space heating is reduced and on which there is larger roof space for PV installation. In fact, area to reduction correlation through all dwellings is positive though the correlation coefficient is moderately weak (r=0.4).

As would be expected, smaller PV arrays provided greater SC ratios. This was also seen empirically in the ERIC (Energy Resources for Integrated Communities) project [24] where dwellings with 1.5 kWp, 2.25 kWp and 2.5 kWp resulted in total electricity consumption correlation to SC of r = 0.61, r = 0.47 and r = 0.31 respectively. Therefore, though it is tempting to question the value of the impact of such small PV systems, smaller PV arrays were more efficiently used in these dwellings. In addition, batteries help use more of the generated electricity, further increasing the cost efficiency of the PV.

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WILL CITIES SURVIVE?

University trial study of indoor air quality attributes of interior building materials and finishes

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ABSTRACT: Researchers hypothesized that students would reach high levels of Bloom taxonomy (remember, understand, apply, evaluate, create; Anderson & Krathwohl, 2001) after exposure to Indoor Air Quality (IAQ) concepts through "hands-on" laboratory activity to be directed by researchers/educators in Fall semester, 2021. Researchers examined IAQ in a trial study in August 2021. In a university laboratory-classroom, researchers empirically tested samples of eight common interior building materials and finishes (four coatings/paint preparations, four wood products). They utilized an IAQ monitor to measure five attributes: temperature, humidity, CO2, VOCs (Volatile Organic Compounds), PM2.5 (particulate matter 2.5 μg/m³) that can potentially impact health, comfort, and productivity of building occupants. Researchers refined methodology for upcoming student activity; photo-documented tests; developed, tested, and revised spreadsheet to organize observations; determined logistics. The IAQ monitor tests revealed temperature: 23⁰C; relative humidity: 65%. IAQ attributes of samples showed variability. Spray paint produced highest values: CO_2 (486.17), VOC (38,820), PM2.5 (1000). Researchers concluded the upcoming IAQ lab activity, which was to be conducted as part of an undergraduate building materials and finishes course, should be modified: address additional samples; time treatment applications; utilize pre-test and post-test surveys to test students' IAQ knowledge as related to Bloom's taxonomy; assign student readings.
KEYWORDS: Indoor Air Quality, Student learning, VOC, Health, Interior design

1. INTRODUCTION

In the United States of America, design program accreditation standards consider Indoor Air Quality (IAQ) of interior materials and finishes to be important and require evidence of student work to ensure that programs meet IAQ standards to grant accreditation [1]. The Council for Interior Design Accreditation (CIDA) states in Standard 14 (Environmental Systems and Human Wellbeing) that "Interior designers use the principles of acoustics, thermal comfort, *indoor air quality*, and water and waste systems in relation to environmental impact and human wellbeing." The intent of Standard 14 is to "ensure that graduates are able to contribute to the development of appropriate strategies for achieving wellbeing, comfort, and performance within interior environments, and that they are aware of the environmental impact of their design decisions." Three student learning outcomes as listed under CIDA Standard 14 emphasize the need for students to understand indoor quality. These include a) students understand that design decisions relating to acoustics, thermal comfort, and indoor air quality impact human wellbeing and the environment, b) students understand the principles of indoor air quality, and c) students understand how the selection and application of products and systems impact *indoor air quality.* CIDA indicates that interior design programs should undertake this initiative to educate students on the relevance and importance of indoor air quality in the context of health and wellbeing of individuals occupying any space and using it. Examples of relevant topics could include pollutant source control, filtration, ventilation variables, *CO2 monitoring*, and/or mold prevention" (p. II-28) [1]. It is important to note that the recently released CIDA Standards 2022, "effective for site visits taking place after July 1, 2022" [2] also include similar indoor air quality requirements. This infers that IAQ will remain important to educational efforts.

Previously, other researchers have studied interior materials and IAQ [3]. Others have investigated Indoor Air Quality in University settings [4]. Current design textbooks emphasize the importance of IAQ [5]. Use of different materials could result in different IAQ values, and some materials might emit Volatile Organic Compounds (VOCs). VOCs such as benzene, toluene, ethylene limonene are hydrocarbon compounds that can easily evaporate, and they are also highly toxic [6]. VOCs may negatively impact human health by causing various symptoms including those related to optical and respiratory systems [7]. While the VOCs and their concentration levels are important risk factors for developing respiratory illnesses, equally or more important is the size of particulate matter (PM) in the air. Particles that have an aerodynamic diameter of 2.5μm (PM2.5) or less have a much greater risk to health when compared to particles with an aerodynamic diameter greater than 10μm (PM_{10}) as they can go deep into the alveoli [8]. As a result, the likelihood of developing lung cancer is higher with PM2.5 [9]. Thus, it is very important for interior design students to understand this information. No published studies were found in which undergraduate design students participated in empirical IAQ research. The current researchers hypothesized students would reach high levels of Bloom taxonomy (*remember, understand, apply, evaluate, create*) [10] after exposure to Indoor Air Quality (IAQ) concepts through a "hands-on" laboratory activity to be directed by researchers/educators in Fall semester, 2021. The current study reports on the trial study during which researchers developed and tested their methodology for the student activity.

2. METHODS

Researchers examined IAQ in a trial study in August 2021 in a university laboratory-classroom setting (refer to Figure 1). They utilized an IAQ monitor (Awair Element) to measure five attributes: temperature, humidity, CO_2, total VOCs, PM2.5 (particulate matter 2.5 μg/m³) that can potentially impact health, comfort, and productivity of building occupants [11]. The IAQ monitor (refer to Figure 2) was connected to a smartphone using an Awair Home app (refer to Figure 3). Researchers empirically tested samples of eight common interior building materials and finishes (four coatings/paint preparations and four wood products). The temperature and humidity values were recorded only once as these values did not change during the experiment. However, the $C0_2$, TVOC and PM2.5 values were recorded periodically.

Figure 1. Researchers recording IAQ values

Figure 2. IAQ monitoring device

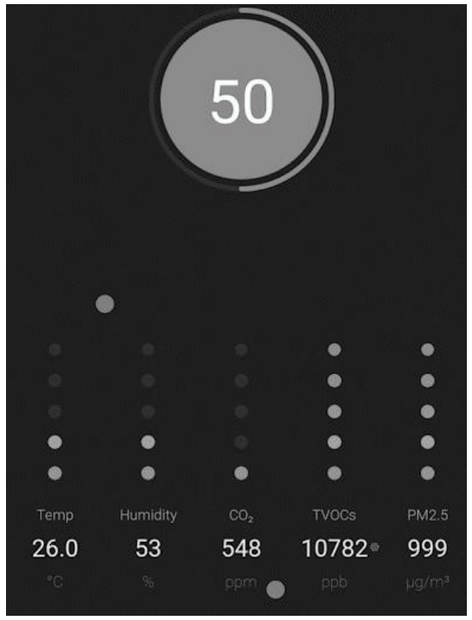

Figure 3. IAQ mobile phone app

The researchers met and refined their methodology after pilot testing with different materials. The researchers also photo-documented the IAQ tests and took detailed notes. They also developed, tested, and revised spreadsheets to organize all the observations and recordings to be made during the study. They also determined the overall logistics and diligently planned different activities to be carried out during the study. The researchers utilized electric sawing and hand sanding, occurring at different distances from the IAQ monitor to determine final methods for upcoming student activity. Researchers also utilized a hairdryer to warm some wood samples. They applied the paints/coatings with disposable paint brushes onto

a cardboard substrate (refer to Figure 4). A new paintbrush was used for each new trial a paintbrush was needed to avoid any contamination and carry over of the paint from prior trials. Researchers experimented with different sizes and compositions of substrates for finish applications during the test and decided on nominal seven inch (17.78 cm) square cardboard panels, which they recycled from shipping box waste. A detailed record of all the material used was documented (refer to Figure 5). Eight different materials were used: 1) Oriented strand board (sawn), 2) Oriented strand board (sanded 1.5m away), 3) Oriented strand board (sanded 0.15m away), 4) Oriented strand board (previously sanded 1.5m away warmed with hair dryer), 5) Penetrating wood stain, 6) Indoor paint, 7) Oil-based odourless stain blocker, and 8) Interior/exterior spray paint. Materials were manipulated (i.e., tugging and twisting carpet samples to simulate installation) and finishes were applied for one minute per sample. The measurements for CO_2, TVOC and PM 2.5 was monitored and recorded on a recording sheet. Small, electric, clip-on fans were temporarily affixed to laboratory tables and energized between samples to help to dissipate VOCs during the testing procedures. They were intended to bring the IAQ readings back to baseline after each test of a material or finish. Detailed filed notes were also taken during the experiment by the researchers (refer to Figure 6).

Figure 4. Applying paint on cardboard

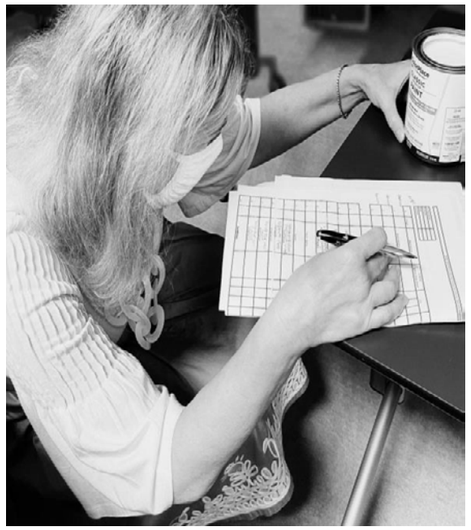

Figure 5. Recording material information

Figure 6. Taking field notes on different IAQ values

3. RESULTS

The researchers' field notes revealed overall IAQ attributes as follows: temperature: 23^0C and relative humidity: 65%. Further, researchers recorded a total of 219 (N=219) individual measurements of IAQ attributes for the tested samples. The IAQ monitor tests showed variability across samples. Refer to Table 1 for minimum (min), maximum (max.) and average (avg.) scores for each material for CO_2, VOC and PM2.5. The oriented strand board (previously sanded 1.5m away warmed with hair dryer) was found to have the highest CO_2 value recorded. However, the exterior/interior spray paint was found to have the highest values for both the total VOCs (38,820ppb) and PM2.5 (1000ppm). Values that are greater than 8,332ppb (parts per billion) for TVOC values and 75µg/m^3 for PM2.5 values could result in serious health concerns including cognitive impairment, overworked live and kidneys, respiratory illness and/or cancer [6].

The interior design program, within which this current IAQ study was conducted, has recently been advised that they received CIDA re-accreditation. The next site visit for the interior design program will be in six years, during which time they will need to provide new evidence of student work with IAQ.

Table 1. Materials and Finishes IAQ Attribute Summary

Material		CO2 (ppm)	Total VOC (ppb)	PM 2.5 (µg/m3)
1	Min	484.0	20.0	1.0
	Max	513.0	26.0	53.0
	Avg	500.6	22.1	24.0
2	Min	511.0	20.0	1.0
	Max	516.0	25.0	13.0
	Avg	513.0	23.5	8.3
3	Min	513.0	20.0	1.0
	Max	525.0	32.0	128.0
	Avg	516.3	23.0	61.5
4	Min	514.0	20.0	1.0
	Max	698.0	23.0	32.0
	Avg	599.0	21.0	17.2
5	Min	505.0	20.0	1.0
	Max	529.0	1762.0	6.0
	Avg	512.0	671.2	4.2
6	Min	507.0	20.0	1.0
	Max	556.0	275.0	8.0
	Avg	540.5	125.3	4.2
7	Min	500.0	20.0	1.0
	Max	502.0	468.0	2.0
	Avg	501.0	199.8	1.5
8	Min	486.0	20.0	1.0
	Max	487.0	38820.0	1000.0
	Avg	486.2	13342.0	369.2

3.1 Positive Experiences and Student Feedback

While students did not participate in the trial study reported in this manuscript, they participated in IAQ monitoring activities a few weeks following, in class, after the completion of the trial study and refinements to the methodology. 100% (N=26) of the students enrolled in the undergraduate materials and finishes course eventually participated. The students seemed to be very engaged, and all completed "recording sheets", spreadsheet documents that required students to actively follow along with the IAQ monitoring of the materials and finishes and to record data related to the IAQ activity.

4. CONCLUSION

Researchers concluded the upcoming IAQ student lab activity, which was to be conducted as part of an undergraduate building materials and finishes course, should be modified: address additional samples; time treatment applications; utilize pre-test and post-test surveys to test students' IAQ knowledge as related to Bloom's taxonomy; readings should be assigned.

4.1 Study Limitations

The intent of the current trial study was for the researchers to refine and test the new methodology they were developing for the next iteration of IAQ studies they would lead with student participation. The researchers were scheduled to lead a more extensive, in-class, student activity in the near future. The current trial study was conducted with only eight selected building materials and finishes. Although there are a plethora of building materials and finishes in use today in modern construction practices, the researchers in the current study were limited by various factors in acquiring and testing the samples. One factor was finances. The researchers needed to use materials and finishes they could obtain at no cost as there were no supply fees assessed in the upcoming course and no available funding for supplies in the budget. The availability of only one IAQ monitor to support all of the tested samples hindered the experimentation progress and was time-consuming. The IAQ monitor was not a data logger, so researchers had to vigilantly record, by hand, the numerical results which briefly appeared on the monitor's screen. Researchers were cautious to select materials and finishes that were suitable for use in the University laboratory-classroom (which possessed no sinks, countertops or eyewash stations and only limited storage). The researchers also wanted to select only interior building materials and finishes for this trial study so they would be applicable to the interior finishes and materials course in which the upcoming student testing activities were to take place. The researchers also selected a variety of materials and finishes to test that they anticipated

would have variance in outcomes. The facilities and existing furniture layout in the laboratory-classroom further limited the researchers in the current trial study. The research site doubled as a heavily scheduled classroom and a limited laboratory. Facility scheduling logistics reduced their access to the laboratory-classroom for advance preparations and study breakdown. The study took place during the Global Pandemic and restrictions on moving furniture in university laboratories and classrooms to be occupied by students prevented re-arrangement of the laboratory-classroom to facilitate access and movement. Researchers also needed to select materials and finishes that were relatively easy and quick for students to handle and not harmful to students during short exposure times. 26 students were enrolled in the upcoming course, which was to include the student testing activities, and the researchers wanted to set-up the laboratory-classroom for the trial study as a "dress rehearsal", intended to mimic the physical environment anticipated for the next iterations of the study, to be held during a regular class period with student participants.

Researchers could not test their hypothesis that students will reach high levels of Bloom taxonomy (remember, understand, apply, evaluate, create) [9] after exposure to Indoor Air Quality (IAQ) concepts through "hands-on" laboratory activity at the conclusion of the current study, as it reports only on the (pre-participant) trial study.

4.2 Recommendations for Future Resaerch

The researchers plan to improve and replicate this study, annually, in the undergraduate materials and finishes course. They will compare data longitudinally over 3-5 years of testing. They recommended modifications to some of the methodology in the future for their IAQ tests. Their suggestions include the purchase of additional monitors which could be set-up at separate "stations" in the classroom-laboratory. The data from multiple materials and finishes could be monitored and recorded simultaneously during future faculty-led student activities, allowing for more capacity during a class period. Additional and more varied materials and finishes should be utilized in future studies. The timeframe of finish applications should be extended to two minutes.

The laboratory-classroom was dual purpose and was located in an aging facility. The laboratory-classroom was not originally designed for IAQ testing and monitoring. Ventilation was an issue in the current study. More portable fans are recommended in the future to improve ventilation in the laboratory-classroom since some materials or finishes were particularly slow to dissipate during the trial study. The laboratory-classroom did not contain any fume hoods. Multiple fans are anticipated to reduce the waiting time required for returning IAQ to baseline after each material or finish was tested.

Researchers also recommend that additional studies be conducted with students after all student-participants are provided with IAQ education via reference materials (i.e., Safety Data Sheets pertaining to the specific materials and finishes to be tested), as well as readings and lectures. The researchers recommend that other faculty in similar or allied academic programs (i.e., architecture and engineering) implement a similar methodology with the students in their courses. Further, students should be surveyed to determine their perceptions of the IAQ monitoring activities and their learning outcomes. Such efforts regarding IAQ monitoring in interior design and other courses may also enhance programs seeking to meet accreditation standards which require evidence of IAQ understanding and which recommend IAQ monitoring activities.

Future studies with student participants should test the researchers' hypothesis that students will reach high levels of Bloom taxonomy (remember, understand, apply, evaluate, create) [9] after exposure to Indoor Air Quality (IAQ) concepts through "hands-on" laboratory activity. Extensive queries into students' pre- and post-study perceptions should be conducted.

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Integrating Sustainability Issues into a Comprehensive Architectural Design Studio:
A Case Study Approach to the Development of a Framework

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ABSTRACT: To meet the performative goals of buildings, including energy efficiency, high indoor environmental quality, and occupant health and wellness, architectural design requires a collaborative process engaging various professionals including architects, engineers, and contractors. Successful collaboration in this process achieves high-performance building design, which may reduce the carbon footprint of the building. For training the coordinators of this collaborative process, typically building designers, comprehensive design has been emphasized in architectural education, and most architecture programs in the US offer a comprehensive design studio (CDS) as a mandatory course. The present study introduces three case studies on CDS teaching and attempts to identify the characteristics of a successful CDS with an emphasis on how sustainability issues could be integrated into the conventional comprehensive studio framework. The case studies included the relevant document analysis and communication with the instructors. The focuses of the investigated cases were building envelope systems, building performance, and building information modeling (BIM), and the common challenge was the limitation of time to address the broad study area. This indicates that students may need more opportunities for the application of knowledge to projects starting from the earlier stages of their education.

KEYWORDS: Comprehensive Design, Integrative Design, Sustainability, Architectural Education, Pedagogy

1. INTRODUCTION

Today, architects are being asked to design buildings for various performative goals including energy efficiency, high indoor environmental quality, and occupant health and wellness. To meet these goals in practice, architectural design is a collaborative process engaging various professionals including, among others, architects, engineers, and contractors. Typically, the architect leads the design development in communication with the project team members who are responsible for designing the various building systems. Through the education to be a designer and coordinator, it is essential to know how structure, enclosure, and multiple building systems interact and integrate into a building design.

The complexity of this endeavor is the reason comprehensive design has been emphasized in architectural education. Recently, there has been a concomitant interest in high-performance and sustainable design, which further emphasizes the need for a comprehensive approach. To promote the necessary knowledgebase, most architecture programs in the US offer a comprehensive design studio as a mandatory course. Although there has been a consensus about the need for a comprehensive design approach, there have been few discussions on how the design studio should be defined and structured in architectural education to support the aforementioned goals.

The present study explored various comprehensive design studios offered in architecture programs in the US and conducted a comparative analysis. The research goal was to identify the characteristics of a successful comprehensive design studio and how the pedagogical model can be approached. To achieve this goal, three cases in different architecture programs were selected, and case studies, including the relevant document analysis and the communication with the instructors, were conducted. Emphasis was placed on how sustainability issues could be integrated into the conventional comprehensive studio framework.

2. BACKGROUND

Bovill, Gardner, and Wiedemann (1997) stated that architects are "rarely the maker of the built form," and Comprehensive Design Studio (CDS) teaching demonstrates that "design does not end with the broad architectural idea" (p. 84). CDS shifts "the pedagogic focus, time and effort from schematic to design development" (Bermudez & Neiman, 2005, p. 176). Also, CDS provides students with more critical exposure to the technical parameters and helps them utilize the information for their design iterations in the schematic design phase (Chung, 2014). Due to this specificity, the studies regarding CDS teaching have been published in the literature, particularly in journals and conferences regarding sustainable buildings and architectural education. Recently, with increasing concerns about climate change, there has been a trend to integrate various sustainability issues into the CDS framework.

Chung (2014) integrated building performance issues, that were previously taught in a building science lecture course, into his CDS framework. Applying the knowledge learned from the lecture to their own projects, students could test various types of building performance analyses as a meaningful design tool. In the case of Homer (2006), structural issues were integrated into the CDS framework in collaboration with the architectural engineering faculty and students. Criticizing the separation of "formalist architecture" and "rationalist architecture" in current education, the instructors of the studio emphasized the necessity of interdisciplinary education with more a holistic design approach (p. 1).

Ambrose (2009) and Stivers (2012) focused on building information modeling (BIM) as an educational platform for CDS education. Ambrose (2009) believed that BIM, which is based on "systems thinking and virtual simulations," would be useful for teaching today's CDS, and using BIM for CDS education would bring about a new way of thinking (p. 757). Similarly, Stivers (2012) introduced a team-taught CDS for a mixed student group from architecture and architectural engineering programs. In this studio, building information modeling (BIM) was employed as the studio design and communication platform due to its benefits for collaborative work.

While the aforementioned articles and papers presented specific study areas or tools, Haglund (2008) focused more on design competitions and grant opportunities as a part of the studio framework. He introduced two CDS studios, which used different design competitions, and compared the experiences to each other. He found that a more successful studio depended on the project selection, studio collaborators, and approach to the design issues as professionals. The studio projects won awards in various design competitions as well as a grant with an interdisciplinary team including the Bio-Regional Planning, Conservation, and Social Sciences departments (p. 3).

While the aforementioned articles and papers presented case-based studies, Bermudez and Neiman (2005) discussed the major challenges of CDS teaching based on multiple CDS cases. They defined a CDS as "the academic environment that comes the closest to the practice of architectural design in an office" (Bermudez & Neiman, 2005, p. 172). Due to this environment that is typically managed by a team at an office with a full-time (or an extended) work schedule, CDS instructors and students tend to suffer from a lack of time that leads to underdeveloped projects and uneven learning outcomes. They suggested the following strategies as a solution: an intensive design workshop at the beginning of the semester, teamwork, curricular integration of the technical issues, critical ideology, and analog-digital media migration (Bermudez & Neiman, 2005, p. 174).

3. METHODOLOGY

The present study explored various comprehensive design studios offered in architecture programs in the US and conducted a comparative analysis. The research goal was to investigate the benefits and challenges of the comprehensive design studio (CDS) pedagogical models that introduced sustainability issues. To achieve this, three cases in different architecture programs were selected and analyzed based on the published articles about the courses and course materials. Emphasis was placed on how sustainability issues could be integrated into a conventional CDS framework.

3.1 Case study approach

A case study empirically investigates "a phenomenon or setting" within a real-world context (Groat & Wang, 2013, p. 418) and concentrates on "developing multifaceted analysis of a phenomenon" by using 'thick description' (Silverman & Patterson, 2014, p. 9). Even though a case study has a weakness in generalizability, it offers a "holistic view of a certain phenomenon or series of events" (Noor, 2008, p. 1603). Also, it shows "the embeddedness of the case in its context," thus its real-life situation can be more compelling (Groat & Wang, 2013, p. 441).

3.2 Data collection and analysis

To select the cases, the literature on CDS teaching was thoroughly reviewed and categorized. Based on the literature review, three major issues in sustainability that were integrated into various design studios were identified: building envelope systems, building performance, and the integration of building information modeling (BIM). One case from each of the three categories, was selected for further investigation. One of the important criteria for selecting the cases was the ease of data collection, including the syllabus, assignment briefs,

and student work. The collected data were categorized and compared with each other to understand the commonalities and differences.

4. RESULTS AND DISCUSSIONS

The common challenges of the selected cases were managing the limited time and finding the balance between creativity and technology. The common benefits of the studios were as previously described in the literature: the "insightful balance between theory and practice" (Bermudez & Neiman, 2005, p. 176) and the bridge between academia and professional practice (Bovill et al., 1997; Stivers, 2012). The following sections summarize further details of each case.

4.1 Building envelope systems

In Case A, the studio was composed of the two following design phases. In Phase 1, students designed a High School Center for the Performing Arts based on a given building program. They developed and represented the design ideas with architectural drawings that included site plans, floor plans, elevations, sections, and models. In Phase 2, building envelope systems were specifically highlighted, which required wall sections and section details of the building that students developed in Phase 1. Each phase was connected to a different design competition, and students had an option to submit their proposals to the competition at the end of each phase. The first competition was organized by an association specializing in space design for education, and the second competition was organized by an association with expertise in building envelope systems.

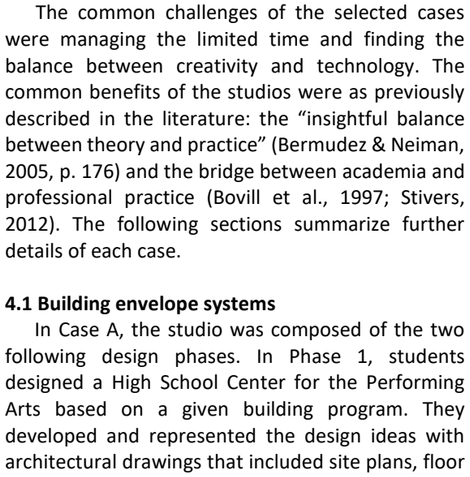

Figure 1:
Preliminary sketches of the floor plans and building sections ©Jacklynn Benfield

Professionals from the associations were invited to the studio reviews and supported the students' idea development. Figure 1 demonstrates a student project developed in Phase 1.

Within the aforementioned framework, students studied, discussed, and presented the following areas of their building design in the studio throughout the semester:

1. Project thesis–-the central ideas of the design approach
2. Pre-design–interaction with the building program
3. Site design - responses to contextual and physical site characteristics
4. Codes and regulations – responses to relevant codes and regulations including the principles of life-safety and accessibility standards
5. Structural systems – principles of structural systems including their ability to withstand gravitational, seismic, and lateral forces, how the selected structural systems support the design thesis and express the underlying ideas
6. Environmental systems – how the environmental systems integrate with the aesthetic qualities of the design, address building orientation, employ passive and active strategies for thermal comfort and indoor air quality, provide good-quality lighting, and address acoustical concerns
7. Building envelope systems and assemblies – building envelope systems and how the systems address the aesthetics, moisture transfer, durability, energy, and material resources
8. Building service systems - lighting, mechanical, plumbing, electrical, communication, vertical transportation, security, and fire protection systems

While these areas followed the typical requirements in a CDS, the specific focus on the building envelope in Phase 2 with the involvement of building envelope experts was a distinguishing part of this studio, which enabled more in-depth learning about building envelope systems and details. Through conversations with the experts, students gained a better understanding of their building skins and how technical issues affect the design. Figure 2 shows a wall section drawn by a student in the second phase.

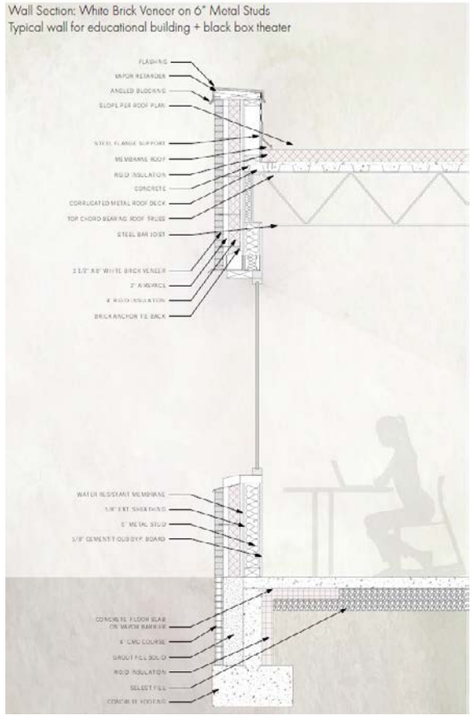

Figure 2:
Wall sections ©Jacklynn Benfield

4.2 Building performance

Case B was a team-taught graduate-level CDS that focused on low-energy housing projects. Considering the transition of the architectural design trend from an "aesthetic and assembly-oriented trajectory" to a "comprehensive understanding of the relationship between design thinking and building performance" under the goal of sustainable design, this studio addressed the building performance issues in collaboration with the Master of Science in High- Performance Building program (Gamble, Gentry, Augenbroe, & Technology, 2015, p. 68). Utilizing design competitions as a driver of the project, the studio consisted of the following stages (Gamble & Rakha, 2019):

1. Body, Space, and Systems Ideation – focusing on space programming/planning and building systems
2. Body, Enclosure, and Site Ideation - focusing on the site analysis/planning and building envelope
3. 2 Family Prototype Aggregate - development of scalable 2-family domestic prototype
4. Multi-scale Family Prototype Aggregate – development of multi-family domestic prototype

Following this structure, the Master of Architecture students had weekly meetings with the Master of Science students who served as their building performance consultants. In the meetings, various technical issues were discussed in-depth, and building performance analyses were applied to students' projects. The students collaborated for building performance simulations of the project using various simulation tools that can be plugged into Autodesk or Rhino/Grasshopper software. Conducting the building performance simulations from the early stages of design allowed the students to develop more environment-responsive design ideas and broaden the topics of their applied research. Through the meetings and simulations, the environmental impacts of the proposed passive and active design strategies were tested. A specific focus was technically "provable" parts of the building's performance including the energy use and the greenhouse gas emissions of the project (Gamble et al., 2015). Figure 3 shows one of the lighting performance studies conducted by a student team during the studio.

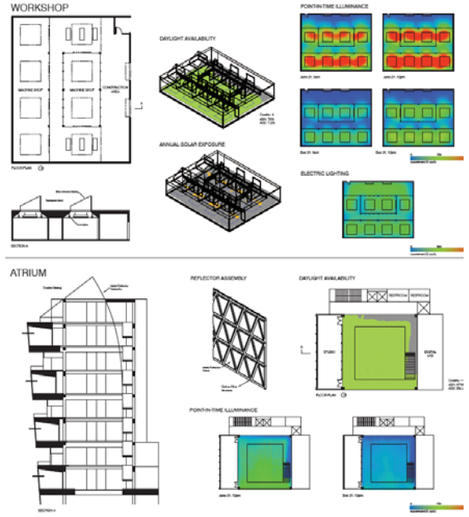

Figure 3:
Lighting performance simulations © www.zedhstudio.com

In addition to the collaborations among the students, the dissemination of the design outcomes and the connection with various industrial partners were also a remarkable part of the studio. The industrial partners, encompassing human-scale furniture, building-scale performance issues, and community-scale sustainability, sponsored the studio and served as external critics for the studio reviews. Moreover, the student work and the studio activities were published on the studio website each

semester, which helped students stay motivated and expose their work to the public. These efforts to communicate with a third party, such as sponsors and public, became an effective way of gaining a fresh perspective and spreading the vision of the studio about sustainable architecture to the realm outside academia. Although the collaborations primarily concentrated on the incorporation of building physics and energy-efficient design technologies into the studio, such as construction methods and innovative building materials, the instructors acknowledge that urban-scale issues should be a key part of the project as well, which may prompt more community engagement and debates on sustainable housing in "urban areas with increasing density" (Gamble et al., 2015, p. 85). Figure 4 shows one of the outcomes of this studio.

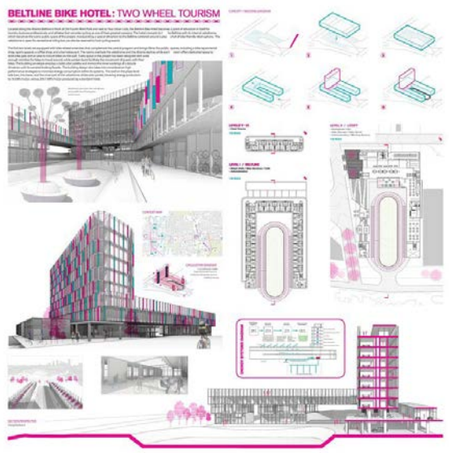

Figure 4:
Beltline bike hotel project © Gabriella Melendez

4.3 Integration of BIM

In Case C, Building Information Modeling (BIM) was employed as the design idea development and assembly platform for the studio's "systems thinking" approach proposed by Meadows (2008). A system refers to an "interconnected set of elements that is coherently organized in a way that achieves something" and is composed of "elements, interconnections, and a function or purpose" (Meadows, 2008, p. 11). The studio framework emphasized these three components that can be translated into Adaptive Assemblies, building programs, and site information in architectural projects. Adaptive Assemblies in this studio was an exercise to develop three main structure and building envelope systems, a porous wall, a retaining wall, and a green roof assembly, that show the building materials and key factors responding to the site condition and building program (Palagi, 2019).

Different from the conventional building design process, which typically progresses from large-scale volume studies to small-scale section studies, this studio required the project to begin with an Adaptive Assemblies exercise that included section detail studies. This reversed approach allowed the students to explore the materiality of the buildings and human-scale experiences first, which could become a logic for creating a building form. With this approach, students could read their project as a system rather than an aesthetic object. The axonometric studies in the second stage connected the microscale studies with the macroscale circulation and spatial adjacencies. The process of this transition from microscale to macroscale is illustrated in Figure 5.

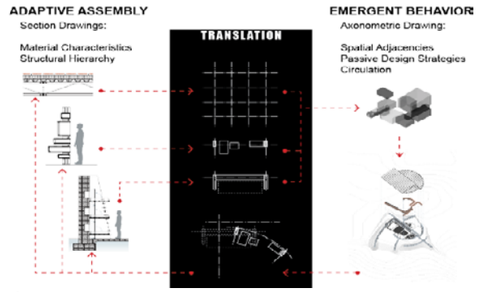

Figure 5:
Process of translation between the two methods of investigations – Adaptive Assembly and Axonometric studies © A. Verastegui, Kris Palagi

The primary platform for these investigations was the parametric modeling environment in Revit, the most popular building information modeling (BIM) software. Since more and more architects and engineers utilize BIM in the industry, students could be prepared for their future collaborations with this opportunity of using a BIM platform for their projects. Furthermore, the parametric function of the tool and the embedded information on the materials and structural members supported students' systematic and multidisciplinary thinking. Stivers (2012) mentioned that the real-time "quantitative and qualitative feedback" that designers receive from BIM can justify the concept "beyond its subjective functional or aesthetic qualities," and this interaction ultimately impacts the designers' thinking processes. Despite the benefits of using BIM in the studio framework, the instructors found that the application of BIM was more challenging for students than professionals, specifically due to the limited time and the difficulty in finding a balance between critical thinking and automated design.

Landscape, community, and social equity issues were also addressed in Case C. In collaboration with a landscape design/civil engineering studio, this studio proposed a pavilion for a community farm that could be an architectural solution to the food desert problem in the project site area. The regular meetings with landscape and civil engineering student groups throughout the semester gave students an opportunity for interdisciplinary thinking and integrating community issues into an architectural project. However, time management was the challenging part of the studio, specifically with the gap between the community and the building scales. Figure 6 shows a student project in Case C, which proposed an Urban Food Hub Distribution Center.

Figure 6:
Urban Food Hub Distribution Center © Dylan Roth

5. CONCLUSION

The present study investigated different types of CDS education and identified the common challenges and benefits of integrating sustainability issues into comprehensive design studios. CDS generally occurs at the end of an architectural education, and students have an opportunity to apply the knowledge learned in lecture courses to their projects (Stivers, 2012). The studio's duration was insufficient to accomplish work reaching the level of design development, in part owing to students' lack of knowledge and experience. Considering that this was the most challenging part of the studio teaching in all cases, students may need to have more opportunities for the application of knowledge to their projects starting from the earlier stages of their education. Despite the challenges, all the investigated cases were successful enough to win awards in various design competitions and give students an opportunity to face a broader audience outside their programs. The limitation of the present study may be the number of investigated cases, which may not be sufficient to generalize the findings. Therefore, future studies may be expanded to additional cases and can be a catalyst for further discussions among architectural researchers, educators, and professionals.

ACKNOWLEDGEMENTS

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Delivering the Sustainable Development Goals

The role of the architecture professional framework in the Urban context

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ABSTRACT: This paper explores the scope that the role of the architect offers in the delivery of the United Nations Sustainable Development Goals (SDGs), with a particular emphasis on practice in the urban context. During the work of the Royal Institute of British Architects' (RIBA) Ethics and Sustainable Development Commission a critical review of the potential relationship between architectural practice and the SDGs, quantitatively and qualitatively evaluating this scope was undertaken. This paper seeks to further this analysis, while considering the extent to which architectural education, as described and framed by both formal (Architects Registration Board (ARB) and RIBA validation criteria) as well as two informal frameworks (the Cross-Industry Action Group's (CIAG) Climate Framework and the Architects Climate Action Network's (ACAN) Climate Curriculum Education Toolkit v1.1). This paper presents and discusses a systematic critical content analysis of these educational criteria against the RIBA commissions' review of potential influence of practice and provides a clear critique that, without reinforcement and enhancement of educational criteria, Architectural practice will not be enabled to deliver on its potential to support the development and delivery of a holistically sustainable future, particularly in the urban context.
KEYWORDS: Sustainable Development Goals, Architect, Architectural Practice, Education, Urban.

1. INTRODUCTION

Since their publication in 2015 [1], the 17 Sustainable Development Goals (SDGs) have been adopted internationally, across government, industries, institutions and academic disciplines. The SDGs are intended to be universal and through action, collaboration and alignment across the world, their integrated framework aims to scaffold the delivery of sustainable development across its three pillars (economic, environmental and social). In the context of UK Architecture, the SDGs formed the basis for and heavily informed the work of the Royal Institute of British Architect's (RIBA) Ethics and Sustainable Development (ESD) Commission during 2018-2020 [2]. The Commission, among its wider aims, sought to clarify the role of architectural professional practice and architectural education to support the global ambition underpinning the SDGs. Furthermore, SDGs have implicitly and explicitly shaped the work of the Cross Industry Action Group's (CIAG) Climate Framework [3] and informed the Architect's Climate Action Network's (ACAN) Education Toolkit [4].

While it is undisputed that SDG 11 *'to make cities and human settlements inclusive, safe, resilient and sustainable'* provides a clear role for architecture and the wider built environment to engage in sustainable development at an urban scale, a closer look, presented here, highlights the potential that the architectural profession holds in playing a broad, coordinating and facilitating role across the wider SDG scope. It is argued here, that this offers an opportunity for the profession to reassert its central role in synthesising the complexities presented by design and construction of quality, ethically sound and hence sustainable built environments.

Figure 1: The Sustainable Development Goals [5]

2. METHODOLOGY

The insights presented here are the result of a contextualised content analysis of the SDGs and their targets as described in the core United Nations documentation [1] in relation to the potential for influence by the UK architecture profession. This is based on work undertaken and verified through the auspices of the RIBA ESD Commission, whose membership provided expert review of this aspect of the work presented here [6]. Each SDG has a number of constituent targets (average 10 / range 5 – 19) laid out. An example of a Goal and its constituent targets is provided below (Figure 2). It is noteworthy to appreciate that the constituent targets have 2 categorisations: '*Outcome'* (numbered) and "*Means of Implementation"* (lower case alpha). The locus of influence in terms of target type will be further considered during the analysis.

Goal 11, Sustainable Cities and Communities: Make cities and human settlements inclusive, safe, resilient and sustainable	Outcome	11.1	By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums
		11.2	By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons
		11.3	By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries
		11.4	Strengthen efforts to protect and safeguard the world's cultural and natural heritage
		11.5	By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations
		11.6	By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management
		11.7	By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities
	Means of implementation	11.a	Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning
		11.b	By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015\2030, holistic disaster risk management at all levels
		11.c	Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials

Figure 2: Example of SDG 11 and its constituent Targets

The content analysis presented here reviewed the potential for architectural practice to influence each of these targets, using a 4 point qualitative scale reflecting a no, low, medium or high potential for practice influence. Further, the scope of existing educational frameworks is also reviewed, using the lens of the SDGs. These include: the revised Architects' Registration Board (ARB) validation criteria [7], whereby successful achievement of all 3 parts of validated study provides for registration as an Architect in the UK; the RIBA validation criteria [8] achievement of which enables membership of this association. These formal frameworks, are each complementary to the QAA Benchmark for Architecture [9] and were reviewed alongside two informal educational frameworks: the CIAG Climate Framework [3], developed *"to unite the industry and academia, in the effort to upskill and build our collective capacity for climate action"*; and the ACAN Climate Curriculum Education Toolkit [4], developed **"***to provide guidance & resources for architecture schools to move rapidly towards a new climate education".*

The content analysis of these educational frameworks presented here aims to identify gaps in current educational statutory requirements, against the broader ambitions for the architectural profession to support and promote the delivery of the SDGs across the built environment. The focus here and in the discussion is on the locus of higher-level potential for professional influence intersecting with an absence of clear pedagogical focus in the educational frameworks.

3. RESULTS

The results presented below are presented in 3 sections. Where section 3.1 presents the review undertaken by the RIBA ESD Commission at the level of targets, evaluating theoretical influence by professional Architectural practice. Section 3.2 represents a comparable content analysis review of the 4 educational frameworks. The discussion section then presents specific critical review of the educational frameworks for those targets that were identified by the RIBA ESD Commission with potential high level of influence by the profession.

3.1 Architectural Profession's Theoretical Potential influence on SDG Targets.

Following the content analysis of the SDGs against the potential for professional influence by architects in practice, it is clear that the scope for influence is focussed mainly in five SDGs: Goal 11: *(Make cities and human settlements inclusive, safe, resilient and sustainable);* Goal 12 *(Ensure sustainable consumption and production patterns)*; Goal 13 *(Take urgent action to combat climate change and its impacts)*; Goal 7 (*Ensure access to affordable, reliable, sustainable and modern energy for all)* and Goal 6 *(Ensure availability and sustainable management of water and sanitation for all)*. While Goal 14 - *Conserve and sustainably use the oceans, seas and marine resources for sustainable development*, was found to be the furthest removed from architectural influence.

Goals & Targets	Total no. of Targets	Potential Professional Influence			
		Low (1)	Med (2)	High (3)	Weighted Avg.
Goal 11, Sustainable Cities and Communities	10	0	0	10	3.00
Goal 12, Responsible production and consumption	11	1	1	8	2.45
Goal 13, Climate Action	5	0	1	3	2.20
Goal 7, Affordable and Clean Energy	5	1	2	2	2.20
Goal 6, Clean Water and Sanitation	8	2	3	3	2.13
Goal 4, Quality Education	10	0	2	5	1.90
Goal 16, Peace, justice and strong institutions	12	1	3	5	1.83
Goal 8, Decent Work and Economic Growth	12	4	1	5	1.75
Goal 15, Life on land	12	1	4	4	1.75
Goal 9, Industry, Innovation and Infrastructure	8	0	2	3	1.63
Goal 17, Partnerships for the Goals	19	0	0	9	1.42
Goal 10, Reduced inequalities	10	1	2	3	1.40
Goal 5, Gender Equality	9	2	2	2	1.33
Goal 3, Good health and Well-being	13	5	3	2	1.31
Goal 1, No Poverty	7	2	2	1	1.29
Goal 2, Zero Hunger	8	5	2	0	1.13
Goal 14, Life below water	10	0	3	1	0.90

Figure 3: Summary Relationship between Architectural Practice and the SDGs

3.2 Architectural Education and the SDGs

As noted earlier 4 educational frameworks were reviewed for this study: ***1. the ARB Criteria*** [7] comprises "General Criteria", (GC) which describe subject material to be addressed by students within ARB prescribed courses alongside "Professional Criteria" (PC) for Part 3 as well as "Graduate Attributes" (GA); ***2. the RIBA Validation Criteria*** [8], describes the 6 Themes and Values (T&V) that must be reflected in student's work in order for courses to be validated, alongside graduate attributes (GA) for

parts 1 & 2 as well as additional T&V for Part 3 (notably these are encouraged to be read alongside the RIBA sustainable Outcomes publication [10], that reinforces association with 9 of the SDGs (3, 6, 7, 8, 9, 11, 12, 13 & 15); ***3. The ACAN Toolkit*** [3] is framed by 9 Principles alongside Teaching Ideas and ***4. The CIAG Framework*** [4] presents global & built environment contexts and common threads as essential background knowledge to 6 no. overarching themes.

Goals & Targets	Coverage in Educational Criteria & Frameworks				Average
	No (0)	Low (1)	Med (2)	High (3)	
	ARB Criteria	ACAN Toolkit	RIBA Criteria	CIAG Framework	
Goal 13, Climate Action	1	2	3	3	2.25
Goal 7, Affordable and Clean Energy	1	2	3	2	2
Goal 12, Responsible production and consumption	1	1	2	3	1.75
Goal 15, Life on land	1	2	2	2	1.75
Goal 11, Sustainable Cities and Communities	1	1	3	2	1.75
Goal 4, Quality Education	1	2	1	2	1.5
Goal 3, Good health and Well-being	1	1	2	2	1.5
Goal 6, Clean Water and Sanitation	1	1	2	2	1.5
Goal 16, Peace, justice and strong institutions	1	1	1	2	1.25
Goal 14, Life below water	1	1	1	1	1
Goal 8, Decent Work and Economic Growth	1	0	2	1	1
Goal 9, Industry, Innovation and Infrastructure	1	0	2	1	1
Goal 1, No Poverty	0	1	1	1	0.75
Goal 17, Partnerships for the Goals	0	2	0	1	0.75
Goal 2, Zero Hunger	0	0	0	2	0.5
Goal 10, Reduced inequalities	0	1	0	1	0.5
Goal 5, Gender Equality	0	0	1	0	0.25
Weighted Average (3 = Max)	0.71	1.06	1.53	1.65	1.24

Figure 4: Summary Relationship between Architectural Education Criteria & Frameworks and the SDGs

Following the content analysis of these educational criteria and frameworks against the 17 SDGs, the focus for coverage is also found in 5 SDGs. However, while goals 7, 11, 12 and 13 are aligned to the findings of the professional review; Goal 15 – (*Protect, restore and promote sustainable use of terrestrial ecosystems…)* represents a different focus. Further, it can be seen that the ARB criteria, one of the formal, curriculum frameworks is least aligned, not surprising since it makes no reference to the SDGs; while the CIAG framework, an informal guidance document, is most explicitly aligned to 12 of the SDGs, indeed this stated relationship is illustrated in Figure 5.

Figure 5: The CIAG framework & the SDGs [4]

4. DISCUSSION

The following critical review presents an SDG target level assessment of the extent to which those targets that were identified by the RIBA ESD Commission with a high potential for impact by the profession, are addressed within the 4 educational frameworks (NB: Only SDG 2 is not considered here). A simple RAG rating system is employed to illustrate coverage within the frameworks, where red indicates no explicit coverage, amber, some relevant criteria and green, clear coverage. Where there is no green rating for a target in any framework, this is taken to indicate a gap in educational guidance.

For **Goal 1.** *End poverty in all its forms everywhere* there is 1 (O) target that has a high potential for influence through architectural practice Across the educational frameworks it can be seen that there are no gaps in educational coverage for this SDG, although no formal validation criteria address this target.

SDG 1. High Potential Targets		ARB	ACAN	RIBA	CIAG
1.5	Reduce exposure & vulnerability to extreme events & disasters				

Figure 6. SDG 1 High Potential Target – Educational Framework Coverage

For **Goal 3.** *Ensure healthy lives and promote well-being for all at all ages* there are 2 (O) targets that have a high potential for influence through architectural practice. Where target 3.6 (*Halve the number of global deaths and injuries from road traffic accidents*) is not addressed clearly in the educational frameworks. However, all raise the need for consideration of sustainable, active and public transport and such action, is likely to lead to beneficial impact on target 3.6.

SDG 3. High Potential Targets		ARB	ACAN	RIBA	CIAG
3.6	Halve the no of global deaths & injuries from road traffic accidents				
3.9	Substantially reduce air, water and soil pollution & contamination				

Figure 7. SDG 3 High Potential Target – Educational Framework Coverage

For **Goal 4.** *Ensure inclusive and equitable quality education and promote lifelong learning Opportunities for all* there are 3 targets (2 (O) / 1 (MoI)) that have a high potential for influence. While, across the educational frameworks there are no gaps in educational coverage for this SDG.

SDG 4. High Potential Targets		ARB	ACAN	RIBA	CIAG
4.4	Skills development				
4.7	Develop knowledge & skills for SD				
4.a	Build & upgrade education facilities				

Figure 8. SDG 4 High Potential Target – Educational Framework Coverage

For **Goal 5.** Achieve gender equality and empower all women and girls there are 2 (O) targets that have a high potential for influence through architectural practice. For target 5.1 (*End all forms of gender discrimination*) and 5.5 (*Ensure women's full and effective participation at all levels of decision making*) there is no explicit coverage in the educational frameworks. Given the ongoing concerns for gender and diversity in the architectural profession, as evidenced by the RIBA's 2018 publication [10] *Close the Gap: Improving gender equality in practice,* that reported *"Architecture has proportionally fewer women compared to law or medicine and the profession also needs to be more accessible for lower income candidates, ethnic minorities and architects who have qualified internationally."* The low profile of this agenda in the educational frameworks is thus of concern.

SDG 5. High Potential Targets		ARB	ACAN	RIBA	CIAG
5.1	End all forms of gender discrimination				
5.5	Ensure women's full & effective participation at all levels				

Figure 9. SDG 5 High Potential Target – Educational Framework Coverage

For **Goal 6.** *Ensure availability and sustainable management of water and sanitation for all* there are 3 targets (2 (O) / 1 (MoI)) that have a high potential for influence through architectural practice. Where target 6.a *International support for water and sanitation* requires further enhancement. In particular the global context, and support of global sustainable development would benefit from reinforcement in the context of ethical and professional practice.

SDG 6. High Potential Targets		ARB	ACAN	RIBA	CIAG
6.3	Improve water quality, increase recycling & reuse				
6.4	Increase water-use efficiency				
6.a	International support for water & sanitation				

Figure 10. SDG 6 High Potential Targets – Educational Framework Coverage

For **Goal 7.** *Ensure access to affordable, reliable, sustainable and modern energy for all* there are 2 targets (1 (O) / 1 (MoI)) that have a high potential for influence through architectural practice. Across the educational frameworks there are no gaps in educational coverage for this SDG.

SDG 7. High Potential Targets		ARB	ACAN	RIBA	CIAG
7.3	Energy efficiency				
7.a	Facilitate access to clean energy research & technology				

Figure 11. SDG 7 High Potential Targets – Educational Framework Coverage

For **Goal 8.** *Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all* there are 5 (O) targets that have a high potential for influence through architectural practice. Across the educational frameworks there are no gaps in educational coverage for this SDG, although no formal validation criteria address targets 8.2, 8.7 or 8.8.

SDG 8. High Potential Targets		ARB	ACAN	RIBA	CIAG
8.2	Achieve higher levels of economic productivity				
8.4	Improve global resource efficiency in consumption & production				
8.5	Achieve full & productive employment				
8.7	Eradicate forced labour, modern slavery, human trafficking & child labour				
8.8	Protect labour rights				

Figure 12. SDG 8 High Potential Targets – Educational Framework Coverage

For **Goal 9.** *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation* there are 3 (O) targets and for For **Goal 10.** *Reduce inequality within and among countries* there are 3 (O) that have a high potential for influence through architectural practice. Across the educational frameworks there are no gaps in educational coverage for these SDGs.

SDG 9. High Potential Targets		ARB	ACAN	RIBA	CIAG
9.1	Developing quality, reliable, sustainable & resilient infrastructure				
9.4	Upgrading infrastructure & retrofit industries to make them sustainable				
9.5	Upgrade the research & technological capabilities of all sectors				

Figure 13. SDG 9 High Potential Targets – Educational Framework Coverage

SDG 10. High Potential Targets		ARB	ACAN	RIBA	CIAG
10.2	Empower & promote the social, economic & political inclusion of all				
10.3	Ensure equal opportunity & reduce inequalities of outcome				
10.7	Facilitate orderly, safe, regular and responsible migration & mobility of people				

Figure 14. SDG 10 High Potential Targets – Educational Framework Coverage

For **Goal 11.** *Make cities and human settlements inclusive, safe, resilient and sustainable*, there are 10 targets (7 (O) / 3 (MoI)) with high potential for influence through architectural practice. However, the themes relating to housing (11.1), cultural and natural heritage 11.4), green and public spaces (11.7) and the support of least developed countries (11.c) require further enhancement and no formal validation criteria address any of these Urban related targets.

SDG 11. High Potential Targets		ARB	ACAN	RIBA	CIAG
11.1	Housing / Slums				
11.2	Sustainable transport				
11.3	Sustainable Urban planning				
11.4	cultural and natural heritage				
11.5	natural disaster				
11.6	urban air quality and waste management				
11.7	green and public spaces				
11.a	Urban peri urban / rural links				
11.b	integrated sustainable planning				
11.c	Support least developed countries				

Figure 15. SDG 11 High Potential Targets – Educational Framework Coverage

For **Goal 12.** *Ensure sustainable consumption and production patterns*, there are 8 targets (7 (O) / 1

(MoI)) that have a high potential for influence through architectural practice. While the target addressing Sustainability company reporting (12.6) requires further enhancement.

SDG 12. High Potential Targets		ARB	ACAN	RIBA	CIAG
12.1	Sus Consumption & Production Patterns				
12.2	Natural resources use & management				
12.4	Environmentally sound waste management				
12.5	Reduce waste production				
12.6	Sustainability company reporting				
12.7	Sustainable public procurement practices				
12.8	SD & lifestyle promotion				
12.a	Sustainable patterns of consumption & production				

Figure 16. SDG 12 High Potential Targets – Educational Framework Coverage

For **Goal 13.** *Take urgent action to combat climate change and its impacts* there are 3 (O) targets that have a high potential for influence. Across the educational frameworks no gaps in educational coverage were found, although no formal validation criteria address target 13.1 *climate related hazards and natural hazards.*

SDG 13. High Potential Targets		ARB	ACAN	RIBA	CIAG
13.1	climate-related hazards and natural disasters				
13.2	climate change strategies and planning				
13.3	climate change awareness / education				

Figure 17. SDG 13 High Potential Targets – Educational Framework Coverage

For **Goal 14.** *Conserve and sustainably use the oceans, seas and marine resources for Sustainable development* there is 1 (O) target that has a high potential for influence through architectural practice, that is well considered across the educational frameworks.

SDG 14. High Potential Targets		ARB	ACAN	RIBA	CIAG
14.2	Sustainable management protection & restoration of water ecosystems				

Figure 18. SDG 14 High Potential Targets – Educational Framework Coverage

For **Goal 15.** *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss* there are 4 (O) targets that have a high potential for influence through architectural practice. It can be seen here that there is complete coverage of all of these targets across the educational frameworks.

SDG 15. High Potential Targets		ARB	ACAN	RIBA	CIAG
15.3	Restoration of degraded land & soil				
15.2	Reduce the degradation of natural habitats				
15.8	Reducing the impact of invasive alien species on ecosystems				
15.9	Integrating ecosystem & biodiversity values into planning				

Figure 19. SDG 15 High Potential Targets – Educational Framework Coverage

For **Goal 16.** *Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels* there are 5 targets (4 (O) / 1 (MoI)) that have a high potential for influence It is however, clear that the targets relating to *reducing corruption and bribery* (16.5) *and developing effective accountable and transparent institutions* (1.6) require further enhancement.

SDG 16. High Potential Targets		ARB	ACAN	RIBA	CIAG
16.3	Promoting the rule of law				
16.5	Reducing corruption & bribery				
16.6	Developing effective, accountable & transparent institutions				
16.7	Ensuring responsive, inclusive, participatory & representative decision-making				
16.b	Promoting non-discriminatory SD policies				

Figure 20. SDG 16 High Potential Targets – Educational Framework Coverage

For **Goal 17.** *Strengthen the means of implementation and revitalize the Global Partnership for SD* there are 9 (O) targets that have a high potential for influence through architectural practice. It is apparent that the target relating to respect of each country's leadership in poverty eradication and sustainable development (17.15) requires further enhancement. While targets 17.17, *encourage and promote effective partnerships* and 17.18 *enhance capacity building support to developing countries*, on data availability are not addressed through formal validation criteria.

SDG 17. High Potential Targets		ARB	ACAN	RIBA	CIAG
17.6	Enhance global cooperation on & access to science, technology & innovation				
17.7	Promote environmentally sound technologies globally				
17.9	Enhance capacity-building in developing countries to support SDGs				
17.14	Enhance policy coherence for sustainable development				
17.15	Respect each country's leadership in poverty eradication and SD				
17.16	Enhance the Global Partnership for SD, & achievement of the SDGs				
17.17	Encourage & promote effective partnerships				
17.18	enhance capacity-building support to developing countries, on data				
17.19	Develop metrics for progress on SD				

Figure 21. SDG 17 High Potential Targets – Educational Framework Coverage

In summary it can be seen that the loci of potential influence for delivery of the SDGs by the architectural profession, is, as yet, not explicitly fully mirrored by either the formal educational validation criteria nor by the emerging informal educational frameworks. The gaps in this analysis of educational validation coverage found 39% of potential high impact SDG targets were not clearly addressed (nos. 1.5, 3.6, 5.1, 5.5, 6.a, 8.2, 8.7, 8.8, ***11.1, 11.2, 11.3, 11.4, 11.5, 11.6, 11.7, 11.a, 11.b, 11.c,*** 12.6, 13.1, 16.5, 16.6, , 17.7, 17.17 & 17.18 (25 of 64no)). However, when all frameworks were taken in combination these gaps were reduced to just 17% (nos. 3.6, 5.1, 5.5, 6.a, ***11.1, 11.4, 11.7, 11.c,*** 12.6, 16.5 & 16.6 (11 of 64no)).

In the absence of such alignment it is difficult to understand how the potential influence, as illustrated in figure 3 can be realised in practice. Especially, while only 41% of Higher Education institutions offering RIBA / ARB accredited education in Architecture are also signatories of the SDG Accord, a public declaration that HEIs will *"Align all major efforts with the Sustainable Development Goals, targets and indicators, including through our education, research, leadership, operational and engagement activities".[11]*

It is hoped that the much-awaited recast of the ARB validation criteria will respond to the gaps in educational frameworks identified here, aligning itself to the SDGs and wider global drivers, reinforcing the potential that the Architectural profession has in delivering a holistic sustainable future across the built environment.

5. CONCLUSION

In its final report, the RIBA Commission invited the RIBA *"...to formally reassert the Institute's unequivocal commitment to placing public interest, social purpose, ethical behaviour and sustainable development at the heart of the Institute's activities and to develop a plan of action based on the UN's 2030 Sustainable Development Goals"*. It is however, notable that many of those targets not currently explicitly addressed are these related to the most significant SDG for the urban environment: **Goal 11**: *Make cities and human settlements inclusive, safe, resilient and sustainable.* Further, it is clear from this study that there is a breadth of potential for the architectural profession to play a key role in driving forward engagement with and delivery of the SDGs, however, what is less clear, is the extent to which architectural education is currently enabling its graduates to be prepared to deliver this transformative action over the vital coming years.

ACKNOWLEDGEMENTS

The work of the commission, its consultative and Youth Consultative groups must be acknowledged [6], as are the continued efforts of ACAN and the CIAG in driving forward this professional agenda.

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Evaluating Irish Architectural Education

Towards integrated equitable design excellence in our cities

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ABSTRACT: There are gaps in the integration of sustainable design into architectural education which produces graduates unable and unskilled to contribute to the provision of healthy, liveable and equitable cities and spaces. In order to examine the current practice of equitable sustainable design integration into architectural education, this paper scales up from consideration of particular sustainability metrics or methods and considers the wider picture of design values, culture, and approach. Though the context is focused on architectural education in Ireland, findings are relevant to other schools of architecture faced with similar integration challenges. Interview memos from 45 educators in Irish and Northern Irish schools of architecture are analysed using NVivo software in a first-step macro analysis. Findings are framed around the role of culture and curricula, the challenges of integrating of sustainability into them and the readiness of graduates to positively contribute to the sustainable design process. The roles of responsibilities of educators are seen to be key, as well as a prevailing 'othering' and overlaying of sustainability and the promotion of particular principles over others within architectural schools.
KEYWORDS: sustainability in architectural education, sustainable design integration, design culture, education for sustainable design, architectural education

1. INTRODUCTION

The need for change in the conception and delivery of education, specifically to respond with immediacy to challenges such as climate change has long been evident. However, attempts to integrate sustainable design thinking into architectural education have had isolated success; with gaps yet to be bridged for full integration (1). The status quo, with a static focus of design teaching confined to traditional themes of 'good' architectural design which focus on visual, aesthetic and material descriptions of architectural excellence persists.

In order to examine the cause of this persistent status quo and recommend new mechanisms or criteria for an integrated sustainable design approach in architectural education, we must look beyond isolated specifics of particular teaching methods and tools and consider the wider picture of design culture in architectural education. This paper examines this question, focusing on the context of architectural education in Ireland.

Architectural education in Ireland – as elsewhere – is fundamental to providing its students with the bedrock design culture upon which student design projects – and their subsequent built projects - are formulated. The teaching methods used, the curriculum, the signaled school values, the staffs' passions as well as wider contextual influences and challenges are elements which all define that school culture, and which make up the design community of each school. The exposure of graduates to these particular design communities shapes their understanding of what an appropriate design solution is for given contexts, and the extent to which that solution is an equitable one where sustainable thinking is integrated into, rather than bolted onto, the design process. Now more than ever, graduates are working, living, and building in urban environments such as cities; and the ways in which they design sets the extent to which our cities will become holistically sustainable and equitable places for all their inhabitants.

1.1 What is 'good' architectural design?

This paper draws on previous work (2) which defined two distinct but overlapping paradigms of architectural excellence; 'Architectural Design Excellence' (ADE); where the focus remains on traditional areas of focus (e.g., materials, spacial needs, function, and aesthetics) and 'Sustainable Performance Excellence' (SPE) where the focus is on more quantitative measured aspects of environmental performance (e.g., energy efficiency, daylighting metrics, embodied energy factors).

This paper examines findings under these lenses; in order to relate school cultural characteristics to an ADE or SPE led educational approach. The diagnoses of such an approach is with a view to advocating for the adoption of a third, as yet unspecified integrated approach – Holistic Design Excellence (HDE) which would adopt the advantages of both paradigms without threatening or subsuming the other.

2. THE ROLE OF ARCHITECTURAL EDUCATION

2.1 What do we teach and what do we learn?

Architectural education is required to instill in students civic responsibilities, being bound by professional codes of ethics that places societal values centrally and seeks to engender graduates who can achieve excellence in architectural design alongside consideration of wider equity issues addressing the interests of society as a whole (3) to shape a better world; as such, graduates are taught to question and direct design from particular points of view (4) to create "good" architecture through the application of dependable professional education (5). However, the relative importance placed on these responsibilities within education, the factors discussed and their placement within a particular design culture determines the level of success with which sustainability, justice and equity are ultimately approached and delivered within design practice. This is particularly crucial in relation to the current climate emergency challenge, which sees an inequitable impact on the most vulnerable community occupants (6). Whilst traditionally architects are considered to have strong skills to effectively address bigger picture social equity issues, significant occupant health and wellbeing issues remain to be resolved (7).

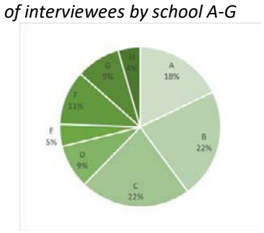
At the heart of the learning outcomes embedded in architectural design education is thus a facilitation of emerging ideas amongst graduates about what constitutes architectural design excellence; and what shapes the framework in which these ideas sit. Integral to this framework is the design culture community of the school and how it frames the role of sustainability and equity within architectural design excellence.

Following analysis of memos of interviews with 45 educators, this paper aims to evaluate this design culture community; and the extent to which it impedes or accelerates the integration of sustainability, the extent to which existing practices of teaching have or can integrate this thinking; as well as the readiness of graduates to deliver upon these to positively impact upon the present and future occupants of the cities and communities in which they work and live. It will discuss these issues, exploring the emphasis of particular decision-making processes that may be more strongly or loosely integrated to holistic, sustainable, and equitable design thinking. As such, this paper explores current principles of architectural design excellence in Irish architectural education, however the themes will have relevance and applicability to architectural education in other contexts facing similar challenges.

3. METHODOLOGY

Purposeful sampling was used to select and interview 45 academic representatives from each of the 8 schools working at different stages, levels and sections of the architectural programmes being delivered in each school. Educators within these schools are key personnel who foster, maintain, and promote the design community within each school. This sample is representative of each of the schools, with smaller schools having a smaller total number of interviewees (Fig 1.); and with interviews continuing until saturation was achieved, as a grounded theory approach to the research was undertaken (8). A semi-structured interview style was adopted and interviews, in the main, took place virtually over 2021 and were recorded and then transcribed. Additionally, directly after each interview detailed reflections on the method, interview observations and emerging themes were recorded. This process involved constant reflection on the emerging theories and themes. These detailed reflections were refined as each interview was transcribed and reviewed. These were then coded and analysed using NVivo software in the first step in a grounded theory data analysis process, and which lay the coding foundations of the second step analysis of the interview transcriptions.

Figure 1:
Breakdown of interviewees by school A-G



3.1 School and interviewees profile

Within the Island of Ireland there are 8 schools of architecture, all set within distinct geographical, physical, and philosophical contexts, and with varying scales. There are 6 schools of architecture in the Republic of Ireland and 2 in Northern Ireland. The schools are anonymized and identified as school A through to H in this study. Although under different regulations and systems, the Northern Irish schools are included in the study as many students and staff attend and move back and forth between the two jurisdictions. The schools vary from being part of universities (5), institutes of technology (2) or technological universities (1)

The schools are geographically dispersed across the island of Ireland and vary in age from older well-established schools to newer ones.

Various programme routes are available with the traditional five-year route the most common. Student numbers vary across the schools with an

average of 34 students per year (Fig. 2). The Architecture schools are positioned mainly in Engineering faculties, followed by Construction Industry related, the Humanities and then the Arts.

For the purpose of this initial coding, which takes the form of a school macro view rather than a specific interviewee micro review, an in-depth profiling of the interviewees themselves is not presented, though interviewees are identified as being either SPE or ADE leaning, with a range of school approaches then included (Fig 3).

Figure 2:
Student numbers

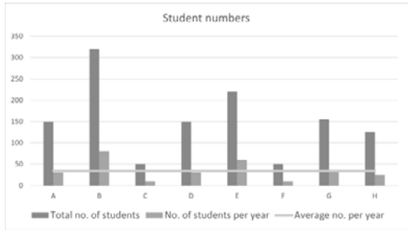
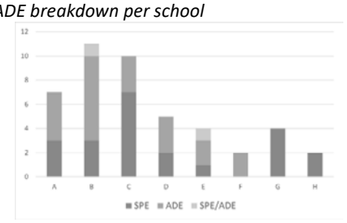


Figure 3:
SPE and ADE breakdown per school



Initial coding revealed 16 broad codes. Though this included themes ranging from faith and morality, relationships and communication, mindset and skillsets, university structures, professional accreditation, role of studio and geographic and own educational influences; this paper focuses on analysis of the 5 most frequent codes which were related to curriculum, sustainability Integration, educators, school culture and students and which also are most relevant in analysing three main research questions, 1. What design curricula and culture frameworks are currently present and what do they emphasise?, 2. What are the challenges in integrating sustainability to these? and 3. Do these sufficiently prepare graduates to positively impact upon the present and future occupants of the cities and communities in which they work and live? Subthemes with most codes related to these questions are discussed below.

3. FINDINGS

3.1 What design curricula and culture frameworks are currently present and emphasized?

The sub-themes with the most codes related to teaching strategies, topics covered, school culture definition and signaling and educator influence. The difficulty in teaching every topic is evident, with educators '*busting [their] guts to teach everything*'. While it is not thought to be possible to cover everything, each project should add to a diverse conversation. However, some conversations are louder than others; covered repeatedly as others are more lightly touched upon, and where sustainability tends to fall into the latter camp. Sustainability for the most part is discussed in terms of an additional 'thing' that needs to be added to the curriculum, and a technological aspect to address. This need to address it as a design performance evaluation is echoed in the traditional tensions between design and technology- the '*poet and the pragmatic*' - which are still evident; with two main teaching strategies present to merge the two: separation or integration to design studio. Two camps are still evident in terms of how studio teaching represents spaces: '*Dreamworld*' (beautiful moody, semi real, pictorial) versus '*RealWorld*' (more realistic the better). These camps align broadly to the authors established concepts of ADE – Dreamworld and SPE- Realworld, with the HDE world that merges the two still not evident.

This is further reflected in a clear tension between the freedom of university and the reality of students learning how to build in the '*Realworld*', and a questioning over the imparting of a skillset or a mindset and the role of professional accreditation in driving curriculum content. Some theory and themes are seen as being first principles (e.g., context, site, regulations, function) that students need to [learn to] have in their heads and others (e.g., cost) as being too practice/reality focused. It is apparent for many that sustainability issues are not seen as part of the first principles theory.

In terms of teaching strategies, a common approach is to view the earlier 1-3 years as laying a foundation; instilling basic competencies that meet professional accreditation needs, and then allowing more complexity, speculation, freedom of thought, abstraction, and open-ended design in later years. Others however feel that architectural education is too broad for too long and should focus much earlier. The year being taught, the project scale and type is relevant in educators emphasizing particular topics and scales of investigation. However, a current obsession with the creation of 'object' buildings as project outputs and the solution to *all* architectural problems is a pervasive theme, with many questioning whether a more radical and flexible pedagogy would broaden solutions.

Studio is seen as the main driver to apply knowledge and signal design values, culture, and approaches. In Irish education, there is widespread use of practitioners as studio educators with temporary contracts. Studios are then related to their practice approach, which is seen as a strength where this yields passionate educators but a weakness when there is little explicit reflection or discussion on what those educator positions are, or what has influenced them. Likewise, the scale of the studio projects relates to the scale of the practice projects which can be limiting. Others noted however that is a *style of process* and not a *design style* being taught, and that their own design values were separated from the design values they taught students; that they '*would not press*' their own personal approach upon students. There appears to be an emerging theme here in terms of a difference in awareness/approach between academic and practitioner educators, with practioners not versed in general pedagogical approaches or aware of wider school values, and due to their limiting contract type without the resources to do so.

The link then between programme and module documentation (e.g., briefs, learning outcomes and assessment methods) and what is actually emphasized and taught in studio is seen as immaterial; easily overridden by educators; with a clear disconnect between what is said that is being taught and what is assessed. In this way the role of the educator is a major responsibility, with huge power and influence exerted. Educators are viewed as leaders, role models, presenting to students *'what they are being built for'*, leading them into a particular world view of architecture. Teaching is thus related to the ethos and values of the practitioner, with these driving the studio and the approach to design, which can be viewed as their '*fiefdom*'. This echoes traditional master and student roles, with educators who '*know everything*' rather than learning alongside students.

3.2 What are the challenges in integrating sustainability to school cultures and curricula?

The sub-themes with the most codes are related to challenges with integrating sustainability to curricula, teaching methods and content for sustainability, educator influence, theory versus practice and opportunities.

The need for integration of sustainability within curricula is very apparent, with some describing it as '*inevitable*'; and the student demand for it palpable. From the staff point of view there is also a will there to integrate it, which many feel could be done '*without too much pain*' however it is acknowledged that it is a new way of thinking, with a significant change in emphasis.

As seen previously sustainability is equated with technological performance, material detailing and -at its broadest - with the Sustainable Development Goals; though these are thought to be so vague to be unapplicable (this relates to an SPE approach). As such it is still overlaid rather than integrated. There is some suggestion that sustainability is more than this, for example history and theory topics could evaluate a '*green elephant card*' in their discussion of precedent.

Although there has been a growth in some ideas which were once radical becoming standard (e.g., showing future flood levels on sections), a danger is seen where sustainability is in words only, where the school say they 'do' sustainability but when student output and briefs are examined more closely it's not there. There is a desire to be able to tick the boxes, point to the 'sustainable bit' of projects or indeed wheel out the sustainability 'expert' for crits and presentations.

For many educators, though their climate literacy is growing, the term 'sustainability' brings baggage, deemed to mean surface level/details, façade, and materials and some – in honesty- proclaim to know as little as the students do, or not enough to pass the knowledge onto students. Where educators have a good understanding of the issues, it is discussed but not overtly pushed, with a view that some of the themes that make up the *'craft'* of architecture are not exclusively *'green'* or *'not green'*.

Any change in curriculum or school culture is difficult to make – particularly as these are seen as *'lumbering, creaking, non-flexible beast[s]'*. Additionally, integrating sustainability is seen as a *'double edged sword'* –that there is a potential danger that it can be the only thing that is championed and '*other things get left behind*'; the need to weave it into and not overthrow 'traditional' design work is evident.

Sustainability is not the primary driver for design, and where schools are using zero carbon ideas as drivers, they are coming in at the middle to end of projects, a detour and very much about application of technology and construction (SPE) rather than a mindset approach at the start of the design process (HDE). Where inroads have been made to integrate it, major structural curriculum changes were required with huge resources and educator and student consulting required.

This cultural difficulty is apparent, with sustainability seen as a threat to the existential as it involves guides, audits, and checks and therefore can be dismissed and mocked as not architecture related (ADE). Many also feel sustainability is an opportune political agenda, and that focusing on it will narrow studio output and displace the craft of architecture (ADE).

Some equate the change of thinking required as part of a larger existential crisis that the whole of architectural education is currently undergoing, that architecture is a *'bit lost'* at the moment; however, others proport that there is lots to do for architects within the sustainability arena - there are interesting practical and ethical discussions that could be born out of it. The barriers then are less about fear and more about a *'sniffiness'* concerning what is seen as an intrusion and a bogging down by what are seen as mundane things outside the true *'craft'* of architectural design excellence (ADE).

3.3 How ready are graduates?

The sub-themes with the most codes are related to student skills, knowledge and attributes, student values and background and the overall purpose of education.

Education is viewed as the need to give students a foundation built on knowledge; however, it is their position in relation to that knowledge (*'teaching students to think'*) that is seen as critical, with graduates needing to have a position and not just be a *'tool'* in practice.

At the start of the student learning journey, programmes, brief setting, and teaching methods need to be sensitive to student backgrounds – both physical, personal and educational - as they influence how students learn, with many defaulting to what they think educators want them to say, in a pavlovian response that is signaled early on. In this way the school culture and educator influence is a major driver of student design approach where a direct line can be drawn between it and student attributes, with students a reflection of their educator's interests. Graduates are taught values, what is good and what is bad. However, they get mixed messages on what is "good" architecture and perceive the educator's view as the only one. It is seen as unhealthy when students are beholden to one opinion and view it as the *only* opinion. At the end of their learning journey therefore, for graduates to be able to exert positive change in their cities and communities students need to be taught sustainability principles and values as innate (HDE) , so it ends up being automatically what they do. This paper posits however that there is still huge disagreement on sustainability as being an innate value that kickstarts a design process rather than a topic to be evaluated somewhere along the way.

4. DISCUSSION

Findings include the resistance of sustainability as a threat to *'real'* design, the role and lack of transparency regarding educator values and the role of school culture; including staff contracts and roles. Sustainability requires didactic teaching methods which embed it in every module. This theory is not necessarily new, but it is clear it is not thoroughly being integrated in Irish architectural education, though on paper it might be there.

Though Students are hungry for sustainably it is evident they are unclear of how architecture is supposed to solve these big global problems. This again suggests an overlaying rather than an integration is happening. This 'othering' of sustainability is a theme that occurs again and again. The reality of pursuing sustainability is seen as tricky as there are still a lot of basics in terms of what makes a good building *in addition* to a sustainability agenda, where sustainability is not viewed as part of or belonging to those foundational basics. Design studio is driven by certain parameters (eg form, space, order), there is a *'craft'* that must be learnt and sustainability sits outside that craft (ADE).

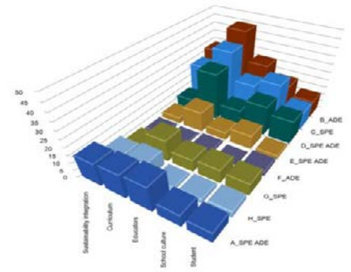
Sustainability is not viewed as a cultural endeavour, with a lack of theoretical context and discourse on sustainable design highlighted. Sustainability is viewed as largely independent of Architecture, not an architecturally defining thing (ADE), instead a technical problem (SPE) which is another constraint that must be dealt with and not themes that are generative of architecture. Where Architecture (with a capital A) is seen as cultural to its core, sustainability is not.

The responsibility of educators in this is critical. What an educator is interested in leads the educational discussions and when every educator has the same [undeclared] interest this is problematic, particularly when new knowledge and skills, such as those related to sustainability, need to be acquiree. It can be very difficult to shake people out of their teaching habits if there is a deep-seated belief that their way is right. The repetition of certain topics, with a lighter or heavier touch is directly linked to the educator and what they emphasize or not. There is pressure on the educator to be *'on'*, that how and what they teach is linked to their personhood, and that part of their role is to demonstrate to students *'[their] version of life'*. It is unclear if this is similar in other disciplines, but what is apparent is the need to acknowledge this aspect openly. The importance therefore of having a diversity of educators and of openly mapping and planning studios around educator interests and values is critical. Aligning teaching teams on values rather than pragmatic issues needs to be considered and if there is a school approach new staff need to be aware of it. Educators may need to separate their values from school ones.

A common teaching strategy is to impart knowledge by repeating basics, but it is not clear who defines those basics. The emphasis needs to shift to start to infuse and embed other ideas into briefs. For this shift in emphasis to be successful, there needs to be leadership to spark it, whether that be the school making changes or accreditation body requirements. Though this structural change is needed, what is more critical is having engaged teachers, and studios which focus on real problems, on the ground issues or live clients which will engage people and has the potential to have a stronger impact than *'you've got to do that'*. The challenge is how you do this in a way that isn't in conflict with the individual or the school culture.

Interestingly, these findings are reinforced quite uniformly across identified school types (Fig 4) with differences in quantity of themes more related to school size, and no overall trends observed at this level which differentiate depth of feeling on themes from one school type over another.

Figure 4:
Themes per school and school type (SPE/ADE/SPE ADE)



4.CONCLUSION

It is still 'beautiful' buildings that get accolades, and although sustainability issues are critical ones, they have not managed to become an issue on an equal footing – the debate over the proportion of art to beauty to mindset to skillset is still raging. If, however, the purpose of education is to teach students to think, there is a need to encourage initiatives which promote self-directed learning that are environmentally and socially conscious, and a need to reframe the overall pedagogical questions being asked away from an othering of ADE versus SPE but towards a HDE.

The Irish education system has institutional and professional frameworks which makes these findings particular to the Irish context, in particular the structure of contract types which see a high proportion of practitioner staff with the most responsibility for instilling in students their ways of thinking; without the time or resources to upskill in climate literacy and without the same access to wider academic supports. Notwithstanding this, (and with the grounded theory meaning any literature review comparison follows analysis), these findings are broadly in line with recent literature which reviewed global approaches in teaching and integrating sustainability; in particular in relation to the need [still] for a more effective approach, curriculum reframing and sustainability as a continuing contested issue (9).

Different schools will have different approaches, whether they are Irish, European, or worldwide. The challenge with integrating sustainability is in allowing a school culture whilst having a flexible and adaptable sustainable design approach that is incorporated into rather than displacing of the craft of architecture; to create an HDE. As such the 'gig' will not be different in each school but how each school responds to it will be. Immersion in HDE as a culture needs to take place rather than the current ongoing application of SPE theory and tools, expecting different results.

The next step is more detailed analysis of the interviewees, which will continue to address the question on how to achieve this – what are the components and strategies needed for a successful HDE school culture and how can you have an overall sustainable school approach without it threatening and diluting school and inter school culture?

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A thousand Thunbergs collaborate towards Net-Zero

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ABSTRACT: India's building sector contributes to 39% of greenhouse gas emissions. Communities have begun to face climate change through heatwaves, droughts, floods, and cloud bursts. Our buildings need to become net-zero, but the building sector currently does not have the capacity to implement net-zero energy buildings. The education curricula also do not provide the necessary training and tools necessary for the workforce to address climate change. The Solar Decathlon India Challenge intends to address this gap by enabling students to learn and design real net-zero buildings. The participating teams were provided learning resources and tools intended to build their capacity in this area. The authors analysed the final reports submitted by the teams to understand if they were able to fulfil the requirements of the Challenge and produce evidence-based designs for their projects. The findings showed that the teams claimed to propose strategies to optimize building performance, but many did not provide evidence and analysis to support their claims. The findings saw that up to 95% of the teams proposed strategies on Energy Conservation Measures (ECMs), while 80% provided evidence for the different types of ECMs. 95% of teams provided evidence for ECMs to reduce envelope loads, and 23% gave evidence for natural ventilation strategies. 95% of teams addressed the 10 contest areas. Up to 95% teams provided evidence for energy and water contests, and 45% of teams provided evidence for affordability and resilience. A total of 43 innovations were proposed by 21 teams, and 47% of the innovations had a direct impact on climate change mitigation. Areas of weakness in the students' ability to provide evidence-based designs need to be identified. Additional resources to improve them and integrate the programme into built-environment education are important to enable stronger capacity building.
KEYWORDS: Architecture, Buildings, Building Performance, Capacity building, Climate action, Education, Energy, Evidence-based design, Net-Zero, Pedagogy, Resilient

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) report, followed by the Glasgow COP26 summit, are unequivocal that climate change is a reality and that it is anthropogenic (IPCC, 2021). Globally communities are already witnessing extreme and unpredictable weather events such as floods, cloudbursts, heatwaves, and droughts with increasing frequencies. In India, summer temperatures are crossing 45°C, and rains have wreaked havoc across coastal regions (Mahapatra, 2018). India is a rapidly urbanising economy with increasing per-capita emissions across sectors. The building sector alone contributes 33% to carbon emissions (RMI India, 2021), and this will increase as we add more cooling to achieve thermal comfort. At COP26, India committed to achieving net-zero by 2070, and this offers the building sector an opportunity to modernise and future-proof our infrastructure in the decades to follow. Net-Zero Energy Buildings (NZEBs) can help reduce energy demand in buildings as they are energy efficient and give back clean electricity to the grid. In the face of the climate crisis, these buildings are the first defence for inhabitants and communities against climate related hazards.

India currently lacks the capacity to design and build NZEBs at the scale needed. Energy codes and rating systems have been introduced, but their uptake and enforcement are weak, and the building sector largely operates in a business-as-usual mode (Garg & Bhadra, 2020). Furthermore, there is a capacity gap among building professionals in designing and implementing NZEBs. Over 500,000 students in India graduate annually out of courses related to the built environment, but a meagre 50 are formally trained to deliver NZEBs (Bhadra et al., 2021). A review of the current education system related to building professions showed that students are not given the training and resources necessary to address climate change in their careers (Manu et al., 2017). Solar Decathlon India (SDI) attempts to address this gap and provides students with learning resources and tools intended to train these professionals in this area. It is an annual 9-month challenge for students to learn and design net-zero-energy, net-zero-water, and climate resilient buildings by partnering with real estate developers and working on real building projects. Modelled on the US Solar Decathlon, SDI intends to create a net-zero design capable workforce by collaborating with industry experts, in India. Solar Decathlons across the world have trained over 30,000 students, and prepared them to enter the clean energy workforce (US Department of Energy & Energy Endeavour Foundation, 2016).

In SDI, which was launched in 2020, students from any undergraduate and post-graduate course from Indian institutions, could participate and learn building science and net-zero design techniques. They formed teams and competed against each other and developed solutions for real building projects. SDI provided the teams with a variety of resources, intended to build their capacity to compete in the Design Challenge. They were provided online Self-Learning Modules (SLMs) on theories and concepts of designing NZEBS, and technical webinars delivered by industry experts who talked about the NZEBs that they have worked on. To help with practical application, tools for cost-benefit analysis and water calculation, licenses to building simulation software, and online simulation training sessions were provided. The teams were also given access to a group of industry expert mentors, called the Technical Resource Group, who are also past participants of Solar Decathlons around the world.

Over the 9-months, the teams submitted 4 deliverables demonstrating their integrated building designs and reported on the ten contest areas of the decathlon namely, Energy Performance, Water Performance, Resilience, Environmental Quality and Comfort, Affordability, Architectural Design, Engineering Design and Operations, Scalability and Market Potential, Innovation and Presentation. SDI also provided a Competition Guide (Solar Decathlon India, 2018) that was intended to guide teams on how to report on the ten contests and the technical information that they should provide in their reports. After each submission, teams received critical feedback from the jury and reviewers.

In the first year, the 2020-21 Design Challenge, 948 students participated and collaborated with 70 industry experts, 165 faculty mentors, 53 real estate developers, and 63 building industry partners. They worked on Whole Building Designs of 12 million sq. ft of real estate and showed reduction possibilities of up to 6 million tons of CO_2 emissions. While reflecting on the impact of the Design Challenge at the end of the first year, the members of the organising team were curious to know whether the teams were able to fulfil the requirements of the Challenge and produce evidence-based designs for their projects.

The organising team studied the final deliverables submitted by the finalist teams. The objectives of the study were:

1. To assess whether the teams
    a. proposed Energy Conservation Measures (ECMs),
    b. addressed the 10 contests of the decathlon
    c. proposed innovations that were intended to mitigate climate change
2. To assess whether teams provided evidence to support their proposed strategies

This paper reports on the method and findings of these assessments. This will enable us to ascertain gaps in the students' learning towards designing NZEBs and identify additional learning resources or milestones in the programme that could help improve their learning.

2. METHODOLOGY

The research was conducted by analysing the Final Design reports submitted by the 22 teams who were chosen as finalists by a group of expert reviewers. These reports contained detailed design documentation related to their projects. The data in the study is limited to the information provided in the reports, and they assess the students' ability to respond to the requirements of the contest. No additional investigation was undertaken to understand the gaps in the reports submitted by the teams. The authors were coordinators for the jurying process of the reports and were familiar with the overall process of the Design Challenge. They had access to the submissions as well as insights into the discussions of the jury.

The research includes three separate analyses. Analysis 1 studied the ECMs that the teams proposed in their designs. First, the authors listed the ECMs that a team proposed and investigated whether they claimed to integrate it into their design. A score of 1 point was given to a team that claimed to integrate an ECM into their project and 0 to those that did not. Next, the reports were investigated for whether the teams provided evidence for the ECMs that they claimed to integrate into their projects. A score of 1 point was given to a team that provided evidence and 0 to those that did not. Overall, 95% of the teams reported on ECMs in their reports. For the different types of ECMs, a range of 64-95% teams claimed to integrate them into their designs, while 23-82% of the teams provided evidence to support their claims.

Analysis 2 studied the different contest areas and how the teams addressed them. The contest areas that were chosen for the analysis were Energy performance, Water performance, Affordability, Resilience on passive performance, Resilience on days of autonomy, Indoor Environmental Quality (IEQ) on Thermal comfort and IEQ on adequate ventilation. A credit score of 1 point was given to a team that attempted to address a contest area and 0 to those that did not. The reports were then investigated for whether the teams provided evidence for each contest area. A credit score of 1 point was given to a team that provided evidence for a contest area and 0 to those that did not. We found that 95% of the teams

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addressed the contest areas. For the different contest areas, a range of 68-95% teams claimed to address the contests, while 45-95% teams provided evidence.

Analysis 3 studied the innovations that the teams proposed and whether the innovations would result in climate change mitigation. A credit score of 1 point was given to a team that proposed an innovation related to climate change mitigation and 0 to those that did not. A total of 43 innovations were proposed by 21 teams, and 47% of the innovations had an impact on climate change mitigation.

The results were analysed to identify gaps in the programme and the challenges of up-skilling students at a large scale.

3. RESULTS

The following results are reported based on the three analyses.

Analysis 1: Energy Conservation Measures

This analysis was carried out on the ECMs that the teams explored with respect to the building envelope (Form, Orientation, Window-to-Wall Ratio (WWR), Fenestration Assembly, Wall-Roof Assemblies, Shading and Daylighting) and integrated systems (Natural Ventilation, HVAC, Lighting, and Equipment). Figure 1 shows the percentage of teams that claimed to integrate a strategy and the number of teams that provided evidence to support their claim.

In this analysis, the authors found that 95% of the teams explored strategies related to wall-roof assemblies as a measure to reduce envelope loads. This is also the strategy with the highest number of teams (82%) providing evidence to support their claim. The teams provided their simulation results as evidence to show how the U-value of a material used for a wall or roof plays an important role in minimizing the heat gain inside the building. This has been explained in the 'Heat Transfer' module provided to the teams as part of the SLMs. They also used the building simulation software provided to them to conduct wall-roof simulations and analyses to optimise building energy consumption.

As the students discussed ECMs to optimize energy and claimed to integrate them into their projects, it shows their awareness of building science. While 86% of the teams reported on strategies for natural ventilation, only 23% of the teams provided any evidence in the form of manual calculations or Computational Fluid Dynamics (CFD) analysis. SLMs on Natural Ventilation and spreadsheet-based tools to calculate ventilation in spaces were provided to the teams, but CFD software and training were not provided.

Daylighting was not a requirement of the Challenge, and no resources related to daylighting were not provided. However, 77% of teams managed to report on this strategy, with 55% providing specific evidence of performance. The teams seemed to have some understanding of daylighting from the existing architecture and built environment curricula.

Equipment load design was the ECM least explored by the teams. While 64% of the teams reported on strategies related to equipment design, only 45% of the teams provided evidence. Learning resources related to equipment load calculation was provided in the SLMs, but it appears that they were unable to do a market analysis to select low energy equipment to improve building performance.

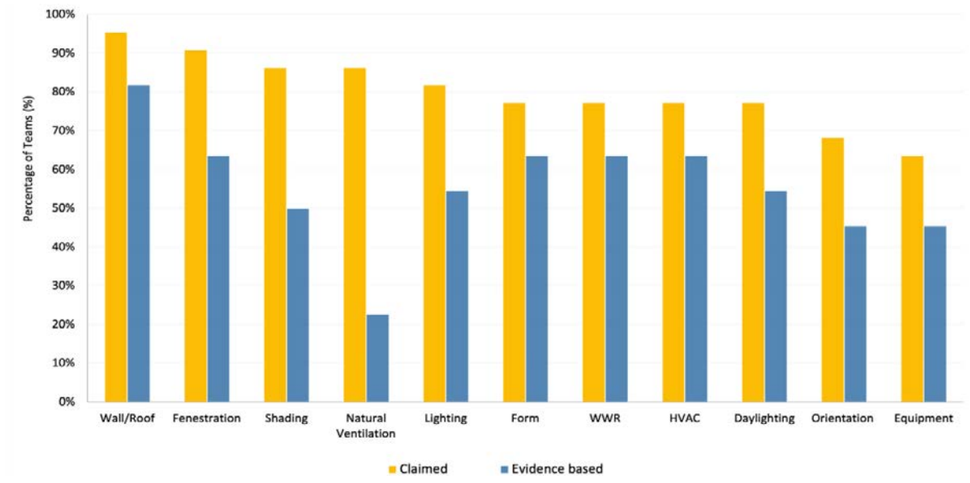

Figure 1 Percentage of teams that claimed to integrate strategies vs percentage of teams that provided evidence

Other strategies that the teams reported and provided evidence for are Form, WWR, Shading, and HVAC. Overall, the teams proposed multiple ECMs and solutions to optimise designs but, there was a lack of evidence-based design implementation of these strategies. Proposing ECMs for optimization comes with awareness of building science concepts. However, the lack of evidence to support the ECMs is possibly because they need more in-depth understanding of these concepts. It is also possible that the teams did not provide evidence because they were not familiar with building simulations.

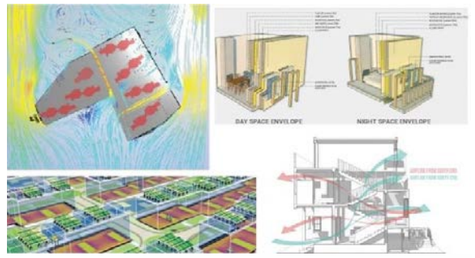

Figure 2 Simulations and design ideas by the teams

Analysis 2: The Contests

Five contests were chosen for the analysis: Energy; Water, Affordability, Resilience in a) passive performance, and b) days of autonomy, and Indoor Environmental Quality (IEQ) in a) Thermal Comfort and b) Adequate Ventilation. Figure 3 shows the overall results of this analysis. On the Water and Energy contests, 95% of the teams reported, and provided evidence using analyses. Since these contest areas have the largest percentage of teams reporting and providing evidence, it appears that students were able to understand the concepts of energy and water well.

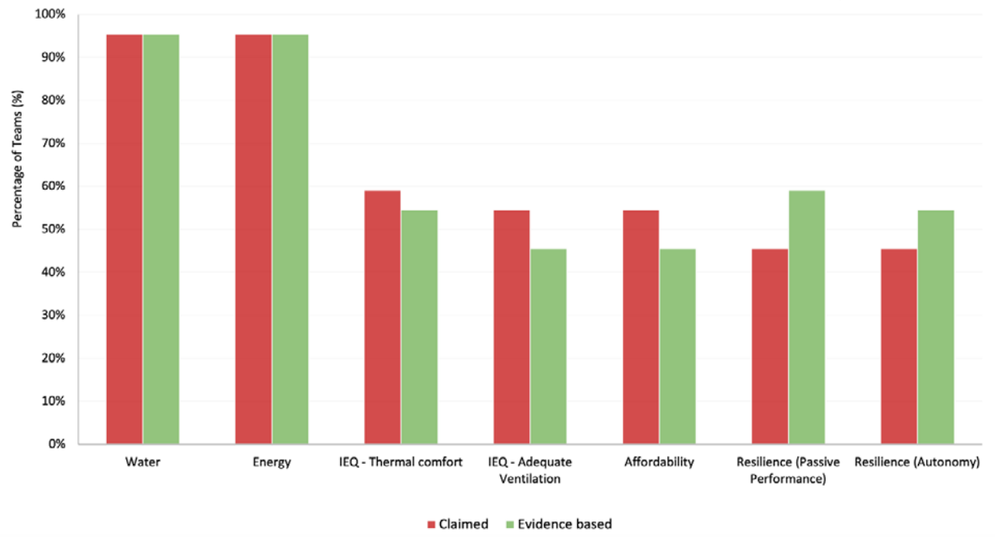

Figure 3 Percentage of teams that addressed the contest vs percentage of teams that provided evidence

While 86% of the teams reported on strategies for thermal comfort, only 55% of the teams provided any evidence in the form of simulations to demonstrate thermal comfort achieved in key spaces during occupied hours and modes of operation. Students were provided with SLMs and resources to demonstrate comfort in the spaces.

Affordability is another contest that the teams had difficulty addressing (73%) and providing evidence (55%). Although, the reporting metrics for affordability was prescribed in the Competition Guide, and various resources for calculating the cost estimations for their project were provided, there seems to be a lack of confidence in reporting on these calculations. The teams may have faced difficulties in procuring rates from the market.

The Resilience contest had the least number of teams reporting strategies. Only 68% of the teams reported strategies on this contest, and only 45% were able to provide minimal evidence to their analyses. Resilience appears to be a new concept to the teams, and they found it difficult to address this contest. An SLM specific to the topic of Resilience was provided, and the reporting metrics were prescribed in the Competition Guide. However, the teams were unable to address it. It can be inferred that more resources need to be provided on calculations and analyses to show autonomy during disasters. It is also important to note that awareness on the topic of resilience is lacking at a pedagogical level and needs to be integrated into the curriculum.

The lack of evidence in the contests except Energy and Water, might be due to inadequate availability of

open-source case studies and literature on the other topics. It could also be due to the lack of guidance from faculty and experts in the industry with whom the teams collaborate for their designs.

Analysis 3: Innovation

This analysis was carried out to evaluate how the teams reported on the Innovation contest and their application of innovative techniques, technologies, and creative business models to enhance performance in the other contest areas. The innovative strategies proposed by the teams were evaluated on whether they were directed towards mitigating climate change. The results showed that 95% of the teams attempted the innovation contest, and a total of 43 innovations were analysed for this study.

Many teams reported interesting innovations like Nanomembrane Technology, Kinetic Façades, Fibre-optic Lamps, Piezoelectric Tiles, Space Syntax, Flexible Furniture design and many more. These innovations addressed aspects of the projects including scaling up, reducing cost, or improving the return on investment for the target market. Out of 43 innovations, 32% addressed specific problems related to climate change that the teams identified. The teams presented these innovations as a solution to mitigating climate change and demonstrated the potential of reducing the environmental impacts of their projects. Some examples include Agrocrete blocks for the facade, Cooling-as-a-Service (CaaS), and reusing shipping containers for the building envelope.

The teams found it difficult to identify the challenges involved in scaling up their innovations and proposing strategies to address those challenges. Most of the innovations also lacked descriptions and quantification of the anticipated impact if they are scaled-up. While the Challenge did not require teams to propose innovations specifically for climate change mitigation, it is interesting that the teams thought about climate issues and actively tried to address them using their innovations.

4. DISCUSSION

The findings from Analysis 1 showed that the students did not provide analysis results and evidence for their ECMs. Even though energy simulation software were provided to all the participants, they were not provided training and had to learn simulations through resources that their institutions could provide, or with online tutorials and discussion groups. It is possible that the students had difficulty in assessing design options and ECMs due to their lack of familiarity with simulations. Therefore, in year 2 the 2021-22 Challenge, a five-part simulation training was conducted where simulation experts explained the process of modelling and simulating buildings for optimization. Additionally, a live session with an expert was organised where students asked their simulation related questions. The faculty mentors of the participating teams provided feedback that the trainings were useful and gave students a head-start. However, a comparative analysis with the reports from year 2 is needed to see if the trainings resulted in more evidence-based designs.

Analysis 2 showed that the students found it difficult to report on Affordability, Resilience, and Scalability and Market Potential. This could be because these topics are not covered in their college curriculum and the faculty mentors may not be experts in these topics.

The results of Analysis 3 showed that most of the teams reported on the innovation contest. Some teams proposed new technologies or solutions, while others researched technologies available in the market and creatively incorporated them into their designs. The innovation contest did not provide a clear expectation on what it should address. This was refined in year 2, and a clearer description with a detailed outline was provided. This included the need for market and customer research, assessing the readiness of technologies, costing, and strategies for scaling up. In year 2, the organisers conducted a Faculty Development Programme where experts pointed out the gaps in the current curricula and drew attention towards specific skills and perspectives that the students need to develop on these topics. A 'social lean canvas' framework was provided so that the faculty could guide their students towards developing holistic innovations.

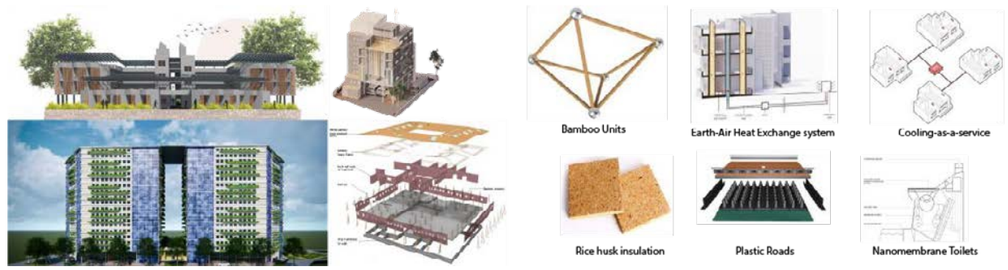

Figure 4 A few final design renders and innovations proposed by the teams

5. CONCLUSIONS

This paper investigated and analysed the submissions of the Finalist teams in the SDI 2020-21 Challenge. This investigation focussed on whether the teams used the resources provided by SDI and came up with evidence-based net-zero designs.

While most teams claimed to integrate the ECMs typically included in whole building high performance designs, the teams did not provide evidence to support most of the ECMs. The only area that stood out was the optimization of wall-roof assemblies to reduce envelope loads, where maximum teams provided evidence. Areas that students are unfamiliar with, or which were not part of their curriculum, such as Resilience and Innovation, were addressed poorly. The students as well as their faculty mentors need more mentoring in these areas.

It is unclear if the resources provided by SDI helped the teams to identify and integrate ECMs into their projects, address the contests and guide them towards well-rounded innovations. To bring further clarity, the authors curated a set of questions that can be answered with future research.

- Were the teams unable to provide analyses due to lack of capacity or other reasons such as page limitations?
- Is evidence-based design too technical and onerous for students of architecture and engineering in their design process?
- Is there a need to include these within the curriculum, to mobilise climate action?
- Are the teams curtailed by the inadequacy of resources and guidance in the open forum to learn in depth about the concepts of Thermal Comfort, Resilience, and Affordability?
- Do the teams have difficulty understanding the technicalities of finance and calculations?
- Did the teams report innovations to mitigate climate change intentionally?
- Do the teams have limited resources to identify the challenges in scaling-up their innovations?

In the coming years, the organisers plan to identify specific gap areas in the programme and improve them so that the teams have access to more resources and training that will help them arrive at evidence-based designs. To identify these gaps, interviews and focused-group discussions can be conducted with the students and faculty. This will also give more information on their design intent. Based on the results, it is evident that the programme has enabled students and faculty to think about buildings in the direction of performance-based designs. With about 1,000 students and 150 faculty mentors participated in the 2020-21 Challenge, SDI has proved to be a huge mobiliser to bring attention and focus on building design that can respond to climate change.

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Reflective practice in lighting education for the dialogue with the breakthrough changes

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ABSTRACT: The aim of the study was to develop a new curriculum for lighting education, using the reflective practice theory. The theory was applied at two levels: to educate students more efficiently, via improvement and adaptation of the program, and as background for the design practical workshops constituting part of the course. Twelve groups of students of architecture, interior design, and landscape architecture, attending the 5th semester of studies in the academic year 2018/19 and 2021/22 participated in the study. The experiment was aimed to investigate the impact of learning through and from experience. The study entailed the syllabus redesigning, as to adjust it to the process of reflection in action. Due unexpected fifth wave of the COVID-19 pandemic, the experiment of the year 2021/2022 has been interrupted. However, it can be said that the initial results showed a significant difference in the course assessment. The students had ranked it highly, underlining the fact that the course expanded their knowledge and equipped them with new skills. The reflective practice theory is considered to be an appropriate method of learning. Nevertheless, the experiment showed that without flexibility, adaptation, efficacy, and practice, students will not be able to make maximum progress.
KEYWORDS: Reflective Practice, Lighting education, Learning process

1. INTRODUCTION

University-level engineering education been getting increasingly complex in the constantly changing world. Engineering skills and knowledge have long constituted the basis of innovation and technological development, leading to long-term economic growth as well as helping solve social problems. Engineers have the responsibility to adapt to the changing circumstances, as to meet the needs of the society (National Academy of Engineering, 2019). In this context, opportunities for lifelong learning and improvement are of key significance. Development of these skills has now become a major educational challenge in engineering (Kamp, 2016). Universities struggle trying to adopt different teaching strategies (Kamp, 2016), (Duderstadt, 2010). In academic education, this process can be facilitated by applying the *reflective practice* theory to both shape new syllabuses and to improve the educational process.

2. REFLECTIVE PRACTICE IN PRACTICE

2.1 The theory of reflective practice

Reflective practice theory and its development, e.g. reflective critical thinking, has been lately discussed in scientific journals (Roco & Barberà, 2020), (Parker et al., 2020). It is becoming more and more appreciated in a range of disciplines, e.g. economics, education, psychology and health (Robinson et al., 2019), (Galutira, 2018).

In terms of engineering sciences, there are relatively few publications dealing with this topic, although the concept of *reflective practice* was developed by an MIT urban planning professor Donald Schön and a Harvard professor of management Chris Argyris (Schön & Argyris, 1974). It later enabled development of the theory of organizational learning. In a practical sense, it also contributed to the redesigning of the methods used at the MIT Department of Urban Studies and Planning, by changing the learning strategy and development of the associated tools. This theory has found many followers and has now turned into the theory of reflective learning (Aryani et al., 2017), which significantly extends the original assumptions. Still, there are followers who use this theory in various education-related disciplines and thus it has been interpreted in various ways (Loughran, 2002). Quite frequently, however, the term "reflective" is simplified. Schön considered the theory as one of the basic elements, but not a critical one (Schön, 1983). His allegation was that it is crucial to "reflect on work". According to him, it is fundamental to improve knowledge and benefit from experience. He noted that it is important to have knowledge of the theories related to the issue, but one also needs to think about how this knowledge is used and what tools are employed. In other words, it pertained to experiencing the entire process and drawing as many conclusions as possible from it, not only in terms of the work done, but with relation to its elements and stages as well. He argued that in the traditional sense, the action to a problem bases upon the options offered by the available tools and knowledge. However, this does not lead to skill development, but rather to plain repetition of existing patterns of problem solving.

But besides mere problem-solving *reflective practice* also includes self-improvement. Any experience involves the learning from it and develops competences.

It is believed the application of *reflective practice* theory leads to self-development because one consciously gains experience throughout the process and experience is helpful for better understanding of the reality.

Moreover, through conscious application of the theory, one continuously learns during the process. This theory also increases openness to other people through observation and understanding of their actions and by learning from them.

The following competencies get to be built up as a result: building positive reaction to change and ability to learn in order to improve the results.

Other competencies developed include openness to teamwork and joint activities, objectivity and, finally, continuous professional development.

Figure 1:
Development of competences based on the reflective practice theory.

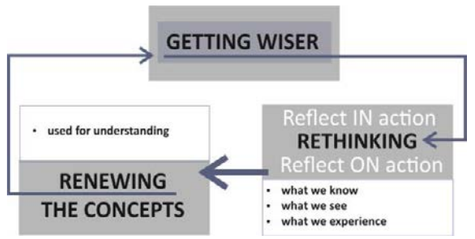


Figure 1 is a simplified illustration of the skill development process. Such an approach to problem solving is extremely important considering the today's dynamically developing circumstances. This seems even more crucial in terms of engineering sciences – a field in which technology has been advancing so quickly. It seems that development of students' ability to work on reflection, to use that reflection to solve problems and to adopt the old or create new solutions in practical situations, becomes a hunting challenge for the engineering educators. As per Schön, a belief exists that if students have the ability to renew theories (the adopted and the unused ones), along with the conceptual framework behind them, in the future they will be able to dialogue with the breakthrough changes that the future will bring (Schön, 1987). That is why it is so important to manifest greater application of this theory in the education of future engineers. This is especially important in those fields of study, in which technology has been developing rapidly, in connection with the digital revolution (Nyka, 2019). One of such fields of study is lighting.

2.2 Challenges of lighting design education

Recently, some articles have been published about the challenges in lighting education, particularly in architecture-related university-level education (Giuliani et al., 2019), (Sokół & Martyniuk-Pęczek, 2019). The studies discuss the training needs resulting from the development of technology and the knowledge about the influence of light on human functioning. Lighting is multidisciplinary and can pertain to such disciplines as: daylight, electric light, smart light, architectural lighting, light and energy efficiency, light and physics, light and biology, light and health. Teaching lighting design requires maximum effort, to relay the most important elements of knowledge in a short time.

When studying lighting, the main outcomes of the knowledge acquisition are the theoretical knowledge, which can be based on experience in the field of both electric and daylight light and lighting. The knowledge ought to have its grounds in the understanding and perception of space as well as in social behaviour and human health, both of which light has major influence on. Secondly, students ought to be able to demonstrate the knowledge and to comprehend the methods, the processes, the theories, and the very advanced tools of architectural lighting design as well as their impact on the shaping of space. It is crucial to teach the students how to relate that knowledge and comprehension to the impact on the existing natural environment. What is more, it is crucial that students are familiar with and have the knowledge of the modern lighting technology, understand its principles and are able to adapt to the new changing conditions imposed by the digital revolution. Analysis of the syllabuses for the Lighting course taught at Architecture, indicates the need to meet the demand for experience in lighting. The above-outlined challenges allowed the Authors to design a course that would meet these expectations.

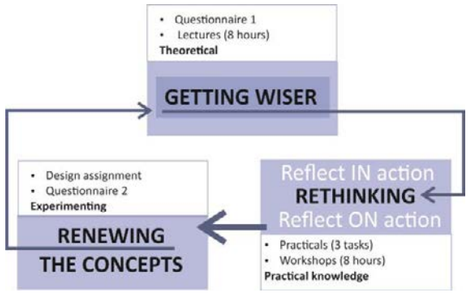
3. IMPLEMENTATION OF REFLECTIVE PRACTICE INTO THE LIGHTING EDUCATION CURRICULA

The experiment of introducing a new teaching formula took place throughout the 2018/2019 and 2021/2022 academic years, at the Sopot University of Applied Sciences. In the academic year 2019/2020 and 2020/2021 the experiment could not be preceded due to the COVID-19 pandemic. The online teaching formula was introduced, and no lighting workshops could have been organized. Unfortunately, the experiment was also disturbed just after the beginning of academic year 2021/2022, as in November 2021 the fifth wave of virus has reached Poland. The universities had to switch to online teaching mode again. The lighting workshops could not take place. That is the reason this article focuses on the experiment done in the academic year 2018/2019.

The first experiment in 2018 entailed involvement of students of the 5th semester of Architecture / Interior Design / Landscape Design. Importantly, these majors have a practical profile, so the graduates expected to master practical skills. Additionally, one important element was the fact that 29 of the students surveyed were part-time students (19 were full-time students). This is an important aspect, because most of them worked in the profession or in related fields. These students could be expected to be more mature, in terms of observation, experience acquisition and experimenting. The Lighting course involved relatively few hours, i.e., 8 lectures, 22 hours of design studio classes and 8 hours of workshop. The total number of the ECTS points assigned to the course was 4.

The *reflective practice* theory was applied on two levels. First, it was used to restructure the program (syllabus), as to improve the educational process. Due to the wide range of the topics involved in the field, the focus was on electric lighting. Based on the student Open-Ended questionnaire (37 answered questionnaires), a syllabus was prepared, which was meant to meet the students' educational needs. The questionnaire surveyed their ability to assess what course content they would like to master, broken down into knowledge and skills. The survey objective was to assess which part of the course content they are most interested in the theoretical framework, practical knowledge, experimenting with light, practical skills. Based on the questionnaires, the content of both the lectures and the practical workshops was developed. Main focus was on the practical part of the course content. Methodology of syllabus preparation in itself does not seem to be very innovative, but due to limited time and the huge amount of knowledge to be relayed, it had to be maximally condensed, enabling independent expansion of one's knowledge on his/her own.

Figure 2:
Course syllabus reconstruction, showing individual elements of the competence extension process



The second level of the *reflective practice* theory implementation, therefore, involved its application for development of the practical workshops. Figure 2 shows the elements of the course syllabus translation and reconstruction process on the *reflective practice* theory wheel. The course has been reconstructed into 3 parts: theoretical framework, practical knowledge, and skills, experimenting. These parts translated into progressive practical workshops and later the professional wisdom presented in the final design assignment.

The theoretical part incorporated 8 hours of lectures into the course. The overall theoretical framework involved presentation of: the nature of light, the basics of lighting technology, and the theoretical foundations of lighting design. In the practical knowledge and skills development part, two primary elements of the reflective practice theory were used, namely "reflect in action" and "reflect on action". The students had three tasks. The first one entailed observation of space and the changing light as well as the noting of differences. The second entailed the observers' reflection on the phenomenon of light and correlation of that reflection to a situation of artificial lighting application. This task was aimed at analysis of a given situation, the decision-making process and quick reaction. The final task involved a review of the theory. One important part of the course entailed experimenting and participation in the Lighting workshops, which involved an advanced reflection task. It entailed the experiencing, observing, and understanding the phenomenon of light interaction with matter. The Lighting workshops took place in the Lighting Application Center in Piła and lasted 8 hours. The workshops ended with a walk after dark around the city, in order to assess and analyze the lighting phenomena that can be observed within an urban tissue. The experiment ended with a design assignment. Knowledge and the skills were tested and verified via development of an interior lighting design for an apartment or a hotel room. Figure 3 presents examples of the projects and the tasks with a design assignment. The content has been arranged in a logical sequence, in accordance with the reflective practice. Conclusion of the course involved an evaluation questionnaire. 46 students took part in the survey, who rated the manner the course conduction very highly.

Figure 3:
Workflow - Examples of course tasks

Note: Some of the pictures used in this graph are credited as follows: Task 1 – M. Krzaczek; Task 3 – N. Urbanik, A. Brzezińska; Design assignment – M. Miłosz, M. Siemońska, P. Kąkol

4. RESULTS

Due to the global pandemic and dynamic lockdown situations, the results could be obtained only during this one experiment. Despite the shortcomings of the methods presented and the deficiencies in research tools, especially the reliability of the survey (a small group of respondents), analysis of the results indicates several significant benefits resulting from the application of the theory of *reflective practice* both in the process of curricula development and the course task development during class implementation.

The literature overview indicated, among others on the example of the MIT DUSP, how the *reflective practice* theory has emerged in engineering sciences, how it has taught critical thinking skills to the students and how it has allowed them to adapt to changes. The literature overview also demonstrated the essence of this theory and its application, but also indicated the influence it had on the teaching methodology.

The results of the experiment involving application of the *reflective practice* theory can be divided into two layers: 1) those concerning the shaping of the course syllabus, 2) those concerning the content of the practical workshops. These elements formed a sequence consistent with the *reflective practice* theory: Getting Wiser, Rethinking, Reviewing the concepts.

1) The process of shaping the syllabus was based on a verification of the students' needs (the Open-Ended questionnaire), during the course, and an assessment after its completion. The results of the preliminary student survey questionnaire showed that the students' needs to learn new skills are mainly formed around knowledge and its practical application, which is specific for engineering majors and practical training education. The results of the questionnaires are presented, in a simplified form, in Table 1. The scope of the need to master knowledge was broader than what could be fit into the curriculum during a semester, thus it was important to incorporate tasks that would require the students to further educate themselves through reflection.

Table 1:
The survey results demonstrating the students' needs prior to the course initiation

Scope	*Detailed needs*	*% share of*

		answers
Theoretical Framework	*Lighting terms and definitions, light measurement*	*15%*
Practical knowledge	• *How to use the color of light in architecture?* • *How to use different types of light?* • *How to create an atmosphere?* • *What are the principles of lighting?*	*45%*
Practical skills	• *How to combine theory with practice?* • *How to use modern technology?*	*35%*
Experimenting with light	*Ability to recognize the type of lighting*	*3%*
User needs	*Light that reflects the users' needs*	*2%*

2) Application of the method when developing the tasks for practical workshops required the academic teachers to analyze what elements of reflection will be used and which of those elements are linked with the course content preceding the thereof. The practical workshops were preceded by a series of 8 hours of lectures on: The nature of light, Light in architecture, Definitions and terms in lighting, Theoretical fundamentals of light design, Principles of interior lighting design. A need to develop 3 tasks and one workshop emerged, because only such arrangement allowed complete verification of the knowledge content included in the lectures. The results derived based on the practical workshops were structured quite high - as presented in Table 3.

Table 3:

Summary of the scope of practical workshops against the elements of the Reflective Practice theory, in comparison with the results

Topic	Scope	Duration	Grade average for individual elements (scope 2-5)
	Rethinking		
Observation of the nature of light	*Observation and noting of a given object and its background at a specified time - registration of lighting changes*	*1 week*	4.5
Comparison of light phenomena	*Observation of the phenomenon, interpretation and authorial comparison*	*1 week*	4.75
Assigning the lighting concepts to the perception conditions	*Task in the form of a test in class. Students develop a schematic concept indicating assessment of the light perception conditions*	*1 hour*	4.4
	Reviewing the concepts		
Lighting workshop	*Participation in the practical workshops presenting various lighting states, analysis of the lighting conditions, analysis of the solutions applied*	*1 day – 8 hours*	-
Design	*Hotel room interior lighting conceptualization*	*6 weeks*	4.70

The grades were calculated based on presentations and a joint discussion. They were awarded by a group of students, after each project has been analyzed. The teacher played the role of a moderator. The students showed great sensitivity to reflection, which was particularly visible in the task, in which the average grade was higher than 4.6. The results for the task involving assignation of a lighting concept to the perception conditions were weaker. This may result from the fact that this task required not only an intuitive answer to the problem, but also a reference to a design theory contained in the lectures.

The Lighting workshops were conducted in the form of a presentation and a discussion of the issues presented. The students participated through experiencing a changing light environment. The workshop was designed to evoke critical thinking in the students, by reviewing the concepts presented and discussed. The conclusions drawn from these workshops had direct impact on the last element, i.e., the design assignment. The designs presented by the students have shown deep reflection on the use of effects and the perception of light. The results of the work were rated highly by the lecturers. Over 75% of the students received very good grades for the course. The following made up the grade: correctness of the solutions used, introduction of new, innovative ones, the aesthetic quality of the work.

The results of the questionnaires, after the course evaluation, indicate a very high level of satisfaction with the method of relaying knowledge. The students' overall satisfaction with the possibility to acquire new knowledge and skills was ranked best. The students evaluated lecturer engagement and as very high and material presentation as legible and understandable. The students' commitment to the course was rated the lowest. This is an interesting result, because with so much emphasis on *reflective practice*, the students should be able to notice that many decision-making steps depended on their commitment.

The success of the experiment inspired the authors to continue this method in arranging further classes. In 2019/2020, the scheme and syllabus of lighting classes were repeated. Unfortunately, due to the COVID-19 pandemic not all the components could be carried out. All three tasks were assigned, however the element of reviewing the concepts during the lighting workshops could not take place. Moreover, it was not possible to proceed with the evaluation campaign. For this reason, the results from 2019/2020 were not included in the article. However, due to the similar effects of education, it can be assumed that students obtained similar competences. The new pandemic situation pushed the authors to use *reflective practice* again but in a different approach which could be presented in next articles.

5. CONCLUSION

The experiment involving a two-level application of reflective practice in the process of developing a lighting course, demonstrated significant impact of the critical thinking model incorporated into the learning process. The results of the work done during the semester as well as the participants' reflective and critical thinking skills led to a very good end result, in the form of the project concepts developed. In comparison with the previous years, the results have improved significantly after intervening in the syllabus. Application of the theory of *reflective practice* improved the participants' skills, including conceptual thinking, the use of conceptual skills, analysis, and synthesis of the skills, as well as development of new theories, based on those skills. Interestingly, intuition turned out to be an important element of reflection. It was used at the time of decision-making when there was not enough knowledge needed to make a decision. At such moments more mature students performed better.

In conclusion, it can be stated that *reflective practice* refers to how a student mind works and how it uses and creates theories in practical situations. In this experiment, it could be noticed that the elements that turned out to be essential were both invisible and visible, tangible and intangible. Nevertheless, the lesson that has been learned is that *reflective practice* entails flexibility, adaptation, and efficacy and should be introduced in other courses taught at the faculties and architecture departments in Polish higher education institutions and universities.. Perhaps then future architects will be better prepared for the ever-changing conditions in which we live and function in the modern world.

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WILL CITIES SURVIVE?

Thermal performance of roofs in a naturally ventilated classroom in warm humid climate

A case in Vijayawada, India

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ABSTRACT: India has the largest student population in the world exceeding 100 million with 3 million teachers and 0.63 million primary and upper primary schools. Most of the schools in India are naturally ventilated. Occupant health and productivity in schools depend largely on the Indoor Environment Quality (IEQ). Therefore, this study attempts to evaluate the thermal performance of different roof assemblies in a naturally ventilated school building. A naturally ventilated school building at Vijayawada was chosen for the study and the climate parameters were monitored for eight working hours of the school using data loggers. Nine roof alternatives used in the region were simulated to find their effectiveness in terms of Temperature Difference Ratio (TDR), and Discomfort Hours. The study found that a double roof along with a cool roof tile improved the thermal performance of the classroom. The annual average discomfort hours reduced significantly from 45% in the RCC roof to 15% in the double roof plus cool roof tile. Further, based on the study, an improvised double roof using hollow ceramic blocks was developed and it was found that the discomfort hours were reduced to 10%, as it provided shading, improved cooling through cool roof tiles, and accelerated radiant cooling.
KEYWORDS: Thermal performance, Passive strategies, Naturally ventilated building, Alternative roof techniques, Temperature Difference Ratio, Discomfort hours

1. INTRODUCTION

India has the largest student population in the world exceeding 100 million with 3 million teachers and 0.63 million primary and upper primary schools (Chithra et al., 2012). Students spend 1/3 of a day and normally 6 days a week in school (Guntharee et al., 2015). Most of the schools in India are naturally ventilated. Occupant health and productivity in schools depend largely on the Indoor Environment Quality (IEQ). Amongst the thermal, visual, acoustic, and indoor air quality parameters of IEQ, the thermal comfort in a naturally ventilated building influences the health and productivity significantly (Munonye et al., 2018). Therefore, this study attempts to evaluate the thermal performance of different roof alternatives in a naturally ventilated school building and suggests an alternative roof to enhance the thermal performance.

2. LITERATURE REVIEW

Appropriate choice of materials for the building envelope is the most critical element in buildings to improve comfort in naturally ventilated buildings and reduce energy demand in air-conditioned buildings (Eco-Niwas Samhita, 2018). Heat gain in buildings occurs through different components of the building envelope. The roof is the primary source of heat gain in the tropical climates. Roofs account for about 40-70% of the total heat gain in the buildings, depending upon the location (Madhumathi et al., 2014) (Vijaykumar et al., 2007) (Abuseif et al., 2018). During a clear sky condition, solar radiation of up to about 1000 W/m^2 can be incident on a roof surface, and 20% to 90% of this radiation is typically absorbed by the buildings (Madhumathi et al., 2013) (Suehrcke et al., 2008)

In hot and humid climates, the ventilation of attic space improves the thermal performance of sloped roofs, wherein the impact of orientation is negligible. However, in flat roofs, the reflectance of the external materials affects the thermal performance significantly (Abuseif et al., 2018) (Jayasinghe et al., 2003). In the vernacular architecture, the roofs were designed to reflect the social, cultural and traditional beliefs of a community which also modified the indoor temperature adapting it to the varying climatic conditions. The high-pitched roofs in Southeast Asia were intentionally designed with minimal openings to keep the interior cool, while ensuring adequate ventilation through stack effect in response to the hot and humid climate (Zune et al., 2020). Similarly, in the traditional Malay house, both stack effect and wind-driven concepts were widely used in its construction (Roslan et al., 2016).

A study on the performance of 14 different roof constructions in North Cyprus revealed that the inclined timber roof with a ventilated attic space and terrace roofs with thermal insulation on the internal surface performed the best during overheated periods in summer (Özdeniz et al., 2005). Further, Lima-Tellez, et al. found that the implementation of a ventilated roof under warm climates in Mexico significantly reduced the building's annual total heat gain by 50-60% and its electricity consumption (Lima-Téllez et al., 2022). In warm climates, reflective foil was found to be effective when compared to mass insulation and their impact in hot humid climates are yet to be explored (Mohd Ashhar et al., 2022). In warm humid climates, a light metal roof with low reflectivity and high emissivity tends to significantly reduce the internal surface temperature (Torres-Quezada et al., 2019). Further, in tropical climates, the poor thermal performance of cyclone resistant concrete slabs can be improved by resistive insulation. However, the thickness of the insulation plays a vital role in the reduction of slab soffit temperature (Halwatura et al., 2008).

Green roofs were effective in hot humid climates as it reduced the surface temperature of roofs thereby improving their thermal performance (Khotbehsara et al., 2019) The green roof decreased the exterior surface temperatures by 20.5°C when compared to a concrete roof in a semi warm climate during daytime attributed mainly to the irrigation effects (Chagolla-Aranda et al., 2017). Yazdani and Baneshi found that regular irrigation of green roofs helped in reducing the annual thermal loads up to 66% when compared to a conventional concrete roof (Yazdani et al., 2021).

The influence of evaporative cooling on the heat gain reduction in roofs are notable in humid climates (Veiga et al., 2020). Water spraying offers promising potential in cooling the roofs and building structures. Ethylene Tetra Fluro Ethylene (ETFE) when sprayed on roofs improved the indoor thermal comfort effectively wherein the reduction in indoor surface temperatures varied from 0.2°C to 4.9°C (Mao H et al., 2021). Dharmasastha et al. investigated the thermal behavior of a hybrid roof system called the thermally activated glass fiber reinforced gypsum (TAGFRG) with regards to the temperature gradients, thermal images of the interior and exterior roof surfaces (Dharmasastha et al., 2020). It was also found that a tiled roof with reflective thermal insulation has higher thermal performance in warm humid climates as it promotes the reduction in thermal gains (Michels et al., 2021). Kabre developed a new Thermal performance index (TPI*) for unconditioned spaces which assessed the percentage performance on a scale between the best and the worst performing roofs for warm humid tropics (Kabre et al., 2010). However, while designing buildings, it is unfortunate to know that the selection of appropriate materials for the roof is provided the least importance and as a result, the roofs are generally casted with Reinforced Cement Concrete (RCC) with no thermal treatment. One of the primary reasons for this is the lack of awareness of different roofing types and their effectiveness in improving thermal performance. Therefore, this study attempts to evaluate the thermal performance of different roof assemblies in a naturally ventilated building.

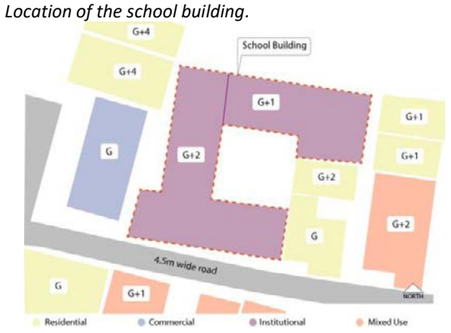
3. METHODS

The study was conducted in five stages: (i) a naturally ventilated school building with a conventional RCC roof was selected for the study, (ii) air temperature in the naturally ventilated classroom on the top floor was monitored using a data logger, (iii) the classroom was simulated in Design Builder, (iv) the on-site data was compared with the simulated data to validate the model, (v) the thermal performance of different types of roofs were assessed in the validated simulation model.

3.1 Site Selection

A naturally ventilated school building in Labbipet, located within the city centre of Vijayawada was selected for the study. The building is located within the residential colony, surrounded by residential buildings in the East, commercial buildings in the West, vacant plot in the North, and a 4.5m wide road in the South as shown in (Fig. 1).

Figure 1:
Location of the school building.



3.2 Onsite field measurements

Air temperatures were recorded in a classroom located on the top floor, for eight working hours (8:30am to 4:30pm) of the school on a typical day in February 2020, using HOBO data logger placed at 1.5m above the ground level, in the interior wall of the classroom (Fig. 2). The area of the classroom is 26.8m^2, and was occupied by 32 students. The materials used in various building components are shown in Table 1.

3.3 Simulation modelling

A model was created using Design Builder (dynamic simulation software), for simulation with the same building materials used in the existing building. The energy plus weather file of Vijayawada from the ISHRAE weather file was used for the simulation.

Figure 2:
(a) Interior view of the classroom; (b) Location of the data logger in the classroom.

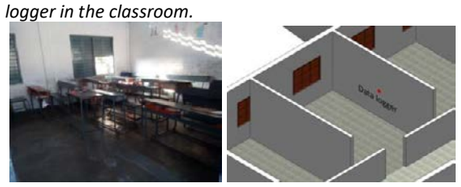


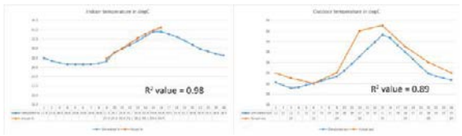
Table 1:
Building materials used in the classroom

Element	Thickness/size	Description
Roof	150mm	RCC with whitewashed interior, absence of weathering course
Floor	150mm	RCC slab with cement finish
Internal wall	150mm	brick wall with plastering and whitewash
External wall	250mm	brick wall with plastering and whitewash
Window	1.8m x 1.2m	11% Window to Floor Ratio (wooden frame with wooden shutter)

3.4 Validation of simulation model

The onsite field measurements were compared with the simulated results for the same date and time, to validate the accuracy of the simulation model. The temperature curve of the actual measured values and simulated result was compared using the root mean square difference (r^2). It was seen that the actual and simulated results had a significant correlation with r^2 value of 0.98 for indoor temperatures and 0.89 for outdoor temperatures (Fig. 3). Earlier studies have shown that the r^2 value of 0.8 and above are acceptable.

Figure 3:
Comparison of actual and simulated results of (a) indoor air temperatures and (b) outdoor air temperatures.



3.5 Assessing the thermal performance of roofs

The thermal performance of nine roof alternatives commonly used in Vijayawada as shown in Fig. 4 were assessed. The conventional RCC roof was considered as the base case and the same was replaced with other roof alternatives while maintaining all other parameters as the same in the validated model. The roof alternatives were simulated for a typical summer month (May) to assess their thermal performance. The thermal properties of the alternative materials were considered as per Energy Conservation Building Code (ECBC) for residential building 2018 [4]. The average monthly maximum temperature, annual average discomfort hours, and Temperature Difference Ratio (TDR) proposed by Givoni, were compared for all the roof alternatives. The higher values of TDR indicated better thermal performance of the roofs. The negative value of TDR indicates that the average maximum temperature inside the test cell is higher than that of outdoors (Amos-Abanyie et al., 2013).

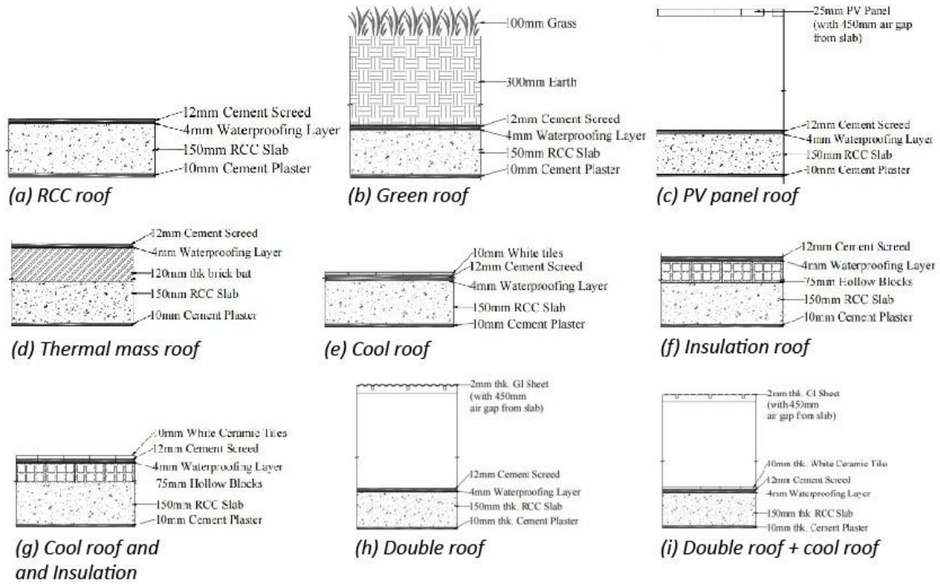
4. FINDINGS

The thermal performance of the conventional RCC roof was assessed through simulation in Design builder and the results were validated through field measurements (Fig.3). The exterior surface of the roof was painted gray (due to weathering) and the interior surface was painted white. The average monthly maximum temperature of the base case was found to be 36.1°C for the summer month and the calculated TDR value was -0.43. The annual average discomfort hours were 43% in the base case. In order to reduce the percentage of discomfort hours, roof alternatives that existed in the study area with combination of different strategies such as vegetation, shading, thermal mass, insulation, reflectance/emittance, and evaporative cooling were identified and simulated. Table 2 shows the thermal performance of the different roofs.

The green roof has a layer of vegetation (grass) on top of the typical RCC roof. The layer of earth and vegetation reduced the heat gain of the RCC slab. The study found a reduction of 0.6°C in the average monthly maximum temperature (35.5°C) with a TDR value of -0.36. The annual average discomfort hours reduced significantly from the base case from 43% to 33%. The presence of vegetation on top of the roof increased the comfort hours due to evaporative cooling similar to previous studies (Halwatura et al., 2019).

The effect of shading the roofs were assessed through a Photovoltaic panel roof. The 25mm thick PV panels placed on top of the RCC roof shaded the roof and resulted in the reduction of air

Figure 4:
Cross sections of the selected roof types



temperatures. The 450mm air gap provided between the PV panels and RCC roof enabled the removal of heat from the roof slab through ventilation. The average monthly maximum temperature and the TDR was found to be the same as that of the green roof (35.5°C & -0.36). However, the annual average discomfort hours were reduced to 28%, which was 5% less than that of the green roof. The study found that shading the roof was effective when compared to evaporative cooling in reducing the annual average comfort discomfort hours.

Table 2:
Thermal performance of different roof types with temperature variation and annual discomfort hours

Roof types	Maximum indoor temperature in °C	Temperature difference ratio (TDR)	Average annual discomfort hours (%)
RCC Roof	36.1	-0.43	45
Green Roof	35.5	-0.36	33
PV Panel Roof	35.5	-0.36	28
Thermal Mass Roof	35.4	-0.35	27
Cool Roof	35.2	-0.33	27
Insulation Roof	35.1	-0.31	23
Cool Roof and Insulation	34.9	-0.29	22
Double roof	34.4	-0.23	16
Double roof + Cool Roof	34.2	-0.20	15

Earlier studies have found that increasing the thickness can reduce the heat gain with significant increase in the time lag. RCC roof slab with an additional layer of brickbat on top was simulated to understand the impact of thermal mass on the discomfort hours. It was found that there was no significant decrease in average monthly maximum temperatures and TDR from that of the green roof and PV panel roof. There was only one percentage decrease (27%) in the annual average discomfort hours when compared to the PV panel roof. A cool roof with reflective ceramic tiles on top of the RCC slab was then simulated to identify the impact of reflectance of solar radiation on the thermal behaviour. The average monthly maximum temperature (35.2oC), TDR (-0.33) and the average annual discomfort hours (27%) were similar to that of the roof with increased thermal mass.

Providing insulation on the external surface of the roof reduces heat gain significantly. When a 25mm thick hollow block was placed on top of the RCC roof, the simulation results showed that the air gap in the hollow blocks helped in the insulation of roof. Though there was no significant reduction in the average monthly maximum temperature (35.1°C) and TDR (-0.31), the annual average discomfort hours reduced to 23%, which was 4% lesser than the cool roof and thermal mass roof. Further, in order to assess the coupled effect of insulated roof and cool roof, a layer of white ceramic tile was placed on top of the insulated roof and simulated. The ability of the white ceramic tile

to reflect the incident solar radiation reduced the annual average discomfort hours to 22%, which was 1% lesser than that of the insulated roof. The average monthly maximum temperature and the TDR reduced by 0.2°C and -0.02 respectively.

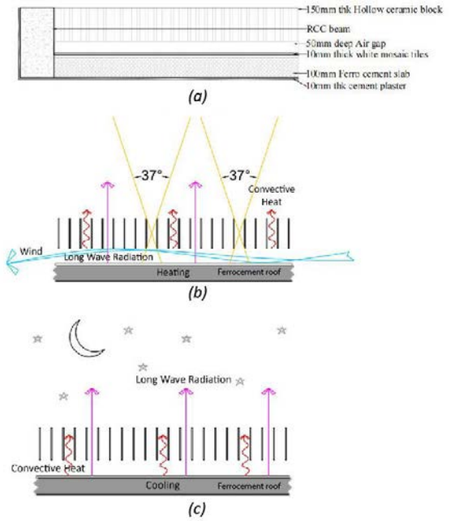
A double roof consists of a secondary roof on top of the primary roof with an air gap in between and provides sufficient shading to the primary roof structure. A 2mm thick galvanized iron (GI) sheet was placed above the RCC slab with an air gap of 450mm thick and the same was simulated to assess their thermal performance. The study revealed a significant reduction in the annual average discomfort hours (16%), due to the shading effect of the GI sheet, suggesting that a double roof is a simple technique that could be adopted to improve the thermal performance of roof in Vijayawada. The average monthly maximum temperature and the TDR also reduced significantly and were found to be as 34.4°C and -0.23 respectively. In order to reduce the heat gain of the RCC roof slab in the double roof, white ceramic tiles were placed on top of the RCC slab to reflect the incident solar radiation, that combines the effect of cool roof with double roof. The simulation resulted in a reduction of 1% in the annual average discomfort hours, from that of the double roof. Also, the average monthly maximum temperature and the TDR reduced by 0.2°C and -0.03 respectively from that of the double roof.

The study found that double roof along with the properties of the cool roof performed the best amongst all the roofing strategies analyzed and improved the thermal performance of the classroom significantly. The average monthly maximum temperature reduced from 36.1°C in the RCC roof to 34.2°C in the double roof with cool roof tile. The Temperature Difference Ratio and the annual average discomfort hours also reduced significantly from -0.43 (RCC roof) to -0.20 (double roof with cool roof) and from 45% (RCC roof) to 15% (double roof with cool roof) respectively.

4.1 Proposed roof alternative

Based on the analysis of different roof types and their thermal performance, the authors proposed a new roof type by using hollow ceramic block and ferro cement slab instead of the GI sheet and RCC slab in the double roof with cool roof in order to enhance the radiant cooling at night and reduce the heat gain of the slab, as shown in Fig. 5. The thermal performance of the proposed roof was then assessed through simulation. The results revealed that the annual average discomfort hours reduced to 10%, which was 35% lesser that that of the conventional RCC roof, indicating that the classrooms would be comfortable during 90% of the hours. The average monthly maximum temperatures also reduced to 33.0°C, which was 3.1°C lesser than that of the RCC roof.

Figure 5:
(a) Section of proposed roof alternative; (b) Thermal performance of roof during the day (c) Thermal performance of roof during the night



The Ferro cement slab reduced the heat gain, while the white ceramic tile increased the emittance of incident solar radiation thereby reducing heat gain through radiation. The air gap between the ceramic tile and hollow ceramic block obstructed the heat gain through conduction, the hollow ceramic block minimized the heat gain through convection and enhanced the radiant cooling to the night sky. Thus, the proposed roof performed the best thermally, amongst other existing roof types at Vijayawada.

5. CONCLUSION

Roof being one of the most important building elements in improving the indoor thermal comfort conditions especially in the tropics, the study revealed that it is possible to improve the indoor comfort conditions significantly by designing a suitable roof type that shades the roof slab by combining the properties of insulation, thermal mass, emittance, evaporative cooling, night ventilation etc., through appropriate choice of building materials. The double roof with cool roof tile performed the best among all the existing roof types and improved the thermal performance significantly in naturally ventilated classrooms in the warm humid climate of Vijayawada, India. Further, the proposed new roof type that modified the existing double roof with cool roof by using hollow ceramic block and ferro cement, enhanced the thermal performance by improving the comfort hours to 90% making it suitable for consideration as an alternative roofing technique in Vijayawada. The alternative roofing technique proposed in this study is very effective in warm and humid climates due to its low thermal mass, high night sky cooling, and moderate shading, whereas it may not be effective in other climate conditions and would require some modification to suit the climate type.

Studies have shown that children in developing countries are greatly affected by poor indoor environmental quality (IEQ) in the naturally ventilated classrooms resulting in the degradation of health and productivity. The study confirms that it is possible to improve the health and productivity of the children in naturally ventilated classrooms through appropriate design and choice of building materials for the building envelope.

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Simplification of a vegetation arrangement for transport it to a computational thermal evaluation model

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ABSTRACT: In this paper, a test thermal cube is used as a means of "transporting" the thermal behavior of a sample of a lightened green roof system based on aerial root plants that does not use substrate. The procedure was developed in 4 stages: 1) the thermal properties of the materials of the green roof system were measured, including the Hylocereus undatus plant, which is the basis of this system; 2) The green roof sample was placed on the top of a test thermal cube and the interior temperature was monitored. Simultaneously, the weather conditions were measured with a meteorological station on site; 3) the weather data monitored on site was converted into an EPW format data file; 4) the thermal cube was modelled in the Design Builder software with the data measured in stage 1, by means of a simplification of the vegetation, without the participation of transpiration due to being CAM metabolism. The thermal evaluations in Design Builder allow us to observe that the behavior of the monitored thermal cube and the simulated one in software are very close, thus validating the green roof system for use in a building.
KEYWORDS: Green roof; Weather data file conversion; Transporting thermal properties; Software simulation.

1. INTRODUCTION

Thermal simulation of materials applied to buildings through the use of computer programs is currently very accessible and its results have a high level of certainty. However, when computational models are built with new construction systems, it is convenient to validate their behavior under the real climatic conditions, because the thermal calculation programs in buildings require that the construction systems used be simplified as much as possible to reduce calculation times and to make simulation more accessible. In this work, the simulations of the thermal behavior of the greening system, were carried out with the Design Builder software (DSB).

This work shows the thermal measurement process of a green roof and wall system, and its geometric simplification to be fed to a thermal simulation software.

2. BACKGROUND

The author of the present work developed a patented new green-roofing system called "LIGHT NATURATION SYSTEM FOR ROOFS AND / OR WALLS, BASED ON MEMBRANES AND VEGETATION OF THE GENUS HYLOCEREUS" [1], which is a system basically formed by four different types of membrane and the cover vegetation of the genus *Hylocereus* that are placed on the roof or wall of buildings (Figure 1).

Due the vegetation displayed in this greening system is a very irregular material, field measurements were made to compare them with the model fed in DSB, in order to ensure that the computational model behaves similarly to the real model, and this way to validate the data feeding procedure of the greening system in DSB.

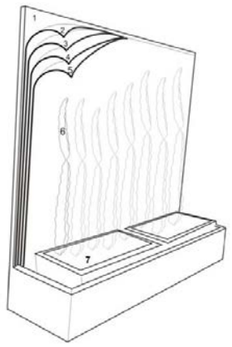


Figure 1. Basic scheme of the "Light Naturation System for Roofs and / or Walls, Based On Membranes and Vegetation of Genus Hylocereus". Nomenclature: 1). Building surface; 2). PVC waterproof membrane; 3). Polyester membrane; 4). Polypropylene mesh; 5). Coconut fiber membrane; 6). Vegetation; 7). Substratum.

This study took into account the study carried out by Niachou and Santamouris [2] of the measurements of a vegetation cover on site and its evaluation in a mathematical model. Likewise, the calibration and validation procedure of the model, for its numerical simulation, developed by Homing and Jim [3].

3. MEASUREMENT OF THERMAL VALUES

Thermal values of each component of the "LIGHT NATURATION SYSTEM FOR ROOFS AND / OR WALLS, BASED ON MEMBRANES AND VEGETATION OF THE GENUS HYLOCEREUS", were previously measured in the laboratory, the parameters described by Lira-Cortés and Lira-Cortes [4], adapted to tools and materials available at the Solar Energy Laboratory of the Universidad Autónoma Metropolitana Azcapotzalco, reproducing the hot plate and cold plate measurement system also based on the parameters established in the ASTM standard [5]. Scheme in Figure 2 shows the elements involved in measuring the conductivity of a material sample.

Although thermal values of most of materials measured are known, they were all measured to compare them with bibliographic values and thus validate the measurement process and thus the values obtained from the vegetation. The conductivity of the materials was measured with an Adam module of 8 thermal couple, a Stacco Energy voltage variator, a hot plate made with electric mica of 5.5 cm in diameter with a resistance of 2.3 Ω. Data were recorded in a computer with the Lap View 7.1 software from National Instruments (Figure 3).

Because the *Hylocereus undatus* plant is a succulent with a flat side that clings to surfaces, its conductivity was measured in the same way as other non-living materials. Values are shown in table 1.

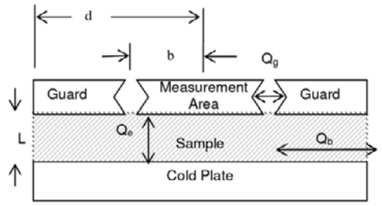
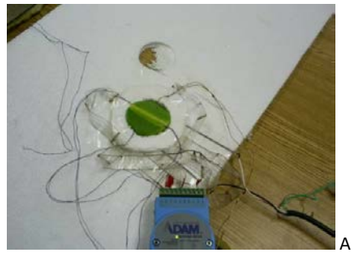


Figure 2. Material measurement scheme



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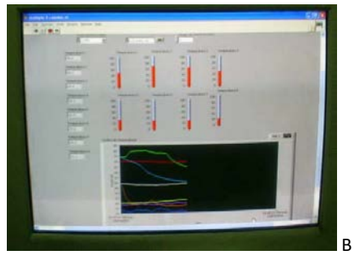

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Figure 3. A) Material measurement with Adam module of 8 thermal couple; B) Data record in a computer with the Lap View 7.1 software from National Instruments.

Table 1. Thermal values of the materials integrated in the construction system

Material	Conductivity λ (W/ m°C)	Specific heat Cp J/kg°C	Density ρ (g/cm³)
Plant	0.25	4,938	0.89
PVC Membrane	0.19	1,004	1.4
Polyester Membrane	0.05	1,200	0.13
Coconut Membrane	0.12	958	0.09
drainage Membrane	0.26	634.3	0.15

4. FIELD MONITORING

Two polystyrene cubes were built and monitored, in order to use them as "witnesses" or means of transporting the thermal behavior of the greening system to the DSB model. Two cubes were monitored in the field, and later they were modelled in DSB, with the aim of achieve the closest possible behavior, and in this way it will be assumed that the simplification of the greening system can be applied to DSB models reliably.

Considering the experience of Ojeda and Esparza [6], the cubes are made of polystyrene of 1 x 1 x 1 m. In the first one, the greening system was placed on the

top cover of a matte grey painted steel sheet, with an absorptance of 0.5. The second cube, served as a control, in which the upper lid is made of steel sheet with matte grey paint with an absorptance equal to 0.5. This material was used in the control cube because it is a material with known values, which can be simulated very easily in the Design Builder and obtain very reliable results (Figure 3). The cubes were measured for one month.

Figure 3. Field measurement of thermal cubes. Cube 1 is used as a control, with a grey painted metal lid. Cube 2 corresponds to the greening system measured.

5.WEATHER DATA FILE

Weather conditions were monitored with an ONSET weather station, model HOBO U30-NRC. The acquired parameters were: Solar radiation (W/m2); Dry bulb temperature (°C); RH (%); Precipitation (mm); Wind speed (m/s) and direction (degrees). Data was acquired every 10 minutes, according to the criteria established by the Mexican Norm about weather climatological, and hydrological stations [7]. Once the data was acquired every 10 minutes, it was averaged to obtain data every hour, which is the interval in which the data must be sorted in an Excel file for processing.

Since the measurement of climatological data at the site was only carried out for 30 days, it was necessary to insert them into a climatological file that covers a full year. For this, a meteorological data file generated in Meteonorm software is used as a basis, which must be saved as a meteorological EPW file.

The EPW weather file obtained from Meteonorm software [8] was converted to a CSV (comma separated values) file using the Weather Statistics and Conversions V. 5.0.1 application of Energy Plus software, and considering the workflow stablished in the Energy Plus documentation of auxiliary programs [9].

On the Meteonorm file, the hourly data measured on site were substituted, which in this case were the data from September 19 at 12:00 p.m. to November 20 at 11:00 p.m. It is important to note that a zero hour should not be set. The last hour of a day is the 23rd hour.

The Excel file was saved in csv format to continue with the process.

On the other hand, a DEF file was used, which is used as a basis for converting the weather file. According to the text of Auxiliary Energy Plus Programs [op.cit.], "DEF files are used because Some of the data formats have inherent omissions (e.g. TMY does not have location data, BLAST ASCII does not have elevations). In order to overcome this limitation and to provide further flexibility, a definitions file (extension must be .def) is implemented. By naming this with the same "file name" as your input file (in the same folder), the weather converter will read the format and use that data, as appropriate, in the file conversions. The .def file uses Fortran "Namelist" input fields as shown in the example below".

The PDF file is modified in the notepad, inserting the climatic values measured on site, in the desired month.

The conversion of the data from the DEF file was performed in the Weather Statistics and Conversions application of EnergyPlus® with the DEF file saved. Finally, the EPW (Energy Plus weather-file) extension was established as the output format. This file is the one used for the DSB simulation.

5. DSB THERMAL SIMULATION

Thermal cubes measured in field, were simulated in Design Builder, replicating the conditions under which they were measured in the field. In the case of the control cube, all the covers, except the upper one, is made of polystyrene and the upper cover is made of steel sheet. Greening system of cube 2 was simplified by using the thermal values of the vegetation on the upper surface, and the voids left uncovered by the vegetation were handled as sub-surfaces, with the values of the steel sheet with absorbance of 0.5 (Figure 4).

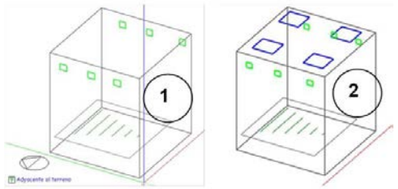

Figure 4: Simulation of thermal cubes in Design Builder. 1) Control cube; 2) Cube with vegetation on the top cover.

It is pertinent to mention that this type of vegetation can be simulated as a conventional material because it has a CAM metabolism (crassulacean acid metabolism). This type of metabolism occurs in Crassulaceae and epiphytic plants that live in desert environments and epiphytic environments of the dry tropical forest. Approximately 7% of the 1,600 known cacti species are epiphytes, according to Nobel and Hartsock [10]. According to Ortiz [11], CAM-metabolism plants (used in this system) presents the absorption of CO_2, and the opening of stomata, mainly during the night; which is contrary to the typical notions about photosynthesis, where during the day the plants capture CO_2 to generate nutrients, subsequently releasing O_2 into the environment; relationship on which the development of life on this planet depends.

Since this plant does not transpire during the day, in this thermal simulation the stomatal-resistance and the leaf area index (LAI) are not considered in the heat losses.

In this experimental process, the vegetation was simulated as a conventional material, due to the absence of daytime transpiration because it spreads adhering to the surface by means of adventitious roots, because it lacks leaves and because it has a water content of up to 90%, according to Ortiz [op.cit], which makes it have properties very similar to those of encapsulated water.

5.1. Fractional vegetation coverage

To determine the subsurface occupied by the plant in the greening system, the fractional vegetation coverage of the model monitored in the field was measured by flat image processing and the sum of the gaps without coverage in Autocad software by Autodesk. It was determined that a layer of the vegetation used covers 63% of the surface (Figure 5).

Figure 5. Vegetation Coverage. Shows the surfaces without coverage

5.2. Absorptance and thermal behavior

Absorptance, in addition to all the values measured and fed to the computational model, as well as the geometric simplifications that were made, the value of absorptance was one of those that most determined that the behavior of the computational model was very similar to that of the cubes measured in the field.

The absorptance of the vegetation was measured with an Ocean Optics Spectrophotometer model FLAME-S-VIS-NIR-ES, with a Tungsten Halogen Source tungsten lamp, 360-2000nm (Figure 6). Absorptance obtained was measured directly on the plant. In this way, the value of reflectance or albedo was 0.19, and the average of absorptance has a value of 0.81.

Figure 6. Spectrophotometer model FLAME-S-VIS-NIR-ES

Other absorptance values measured in this process, which we mention only as a reference, are: 0.92 for *Sedum rubrotinctum*, and 0.85 for a vegetable cover.

5.3. Simulation process

Simulation of the Thermal Cubes was carried out by feeding the same constructive arrangement and the same thermophysical properties of each of the materials into the program. Subsequently, the behavior of the simulated cubes was compared, noting that in the first thermal runs the behavior of the virtual model was different from the natural model even when the thermal properties of the elements were adequate.

The plant cover, having a surface with a cover composed of plants, patches of membrane and shaded holes, also presents non-homogeneous surface properties, for which different values of surface absorptance were tested, within a range of absorptances ranging from 0.5 of the gray painted metal sheet to the vegetation absorptance of 0.81. On the other hand, the emissivity value was not measured and the value of a common material close in composition, such as wood, was taken, setting this value at 0.85 [10].

In this way, surface properties of the vegetation cover were adapted in the program, until a behavior similar to that of the real model was obtained. The thermophysical properties of the plants, previously obtained in the laboratory, were not modified. The absorptance and the visible absorptance were adjusted, which are fields that allow the program to modify. The

emissivity was considered equal to that of a medium-coloured surface, and close to that of wood, which is an organic material for which there is a measured reference. Used values are showed in table 2.

Table 2. Surface values of materials used in the computational simulation

Properties	Value
Absorptance	0.70
Visible Absorptance	0.70
Emittance	0.85

To get these values, more than ten thermal runs were made, comparing them with the behavioral parameters of the thermal cubes measured on site.

Analyzes were made in excel graphs, joining the results of DSB with the data measured on site.

6. Results

Results obtained in the thermal simulation in design builder were compared with the data recorded in the field.

Very similar performance was obtained between cubes measured in the field and those simulated in Design Builder. Some of the differences in the thermal simulations were found to depend on the thermal absorptance that was given to the plant material, which although it was measured, had variations during the field measurements.

The graphs below show the behavior of a typical day. Some of the differences that were found between the Physical Models (PM) and the simulated ones (with the prefix DSB in the graph): The maximum temperature reached by the surface of the sheet (steel sheet) PM is 54.5 ° C and 55 ° C for DSB. The maximum temperature reached by the system with PM plants (greening) is 39.5 ° C and 37 ° C for DSB. The thermal oscillation of temperatures in the typical day compared is 15 ° C in PM and 18 ° C for DSB, which represents a difference of 3 K, which was considered acceptable (Figure 3).

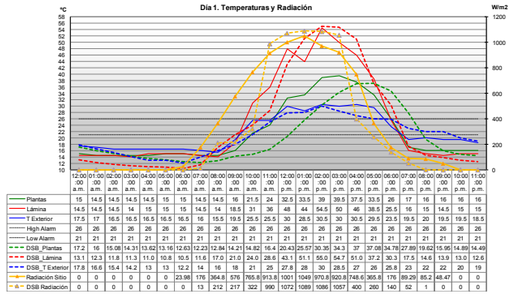

Figure 3. Comparison of the real and virtual conditions of the measurement and the results. The graph shows that under similar temperature and radiation conditions, the virtual and real models follow the same behavior patterns, with a 1-hour lag in the DSB model curve, with respect to the natural model curve. the lines correspond to the following values: Metal with plants (continuous green); Plain metal (solid red); Outside temperature (solid blue); Metal with DSB plants (dotted green); Metal DSB (dotted red); Outer T DSB (dotted blue); On-site radiation (solid yellow); DSB radiation (dotted yellow).
The graph shows that under similar temperature and radiation conditions, the virtual and real Models follow the same behavior patterns.

In the graphs obtained, results are presented that show the behavior of the cubes measured on site against the simulated ones. It is noted that there are differences between the data measured on site with respect to the simulated ones. some differences in the result of the thermal behavior is due to the complexity of the original system and its simplification, and others are due to the resolution of the climate data that is a little different in the two cases. At 11 a.m., when in both cases the outside temperature is 25°C in DSB and 25.5°C in Site, with radiation of 990 W/m2 for DSB and 914 W/m2 for Site, the temperature differential between Sheet (S2) and Sheet with Vegetation (S1) is 12 K. The maximum temperature reached by the surface of Sheet S2 in Site is 54.5°C and 55°C for DSB. The maximum temperature reached by S1 on site is 39.5°C and 37°C for DSB. This gives us a temperature differential between the maximum of S1 with respect to the maximum of S2 of 15°C on site and 18°C for DSB, which represents a difference of 3°C between the visual and real model. For other days of on-site measurement, the differentials between S1 and S2 were 17, 18 and even 20K, which is within the same range recorded for the on-site model.

During the night, at 23:00 hrs, S1 is 1.8°C cooler than S2 for DSB and 1°C for the On-Site model. At 5:00 hrs, S1 is 2.36°C less cold than S2 for DSB and the temperature of the two surfaces is the same on site. At this same hour, the temperature of the cubes on site is 15°C with an external T of 16.5°C, which gives a difference of 1°C; while the temperature of S1 in DSB is 13.16°C, while the Texterior is 13°C, giving a difference of 0.16°C and 2.2°C between Text and S2, which remains within an acceptable range. of behavior with respect to the model measured on site.

3. CONCLUSIONS

Study of new materials, which are not commercial and have not been certified, requires that measurements of their physical properties be generated, and this allows them to be entered into programs that can estimate their performance within a thermal system, improving the quality of the results, compared with the use of biographical values of similar materials.

Although it is a reality that thermal phenomena are not scalable, through the work presented here, a procedure is proposed through which the measurement and "calibration" of the thermal performance of materials, that we are interested in knowing, can be done through the use of thermal cubes measured in the field, and transported to a thermal calculation program, to validate the correct data transportation, and the adequate simplification of its geometry, which is the basis of a reliable computational simulation.

Even when long series of field experiment measurements are not available, their response to climate can be studied by inserting short climatological measurements into files of a complete typical year by converting and generating epw files.

The useful information provided by this work is the data validation of a new material. Based on this information, this system can be used on a building, whether it is a greening system or any other material, with the certainty that its behavior is very close to its performance in real conditions.

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Transferring vernacular passive design strategies to modern dwellings in warm humid regions to reduce thermal discomfort

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ABSTRACT: The combination of high relative humidity and high temperature conditions in warm-humid regions is known to aggravate people's perceived temperature. If not addressed in design, this can result in a significant number of discomfort hours. A review of vernacular dwellings in warm humid climate regions reveals the use of passive design strategies to reduce thermal discomfort. However, thermal comfort in modern dwellings in warm humid regions is mainly maintained by air-conditioners, leading to high annual energy consumption. The adoption of passive design strategies typical to vernacular dwellings offers the opportunity to reduce thermal discomfort and energy use brought on by active measures. In this paper, the authors reviewed four vernacular types in selected warm humid regions of south Asia. The key passive design strategies for thermal comfort were identified (building fabric, natural ventilation, and shading) and their transferability to a typical modern dwelling in the warm humid region of China was tested. Confirming their suitability, subsequent results indicated the reduction of discomfort hours in the tested dwelling by up to 10.5 to 13.5% in the hottest month.
KEYWORDS: Vernacular Building, Thermal Comfort, Sustainability, Passive Strategy, Warm-humid Climate.

1. INTRODUCTION

Buildings in China account for approximately 51% of domestic carbon emissions and 47% of domestic energy consumption with space heating and cooling forming the largest proportion (China Association of Building Energy Efficiency, 2020). In the warm-humid climate of Southern China, there is high dependence on energy-intensive cooling measures to restore comfort. Previous studies indicate that some traditional dwellings in Southern China exhibit potentially effective design strategies to reduce thermal discomfort (Jin & Zhang, 2021). These design strategies are mostly reflected in the use of shading techniques, permeable building fabric elements and natural ventilation approaches (Aflaki et al., 2015). In this study, the authors seek to identify and examine passive design strategies in vernacular buildings found in the warm humid region of Asia, with a focus on the boat-shaped house in Hainan, a unique Southern Chinese dwelling. The aim of this is to identify transferable design strategies suitable for contemporary dwellings. It is intended that this research will support ongoing work needed to help China meet its long-term carbon emissions reduction measures (Energy Transitions Commission, 2020).

The study consists of two main parts commencing with a review of typical vernacular building strategies found in south Asia - the cities of Hanoi, Vietnam; Yangon, Myanmar; George Town, Malaysia; and Hainan, China. Following this, dynamic thermal simulations of the boat-shaped house and the typical modern dwelling type in Southern China were conducted via IES-VE to determine the effectiveness of identified design strategies from comfort perspective.

2. CHINA AND SOUTHEAST ASIA CONTEXT

Climate analyses indicated that all selected cities experience high temperatures ranging from 28°C-38°C in warmer months, and 17°C-29°C in cooler months. With high solar radiation and high relative humidity (RH) ranging between 70% to 100% for warmer months, key design strategies will be focussed on heat mitigation strategies.

In warm-humid climates, the combined effect of high temperatures with small diurnal variations and high RH can aggravate human perception of the actual temperature. This leads to large amount of thermal discomfort hours. To control this, heat mitigation strategies via external shadings, building fabric, and natural ventilation are essential for restoring comfort. External shading has a significant effect on controlling solar heat gain. Building fabric with good thermal properties can balance heat conduction between the indoors and outdoors to mitigate solar heat gain. Also, natural ventilation is crucial for exhausting excessive heat and creating more air movement to extend comfort limit (Zhai et al., 2013). Window-wall-ratio (WWR) should also be considered as whereas larger window openings can promote natural ventilation, solar heat gains must also be curbed via shading.

3. THERMAL PERFORMANCE INVESTIGATION ON LOCAL VERNACULAR ARCHITECTURE IN WARM-HUMID CLIMATE

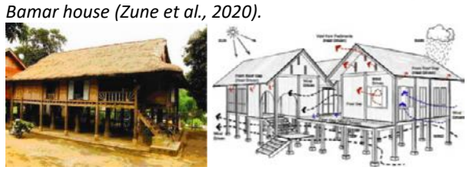
As is shown in Table 1, Key design strategies of three house types in Southeast Asia were summarised for the hottest month of the year (Nicol & Humphreys, 2002; Kubota et al., 2017; Japheth Lim, 2012; Bruges et al., 2018; Historic England, 2016).

Table 1:
Overview of three selected house types in Southeast Asia.

Parameter	Mai Chau house (Vietnam)	Bamar house (Myanmar)	Chinese shophouse (Malaysia)
Mean outdoor temperature (°C)	17 - 30	25 - 31	27 - 28
Adaptive comfort zone (°C)	25 - 32	25 - 32	24 - 29
Depth of shading (m)	0.8	0.5	0.3
Material types for the fabric	Roof: Thatch (U = 0.3), Wall & floor: Bamboo (U = 1.4)	Roof: Thatch (U = 0.3), Wall & floor: bamboo, and timber (U = 1.4)	Roof: Timber (U = 1.4) and tile (U = 3.5), Wall & Floor: Brick (U = 2)
Building fabric properties	Lightweight and well-insulated	Lightweight and well-insulated	High thermal mass (with well-insulated roofs)
Permeability of the fabric	High	High	Low
WWR (%)	27.7	9.4 - 13.9	18
Ventilation strategies	Cross ventilation	Single-sided or cross ventilation	Atria ventilation
Ventilation stack height (m)	2	2.3	/
Actual ventilation rate/ required rate for cooling (m^3/s)	6.04/3.12	Kitchen: 0.25/0.4, Living area: 0.76/0.8	Bedroom: 2.25/1.03, Front Hall: 2.79/0.4
Infiltration rate (ac/h)	30	30	/

The images of these house types are shown in Fig. 1 ('a' and 'b') and 2. As the Mai Chau house and the Bamar house has similar built form, they share similar strategies (Fig.1). The thatched roofs absorb moisture and heat to create evaporative cooling effect which provide good insulation to mitigate solar heat gain. Moreover, lightweight materials with low heat transmission were used for the fabric to prevent heat storage during daytime and maintain a stable temperature difference between indoors and outdoors at nights. The permeable fabrics of both houses contribute to high infiltration in the house that allows more air exchange. Also, eaves were used on all façades to shade unwanted solar gain.

Figure 1:
Left (a) Mai Chau house (Nguyen et al., 2011), right (b) Bamar house (Zune et al., 2020).



The Chinese shophouse has narrow fronts of about 5m and deep rears of about 35m (Fig.2). The thermal buffer zone and lightweight materials used for the roof reduce heat gain from the overhead sun. As heavyweight materials used for the external walls store a lot of solar heat, natural ventilation via openings and consecutive internal courtyards can exhaust excessive heat (Fig.3), especially at night when a larger temperature difference between indoors and outdoors occurs.

Figure 2:
Chinese shophouse (Han & Beisi, 2015).

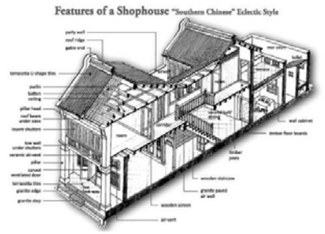


Figure 3:
Ventilation strategies of Chinese shophouse.

As for ventilation, for the Mai Chau house, the WWR of 27.7% can satisfy required air flow rate with a stack height of about 2m to accelerate cross ventilation. For the Bamar house, the actual ventilation rate cannot meet the required rate for

natural cooling because of its insufficient upper vent area and low WWR of 9.4%- 13.9%, even with enough stack height between openings. However, a high amount of infiltration through its permeable fabric can offset the remaining amount of required rate to achieve natural cooling requirement. For the Chinese shophouse, chimney ventilation works well via its openings and internal courtyards, reducing internal heat gain with the medium WWR of 18%. Cross ventilation works effectively for enough air exchange when the WWR is high, otherwise stack ventilation (via chimney or atria) would work better.

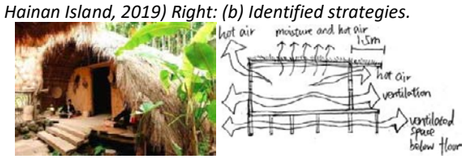
4. THE BOAT-SHAPED HOUSE IN HAINAN ISLAND

4.1 Boat-shaped house in Hainan

The adaptive comfort zone in Hainan was found to be 25°C-32°C for the warmest month. In the warmest months, the mean daytime temperature in Hainan is about 27°C-33°C and 24°C-27°C at night. In cooler months the mean daytime temperature is about 18°C-27°C and 17°C-24°C at night.

Boat-shaped houses are built in a typical size of 14.7m(L) × 6m(W) × 3.2m(H). These houses have no windows, leaving upper vents and the door for ventilation (Fig.4). The thatched roof is a good insulator that reduces excessive solar heat gain, and also allows for high infiltration through its gaps (Historic England, 2016; Hainan Boat-Shaped House: The Watcher of the Li Nationality's Spiritual Home, 2009; Kubota et al., 2017). The nature of the roof also helps protect the house from damage by rainwater. The timber and bamboo floor act as a good insulator with low heat capacity. The rammed earth external wall, with bamboo and coconut leaves on two sides, is more weatherproof, but it is a poorer insulator compared to using only lightweight materials. In some cases, timber is used to construct the external wall.

Figure 4:
Left: (a) Boat-shaped house (Boat house of the Li people in Hainan Island, 2019) Right: (b) Identified strategies.



4.2 The simulation matrix and results

Simulations were focussed on the warmest month (July) to represent the worst scenario in Hainan. The rationale behind this is that, if thermal comfort for the warmest month is ensured, due to small monthly temperature variation, similar conditions would be guaranteed in less warm months. A series of parameters were varied to determine their impact on comfort. Table 2 compares the assumed parameters for each scenario. In 1, the house is ventilated via upper vents (WWR = 3.8%); in 2, the house is ventilated via both upper vents and external doors (WWR = 9.9%); in 3, there are no shading devices; in 4, internal heat gain is considered; in 5, no natural ventilation is considered and in 6, no infiltration is considered. No changes are made to fabric materials and properties at this stage.

Table 2:
Simulation parametric changes for rammed earth construction type of the Hainan boat-house.

Scenario /Parameter	1	2	3	4	5	6
Main materials & U-value	Roof: Thatch (0.3 W/m²K) Wall: Rammed earth (2.1 W/m²K) Floor: Timber (1.4 W/m²K)					
Opening (m²)	3.2	8.24	8.24	8.24	8.24	8.24
Shading (m)	1.5	1.5	-	1.5	1.5	1.5
Ventilation (m³/s)	0.25	0.81	0.81	0.81	-	0.81
Infiltration (m³/s)	2.08	2.08	2.08	2.08	2.08	-
Cooking (W/m²)	-	-	-	6	6	6
People (W/per)	-	-	-	85	85	85

Each upper vent has an area of 1.6m² while the opening area for each door is 2.52m², and upper vents were assumed to be always open. 1.5m deep overhangs were used on southern façades. 30% of the entire fabric of the boat-shaped house was considered as infiltration gap area due to its porous nature. Fully occupied hours were 12pm-3pm, 6pm-7pm, and 8pm-5am. Internal heat gain was considered from Scenario 4 to see its impact on applied strategies. Table 3 shows results for discomfort hours based on different comfort acceptability zones:

Table 3:
Percentage of discomfort hours in July for each simulated scenario for the rammed earth construction type.

Scenario	Discomfort hours in July (%) (80% acceptability)	Discomfort hours in July (%) (90% acceptability)
1	0.7	6.7
2	1.1	8.1
3	1.5	12.5
4	1.8	15.5
5	2.3	20.2
6	11.6	36.6

Overall, almost all excessive internal heat gain was exhausted with high infiltration created by the porous fabric and loosely built structure of the boat-shaped house, and natural ventilation via its openings. With natural ventilation removed, thermal discomfort hours increased by up to 4.7%, while with the removal of infiltration, thermal discomfort hours increased by up to 16.4%. An increase of up to 7.4% of discomfort hours occurred when internal heat gain was considered. When shading was removed, a 4.4%-5.8% increase on thermal discomfort hours occurred.

The thermal performance for the boat-shaped house was examined again for the other construction type using timber for its external walls to explore the impact brought by changes of materials. The U-value of external walls reduced from 2.1 to 0.55 W/m²K because of change of its construction material. 50% of the entire exposed porous fabric was considered as infiltration gap area for the timber case, leading to an increased infiltration rate in July. Three scenarios were compared as explained next and as outlined in Table 4. In scenario 1, the house is ventilated via both upper vents and external doors (WWR = 9.9%). In scenario 2, internal heat gain was considered. Lastly, in scenario 3, no infiltration was considered.

Table 4:
Simulation parametric changes for timber construction type.

Scenario /Parameter	1	2	3
Main materials & U-value	Roof: Thatch (0.3 W/m²K) Wall: Timber (0.55 W/m²K) Floor: Timber (1.4 W/m²K)		
Opening (m²)	8.24	8.24	8.24
Shading (m)	1.5	1.5	1.5
Ventilation (m³/s)	0.81	0.81	0.81
Infiltration (m³/s)	3.14	3.14	-
Cooking (W/m²)	-	6	6
People (W/per)	-	85	85

Table 5 shows results for discomfort hours based on different comfort acceptability zones. The change of external wall fabric led to significant impact on thermal performance of the boat-shaped house. The decrease of external wall U-value led to a decrease of discomfort hours from 1.1 - 8.1% to 0.5 - 5.6 %. A decrease occurred for discomfort hours from 1.8 - 15.5% to 0.8 - 7% when internal heat gain was added. With the removal of infiltration, the range of discomfort hours dropped from the previous 11.6 - 36.6% to 4.4 - 23.4%.

Table 5:
Percentage of discomfort hours in July for each simulated scenario for the timber construction type.

Scenario	Discomfort hours in July (%) (80% acceptability)	Discomfort hours in July (%) (90% acceptability)
1	0.5	5.6
2	0.8	7
3	4.4	23.4

4.3 Discussion

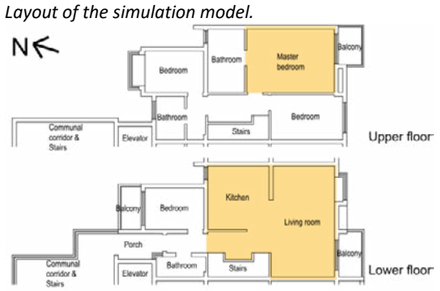
Although external shading reduced a number of discomfort hours, the well-insulated thatched roof worked more effectively to mitigate most overhead solar heat gain. Insulation properties of building fabric do have significant impact on reducing discomfort hours in this region because of the time lag that occurred with the improved thermal properties of the external rammed earth wall. The cross-ventilation strategy worked less effectively due to relatively lower WWR, however high infiltration via gaps of the porous fabric allowed more air exchange which offset the drawback. The sufficient air exchange rate enabled the indoor temperature reduce to the same level as the outdoor temperature. Overall, 86.5%-98.5% of the total hours in July was within 80%-90% acceptability comfort zone for the rammed earth type. Whereas 93%-99.2% of the total hours in July was within 80%-90% acceptability comfort zone for the timber type.

5. OPTIMIZATION OF A TYPICAL MODERN DWELLING TYPE IN WARM-HUMID REGIONS IN CHINA

5.1 Base case typology

The contemporary residential building type for simulation (Fig. 5) is a south-facing mid-floor and mid-terrace flat that is a typical urban housing type in China with nearly no regional difference (Housing in China, 2021) which means the results are likely to have wider reach in terms of applicability of the established strategies.

Figure 5:
Layout of the simulation model.



Concrete and brickwork were observed to be the main construction materials used for this housing type. The focus of this simulation was to test the feasibility and effectiveness of reducing thermal discomfort hours by applying extracted key design strategies to determine the potential to reduce people's dependence on air-conditioners (AC), and total hours for using AC.

5.2 The simulation matrix, results and discussion

Two main living areas, i.e., the living room (including kitchen and dining space) and the master bedroom were examined for their weekly and monthly thermal performance in July (warmest month). Four people were assumed to be the full occupancy for this flat. For both the base case and the optimized case, simulations were undertaken for weekdays and weekends. For the base case, assumptions were made for its building fabric and other inputs as shown in Table 6 and 7:

Table 6:
Building fabric details for the base case.

Building component	Material & thickness
External wall	240mm cavity brick wall
Building external roof	220mm reinforced concrete + 220mm asphalt roofing
Building exposed floor	240mm cast concrete
External window	6mm single-glazed windows
Internal partition	120mm/240mm brickwork
Internal ceiling/floor	120mm reinforced concrete

Table 7:
Modelling inputs for the base case.

Parameter	Living room	Master bedroom
Window area (m^2)	9.02	3.98
Effective aperture area (m^2)	5.07	1.99
Shading (m)	0.75	0.75
Ventilation strategy	Cross	Single-sided
Ventilation (m^3/s)	0.38	0.24
Infiltration (m^3/s)	0.25	0.25
Monthly occupancy for weekdays (h)	117.3	254.8
Monthly occupancy for weekends (h)	117	139.5
Equipment (W/m^2)	13	5
Lighting (W/m^2)	5	5
Cooking (W/m^2)	5	-
People (W/per)	85	85

As mean outdoor temperature of Hainan is 30°C in July within adaptive comfort zone 25°C-32°C, 30°C is assumed to be the usual cooling set point for AC to be turned on, which is the basis of calculation for the amount of discomfort hours. Results showed that the temperature of the living room was between 29.5°C and 33°C throughout the week. The temperature of 73.4% of occupancy hours on weekdays (86.1 hours) and 96.5% (112.5 hours) at weekends was found to be higher than 30°C therefore likely to require AC. Additionally, the indoor temperature of the bedroom was between 29.5°C and 32.5°C which translated to 40% discomfort hours during occupancy on weekdays (101.9 hours) and 50.8% (70.8 hours) at weekends.

Following these simulations, parameters were changed on the optimised model to improve their thermal performance based on extracted design strategies (see Table 8, 9, and 10):

Table 8:
Modelling detail of building fabric after optimization.

Building component	Material
External wall	Lightweight concrete blocks with phenolic foam boards
Building external roof	Reinforced concrete + Phenolic foam + asphalt roofing
Building exposed floor	Cast concrete + Phenolic foam
External window	12mm double-glazed windows
Internal partition	Brickwork + Phenolic foam/ Lightweight concrete blocks + Phenolic foam
Internal ceiling/floor	Reinforced concrete + Phenolic foam

Table 9:
Modelling inputs for the optimized case.

Parameter	Living room	Master bedroom
Window area (m^2)	9.02	4.98
Effective aperture area (m^2)	5.07	2.99
Ventilation strategy	Chimney	Single-sided (higher stack)

Table 10:
Comparison of building fabric U-value of the base case and the optimized case.

U-value (W/m^2K)	Base case	After optimization
External wall	1.5	0.52
External roof	2.34	0.34
Exposed floor	2.37	0.52
Internal partition	120mm: 2.35 240mm: 1.69	120mm: 1.08 240mm: 0.49
Internal ceiling / floor	3.97	1.33
External window	5.69	1.9

Simulation results showed that thermal comfort was significantly improved in the living room and the bedroom (see table 11). For the living room, 59.7% of occupancy hours on weekdays (70 hours) and 87.2% of that (102 hours) at weekends had an indoor temperature above 30°C. Comparing with the base case, discomfort hours decreased by 13.7% weekdays, and 9.3% at weekends. For the bedroom, 38.9% of occupancy hours on weekdays (99 hours) and 40.3% (56.2 hours) at weekends had an indoor temperature above 30°C. Compared with the base case, discomfort hours had a 1.1% decrease on weekdays, and a 10.5% decrease at weekends.

Table 11:
Percentage of total occupancy hours above 30°C that need AC cooling for one week in July (%).

Room	Base case	After optimization
Living room	73.4 ~ 96.5	59.7 ~ 87.2
Master bedroom	40 ~ 50.8	38.9 ~ 40.3

6. CONCLUSIONS AND RECOMMENDATIONS

Air exchange by natural ventilation and infiltration, and building fabric were identified as two factors that determined thermal performance of vernacular dwellings in Southeast Asia and China. The boat-shaped house was found to enhance air movement rate for cooling via its porous fabric, upper vents, and other openings. Limited impact on reducing overhead solar heat gain was found for its external shading. The change of wall fabric to lightweight materials with lower U-value led to the reduced impact of solar radiation. After optimization on building fabric and natural ventilation, discomfort hours reduced by up to 10.5%-13.7% in July. The findings indicate that suitable design strategies for warm-humid climate are:

1. Lightweight materials can mitigate solar heat gain and reduce indoor temperature because of their low thermal conductivity and heat capacity.
2. Materials with higher U-value are suggested only when excellent natural ventilation is possible.
3. Well-insulated roofs work more effectively than external shading on reducing solar heat gain since the sun is mostly overhead due to low latitude.
4. Stack and cross ventilation strategies work best, and both WWR and stack height should be increased to enhance air exchange.

This study has shown that significant reduction of discomfort hours can be achieved via the implementation of the aforementioned design strategies. It is likely that their implementation in existing or new contemporary buildings in warm-humid regions can significantly reduce space cooling requirements. In China, as was noted in section 1.0. this currently accounts for 47% of domestic energy consumption requirements.

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Testing the comfort triangles tool

Improving initial design decisions for natural conditioning

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ABSTRACT: This paper presents a development of the comfort triangle tool used to evaluate the effectiveness of different bioclimatic strategies at an early design stage. This tool emphasises the potential to modify the indoor conditions changing the average daily temperature and moderating the temperature swing. These two variables define a daily temperature curve. The approach stresses the analysis of the dynamic thermal performance of naturally conditioned buildings, rather than a conventional static condition of comfort and thermal balance. The innovation is the visualization of the estimated indoor conditions compared with the simultaneous outdoor conditions, showing how different bioclimatic strategies promote favourable conditions, approaching the comfort triangle, both individually and in combinations. Examples of the application of the triangles in different climate zones are presented and compared with measured conditions. These show that the designer can evaluate possible strategies at an early design stage, before taking definitive project decisions.
KEYWORDS: Natural conditioning, thermal comfort, bioclimatic strategies, temperature swing, average temperature.

1. INTRODUCTION

The latest IPCC report [1] emphasises the urgency of achieving significant reduction in greenhouse gas emissions. Buildings are responsible for a large proportion of the total; buildings and the construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO2) emissions in 2018 [2]. It is therefore important to assess and implement immediate and progressive emissions reductions in this sector. The factors that must be considered include urban planning, building design, energy efficient installations and equipment, improving the existing stock and modifying user behaviour. The design of new buildings is critical as early decisions will have a long-term impact due to the extended useful life and high initial investment.

Bioclimatic strategies for new buildings include 10 measures to modify the average indoor temperature and moderate the amplitude, the difference between daily maximum and minimum temperatures. This paper presents a graphic spreadsheet tool for visualizing the external and internal average values and swings, comparing them with the range of environmental conditions required for comfort according to the occupant's activity levels. The use of the tool is explained, and examples of applications are shown to visualize, test and verify the usefulness and effectiveness in different climates in latitudes from the equator to high latitudes of South America, compared with measured temperatures.

2. THE COMFORT TRIANGLES TOOL

The Comfort Triangles (3) were developed to analyse the dynamic performance of bioclimatic resources, which modify the average indoor temperature, the range of the temperature swing or both simultaneously. The spreadsheet includes a climatic database with over 600 locations in Latin America and other major world cities, which can be quickly selected from pull-down lists.

The tool also allows the selection of one of four different comfort zones, for sedentary activity, sleeping, moderate activity or outdoor conditions. It then shows possible bioclimatic design strategies used to modify the indoor environment with natural conditioning, without conventional energy use. The selection of each strategy allows different intensity levels, for example, varying solar radiation intensities or different air movement velocities. With the selection of these design strategies, the tool indicates the modification of indoor comfort conditions to visualize the effectiveness of different contributions.

For this purpose, the tool emphasizes the dynamic performance of bioclimatic design resources, considering the daily temperature swing and the potential to combine different strategies. For example, solar radiation using passive systems will increase indoor average temperatures but, at the same time, will increase the indoor swing. So, thermal inertia is used to moderate the indoor variation and improved thermal insulation conserves the energy received. Similarly, night ventilation to cool indoor spaces the following day is more effective when combined with thermal inertia.

The tool uses the same database to analyse adaptive comfort, calculate degree days of cooling or heating with variable base temperatures. The results are compared with other bioclimatic design tools such as Olgyay's (3) and Givoni's (4), Climate Consultant (5) and the Mahoney Tables (6), which are included in the tool with the same database. The objective is not to replace existing tools but to provide a complementary approach with a different way of visualizing the relation climate-building-thermal comfort, emphasizing temperature variations and daily swings. Monthly average temperatures are used to analyse typical conditions rather than extremes.

2.1 Bioclimatic design strategies

The 10 bioclimatic strategies that can be used to modify average indoor temperatures and temperatures swings are:

CV. Cross ventilation: cooling by evaporation of transpiration and convection. Reduces effectiveness of insulation and inertia.
TI. Thermal inertia: reduction of temperature swing and complement of solar gains with storage.
DG. Daytime internal heat gains: increases average temperature and swings.
NG. Night-time internal heat gains: increases average temperatures and reduces swings
SG. Solar gains: increases average temperatures and temperature swings.
DV. Daytime selective ventilation: increases average temperatures when indoor-outdoor differences are favourable but may increase swings.
NV. Night-time selective ventilation: can reduce average temperature and swings.
TI. Thermal insulation: increases the effectiveness of heat gains, internal and solar, as well as thermal inertia.
SP. Solar protection: avoids increasing temperatures and controls swings.
HU. Humidification: reduces air temperatures and can moderate swings

2.2 Combinations of design strategies

The list of bioclimatic design strategies shows the importance of combining compatible and complementary strategies, while avoiding incompatible and conflicting ones. All buildings will incorporate some thermal inertia and insulation, so the selection of appropriate levels is important. For example, solar gains will increase average indoor temperatures and swings. This can be moderated by thermal inertia and heat gains can be conserved by thermal insulation, while ventilation can be used eventually to reduce the risk of overheating.

2.3 Permanent and variable strategies

Some strategies such as thermal inertia and insulation are always present, while others such as cross ventilation, solar protection and selective ventilation are variable. Users will close windows when temperatures drop below the comfort zone, and close shutters to avoid unwanted solar gains. They will also open windows if bedroom temperatures are high at night and outdoor temperatures are cooler. The effectiveness of each strategy is adjusted to respond to this typical user behaviour

2.3 Intensity of strategies

Bioclimatic strategies are not binary, 'off' or 'on', and can be graduated. Different levels of thermal insulation and thermal inertia can be chosen to achieve the required environmental modification, a design decision that cannot be modified later. While occupants can adjust windows with the building in use to achieve different levels of air movement as at 27° C slight air movement can improve comfort, but high velocities can be excessive. At times, moderate solar gains are needed while in colder conditions, higher gains are favourable. The Comfort Triangle Tool allows the user to select from four different levels of intensity to visualise, test and evaluate alternatives and combinations.

2.4 Strategies for building design

Strategies such as thermal insulation and inertia can be achieved by selection of appropriate materials in roof, wall and floor construction. However, building form and grouping must be considered to complement the thermal characteristics of building components. Compact forms will complement the effectiveness of thermal insulation. The use of cross ventilation also depends on building design, window location, internal layout and proportions of outdoor spaces. The Tool therefore provides detailed guidance for each strategy, so that the designer can implement each strategy appropriately once it has been selected.

3. APPLICATION OF THE COMFORT TRIANGLES TOOL

The following series of examples apply the Comfort Triangle Tool for climate analysis, sketch design, research and teaching in different climates from the warm humid equatorial regions to mid latitude temperate and cold climates, and upland climates with high temperature swings. The results of the tool have been tested by comparison with simulations and measurements in existing buildings. It should be noted that the Comfort Tool shows the thermal modification tendances and possibilities to approach or reach the comfort zone, but it is not intended to be a precise simulation.

3.1 Sketch design and simulation

Figure 1 shows the Comfort Triangles with data for the Island of Baltra, Galapagos, Ecuador, with a warm humid climate close to the equator. The tool shows

that the indoor temperatures can be maintained close to the comfort zone without recourse to artificial conditioning, using cross ventilation, moderate thermal inertia and effective solar protection, even in buildings with moderate internal gains by day. These strategies were applied in the Seymour Ecological Airport, which achieves comfortable indoor temperatures as shown by the simulations used to verify environmental conditions and conventional energy demand. This naturally conditioned building (7) has been certified LEED Gold.

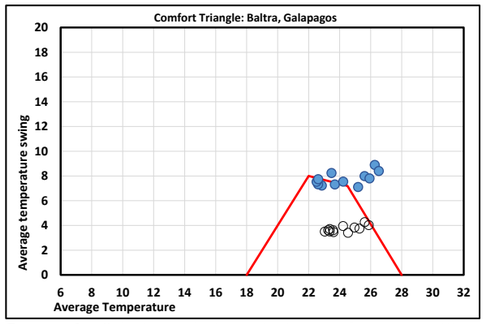

Figure 1: *Selecting design strategies for a maritime equatorial climate, Seymour Ecological Airport, Galapagos Islands, Ecuador, Latitude 0°.*

3.2 Temperature measurements

Figure 2 shows the Comfort Triangle with data for the town of Otavalo. This has been compared with temperature measurements in an existing building to verify the accuracy and suitability of the results of the Comfort Triangles Tool, with further comparisons with measurements in Panamá, Quito, and Buenos Aires.

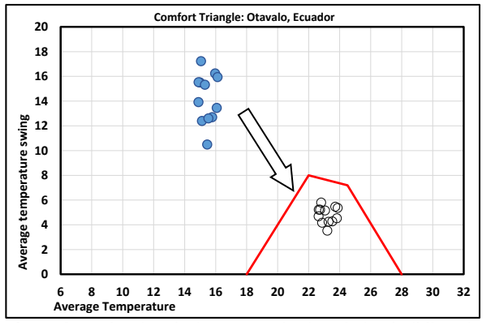

Figure 2*: Evaluating design strategies in existing buildings in an upland equatorial climate, Otavalo, Ecuador, latitude 0°, altitude 2230 m. Strategies include solar and internal gains, thermal insulation and high thermal mass.*

Figure 3 shows the comfort triangles for San Miguel in Greater Buenos Aires, showing that typical indoor conditions are close to or within the comfort zone using thermal inertia, insulation, solar protection in summer and gains in winter, moderate internal gains and cross ventilation in summer. The same selection and implementation of bioclimatic strategies produces different modification in summer and winter. The diagram shows that with appropriate strategies, average indoor winter temperatures can be 8 degrees above outdoor temperatures, while the increase can be limited to 2 degrees. However, the simultaneous reduction of the temperature swings in both seasons also reduces maximum peaks.

Figure 4 for Aeroparque, Buenos Aires local airport on the shore of the River Plate estuary, shows the comparison with figure 3 with the moderating effect of the River Plate, reducing the swing without significant change in the average temperature.

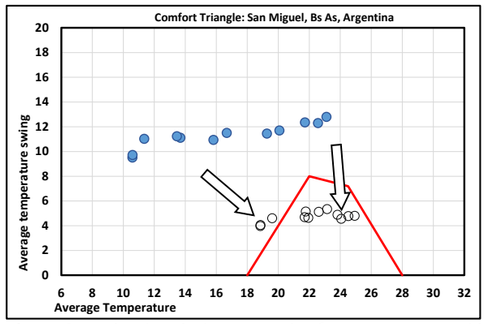

Figure 3: *Evaluating design strategies for a temperate mid latitude climate, San Miguel Buenos Aires, Argentina, Latitude 34° S.*

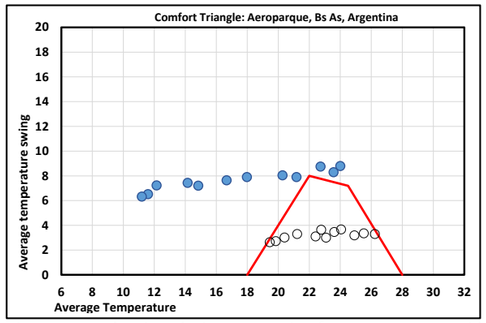

Figure 4: Evaluating design strategies for a temperate mid latitude climate, Aeroparque, Buenos Aires, Argentina, Latitude 34° S.

To relate these studies to conditions in housing, measurements were made at 15 minutes intervals over 10 months in an occupied living room with natural conditioning, heating was only used occasional when temperatures dropped below 18° C. The room has high thermal inertia, compact form, favourable solar orientation and possibility for cross ventilation. Figures 4 and 5 show average indoor and outdoor temperatures during a 5-day cold and hot period in summer and winter respectively.

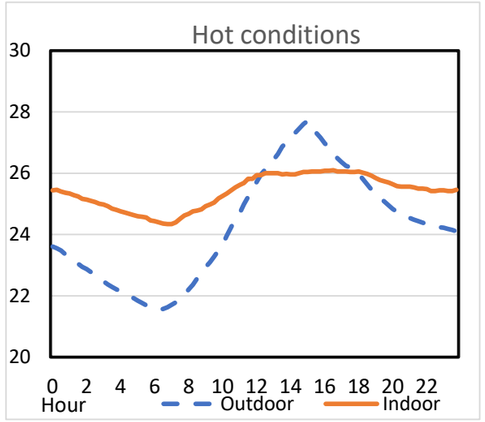

Figure 4. *Indoor and outdoor temperature in a typical summer day in Buenos Aires*

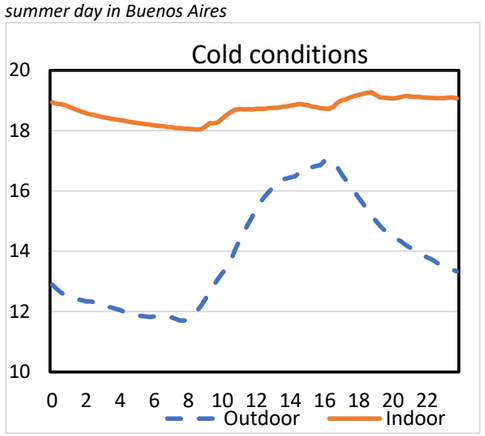

Figure 5. *Indoor and outdoor temperature in a typical winter day in Buenos Aires*

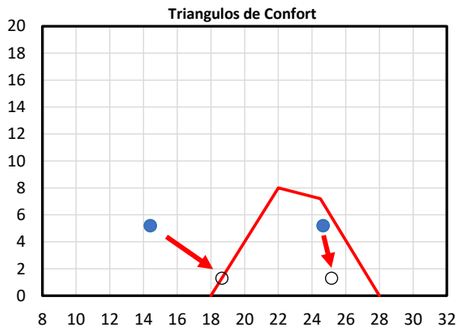

Figure 6: *Measured conditions in typical winter and summer days showing the same conditions as figures 4 and 5, based in the average daily temperatures and the temperature swing.*

Figure 6 shows the contribution of insulation and internal gains in winter, control of heat gains by ventilation and solar protection in summer and moderation of indoor swings in both seasons.

3.3 Use in teaching

The Comfort Triangles Tool was used for teaching bioclimatic design. In a short 12-hour course for architects, the tool was used to explain the environmental design process and then applied by each of the participants to analyse and improve a current project in different regions of Argentina.

6. DISCUSSION

The Comfort Triangle Tool proposes three innovations to promote natural conditioning and reduce dependence on conventional energy. Firstly, the tool emphasizes the importance of design to achieve a favourable control and modification of the daily variation of temperature, rather than the

5. CONCLUSIONS

The tool shows the expected modification of indoor conditions, allowing more detailed simulations at a later stage of project development after the initial selection of appropriate bioclimatic strategies. The examples demonstrate the utility and effectiveness of the Comfort Triangles Tool in project design, evaluation of existing building performance and teaching, promoting the development of near zero-energy buildings through design.

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Bioclimatic evaluations of perforated walls built in Bahareque

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ABSTRACT: Architecture and construction have had a significant development throughout history in terms of quantity of new materials and constructive methods that have made the execution times of the works more agile. However, we know that this industry is one of the most polluting on the planet, representing 40% of primary energy consumption and 33% of CO2 emissions (ZABALA et al., 2011). On the other hand, there are traditional construction methods that have been replaced by new technologies, such as bahareque, which due to its execution has a low impact on its ecological footprint. (ALZATE et al., 2014). In addition, the bioclimatic studies that are known of the bahareque are few, respect to the usable phenomena in architecture. Some of these, study the temperature and quality of the mixture, oriented to local conditions. (MATTONE,2005). This is why the research seeks to enhance the attributes of bahareque by determining its bioclimatic efficiency through drilling strategies that allow the entry of wind and lighting into the house, for its application in a hot-humid climate. 6 prototypes of perforated bahareque walls were analyzed, 3 were built and evaluated in the field. Evaluations were also performed using Autodesk CFD and DIVA for Rhino software.
KEYWORDS: Bahareque, natural lighting, natural ventilation, humidity, temperature.

1. INTRODUCTION

Architecture and construction have had a significant development along the history in terms of quantity of new materials and constructive methods that have made the execution times of the works more agile. However, we know that this industry is one of the most polluting on the planet, representing 40% of primary energy consumption and 33% of CO2 emissions (ZABALA et al., 2011). In part, due to standardization and mass production, making use of raw materials and polluting elements that gene rate greenhouse gas emissions. On the other hand, there are traditional construction methods that have been relegated or replaced by new technologies, such as bahareque, which due to its execution has a low impact on its ecological footprint (ALZATE et al., 2014). In addition, it has earthquake resistant properties, which shows one of the reasons why it has lasted over time (HENNEBERG, 2015) and by which the earthquake resistance standards for bahareque are applied in Colombia (NSR-10, 2010).

In addition, the bioclimatic studies that are known of the bahareque are few, with respect to the usable phenomena in architecture. Some of these, study the temperature and quality of the mixture, oriented to local conditions. (MATTONE,2005). Consequently, this research seeks to determine the efficiency of natural lighting, natural ventilation, and temperature of bahareque walls through drilling strategies that allow the entry of wind and lighting into the house for its application in the city of Florence, Caquetá, from field evaluations, simulations in Autodesk CFD software and DIVA for Rhino.

2. METHOD

To achieve the objectives proposed in this work, a methodology was developed in three phases: exploratory, projective, and evaluative. It is worth mentioning that the evaluative method is present in the first two phases. Exploratory: Study of the bahareque and location of the case study. Project: Design of modules in bahareque and evaluations. Evaluative: On-site and computational evaluations. lower case and numbered in bold.

2.1 Case study

Florencia, Caquetá or also known as the golden gate of the Colombian Amazon, is the setting in which this research is developed, given that it has the material resources at its disposal, thanks to its wide range of plant formations because of the combination of factors such as climate, geology, hydrology and soils; that generate to a greater extent the Andean Forest and the pluvial forest of the Piedmont. (Humboldt, 1998).

This region, being at a latitude 1° from the equator, does not present seasonal changes. Instead, it is located in the tropics, with a hot-humid climate characterized by high temperatures both during the day and at night and by drastic changes in rainfall. Which generates a high percentage of relative humidity.

That with an adequate use of natural materials; in this case, bamboo can make up for the housing deficit left by rapid urban growth. To carry out the bioclimatic evaluations, two social interest housing projects in the La Gloria neighborhood, located in the northwestern part of the municipality, are taken as a case study. These correspond to the Glory stage I and the Andaquíes portal.

3. BAHAREQUE

By the end of the 19th century, construction in bahareque was already becoming a prominent reference in Colombia, as it was an agile and low-cost construction system, since generally the materials for its construction were easily found in the immediate environment, making it difficult to generate additional costs for having to transport materials that are very far from the construction site.

The bahareque is a traditional and vernacular construction technique where the main material used is a combination of bamboo, mud, natural fiber and water; that shape the enclosures and openings of a house with up to 2 floors. The bahareque is a traditional and vernacular construction technique where the main material used is a combination of bamboo, mud, natural fiber, and water; that shape the enclosures and openings of a house with up to 2 floors.

The bahareque technique has different forms of application, among them we find the bahareque, the cemented bahareque; the traditional bahareque. The latter is the most applied in Florencia city, and it consists of the creation of a horizontal framework with bamboo, cane or wood that is set in front of and behind a structure in bamboo or wood. Thus, achieving a vacuum in the middle that is filled with clayey earth mixed with natural fiber and water, which is finished with the coating that is similar to the previous mixture, but adding in some cases lime, sand and cement.

Figure 1:
Bahareque construction system. Own source.

3.1 Bahareque resistance earthquake

The bahareque has been questioned by some and defended by others in terms of its resistance to earthquakes, and it is understandable that these differences exist, since the passage of these phenomena has shown that some buildings have remained standing, and others have not. However, the result of this cannot be given completely to the material, since the building is also composed of the constructive and structural methods that together with the material make a house an earthquake resistant model. So much so, that in the Colombian regulation of earthquake resistant construction (NSR-98), by decree number 52 of 2002, chapter E was included that addresses the technical aspects of the construction of one and two- story cemented bahareque. And it is still in force after the update that was made in 2010 (NSR, 2010).

Hence, the bahareque is a cultural reference and a resistant earthquake that has been forgotten by the arrival of other materials that have diminished its prominence, not because they are necessarily better and that have made the constructions in bahareque disappear. Or as Bedoya says (2011): “The bahareque as a natural reinforced concrete, or perhaps, and perhaps by history, it would be fairer to say that reinforced concrete appears to me as an artificial bahareque”.

3.2 Glass and plastic bottles as systems lighting in the bahareque

The incorporation of recycled materials into walls in bahareque, in this case the bottles of glass, has generated a model of enclosures with diverse environments, using color and light.

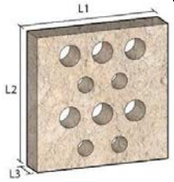
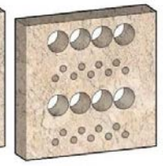
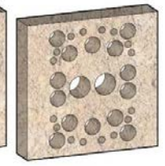
3.3 The bamboo and PVC as systems of ventilation in the bahareque

The perforations in the wall through natural elements such as bamboo allow air to enter the spaces and at the same time natural lighting. And that pretend to have the same function of the openwork blocks that are used very frequently.

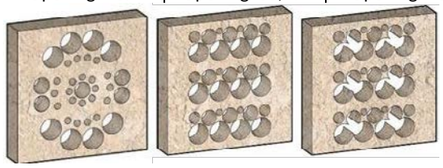
4. EXPLORATORY PROPOSAL OF MODULES IN BAHARAQUE

The perforated bahareque walls proposed in this stage of the research seek to improve the current bioclimatic conditions of House 1 and 2. For this, perforations with different percentages of opening were made, using PVC pipes, glass bottles and bamboo. See figure (2).

Table 1:
Perforated bahareque modules. Own source.

M1	M2	M3
Opening: 16%	Opening: 19%	Opening: 23%
		

M4	M5	M6
Opening: 26%	Opening: 39,1%	Opening: 40%



*L1: 0,50 m | L2: 0,50 m | L3: 0,10 m

4.1 Constructive process of model m1

For the construction of the M1 model, the traditional bahareque technique was used, using bamboo for the structure. For the filling, a mixture was made with equal amounts of earth, sand, natural fiber and water. While for the pre-concrete a little more water was added to the mix. Finally, a combination of earth, sand, lime was used for the concrete in equal quantities and water was added to this. In the case of the perforations, 8cm diameter PVC tubes were used, with a height of 10cm and 4 glass bottles collected from the place were used; 10cm high; 4 cm in diameter at its neck and 6 cm in diameter at its base.

Figure 2*:*
Constructive process of model M1. Own source.

5. MEASUREMENT PARAMETERS

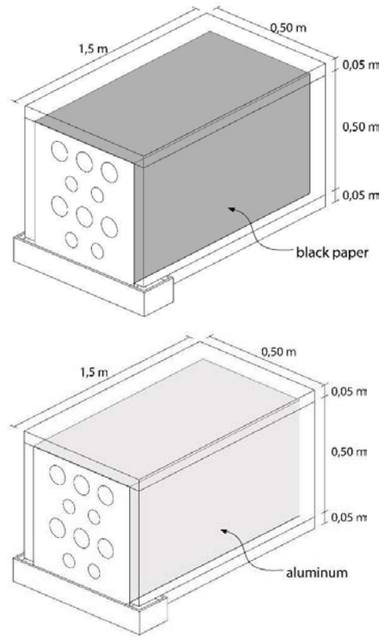
- Ventilation

To evaluate the individual walls, it was created 4m x 1.5m x 1.5m box. Around this, the ventilation tunnel was located, applying a wind speed of 2m / s on the south face of the tunnel and pressure was applied on the north face. Each module was evaluated in 4 different directions: southwest, southeast, east and west. the first two correspond to house 1 and the last; to house 2.

- Temperature, relative humidity, and illumination

To evaluate the individual walls, it was created a 4m x 1.5m x 1.5m box. Around this, the ventilation tunnel was located, applying a wind speed of 2m / s on the south face of the tunnel and pressure was applied on the north face. Each module was evaluated in 4 different directions: southwest, southeast, east and west. the first two correspond to house 1 and the last; to house 2.

Figure 3:
Location of modules for luminance and temperature evaluations. Own source.



The light evaluation was carried out in a space of 0.5m x 0.5m x 1.5m. Each module was evaluated in 4 different directions: southwest, southeast, east and west. The first two correspond to house 1 and the last; to the house 2. Dynamic simulations were carried out in the Autodesk diva program, that is, the light behavior of each module was evaluated in a single simulation throughout the year.

6. TREAMENT OF RESULTS

- Illumination

For the results of the static simulations, the percentages of the illuminated area in the range (100 -1000 lux) were tabulated. Likewise, a comparison was made between the best result of each month minus the second-best result, thus obtaining the difference. While, for the individual dynamic simulations, the difference in the percentage of udi (useful daylight illuminance) was known between each module, in an east-southeast direction and in a west-southwest direction.

- Field work

The data obtained in the field through the lighting sensors and hygrometers were added and averaged.

- Ventilation

For the case of the cfd simulations, the area of the wind shadow that is in the ranges 0 - 0.5 m / s and 0.5 - 1m / s inside the house was taken. The different shadows found in each house, between the mentioned ranges, are added to obtain the total area of the wind speed. Each measurement is carried out both in plan and in section.

7. RESULTS

7.1 Home ventilation 1

Figure 4:
House 1. Own source.

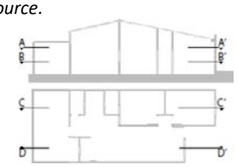


Table 2:
CFD simulation results at House 1. Own source.

	SOUTHEAST		SOUTHWEST		SOUTHEAST		SOUTHWEST	
HOME 1	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	16,9 m²	4,6 m²	7,9 m²	0,01 m²	11,98 m²	0,85 m²	5,55 m²	3,64 m²
HOME 1 + M1	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	10,8 m²	3,54 m²	4,5 m²	0,25 m²	9,6 m²	0,44 m²	4,09 m²	0,28 m²
HOME 1 + M2	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	13,4 m²	0,95 m²	0,76 m²	0,01 5 m²	11,33 m²	0 m²	1,4 m²	0 m²
HOME 1 + M3	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	15,3 m²	5,13 m²	0,19 m²	6,16 m²	8,54 m²	0,04 m²	5,50 m²	0,33 m²
HOME 1 + M4	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	16,0 m²	6,4 m²	1,06 m²	0,03 m²	14,2 m²	0,74 m²	1,8 m²	0 m²

The results do not show a significant change when inserting the bahareque modules, instead, it is evidence that there is more ventilation in house 1 without any modules added or replaced. However, the M2 module shows a better result in the Southwest orientation, cut B-B '.

7.2 Home ventilation 2

Figure 5:
House 2. Own source.

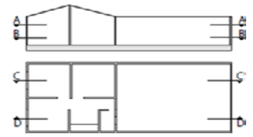


Table 3:
CFD simulation results at House 2. Own source.

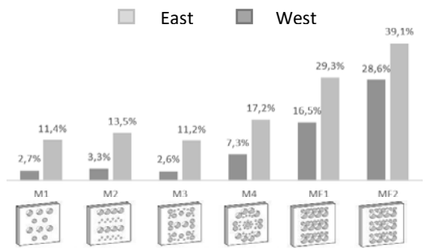
	SOUTHEAST		SOUTHWEST		SOUTHEAST		SOUTHWEST	
HOME 2	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	4,79 m²	7,70 m²	4,9 m²	5,35 m²	1,15 m²	6,71 m²	4,95 m²	0,22 m²
HOME 2 + M1	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	5,54 m²	7,76 m²	4,44 m²	5,4 m²	2,06 m²	1,45 m²	5,03 m²	1,94 m²
HOME 2 + M2	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	5,11 m²	7,31 m²	4,55 m²	5,24 m²	2,8 m²	3,25 m²	3,28 m²	2,1 m²
HOME 2 + M3	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	4,67 m²	7,33 m²	2,4 m²	5,15 m²	1,69 m²	1,0 m²	4,39 m²	1,6 m²
HOME 2 + M4	A-A′	B-B′	A-A′	B-B′	C-C′	D-D′	C-C′	D-D′
0 - 0,5 m/s	4,65 m²	6,8 m²	2,4 m²	4,6 m²	1,89 m²	1,45 m²	3,83 m²	1,71 m²

7.3 Illumination

The results of the individual dynamic simulations of each module in the southeast, southwest, east and west directions are presented below.

Figure 6: *UDI of all modules in a southeast, southwest direction. Own source.*

Figure 7:
UDI of all modules in a east and west direction. Own source.



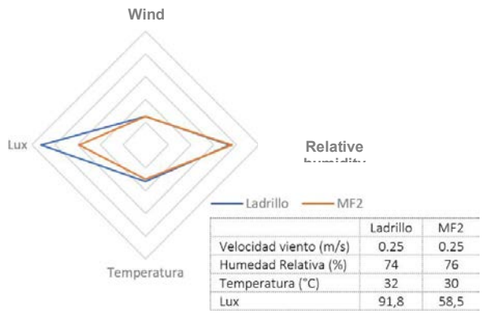
When comparing the MF1 and MF2 modules with respect to the other modules, an improvement of almost three times the useful lighting of the day is observed in the southwest-southeast direction and almost double in the east-west direction.

The best light performance is generated by the MF2 module with an UDI of 31.09 and 21.85% in the southwest and southeast direction respectively. In the west direction 39.06% and 28.65% in the west.

7.4 FIELD EVALUATION

For the final evaluation, modules MF1 and MF2 were compared with M1 and with the materials corresponding to brick, wood and green mesh.

Figure 8:
Measurement result MF2 vs Brick. Own source.



	Ladrillo	MF2
Velocidad viento (m/s)	0.25	0.25
Humedad Relativa (%)	74	76
Temperatura (°C)	32	30
Lux	91,8	58,5

It is important to mention that the previous evaluations were carried out for 20 min, starting at 9:30 a.m. and ending at 12:10, at which point the 9 evaluations of temperature and relative humidity begin, with a duration of 15 min each. a. From the previous results of the bahareque walls we can say that:

- The MF1 and MF2 bahareque modules significantly improved natural lighting compared to the M1 module, since an increase of 22.3% was generated in the MF1 and 48% in the MF2 module.
- The temperature difference between the bahareque walls is not evident, since the results yielded equal temperatures between each evaluation.
- The modulus of wattle and daub MF2 is 2 ° C lower than the brick wall, while the MF1 is 1 ° C lower. On the other hand, the difference between the other materials (green mesh and wood) was not evident with respect to the MF2 module, while compared to the MF1 the difference was 1 degree, with MF1 being less.
- The perforated wood and green mesh modules provide better lighting than the bahareque walls because, the thickness of the wood wall and the transparency of the green mesh generates better lighting than the bahareque walls.
- The wind speed has very similar results in the evaluations, with speeds of 0.23 m / s. However, the comparison of the M1 and MF2 shows an equal speed in both cases of 1m / s.
- Relative humidity varies between 1% and 3% and is above the recommended levels for a home. The proposed bahareque modules MF1 and MF2 significantly improved their efficiency compared to M1 and present advantages over temperatures.

8. DISCUSSION

The proposal put forward in this work for the solution to the housing deficit and the improvement of the habitability conditions showed that the houses built in bahareque with perforations present important efficiency advantages with respect to other construction materials.

In a first analysis, the lighting results of the bahareque modules were lower than the current dwelling, since an analysis methodology different from the final one was used, evaluating the performance of the modules on the 21st of each month of the year (static simulations). The difference arose because a rear window was replaced and filled with perforated bahareque modules, resulting in a considerable loss of natural lighting.

However, there is evidence of an improvement with respect to the dwellings studied, which is undoubtedly due to the incorporation of perforations to the object of study, to the different perforation patterns used in each module and not to replace the project window but to complement it with the perforations of the modules. Something similar happens when evaluating ventilation, since not only its efficiency is determined by the number of perforations it has, nor its opening area, but by the organization or concentration of the perforations. In studies such as those of De Araújo, Bistafa (2011) a similar behavior is evidenced, with the difference that their study evaluated openwork blocks.

Bahareque was also shown to be a natural temperature regulator compared to other evaluated materials. It managed to reduce up to 2 ° C compared to brick and up to 1 ° C compared to wood. Various authors agree that bahareque can be used in the enclosures of the house to obtain a thermally comfortable environment, they also mention that it should continue to investigate its insulating properties. (G. Cuitiño, 2015).

On the other hand, the perforated facade represents a strategy of lighting, thermal and natural ventilation control that allows to have more comfortable interior spaces for its users (Arango, 2016) (Lacau, 2005) (CIS, 2014). In a study carried out by the Center for Social Innovation in 2014, they propose a bahareque wall perforated with pet bottles, taking advantage of access to lighting and regulated ventilation, through the bottle caps. A passive system with active users.

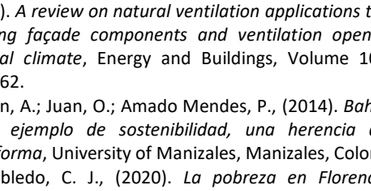
9. CONCLUSION

In relation to the information collected in field trips and the identification of bahareque houses in Florencia Caquetá, it is evident that this construction system has been relegated by other highly polluting traditional systems, which generate carbon footprints that affect the balance of the planet. In addition to the environmental cost generated by these materials, they have a higher monetary cost compared to construction in bahareque, taking into account that the materials are close to the site. Even with this, there is no greater presence of government authorities that regulate these construction systems. Regarding that, I consider that the first thing to do is to educate people about the various constructive-sustainable systems, because in my search, I came across some people who said that bahareque was a sign of poverty. It is necessary for people to find out about the benefits of these noble materials, so as not to fall into the error of thinking that bahareque is an obsolete construction system.

The analysis of the carried-out simulations verifies that the perforated bahareque can be used in the houses to allow the passage of the wind, acquire adequate lighting and generate more thermally comfortable spaces. In addition, the adequate performance of the drilling elements was evidenced; PVC, bamboo and glass bottles that were used for field evaluations and supported the weight of the material. With regard to the analysis of temperature and relative humidity, temperature reductions of up to 2 °C are evidenced compared to other materials such as brick. In addition, the percentages of relative humidity are within the recommended ranges inside the home.

On the other hand, the geometries that achieved these results show that the concentration of the perforations improves their efficiency, since they allow greater entry of lighting into the space.

Figure 9:
Module with multiple openings vs module with concentrated openings



Likewise, ventilation improved, achieving large ventilated areas and guaranteeing cross ventilation. However, these results were general because each geometry varies according to the solar orientation, the days and the hours of the year in which they were evaluated. Therefore, it must be said that, although some modules gave higher percentages in their evaluations, they do not mean that they are the best or the only ones that can be used, it would be necessary to review each situation and determine which is the most appropriate drilling pattern for said situation.

ACKNOWLEDGEMENTS

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Thermal performance testing of water spray window in cooling operation

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ABSTRACT: The water spray window is an energy-saving and cooling system that are equipped with functionality of thermal insulation and energy saving in summer. The cooling experiment of spray water window was conducted in summer in NanNing city, Guangxi province, China, to study water spray's cooling effect on glass and its energy saving efficiency under different window configurations and different thicknesses of interlayers. In the cooling test of the outer surface of glass, compared with contract window, the water spray window can reduce the outer surface temperature of single-glazing glass by 6 ℃ during daytime and 3 ℃ during nighttime, and the temperature of the window's inner surface is also significantly reduced. In the energy-saving test for different window configurations, triple-glazing windows have the highest efficiency of average 24.4%, while the double-glazing windows have the lowest efficiency about 9.9%. Among windows with different interlayer thicknesses, the trickier of the interlayer, the higher its energy-saving efficiency will be. The 200mm interlayer could reach the highest energy-saving efficiency of 35.19%. The results show that water spray windows are quite practical in Southern China featured with hot and humid weather and enjoy good application prospects.
KEYWORDS: Water spray window, Thermal performance, Evaporative cooling, Surface temperature, Energy saving rate

1. INTRODUCTION

In the hot and humid Southern China with long summer and strong sunshine, ordinary windows are prone to overheating and become one of the most important causes of heat loss. Transparent building envelopes such as exterior windows are usually considered to be the weakest part of the building façade[1] and solving the heat transfer problem of windows can contribute to improving the urban environment and reducing building energy consumption. As more countries are promoting their carbon emission reduction measures, it is important to improve the thermal performance of building exterior windows.

New energy-efficient glass has been widely applied, such as adding flow water to the windows. The water flow window researched by Chow, Liu et al. Fill the window interlayer with water to remove the heat from the glass through the flow of water. And the research found that compared with the traditional single-glazing window and double-glazing window, the heat gain of the room with the flowing water window was reduced by 52% and 32%[2]. When low-temperature water is available, the inner surface temperature of a flowing water window can even be reduced to the indoor air temperature, reducing the heat loss through the window[3]. Li et al. found that low-temperature flowing water reduces the heat entering the room through the window glass, helping to maintain a stable indoor air temperature[4]. However, a significant limitation of applying flowing water windows is that it needs a ground source heat pump system to ensure low-temperature water. And the high weight and cost of the window units due to the filling of the middle with a body of water. To address this issue, this research aims to replace water spray windows replace water flow window. The southern China is rainy and humid in the summer. Rain and air conditioning condensate stores large quantities of renewable water through collection systems that have been filtered and sanitized for spray cooling. The evaporation and heat absorption of water vapor from the water spray window can reduce the air temperature, and the water layer formed by the spray can take away the heat from the glass surface, reducing the heat gain of the exterior window and improving the thermal environment of the interior and exterior. It not only improves the thermal performance of the exterior windows and reduces the cooling energy consumption of the building[5], but also improves the urban heat island effect[6].Compared with water flow window, water spray windows are cheaper to build, lighter to weight, easier to make, and less energy consuming. Moreover, glass surface temperature can be adjusted by controlling water pressure and flow rate[7]. However, the cooling performance and energy-saving effect of water spray windows have not yet been related to experimental studies, even in hot and humid summertime in Southern China. Therefore, it is of excellent application value to analyze the thermal performance of water spray window[8, 9], conducting an in-depth study on the cooling law to improve its cooling efficiency[10].

The water spray model has been quantitatively analyzed in the application of various exterior window forms such as single, double, and triple glazing, in terms of the cooling performance and the energy consumption in the experimental room.

2. RESEARCH METHODS

2.1 Experimental setup

The experimental tests were conducted in Nanning, a Southern Chinese city where the hot and humid summer starts in May and ends in October. The two experimental rooms were set on the outdoor ground with a length, width, and height of 2.0m, as shown in Figure 1. The distance in between is about 6m to avoid sun-shading. Both rooms were built with metal sandwich plates with polystyrene sheets(with thermal conductance around 0.028 W/m.℃) as the insulation inside the sandwich. The tested windows were installed on the south-facing wall of the room to receive solar radiation. The east room was designed to test the performance of ordinary glass, while the west room was designed to test the water spray window. Both exterior windows are 1.2m² with 1.2m height and 1.0m width. The single-glazing window was 6mm in thickness, the double-glazing window consisted of two layers of 6mm ordinary glass a 12mm air interlayer, and the triple-glazing window had an additional layer of glass and interlayer, as detailed in Figure 2. A small mobile air conditioning unit with a cooling capacity of 2000W was installed in both rooms to test the air conditioning energy consumption.

Figure 1:
Appearance of the test room.

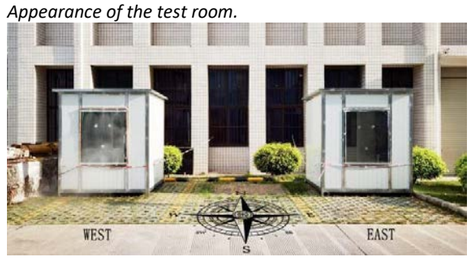
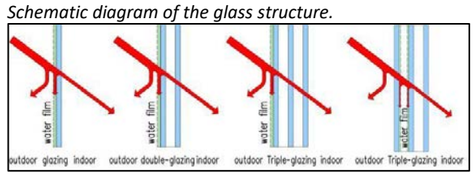
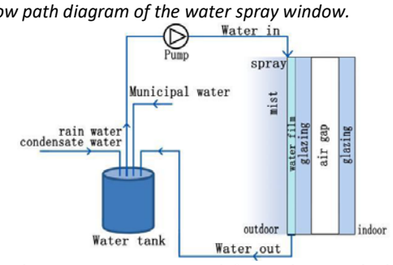


Figure 2:
Schematic diagram of the glass structure.



The water spray window device was set in the outer part of the window, the interlayer, and other locations to test the cooling performance of the glass surface. The on and off switch of the device was controlled by an intelligent timer. The time to spray and the interval time are set in the pump control panel, allowing automatic operation after the setting. The water used for spraying is mainly municipal feed water, transported to the water storage barrel. After being pumped, the water would be transported to the window nozzle for spraying. And the water mist evaporates and absorbs heat after contacting the air and glass surface. The water flowing down from the glass is collected and filtered for recycling, as shown in Figure 3.

Figure 3:
Flow path diagram of the water spray window.



The water mist ejected from the nozzle blocks solar radiation from entering the exterior window. The water mist evaporates and absorbs much heat to reduce the surface temperature outside the window, and the water film sprayed onto the glass absorbs the heat from the glass, flowing down the glass. Those multiple effects cool down the glass surface, improving both the indoor and outdoor environment while reducing air conditioning energy consumption.

The experimental meteorological data was from a small weather station upstairs. The glass surface temperature was measured using a T-type thermocouple with a range of -200°C to 260°C, and the accuracy is ±1.0°C. All sensors were calibrated before the experiment. The temperature sensor on the glass surface was exposed to solar radiation, which may affect its temperature and accuracy. Therefore, the silicone grease was coated with the sensing probe and put a thin aluminum foil with high reflectivity on the outer surface to shield it from sunlight. The above parameters were recorded with an Agilent data logger, which was connected to a laptop for storage or read with a USB.

The experiments were conducted from July to October in 2020 and 2021. The experiments were conducted on sunny days with cumulative daily solar radiation values exceeding 20,000W/m². The weather was very hot, with the average daytime ambient temperature above 30°C. The municipal feed water was around 30°C and supplied in well-insulated pipes.

2.2 Thermal performance analysis

A flowing water layer was formed on the outer surface of the glass after spraying. Part of the solar radiation on the outer surface of the glass was reflected, part of it came into the room through the window, the rest is absorbed by the glass and flowing water. Under this condition, the energy and water flow balance is shown in Figure4; the energy exchange equation[7] between the water film and the surface is：

$$\boldsymbol{\alpha_c(T_a - T_w) + \varepsilon(R_L - \sigma T_w^4) - \alpha_w(T_w - T_s) - l\frac{\alpha_c}{C_m}(X_s - X_a) = C_w W_q \frac{\partial T_w}{\partial z}} \quad (1)$$

where $\boldsymbol{\alpha_c}$ - surface convection coefficient with air [W/(㎡ K)];

$\boldsymbol{\alpha_w}$ - surface convection coefficient with water [W/(㎡ K)];

$\boldsymbol{T}$ - inside temperature[K];

$\boldsymbol{T_a}$ - outdoor air temperature[K];

$\boldsymbol{T_w}$ - temperature of water film[K];

$\boldsymbol{T_s}$ - surface temperature[K];

$\boldsymbol{\varepsilon}$ - emissivity;

$\boldsymbol{R_L}$ - long-wave radiation from surrounding[W/㎡];

$\boldsymbol{\sigma}$ - Stefan-Boltzmann constant[W/(m^2 K^4)];

$\mathbf{l}$ - latent heat[W/(m K)];

$\mathbf{C_m}$ - humid air specific heat[J/(kg K)];

$\mathbf{C_w}$ - water specific heat[J/(kg K)];

$\mathbf{X_s}$ - absolute humidity mixing ratio at temperature $\mathbf{T_s}$ [kg/kg（DA）];

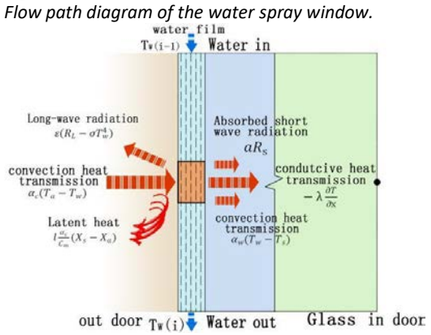
$\mathbf{X_a}$ - absolute humidity mixing ratio at temperature $\mathbf{T_a}$ [kg/kg（DA）];

$\boldsymbol{W_q}$ - water supply[kg/㎡h];

$\mathbf{z}$ - distance from water outlet;

Figure 4:

Flow path diagram of the water spray window.



The energy balance equation of water film and flow layer is as follows：

$$\boldsymbol{aR_s + \alpha_w(T_w - T_s) = -\lambda\frac{\partial T}{\partial \chi}} \quad (2)$$

where a - solar absorptance;

$\boldsymbol{R_s}$ - short-wave(solar) radiation[W/㎡];

$\boldsymbol{\lambda}$ - thermal conductivity[W/(m K)];

$\boldsymbol{\alpha_c}$ is considered to be a function of wind speed and is given by the Jurges equation.

$\boldsymbol{\alpha_w}$is determined as follows:

$$\alpha_w = \frac{Nu\lambda_W}{z} \quad (3)$$

Where Nu is computed from the following equation (Johnson–Rubesin equation):

$$Nu = 0.0296Re^{0.8}Pr^{0.6} \quad (4)$$

Re is determined as $Re = U_w z/\nu$.

λ_w - water thermal conductivity[W/(m K)]

The contrast room and the test room were designed to have a consistent appearance, internal functional divisions, meteorological parameters, indoor air conditioning design parameters, and envelope structure. The energy-saving rate is defined as the ratio of the difference between the air conditioning power consumption in the contrast room and the test room to the consumption in the contrast room, as follows：

$$\eta = \frac{Q_C - Q_{WFW}}{Q_C} \times 100\%$$

Where Q_C is the air conditioning's energy-saving rate，Q_{WFW} is the test power consumption of air conditioners，η is the relative energy saving rate of two rooms.

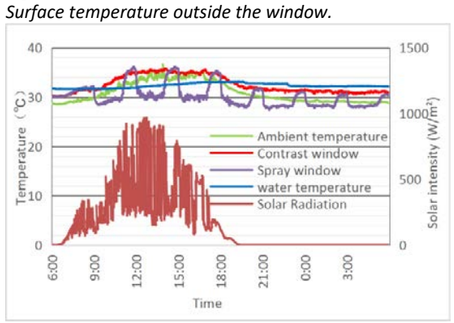
3. RESULTS AND DISCUSSION

3.1 Spray cooling of the glass temperature

To compare the influence of water spraying on the temperature of the external surface of windows, we set up the spraying cooling experiment on the external surface of single-glazing windows in the following period: from 6:00 on August 11th to 6:00 on August 12th, 2020. The system was turned on for seven periods (9:00~11:00, 12:00~14:00, 15:00~17:00, 18:00~20:00, 21:00~ 23:00, 0:00~2:00, 3:00~5:00). The single spray lasts for 2 minutes and an interval of 12 minutes. The meteorological data, water temperature, and temperature data on the test days are shown in Figure 5.

Figure 5:

Surface temperature outside the window.

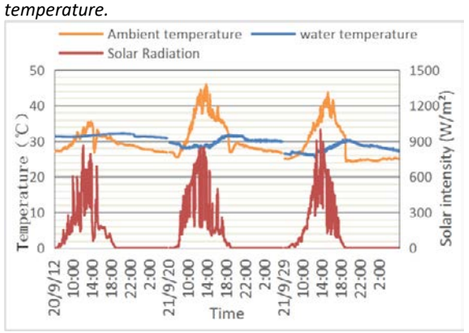


The glass surface's temperature has the most significant decline of 6℃ during the hottest period of the day(12:00 ~ 17:00) and the average temperature of the glass after cooling is 30.5℃. The greater the intensity of solar radiation is, the more pronounced the cooling effect will be. During the morning (9:00 ~ 11:00) and evening (18:00 ~ 20:00) of the day, the average temperature decline is 3.5℃, and the average temperature of the glass is 29℃. These are the two periods with the most intense solar radiation, and the glass temperature changes are over 2℃. Although there is no solar radiation at night(21:00 ~ 5:00), the contrast window surface temperature remains above 30℃. In contrast, the water spray window is about 28℃ with a 3℃ temperature difference, lower than the outdoor. This temperature can make inhabitants comfortable by reducing windows' heat transfer. The air conditioning's energy consumption in cooling could also be cut. This shows that spraying at night is more conducive to improving buildings' indoor thermal environment.

To compare the influence of water spray on the temperature of windows' inner surface, the cooling experiments with water spray was conducted on September 12th, 2020, September 20th, 2021, and September 29th, 2020, for three types of windows, single-glazing windows, double- glazing windows, and triple- glazing windows, respectively. The system was kept on from 8:00 to 6:00 the following day. The single spray lasts for 2minutes and an interval of 12minutes. The meteorological data, water temperature, and temperature data on the test days are shown in Figure 6.

Figure 6:

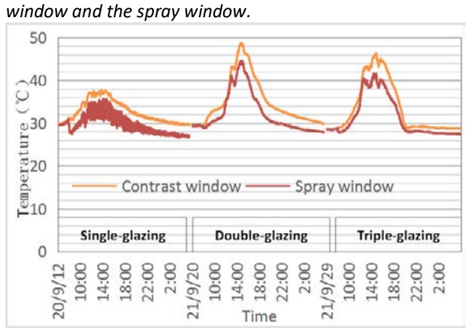
Solar radiation intensity, air temperature, and water temperature.



The heat transfer coefficient greatly influenced the temperature of the inner surface of the window. It was found in all the experiments that the single-glazing glass had the most significant decline in temperature. Since it has a higher heat transfer coefficient, the single-glazing glass was more easily affected by changes in the temperature of the window's external surface. The double-glazing glass had a mild difference in temperature and better cooling performance at night than in the daytime. The triple-glazing glass had better thermal insulating due to its lower heat transfer coefficient. The two layers of air within the windows helped keep warm during the night time. Therefore, the cooling effect at night is milder than in the day. In general, the single-glazing glass had the most significant decline in temperature, while the triple-glazing glass had the mildest change, as shown in Figure 7.

Figure 7:

Contrast the inner surface temperature of the contrast window and the spray window.



3.2 Effect of spray on cooling and energy consumption of different number of glass layers

To test the effect of water spraying on air conditioning energy consumption, the experiments in this regard were conducted on October 2021 at different air conditioning temperatures with water spray on the external windows. The three test windows were kept consistent from previous experiments. Two mobile air conditioners were installed in two rooms with set temperatures of 26°C, 27°C, 28°C, and 29°C, respectively, with the same operation time.

As can be seen from the results, with the increase of temperature, the test room's relative energy-saving rate has been increasing too, and the single-glazing window's energy-saving rate increased from 18.16% to 22.89%. The single-glazing glass is more prone to be affected by the outdoor temperature. The water spraying reduced the temperature of the external surface and the heat that came into the room, indicating that the spray technology is very efficient in cooling for single-glazed windows. The energy-saving rate for double-glazing window increased from 6.23% to 13.19%, with a lower energy consumption compared to single-glazing windows. However, the significant drop in the energy-saving rate indicates that the effect of spraying is limited. The energy-saving rate of spraying for triple-glazing windows increased from 20.03% to 26.58%. Although the previous experiments show that its glass surface temperature had a limited impact from spraying, the overall heat into the room was relatively reduced due to its good thermal insulation performance and a higher proportion of heat taken away by the spray, so it has a more significant impact on the energy-saving rate.

Therefore, spraying is more effective to the triple-glazing window, as shown in Table 1.

Table 1:

List of daily energy-saving rates.

Temperature Setting (℃)	Single-glazing (%)	Double-glazing (%)	Triple-glazing (%)
26	18.16	6.23	20.03
27	19.69	8.24	24.45
28	19.96	12.13	26.51
29	22.89	13.19	26.58
average value	20.17	9.95	24.40

In addition, after comparing the energy-saving rate of the night time period (10:00pm to 8:00am) with the whole day period, it was found that there is a significant difference. The energy-saving rate of the single-glazing window at night is 4% higher than that of daytime; the energy-saving rate of the double-glazing window at night is 1.85% higher than that of day, indicating that the energy saving efficiency of spraying water is better at night than daytime. However, even though the energy-saving rate of triple-glazing windows at night is 9.58% lower than that of daytime, its energy-saving rate drops, as shown in Table 2. That is because the general consumption at night is relatively low, with little space for the water spray to work. As shown in Figure 7, the temperature difference between the two windows at night is insignificant, which explains why the energy-saving rate of triple-glazing window decreases.

Table 2:

List of night energy-saving rates.

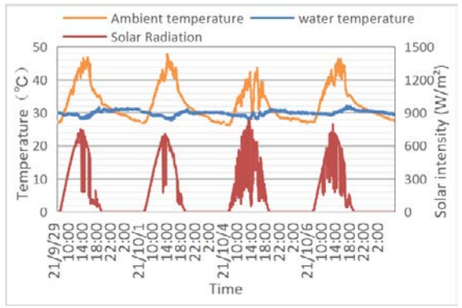
Temperature Setting (℃)	Single-glazing (%)	Double-glazing (%)	Triple-glazing (%)
26	20.60	10.08	18.98
27	21.30	10.30	17.16
28	26.79	12.54	12.54
29	27.91	14.31	10.61
average value	24.15	11.80	14.82

3.3 Effect of spray on the cooling and energy consumption of different sandwich glass Windows

To compare the effect of water spraying on the surface temperature of glass with air-laminated glass of different thicknesses, water spray cooling experiments were conducted on September 29th, October 1st, October 4th, and October 6th, 2021, respectively. All were triple-glazing windows with four different thicknesses of 30mm, 50mm, 100mm, and 200mm in the outer laminated layer. The operation time remained the same with previous experiments. And the meteorological data and test results are shown in Figure 8.

Figure 8:

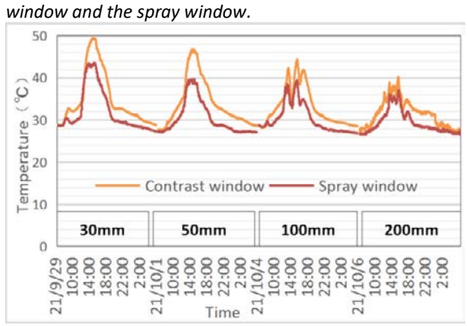
Solar radiation intensity, air temperature, and water temperature



It was found that the inner surface temperature of the water spray window decreased most significantly when the width of the interlayer was 30mm and 50 mm. There was little difference in temperature changes between 50mm and 100 mm interlayers. 200mm interlayer had the mildest drop in temperature. On average, the 50mm interlayer is most effective in cooling, while 100mm and 200mm are basically the same.

Figure 9:

Contrast the inner surface temperature of the contrast window and the spray window.



To test the effect of different thicknesses of interlayer with water spray on the energy consumption of air conditioning, four experiments were conducted on September 30th, October 2nd, October 5th, and October 7th, 2021, respectively. The air conditioning temperature was set at 27°C in the two rooms with the same operation time.

It showed that as the thickness of the interlayer increased, the energy-saving rate throughout the day went up. There was no significant change of the rate from 30mm to 50mm, a 3% increase from 50mm to 100mm, and a 5% increase from 100mm to 200mm. In general, the thicker the interlayer is, the more contact spray has with the air, the higher the cooling efficiency, and the better the energy-saving performance. 200mm interlayer has the best energy-saving rate, meaning the interlayer should be as thick as possible, as shown in Table 3.

Table 3:

List of daily energy-saving rates.

Temperature Setting(℃)	30mm (%)	50mm (%)	100mm (%)	200mm (%)
27	26.38	27.10	30.25	35.19

The energy-saving rate at night also increased as the interlayer got thicker. However, when the thickness went up from 100mm to 200mm, the energy saving rate decreased and even lower than that in the daytime. That is because the general consumption at night is relatively low, with little space for the water spray to work, as shown in Table 4.

Table 4:

List of night energy- saving rates.

Temperature Setting(℃)	30mm (%)	50mm (%)	100mm (%)	200mm (%)
27	31.95	32.18	35.19	30.49

4. CONCLUSION

In the current study, cooling thermal and energy saving performance of single-glazing, double-glazing and triple glazing water spray window were tested to explore the impact and significance of water spray glazing property. According to the following conclusions after analyzing the results on thermal environment regulation and energy consumption reduction:

(1) Compared with ordinary window, water spray window can effectively reduce the temperature of the outer surface of the glass, with 6℃ during the day and about 3℃ at night. At the same time, the inner surface temperature is also reduced substantially with milder temperature changes.

(2) Water spray window has better energy-saving performance. Under different air conditioning temperatures, the cooling energy consumption in the test room with water spray window could be 6%~27%. The higher the air conditioning temperature, the higher the energy-saving rate. Single-glazing window and double-glazing window have higher energy-saving rates at night than daytime.

(3) Water spraying in the interlayer can have better cooling and energy-saving effect than the spray on the outer. The temperature of the inner surface of the window decreases as the interlayer gets thicker, up to 7℃ in temperature reduction with growing energy-saving rate. At night, the energy-saving rate of 30mm~50mm interlayer is higher than the daytime while the 200mm interlayer is lower than the daytime.

(4) Residential buildings, office buildings and shopping malls have large windows and long running time air conditioning in summer. The use of water spray windows can effectively improve the indoor environment and reduce the cooling energy consumption of air conditioning. In addition, the application of water spray windows needs to be combined with the sponge city facilities and the integrated design of windows to solve the problem of water source and structural coordination in order to achieve both aesthetic and cooling effects.

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Integral design: form and function, architecture and engineering should be one with nature

Dutch examples of how cities can survive

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ABSTRACT: Human activity is the dominant influence on climate and the environment. Risks to health from high temperatures are increasing with climate change, and new ways to mitigate urban heat island (UHI) effects are needed as nearly three-quarters of the global population will be living in towns and cities by 2050. We have to act responsibly for the future of humanity. By working with nature cities can become more resilient to the changing climate. The Netherlands as a densely populated country combined with high standards of living had always to (and knows how to) meld the natural environment to suit its needs. New technology will allow roofs, walls, and building façades to be 'greened', creating a filter for pollution, absorbing carbon dioxide by acting as a carbon 'sink', as well as providing natural cooling and insulation to enhance air quality within cities. Bio-inspiration from plants for the future built environment through green infrastructure, and biobased materials might lead to new architectural designs. The paper describes some Dutch examples of Greenery to lower the effects of Global Warming in cities.
KEYWORDS: Green roof, green façade, Integral design with nature

1. INTRODUCTION

People need buildings to protect them against the environmental conditions to be able to work and live in comfortable and healthy indoor air conditions. Architects shaped the built environment since the early beginning of civilization. Building Services engineers make it possible to provide comfort and acceptable indoor Air Quality for building occupants. In the last 50 years, the world has changed enormously: instead of 3.5 billion there are now living more than 7 billion people on earth with more than 50% in cities with an enormous increased standard of living. Collectively, buildings in the EU are responsible for 40% of our energy consumption and 36% of greenhouse gas emissions, which mainly stem from construction, usage, renovation, and demolition [EU 2020]. To meet climate goals and comply with the 2030 climate and energy framework, one of the goals is to gain a 32.5% improvement in energy efficiency with at present almost 75 % of building stock operating inefficiently, see Fig 1.

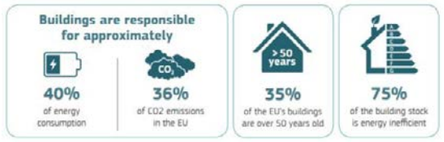

Figure 1. The current energy situation of the building stock [EU 2020].

There is a need to change the way how architects think about their role in the building design process, we cannot try to solve the problems using the same kind of approach that caused them. Form and function should form a synergy instead of being sometimes in conflict with each other. Fortunately, more and more integral approaches are becoming common practice to find the optimal solution between passive and active energy elements and between architecture and building services. The architects and the engineers should work together from the very start of a design project and must aim to reach synergy by combining the knowledge and the experience of all disciplines already in the early stages of the conceptual design. An integral approach is needed to make this possible, which represents a broad view of the world around us that continuously needs to be adapted and developed from sound and documented experiences that emerge out of an interaction between practice, research, and education [Zeiler 2017].

Human activity is the dominant influence on climate and the environment. Risks to health from high temperatures are increasing with climate change, and new ways to mitigate urban heat island (UHI) effects are needed as nearly three-quarters of the global population will be living in towns and cities by 2050. We have to act responsibly for the future of humanity. In the early 1990s researchers began to discuss the contribution that design could make in the development of sustainable development [Bhamra 2019]. One of the pioneers and promotors looking at the added value of greenery in sustainable building design was Ken Yang [1972]. In his book The Green Skyscraper [1999] he laid the basis for designing sustainable intensive buildings and clearly demonstrated the added value of greenery. Looking for integrated techniques from plant science, building physics, and architecture to use plants in the built environment (e.g. green infrastructure: green walls and roofs) for energy reduction, comfort improvement, and to identify opportunities for food production within cities. Important is the right balance in the Sustainability triangle between Environment, Economy, and Society, this forms the basis for responsible design. In the Netherlands, some very interesting examples show that architects and engineers can design as an integral team.

2. BUILDING GREENERY

The resulting design actions should emphasize the benefits of improved energy efficiency of buildings, low-carbon, renewable energy production, and reduction of energy demand. Building greenery, plants & architecture, and bio-inspiration from plants all offer new opportunities for the future built environment. However, it is important to get a true understanding of its values as well. New technology will allow roofs, walls, and building façades to be 'greened', creating a filter for pollution, absorbing carbon dioxide by acting as a carbon 'sink', as well as providing natural cooling and insulation to enhance air quality within cities. Bio-inspiration from plants for the future built environment through green infrastructure, and biobased materials might lead to new architectural designs with benefits for [Wootton-Beard 2018];

- Thermal Comfort– Cooling the atmosphere (indoor and outdoor) to reduce the impact of heat waves
- Energy Use/ Building thermoregulation – Applying an external layer to regulate internal temperature and energy use
- Indoor Environment – Improving air quality, improving hygrothermal conditions, noise
- Outdoor Air pollution – Trapping pollutants in canopy or substrate, removal by absorption or engineered solutions
- Mental health – Visual stimulation, aesthetic quality, and evolutionary preferences

Building greenery, plants & architecture, and bio-inspiration from plants all offer new opportunities for the future built environment. However, it is important to get a true understanding of its values as well. The study by Zhao et al [2019] presents a summary of the added value and benefits of green buildings through a bibliometric research approach. They reviewed in total 2,980 articles published in 2000–2016 and analyzed and the following key research topics were identified: vertical greening systems, green and cool roofs, water efficiency, occupants' satisfaction, and financial benefits of green buildings. This study forms the basis for the discussion of the different greenery aspects combined with the overview by Wootton-Beard [2018] and completed with additional recent Dutch research.

The Netherlands as a densely populated country combined with high standards of living had always to (and knows how to) meld the natural environment to suit its needs [MVDRV 2019]. By working with nature cities can become more resilient to the changing climate. Embracing green roofs and facades helps to achieve liveable, sustainable built spaces [Young 2014]. Furthermore, green roofs retain a high amount of rainwater, so are perfect for harvesting, thus reducing the amount of water reaching urban sewage systems. Green roofs, water roofs, vertical farming, and even high-rise greening with trees like the Bosco-verticale by Stefan Boeri in Milan [Smith 2015] – from large-scale interventions to smaller-scale enrichments, cities in the future will need to look vastly different from cities now [Arup 2015, MVRDV 2019].

3. GREEN AND COOL ROOF

Cool roofs are roofing systems using the cool materials that present a high albedo. In this cluster, Romeo and Zinzi [2013] found that the cool roof application on a non-residential building decreased the roof surface temperature by 20 °C, and that it was effective in reducing cooling and total net energy demand. Green roofs, which are the roofs partially or completed covered with vegetation, are also common in green buildings. Santamouris [2014] reviewed the technologies to mitigate the heat island phenomenon and analyzed the effect of increasing the albedo of cities by cool roofs and using vegetative green roofs for heat island mitigation. Gill et al. [2007] indicated that greening roofs in areas with a high proportion of buildings can significantly lower the surface temperature and reduce the rainwater runoff. The representative research on 'land surface temperature' was undertaken by Wong et al. [2003], who performed a field measurement of the thermal impacts of roof gardens in Singapore and confirmed that roof gardens provided thermal benefits for both buildings and surrounding environments. Additionally, Santamouris et al. [2007] calculated both the cooling and heating load for a whole building with a green roof and for its top floor and

found a great reduction in the building's cooling load in summer as well as the insignificant effect on heating load in winter.
The Netherlands has an estimated 200 million m2 of flat roofs. Most of these roofs could be made green. Ever more municipalities adopted a policy to actively promote green roofs. Not yet on such a wide scale as in some other countries, but it's a start. Most municipalities opt for a grant scheme for both residents and the business sector which contributes to the cost of installing a green roof, usually 50% of the total cost.

Library Technical University of Delft – Delft - 1995
Technical University of Delft designed their library with its intensive greenroof, see Fig. 2.

Figure 2. The library is a building that does not really want to be a building, but a landscape [Mecanoo 2019].

Although nearly fifteen years old, the visionary TU Delft Library is still an excellent example of forward-thinking sustainable design. The 15,000 m2 library contains extensive underground book archives, reading rooms, the university publisher, offices, study spaces, and a bookbinder and book shop. It won the National Steel Award 1998 and Corus Construction Award 2000. Mecanoo Architecten's [Mecanoo 2019] vision was to develop a light-filled landmark that would serve as "a gateway to the digital highway". Extending forty meters above grade and floodlit at night, the cone acts as a beacon on the campus day and night The library is designed as a sloped plane, extending the grass from the ground to the very edge of the roof allowing people to walk to the top. What they achieved is a public place that is not only a core for information, but also features a prodigious public green roof for people to explore, relax and play [Mecanoo 2015]. Enjoyed throughout the year, the green roof is converted into a sledding hill in the winter for further recreation. Visitors can catch some sun on the inclined lawn during the warmer months, and when it snows the roof makes for the best sledding in town — after all, where else are you going to find a hill in the Netherlands? With a renovation in 2009, the green roof has continued to benefit the university, continuing to meet expectations more than two decades after its opening.

Urban rooftop farms Dakakker – Rotterdam - 2017
In Rotterdam, an architecture collective ZUS has reclaimed an old building in the center of the city and built an urban farm on top of the roof, see Fig. 23

Figure 3. DakAkker – Rotterdam [Dakakkers 2019]

The DakAkker is a 1000 m2 rooftopfarm on top of the Schieblock in Rotterdam in The Netherlands [Dakakker 2019]. The DakAkker is the largest open-air roof farm in the Netherlands and one of the largest in Europe. The conditions on the DakAkker are comparable to a Mediterranean climate: dry rocky soil, a lot of wind sometimes quite warm. That is why herbs such as mint, lemon verbena and lavender are grown on the DakAkker, as well as strong plants such as raspberry, rhubarb and pumpkin. The edible flowers of the roof are the top product and are delivered to six restaurants in the immediate vicinity of the rooftop farm.

Based on the gained experience, with a total potential of 18.5 square kilometers of flat rooftops in Rotterdam, the city has set a target of putting 1 square kilometer of that space to good use by 2030. Greening it with plants and trees, adding solar panels, and utilizing it for recreation or even homes.

Roof park Vierhavenstrip – Rotterdam - 2011
On the roof of the shopping center, an area of one kilometer by 80 meters and with a soil depth of 1.5 meters has been used to create good growing conditions for trees and other plants, see Fig. 4. The eastern edge of the park is characterized by a high-rise urban design, with tall trees and hedges acting as structural elements. The western edge is oriented towards the district and has a very green character with themed gardens at the main entrances. Large trees, lawns, a playground, a community garden, and a Mediterranean garden with an orangery offer local residents a great place to relax and meet. The main paths are bordered by water and there is a 70-meter by 7-meter step waterfall on the roof. The Vierhavenstrip rooftop park connects living, shopping, working, study, culture and recreation in a unique way.

Source https://www.rotterdamarchitectuurprijs.nl/dakpark.html
Figure 4. Roof park Vierhavenstrip – Rotterdam

New Bergen – Eindhoven - 2022
The New Bergen project of MVRDV architects is an example [Malone 2017] of a more recent project. It is a residential development combining urban and green qualities in the neighbourhood of Bergen, Eindhoven, see Fig. 5 & 6. This concept is part of MVRDV's urban strategy for cities in need of sustainable densification and has won the 2020 Dutch Rooftop Award last September.

Source https://worldarchitecture.org/article-links/egcnm/mvrdv-s-nieuw-bergen-project-enters-next-phase.html
Figure 5. New Bergen project MVRDV Eindhoven, Netherlands

3. VERTICAL GREENING SYSTEMS
These are usually classified into green façades and living walls in accordance with their growing method [Ottelé et al. 2011, Perini and Rosasco 2013]. Living walls can support the vegetation that is rooted on the walls or in the substrates attached to the walls [Chen et al. 2013] while green façades are made by the climbing plants attached directly to the wall surface [Perini et al. 2011]. Vertical greening systems can be used as passive systems to save energy, with the consideration into the following mechanisms: blockage of solar radiation because of the shadow provided by vegetation, evaporative cooling produced by blocking the wind and by evapotranspiration from substrate and plants, and thermal insulation brought by the substrate and vegetation [Perez et al. 2011]. Additionally, Wong et al. [2010] found that vertical greenery systems lowered the surface temperature of building façades in the tropical area, thereby reducing the cooling load and energy expense. The principle cooling effect is evapotranspiration (Evaporation +Transpiration) [Wootton-Beard 2018] which is fundamentally determined by the availability of moisture (and wind flow), vegetation cover, precipitation, irrigation, and humidity. The vegetation replaces sensible heating with latent heating and reduces the Bowen ratio, the ratio of heat flux to moisture flux near the surface. The vegetation modifies surface roughness and wind flow thus altering the convective heat exchange. Heterogeneity of the greenery is necessary and leads to the best effects on heat loss [Wootton-Beard 2018]. There is a minimum size of 50,000m2 to have a significant cooling effect, so it is only relevant at a town/city scale or for large green spaces. There is not yet any evidence for a network of smaller spaces owing to necessary fetch [Wootton-Beard 2018].
The incorporation of vegetation has a potential impact on the building design process and can on building energy use. The principal effect of greenery on building thermoregulation is that insulation/shading is provided to the building envelope which results in more stable internal temperatures [Wootton-Beard 2018]. Plant albedo values are higher than grey surfaces creating a more stable roof temperature. Also, the shading potential is considerable and can be a cost-effective mitigation measure [Gupta & Gregg 2012]. Rural vegetation reflects 15-25% of shortwave radiation [Armson et al. 2012] however, effectiveness is driven by leaf size, crown area, and Leaf Area Index [Santamouris 2014]. Mangone studied the effect of a vegetation shade canopy of an 11,000 m2 office building on energy consumption and carbon

emissions. The thermal effects of the vegetation canopy were found to have slightly greater effectiveness than the original shading solution [Mangone 2015]. The positive effects of greenery in urban working environments are becoming more clear in the last years as shown by Hiemstra et al [2019]. Greenery in and around offices and other working environments has a positive effect on the health and general well-being of employees. It aids concentration, reduces stress, and increases staff productivity [Hiemstra et al 2019].

City hall - Venlo - 2017

The city hall of Venlo was designed by Kraaijvanger [2019] in on the basis of Cradle to Cradle (C2C) principles (C2C center 2019), see Fig. 6. With 630 flexible workplaces and public functions, the building embodies the ambition to have the entire city and region function. Wellbeing of the occupants was the starting point of an Integral design process: a good building makes people happier and boosts productivity. The spatial design is based on three goals: to bring as much daylight and greenery into the interior as possible, to create routes through the building that stimulate people to move around, encounter others, and use only healthy materials.

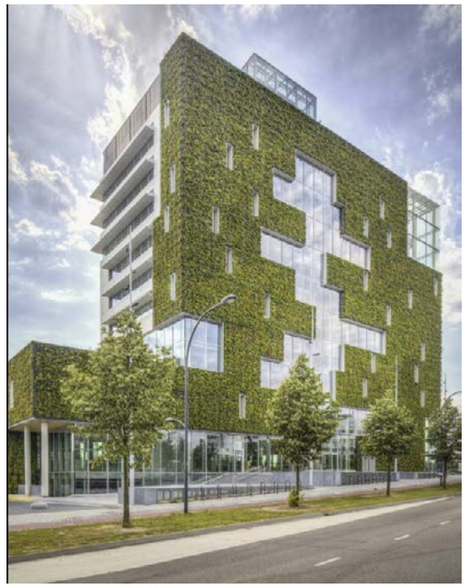

Figure 6. City hall - Venlo [Kraaijvanger 2019]

Around a patio with a helophyte filter for water purification, people can enjoy the greenery, the water, and the views. The building refers to the agricultural tradition of this city and its top floor features a greenhouse with seasonal workplaces and room to grow regional products that also heats and humidifies the air that enters the building. The green air-purifying façade is the largest green building façade in the world and forms a protective shell against traffic and railway pollution. The air in Venlo's new city hall is purer than the air outside and purifies air in a 500m radius around the building. Cradle to cradle principles and holistic thinking in action in a city's buildings.

Vertical Forest – Eindhoven - 2021

In Eindhoven, the Trudo Tower, the first 'Vertical Forest' in the Netherlands, was built in 2021. The building has been given its green appearance by containers planted with trees, shrubs, and perennials and the amount and size of the planting have created a vertical green structure on the façade of each apartment, see Fig. 7.

source: https://www.vdberk.nl/projecten/vertical-forest-eindhoven/

Figure 7. Vertical Forest - Eindhoven

The expertise of architect Stefano Boeri, now internationally known for the green residential towers in Milan, was engaged by the housing corporation Sint-Trudo to realize the 70-meter-high project green apartment complex at Strijp-S. It is the first 'forest tower' intended for social housing. A highly innovative form of urban development that fits seamlessly with the urgency to make cities greener. The 'Vertical Forest' concept requires well-thought-out technical solutions because the growth sites are not optimal by nature. In the run-up to the realization of the forest tower in Milan, many tests and studies were therefore done with regard to the growing conditions of the trees. Wind tests were done and it was investigated in which soil mixture trees can best attach themselves. In Eindhoven, a total of 125 trees have been planted on 19 floors.. In consultation with landscape architect Laura Gatti a more or less indigenous and strong range was chosen to give the forest the very best growth opportunities, diversity in leaf colour, leaf shape, and flowering for an attractive image.

4. DISCUSSION & CONCLUSION

Integral nature-inspired design and modern plant breeding both seek to increase tolerance to climate extremes and try to make the built environment more resilient and efficient use of energy, materials, water, and light [Wootton-Beard 2018]. This paper shows the importance of greenery in sustainable buildings and their effect on the indoor and outside environmental quality (IEQ), based on scientific studies. Living wall and green roof systems are emerging technologies to provide beneficial effects on improvement of living conditions within cities and can be used to reduce sound levels as a passive acoustic insulation system. Several applications of greenery in projects in the Netherlands are presented to illustrate the architectural added value as well.

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9TH PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Patient's thermal comfort assessment of a government hospital during the warm-humid season

A field study in a tropical megacity Dhaka, Bangladesh

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ABSTRACT: Thermal comfort is vital in Bangladesh's fast-growing built environment, especially during the warm-humid season. In a developing country such as Bangladesh, the health sector often overlooks the patient's wellbeing due to financial and organizational constraints. Literature suggests that there has been a substantial research gap in the thermal comfort assessment of government hospitals in Bangladesh. This study aimed to understand the patient's perception of indoor thermal conditions in mechanically ventilated hospital wards and identify their comfort temperatures in the studied context. The data were collected from a questionnaire survey of 200 adult patients (aged 20-40 years) of medicine and surgery wards during the warm-humid season (June-September), along with objective measurements of their thermal environments in a case study hospital. Although all the objective measurements were above ASHRAE recommendations, 45.25% of patients found their thermal environment acceptable due to acclimatization and adaptive behaviour. Through a linear regression analysis, the patients' comfort range was between 28.2°C and 31.8°C, while the comfort temperatures from linear regression and Griffiths method were 30°C and 29.83°C, respectively. However, the 'preferred' temperature was 29.65°C, which is slightly lower than the comfort temperature, proving the thermal adversities during the warm-humid season are quite well tolerated by the patients due to adaptation and acclimatization.
KEYWORDS: Thermal sensation; Thermal acceptability; Comfort temperature range; Griffiths comfort temperature; Preferred temperature; General ward

1. INTRODUCTION

Thermal comfort has become a necessity in recent years due to people's increased tendency to spend more time indoors. Therefore, it is mandatory to maintain an optimum thermal indoor environment and thermal comfort for everybody by creating a comfortable indoor environment, ensuring occupants' health and productivity, and designing high-quality energy-efficient buildings (Olesen, 2007; Skoog, Fransson, & Jagemar, 2005; A. Wagner, Gossauer, Moosmann, Gropp, & Leonhart, 2007). Although the need for thermal comfort studies is universal for all building types, it is essential for sick patients in hospitals, who are more sensitive to their surrounding environment than healthy people. Studies reveal that an uncomfortable thermal environment could induce psychological stress due to the combined effect of the external thermal environment and internal metabolic heat production, which can burden patients' already ailing physical condition and hinder their recovery process (Gagge & Nishi, 2010). On the other hand, a comfortable indoor environment can reduce the stress on patients' health, impart psychological stabilization, and shorten patients' length of stay in hospitals by assisting a smooth healing process (Azizpour et al., 2011; Hwang, Lin, Cheng, & Chien, 2007; D. Wagner, Byrne, & Kolcaba, 2006). Unlike healthy populations, the thermal comfort requirements of patients are quite variable, as patients are less adaptive and have a limited thermal comfort range, depending on their illnesses (Hwang et al., 2007).

Although many thermal comfort investigations have been conducted in hospitals, only a handful was focused on the patient's room or hospital wards. Some of these field studies (Hwang et al., 2007; Khalid, Zaki, Rijal, & Yakub, 2018; Khodakarami, 2008; Skoog et al., 2005; Verheyen, Theys, Allonsius, & Descamps, 2011) on patients rooms revealed that local thermal comfort requirements often vary from international standards like ASHRAE's (ANSI/ASHRAE/ASHE, 2010; Verheyen et al., 2011) recommended comfort temperature range, which is 21-24°C (Air Conditioned), depending on their specific local climate and user's preference. Thermal comfort studies in hospitals of tropical climates found that the comfort parameters, i.e., comfort temperature range, are often higher and wider in tropics than the international standards (Hwang et al., 2007; Khalid et al., 2018; Kushairi, Mahyuddin, Adnan, & Sulaiman, 2015; Yau & Chew, 2009). Because of acclimatization and long-time exposures to tropical weather, people not only became resistant to the high air temperature and relative humidity range but also expected a warmer thermal environment as their neutral requirement.

Bangladesh is also located within the tropics and has high air temperature and relative humidity around the year. Like other tropical locations, previous field studies (Ahmed, Howarth, & Zunde, 1990; Mallick, 1996; Shajahan & Ahmed, 2016; Tariq & Ahmed, 2014) on different buildings in Bangladesh also showed deviations in thermal comfort requirements from international standards. Along with the environmental differences, clothing styles, culture, and habitual use of naturally ventilated buildings (full or hybrid ventilation by ceiling fans) work as essential factors to determine the user's preference of satisfaction (Mallick, 1996). Moreover, in developing countries like Bangladesh, people often feel obliged to accept their situation due to the inevitability of the climate of a place, even when it deviates from their comfort level (Mallick, 1996). So, there is a distinct possibility of variation in patients' perception of the indoor thermal environment in hospital wards which is yet to be explored. Similar to any other building in the region, deviation in patients' thermal comfort requirements compared to developed countries, where the standards originated, is inevitable.

In Bangladesh, most district hospitals are partially dependent on natural resources (air and sunlight) for heating, ventilation, and lighting. In general, hospital wards are not completely naturally ventilated except in the winter. Instead, indoor ventilation often needs the assistance of ceiling or table fans, where and when required. As ceiling fans can only circulate the air within the rooms, the indoor environment is highly dependent on the outdoor environment. As a result, patients may not find the same space comfortable all year round. Although the pre-monsoon season (hot-dry season) has the highest air temperature and the high amount of solar radiation, the monsoon season (warm-humid season) is often considered more crucial due to its potential impact on occupant's thermal comfort due to the high temperature and humidity levels. These environmental conditions, which is often the most lasting condition in the country, have the capability to affect the patient's thermal comfort negatively and make them most uncomfortable. Therefore, it can be assumed that if it is possible to ensure thermal comfort in hospital wards during these most uncomfortable months, the patients may find the wards thermally comfortable most of the time of the year.

Moreover, hospitals tend to consume a significant amount of energy due to their round-the-clock timing. Reduced thermal comfort during the unbearable warm-humid season can enormously increase the amount of energy consumption due to the patient's tendency to rely on ceiling fans consistently to minimize their thermal discomfort. So, this research specifically targeted the warm-humid season to study the indoor thermal conditions of hospital wards and to identify the patient's comfort requirements that can ensure a comfortable indoor thermal environment as well as minimize energy overconsumption. The objectives of this study are as follows-

a) To investigate patients' perception of the thermal environment in hospital wards through their votes on thermal sensation and thermal acceptability;

b) To identify the patients' comfort range, along with their 'comfort' and 'preferred' temperatures in the current context.

2. RESEARCH METHODOLOGY

2.1 Selection of a case study

This study was carried out in one of the Government teaching hospitals of Bangladesh, located in Dhaka (geographical coordinates: 23.8103° N, 90.4125° E). The hospital wards are constructed following a typical layout (Fig. 1), which is common in other teaching hospitals as well. Based on the similarity of layout, age of patients, and availability of similar options for behavioural adjustments, two general surgery wards on the 6th floor and one medicine ward on the 8th floor were selected for this study. The three types (8, 10, and 12 beds) of patient rooms were arranged on the outer side of long corridors with a central Nurse Station, and service facilities were placed on the opposite side of the corridor.

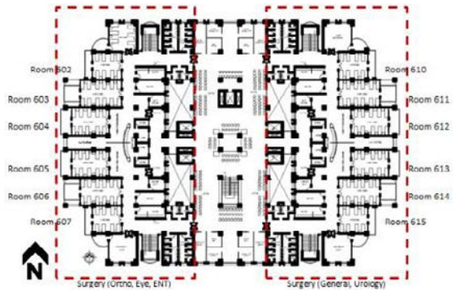

Figure 1: *Typical floor plan*

The east and west walls of the wardrooms had two Thai aluminium sliding glass windows on either side of a wooden door, one opening onto the corridor and the other facing outdoors via a balcony. The indoors had no provision for direct sun

exposure due to balconies at the outer walls. As a result, the windows were often overshadowed, and the rooms were dimly lit by diffused sunlight. All the rooms were equipped with ceiling fans, which remained in full operation during the survey, to ensure the patient's thermal comfort and avoid any health deterioration due to thermal discomfort.

2.2 Selection of patients

To neutralize the non-environmental factors, patients aged 20-40 years with average height and weight, brown skin, and similar social class were chosen for this study. Patients who stayed in the wards for more than three days were selected to allow a certain level of familiarity with adaptation options available within the wards. However, seriously ill patients or patients with certain diseases, such as high or low blood pressure, diabetes, blood deficiency, thyroid problem, and fever, were excluded from the investigation, as these conditions can affect patients' thermal perception. The average clothing insulation for male and female patients were 0.28-0.65 clo and 0.48-0.79 clo, respectively, as estimated from ASHRAE and other studies (ASHRAE, 2010; Havenith et al., 2015; Indraganti, Lee, Zhang, & Arens, 2016). Patients' average metabolic rate was between 0.8 and 1.2 met, also measured from ASHRAE (ASHRAE, 2010).

2.3 Subjective measurements:

For this study, 400 data sets were collected by interviewing 200 adult patients from medicine and surgery wards twice a day (Morning: 08.00-10.00 am and Afternoon: 02.00-04.00 pm). The interviews were conducted with a standard questionnaire, following ASHRAE's Informative Appendix E 'Thermal Environment Survey' (ASHRAE, 2010) and questionnaires used by other researchers working in similar climatic conditions (McCartney & Humphreys, 2002; Shajahan & Ahmed, 2016; Tariq & Ahmed, 2014; Wong & Khoo, 2003). A traditional ASHRAE 7-point scale was used for thermal sensation votes, and the McIntyre's Preference scale was used to vote for their thermal preference (ASHRAE, 2010; McIntyre, 1980). Thermal acceptability was measured on a 2-point scale of 'acceptable' and 'unacceptable'.

2.4 Objective Measurements:

For this research, outdoor environmental data were collected from the online weather tool of the local meteorological station (AWS data) (Bangladesh Meteorological Department, 2019), stationed at the local airport, which is 12.7 km away from the studied hospital. All environmental parameters were calculated from the mean of all the data of the 2 hours survey period. Outdoor measurements were also taken manually, at the height of 1.5 m above the ground surface, to cross-check the online data.

For the indoors, a handheld Digital Thermometer Hygrometer (Zeal PH1000) was used to measure air temperatures and humidity, whereas air velocity was measured by a Mini Thermo-Anemometer (Extech 45118). The environmental parameters were measured thrice (at 1-minute intervals) at the height of 1m or the level of a patient's bed after each questionnaire survey. Data were collected for 14 days over four months (June-September), with days having varied environmental conditions, ranging from sunny to medium rain.

3. RESULT AND ANALYSIS

3.1 Outdoor and indoor environmental parameters

Figure 2 shows the summary of all environmental parameters during the surveyed period. During this time, the outdoor temperatures fluctuated between 28.0 - 36.0°C, with lower temperatures recorded in the morning session and comparatively highest temperatures found at 03.00 pm in the later sessions. A significant variation was observed in humidity levels during this period, i.e., from 63.16% to 98.68%, with the air velocity ranging between 0.01-1.6m/s. These variations were highly dependent on the occurrences of rain during the data collection. Indoor temperatures maintained a narrow range of 29.6 - 33.0°C during the survey, and the humidity levels were between 67.6% and 84.83%, which were consistent with outdoor humidity levels. The indoor air velocity was influenced by the outdoor air velocities and fluctuated between 0.3-1.0 m/s.

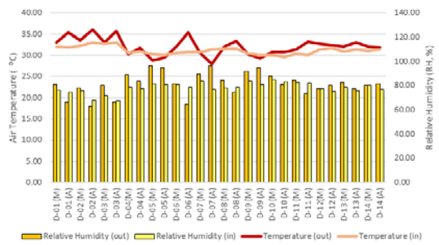

Figure 2: *Indoor and outdoor environmental data recorded during the surveyed period*

3.2 Analysis of subjective responses

3.2.1 Thermal Sensation and thermal preference

Based on the ASHRAE 7-point thermal sensation scale (ASHRAE, 2010), 47.5% of the patients voted their environment as 'slightly hot (+1)' and 8.5% as 'Hot (+2)', whereas 42% voted for 'Perfect (0)'. According to ASHRAE's 7-point thermal sensation scale, when 80% of the occupants vote for the central three categories (vote of -1, 0, +1), the indoor thermal condition can be considered as 'acceptable' (ASHRAE, 2010). In this study, about 91.5% of votes lie within these central categories, indicating that although all the patients were not in ideal thermally acceptable conditions, they were satisfied in general.

In the case of the thermal preference votes on the McIntyre scale (McIntyre, 1980), only 26.5% of patients voted for the central category of the thermal sensation scale, wanting 'no change', whereas a significant 71.86% of patients preferred to feel cooler.

3.2.2 Thermal Acceptability

The comparison between three types of determination methods of assessing thermal acceptability (Fig. 3) indicates that only 45.25% of patients directly accepted their environment as it was, whereas 91.5% of patients voted for the central three categories. The final and strictest method of thermal acceptability, which is the thermal preference scale, shows that only 24.25% of the patients voted for 'no change' during the thermal preference inquiry, which is lower than the votes obtained from other methods. These results indicate that neutral thermal sensations are not always the preferred thermal state.

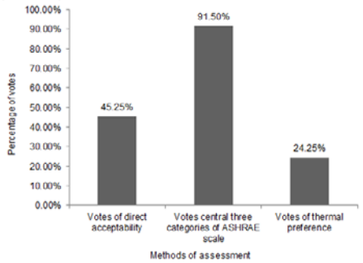

Figure 3: *Comparison between different methods of Thermal acceptability*

3.3 Identifying comfort temperatures:

A linear regression analysis was applied between the patient's thermal sensation votes and their corresponding measured mean air temperature (Fig. 4) to calculate the comfort temperature range statistically. Equation (1) was obtained from it.

$$TSV = 0.564\ T_a - 16.918 \qquad (1)$$

where, *TSV* - thermal sensation vote
T_a - mean indoor air temperature (◦C)

A comfort range of 28.2-31.8°C (i.e., corresponding to TSV -1 to +1) was found from equation (1), which was quite higher than the standard. Also, a comfort temperature of 30.0°C was obtained from the same equation. The comfort temperature range was narrower compared to previous studies (Ahmed et al., 1990; Mallick, 1996; Shajahan & Ahmed, 2016) in Bangladesh, as patients have increased susceptibility to their surroundings compared to the healthy population.

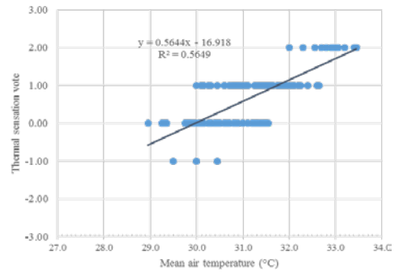

Figure 4: *Comfort temperature from Linear regression analysis*

3.3 Comfort temperature from Griffiths method

Limitations of linear regression methods have been observed in various field studies (MA Humphreys, Rijal, & Nicol, 2013; Nicol, Humphreys, & Roaf, 2012). When the temperature range is narrower, linear regression often becomes unreliable for assessing comfort temperatures (Griffiths, 1990; Nicol et al., 2012). So, the comfort temperatures were investigated again from the modified equation of the Griffiths method (Griffiths, 1990).

$$T_{cg} = T_a + (0 - TSV) / G \qquad (2)$$

where, T_{cg} - Griffiths comfort temperature;
T_a - Mean indoor air temperature;
0 - 'Neutral' on Thermal sensation scale;
TSV - Thermal sensation vote;
G - Griffiths constant.

Table 1 presents Griffiths comfort temperatures, calculated from Equation-2 for three Griffiths constants (0.25, 0.33, 0.50) for their wide acceptability in thermal comfort studies (Kumar, Singh, Loftness, Mathur, & Mathur, 2016; Manu, Shukla, Rawal, Thomas, & De Dear, 2016). The comfort temperature corresponding to the Griffiths constant 0.5 is closer to the value obtained from the linear regression analysis. The comfort temperatures obtained from the other constants are much lower than the neutral comfort temperature found from the linear regression analysis.

From the histogram of Griffiths comfort temperatures for each patient, a mean comfort temperature of 29.83 ± 0.888°C was obtained for Griffiths constant of 0.5 (Fig. 5). The figure also

Table 1: Summary of the calculations of Griffiths comfort temperature

	Regression		Means		Griffiths Comfort temperature		
	Neutral temperature, T_n	Correlation, *r*	Mean air temperature, mTa	Mean thermal sensation vote, mTSV	T_nG1 0.25	T_nG2 0.33	T_nG3 0.5
All votes	30.21	0.752	31.08	0.63	28.58	29.19	29.83
			SD=0.889	SD=0.667	SD=2.086	SD=1.476	SD=0.888

indicated that a large number of patients are thermally comfortable with a temperature near 30°C, which was consistent with the earlier studies in the country (Mallick, 1996; Tariq & Ahmed, 2014). Constant use of ceiling fans and various options for adaptation can be the possible explanations for this high comfort temperature.

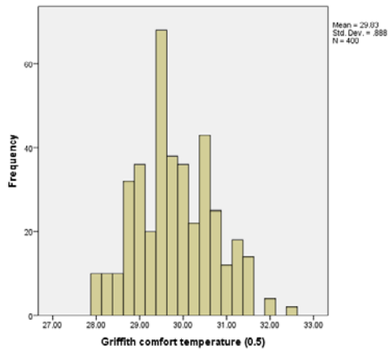

Figure 5: *Griffiths comfort temperatures*

3.4 Identifying 'preferred' temperature

For Probit regression analysis, the preference votes were binned into 0.5°C intervals. Two different probit analyses were performed for thermal preference votes of 'prefer cooler' and 'prefer warmer' categories (Table 2). The Pearson's goodness-of-fit chi-square for the warmer and cooler probit models are chi-square=3.483, degree of freedom (df) =8, p =0.901 and chi-square = 21.21, df =8, p =0.007, respectively. The intersection point of these two fitted probit lines in the probit model indicates the preferred temperature, which is 29.65°C, where the patient neither prefers warmer nor colder conditions (Fig. 6).

Despite being higher than the ASHRAE's recommendations, the preferred temperature was only 0.35°C and 0.18°C lower than the neutral comfort temperature and Griffiths comfort temperature. This finding contradicts Humphrey's hypothesis that people of warmer climates often prefer a cooler environment compared to a neutral one (M Humphreys, 1998). In reality, long-time exposure to tropical climates enabled the patients to feel comfortable and even prefer higher temperatures.

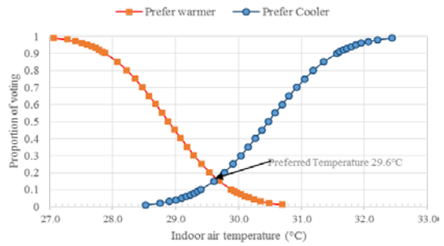

Figure 6: *Preferred temperature using the Probit analysis*

4 CONCLUSION

This study was conducted for a better understanding of the thermal environment inside typical general wards of a government teaching hospital in Dhaka and to investigate patients' thermal comfort during the warm-humid season, which is considered to be the most uncomfortable period of the year in Bangladesh. Despite being habituated to the local climate, about 54.75% of patients in this study voted their immediate thermal environment as 'unacceptable'. The comfort temperature range was found to be between 28.2°C and 31.8°C, which shows that the comfort zone for local patients is at a much higher temperature than ASHRAE's recommendations (ASHRAE, 2010). Through linear regression analysis of thermal sensation votes and Griffiths method, the comfort temperature was found to be 30°C and 29.83°C, which was higher than the ASHRAE standard but lower than the previous thermal comfort studies conducted in Dhaka. Although 91.5% of the patients voted for the central three categories on the thermal sensation scale, 71.86% preferred to be in a cooler environment. The preferred temperature was found to be 29.65˚C, which is slightly lower than the comfort temperature, proving that thermal adversities are quite well tolerated by the patients during the warm-humid season due to adaptation and acclimatization. However, this study could only focus on one hospital for a selected time period due to time, human resources, and budget limitations. Therefore, more detailed studies on hospitals from different parts of the country over an extended period of time will be helpful in establishing generalized thermal comfort standards for hospital wards in urban areas of Bangladesh in the future.

Table 2: Probit analysis statistics for the preferred temperature

Equation	Sample size, N	Standard Error, SE	Sig., *p*	Pearson Goodness-of-Fit Test		
				Chi-square	Degree of freedom, df	Sig., *p*
P_w = -1.129Ta + 36.939	400	0.369	*p* <.001	3.483	8	.901
Pc = 1.188Ta – 36.207	400	0.132	*p* <.001	21.21	8	.007*

P_w=Proportion of preferring warmer; P_c=Proportion of preferring cooler

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Experimental assessment and modeling of a radiant solution for open spaces

Application at a bus stop

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ABSTRACT: The global pandemic caused by COVID-19 has advanced rapidly, disrupting our daily activities. The pandemic has generated a global need for open spaces that are healthy and safe. However, Streetlife challenges the continued rise in temperatures due to the heat island phenomenon combined with climate change. This promotes the development of new bioclimatic techniques or strategies that improve the microclimate and life of cities. These techniques contemplate the reduction of solar radiation, the reduction of the temperature of the surrounding surfaces and, finally, the reduction of the air temperature. In this line, radiant systems are of enormous interest. For this reason and given its foreseeable potential to improve thermal comfort in open spaces and its easy integration, this study studies a new concept of radiant solution adapted for outdoor spaces, specifically at a bus stop. The experimentation is carried out in a test cell to evaluate its behaviour under different design and operating conditions. Evaluating the system's behaviour has allowed its thermal characterisation, achieving high quality and precision results.
KEYWORDS: thermal comfort, radiant system, open spaces, thermal adaptation.

1. INTRODUCTION

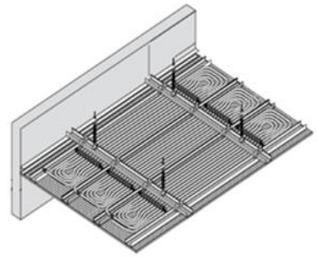
The global pandemic caused by COVID-19 has advanced rapidly, disrupting our daily activities. The pandemic has generated a global need for open spaces that are healthy and safe. However, Streetlife faces the challenge of the continued rise in temperatures due to the heat island phenomenon combined with climate change. [1]. Both phenomena have consequences for the population regarding health, economic development, employment and urban planning, among other aspects.[2]. In many regions of the Mediterranean climate, increased temperatures and drought are already a reality. The climatic data show that, during the central hours of the day, the thermal conditions are not favourable for using open spaces unless part of them is acted so that such conditions are softened. In this context, we must adapt to new solutions to improve the microclimate and the life of cities.

Climate control of an open space requires implementing bioclimatic strategies or techniques that improve its habitability. These techniques contemplate the reduction of solar radiation, the reduction of the temperature of the surrounding surfaces and, finally, the reduction of the air temperature. In this line, radiant systems are of enormous interest—these act by blocking solar radiation and generating cold surfaces simultaneously. Therefore, and given its foreseeable potential to improve thermal comfort in open spaces and its easy integration into them, this study proposes a new concept of radiant solution adapted for outdoor spaces. This conceptual solution comprises conventional elements integrated into a design adapted to this type of space. In this study, the proposed conceptual solution is described, and its experimentation is carried out to evaluate its behaviour under different design and operation conditions. In addition, as previously commented, a thermal characterisation is required to allow efficient control of the system and operation after its integration. Therefore, it is also the object of this study to characterise the thermal behaviour considering the disaggregated effects of the system. This characterisation is carried out from the results obtained in the solution experimentation campaign.

2. EXPERIMENTAL FACILITY

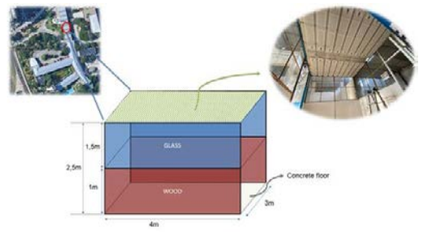
The radiant solution of this study is a modular solution, which facilitates the coupling of successive modules in parallel (figure 1). A module consists of machine-made meanders from multilayer composite pipe placed on a metal structure attached to the ceiling. Each module has dimensions of 1.6 m long by 0.33 m wide. The configuration adopted for the experiments presents ten steps in the tube for each module. The linear length of a 10-tube module is approximately 18 m with an outer diameter of 16 mm and 2 mm thick.

Figure 1:
Three module coupling



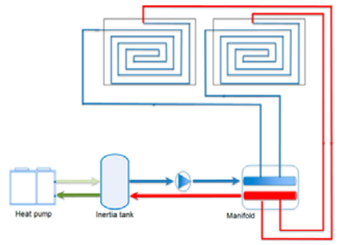
The experimental prototype to test the radiant solution deals with a modular solution, which facilitates the coupling of successive modules in parallel. It takes place in a test cell of 12 m^2, located at the Eduardo Torroja Institute of Construction Sciences in Madrid, Spain.

Figure 2:
Layout.



The proposed experimental prototype consists mainly of the radiant solution, a heat pump to cool or heat the water accumulated in the buffer tank and a pump in charge of driving the water from the buffer tank to the radiant solution through a collector of supply and return of the two available circuits.

Figure 3:
Hydraulic scheme of active surface.



The described system is fully monitored by multiple calibrated sensors coupled to a DAQ

3. METHODS: CHARACTERISATION MODEL

3.1 Theoretical basis

The radiant system's theoretical basis is based on an energy balance. Suppose the energy balance is carried out in an active roof system, wholly isolated from the top. In that case, the variation in water energy refers to the thermal gains due to convection and radiation with the conditioned space ($Q_{cv} + Q_{rad}$).

Therefore, the energy variation of the water that circulates through the radiant cover is formulated according to equation 1:

$$m_w \cdot \rho_w \cdot Cp_w \cdot dT_w/dt = Q_{cv} + Q_{rad} \quad (1)$$

Where m_w is the flow of water that circulates through the radiant cover, ρ_w is the density of water, Cp_w is the specific heat of the water, dT_w/dt is the difference in temperature between the inlet and outlet of the water of the radiant System, Q_{cv} is the convective heat flux between the surface and the surrounding air, Q_{rad} is the radiant heat flux between the surface and the rest of surface.

3.2 Model

To predict the convective and radiant heat flux for the tested radiant canopy system, a model is formulated that allows determining the heat flux as a function of the discharge temperature, the projected air of the radiant canopy based on the number of modules and impulse flow. Among the parameters to highlight of the model:

- The heat flux referred to as the radiant thermal gains are linearised, so the hypothesis is made that the representative temperature difference is less than 100K. Therefore, the error made when linearising the radiation heat flux is acceptable [3]
- The convective heat coefficient is modelled based on the Morgan correlation for a long horizontal cylinder [4]:

$$h_{cv} = K \cdot LMTD_{cv}^{n} \quad (2)$$

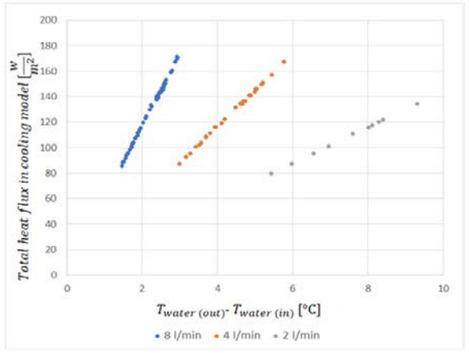
The coefficients K and n are the parameters to be determined based on the data obtained from the experimentation of the experimental prototype.

4. RESULTS

4.1 Identification of parameters and validation

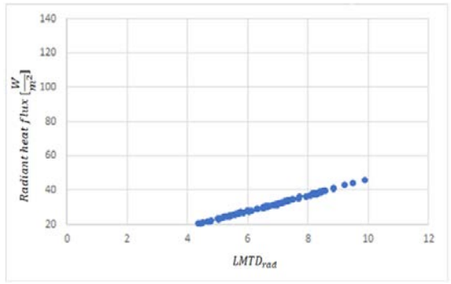
The experiments have been carried out for different water flow rates. As a first result, the variation of absorbed heat flux is obtained as a function of the water flow:

Figure 4:
Total heat flux



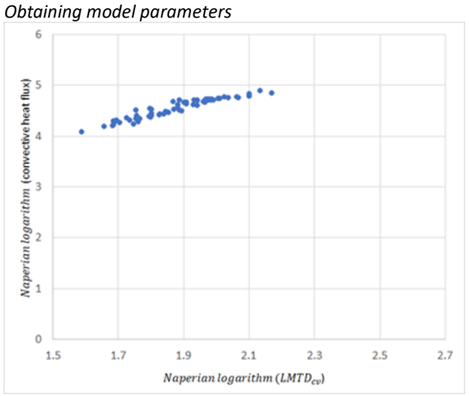
As this flow increases, the thermal jump between the water inlet and outlet decreases.
To determine the absorbed radiant heat flux, it is necessary to know the material's emissivity. The manufacturer's data indicates that the emissivity is 0.85.

Figure 5:
Radiant heat flux



The absorbed radiant heat flux results vary linearly with the LMTD, implying that the radiant transfer coefficient has a constant near the value of 4.6 W/(m^2·°C).
The following figure shows the results of the evolution of heat transfer by convection.

Figure 6:
Obtaining model parameters



It is possible to adjust the expression (eq. 3) using data from figure 5. Experimental data is divided into two groups: group 1 identifies the coefficients (40% of the experimental data) and group 2 validates the expressions (60% of the data). The coefficients for the cooling mode are:

$$h_{cv}=e^{\wedge 1.8127}\cdot LMTD_{cv}^{\wedge 0.4596} \quad (3)$$

The model is run with a series of input data to verify that the expression obtained is valid. The data obtained from the model are the water outlet temperature, and the total heat flux absorbed. These are compared with experimental data to confirm the quality of the model obtained.

Figure 7:
Estimated vs measured values – Heat flux

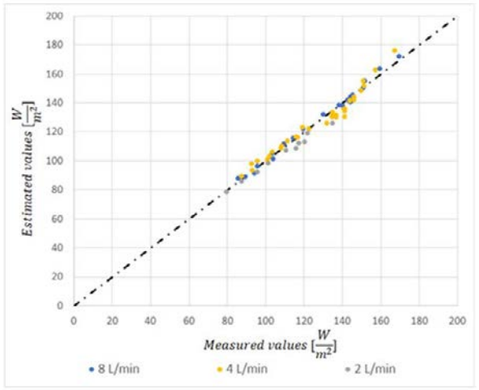
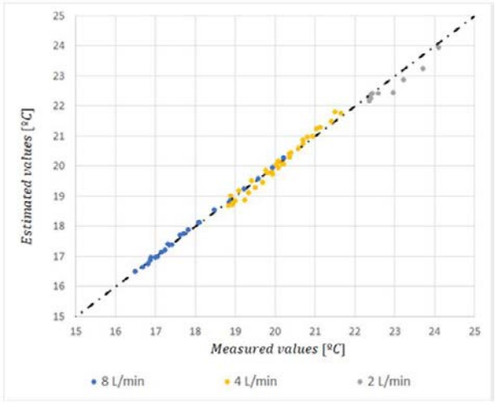


Figure 8:
Estimated vs measured values – Water outlet temperature



The estimated total heat flux and the water temperature at the outlet show errors not exceeding 2% for the experimental data. Therefore, the quality of the model is confirmed.

5. APPLICABILITY

The experimental nucleus and development of the thermal characterisation of the radiant solution of this study reside in the European project LIFE WATERCOOL (LIFE18 CCA / ES / 001122), which is developed in the city of Seville (Spain). The characterised technology will be part of a bus stop to improve the user's thermal sensation in the summer season.

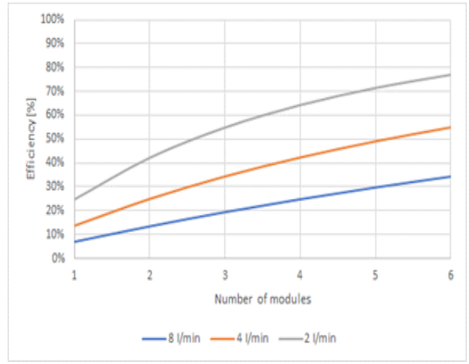
Figure 9:
Bus stop

Thanks to the previously exposed model, it is possible to estimate the thermal performance of the radiant panel in any operating condition. In the case of a bus stop, it is possible to determine the number of modules needed to install and size the cold-water production system.

Since the radiant panel system studied has been assimilated its operation to that of a heat exchanger, the use of the NTU efficiency method is proposed for the model's applicability. The results shown below have been calculated using a mean air temperature of 25°C, a mean radiant temperature of 24°C and an inlet water temperature of 15°C.

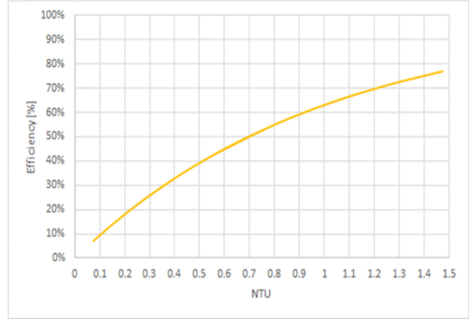
In the first place, the efficiency of the system is evaluated for the three water flows studied based on the number of modules installed. If the water flow is the minimum, the maximum length per m2 of active surface is required to achieve the same efficiency as the other cases. This result allows deciding if a low operation cost (pumping cost) or a high initial cost is more interesting.

Figure 10:
Efficiency vs number of modules



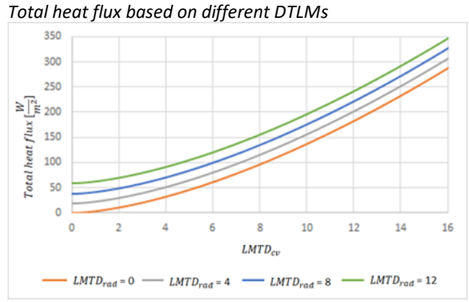
The following result shows the variation of the efficiency as a function of the NTU.

Figure 11:
Efficiency vs NTU



It follows that a higher NTU implies a greater linear length of tubes through which a low flow circulates.
In addition to the results before, the ε-NTU procedure allows evaluating the results for a known solution (108 m of radiant exchanger and water flow of 2 l/min). The total absorbed heat flux is represented for different given radiant LMTD as a function of the convective LMTD.

Figure 12:
Total heat flux based on different DTLMs



Thanks to this result, a pre-design of the radiant panel and the necessary auxiliary equipment is possible.

6. CONCLUSIONS

The experimental work has allowed developing and evaluating a radiant solution integrated into open spaces to improve their habitability. Results show that the radiant effect accounts for 40% of the system's energy consumption in summer and 60% in winter. Also, It is shown that it is possible to achieve a homogeneous temperature (+/- 2ºC) on the ceiling's surface employing the tube exchanger embedded in it.

Obtaining a simplified model has allowed the development and evaluation of the radiant solution proposed for the Life Watercool project. Results show that the radiant effect accounts for 40% of the system's energy consumption in summer conditions. On the other hand, it is possible to maintain the surface temperature practically homogeneous, guaranteeing the exchange of heat with the assistants.

The experimental facility has allowed thermal characterisation by a simplified model. Validation results confirm the high quality and precision of its estimations. The developed model allows obtaining the exchanged heat flow and the return temperature of the water as a function of the environmental conditions surrounding that active surface and the design and operation parameters of that solution.

The experimental results have tested the proposed system's efficiency and have allowed knowing the convective and radiant effects in detail. In addition, the proposed model provides the thermal response of the solution to variations in its design or operating conditions. So, different examples have been described in the discussion section. Furthermore, this application includes the usefulness of the model for decision-making in design phases or even optimal management of such solutions. Finally, it is possible to design the integration of the radiant system into a new space using the model developed.

ACKNOWLEDGEMENTS

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The way forward to aging

Developing a preliminary questionnaire survey instrument to determine elderly peoples' thermal sensation in India

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ABSTRACT: The United Nations Population Fund (UNFPA) report predicted the growth of older people's population from 17.3 crores by 2025 to 24 crores by 2050. It is essential to create a thermally comfortable indoors for people who spend maximum time indoors, especially the older people. Thermal Sensation perceives energy exchanges between the human body and its surroundings. Although the ASHRAE seven-point scale for thermal Sensation is widely used, there are various ways to ask questions, depending on participants' age, education level, and aim of the survey. Current thermal comfort guidelines in India are mainly aimed at persons aged between 20 to 60 years. Several studies indicated differences between younger and older adults' optimal thermal Sensation. As a result, this study investigated the differences in how younger and older persons interpret thermal sensation scales to select one scaling method that the elderly would understand and recognise. The author has identified two prominent questionnaire scaling methods: Emojis/ expressions and colours from Visual Analogue Scale (VAS) to perceive Thermal Sensation votes (TSV). This experiment revealed that the colours scale was more easily recognised and comprehended by elderly participants than the emoji scale compared to younger people.
KEYWORDS: Thermal Sensation, Questionnaire survey, Categorical scale, Visual Analogue scale, Elderly people.

1. INTRODUCTION

Creating a thermally comfortable indoor environment is essential for improving building users' productivity and well-being, particularly for those who spend their maximum time indoors, such as older people.[1] The ANNEX 53 of the International Energy Agency- Energy in the Buildings and Communities (IEA-EBC) programme states that Occupant Behaviour is one of the six parameters inducing building energy use. The fundamental motivation behind the actions and controls taken by the occupants is to achieve a comfortable indoor environment.

The American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE-55) states, "Thermal comfort is a condition of mind which expresses satisfaction with the thermal environment". Thermal Sensation is the most crucial factor in assessing thermal comfort since it reveals occupants' conscious feelings about the level of warmth in the environment and necessitates subjective assessment. Energy exchanges that occur between the human body and the surrounding environment are encoded and perceived by Thermal Sensation.[4] To evaluate factors such as thermal Sensation, preference and acceptability, several thermal comfort indices have been established, in which the Bedford scale, ASHRAE-55 seven-point scale being the most popular.[5] Furthermore, scales can vary depending on the participant's sensitivity. Although the ASHRAE seven-point scale for thermal Sensation is widely used, there are various ways to ask questions, depending on criteria such as the participant's age, education level and the survey's aim. [3,5]

Individuals who have reached the age of 60 are referred to as "elderly," "senior citizens," or "aged." The population of older people has expanded steadily since 1950. According to the 2001 Census of India, there were approximately 7.6 crores of senior citizens in India, up from 10.4 crores in 2011.[6] The United Nations Population Fund (UNFPA) report identified that the population of older people is predicted to grow to 17.3 crores by 2025 and around 24 crores by 2050. The UNFPA states that "the relatively young India of today will turn into a rapidly ageing society in coming decades". Numerous thermal comfort experiments are being conducted in India, each yielding new and unique results. However, thermal comfort studies focusing on the elderly are limited in India. The current thermal comfort guidelines in India are mainly aimed at persons aged between 20 to 60 years old.[1] Several studies

[1,5] indicated that the optimal thermal Sensation of older people differs from that of younger adults.

This study investigates the differences in how younger and elderly people perceive thermal sensation scales to recommend one scale that is easily understandable and recognisable by the elderly. The outcome of this research is an attempt to investigate the various methods to evaluate the thermal sensation scale and identify the preferable method by different age groups. To the extent of the author's knowledge, this study is the first attempt to determine the preferable scale for conducting the subjective evaluation in thermal comfort studies, especially for elderly people in India.

2. METHODOLOGY

The questionnaire survey is "a technique for gathering statistical information about the attributes, attitudes or actions of a population by administering standardised questions to some or all of its members".[2] There is a range of approaches to perform questionnaire surveys in thermal comfort research. Researchers can conduct face to face interviews in offline mode using paper form surveys as well as the self-administered questionnaire can be mailed or sent via the internet.

The author has chosen the ASHRAE -55 seven-point scales (cold, cool, slightly cool, neutral, slightly warm, warm, hot) to evaluate Thermal Sensation Vote (TSV) to meet the research's goal. Many thermal comfort studies have employed seven-point rating scales since seven is a distinguishing number for judging between levels of sensations without confusion.

In the research of thermal environments, several subjective scales have been established for surveys to assess thermal comfort of different age groups, in which categorical scales are the most common one; whereas in Visual Analogue Scales (VAS) are widely used in psychological studies to assess subjective

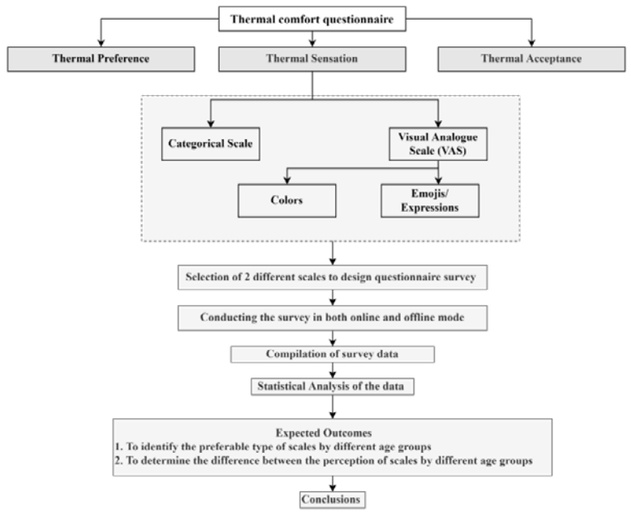

Figure 1: The Methodology flow chart

COLD	COOL	SLIGHTLY COOL	NEUTRAL	SLIGHTLY WARM	WARM	HOT
R= 47 G= 85 B= 151	R= 143 G= 170 B= 220	R= 180 G= 199 B= 231	R= 242 G= 242 B= 242	R= 255 G= 189 B= 159	R= 255 G= 143 B= 93	R= 246 G= 76 B= 0

Figure 2a: Colours scale with RGB values

COLD	COOL	SLIGHTLY COOL	NEUTRAL	SLIGHTLY WARM	WARM	HOT
Frozen cold	More cold	Winter hat	Two thumbs up	Wiping sweat	Excess Sweating	Hot face sweating

Figure 2b: Emojis/ expressions scale with clue words

responses of people about their pain, feelings, mood, and other aspects. [3,5] According to the definition of thermal comfort, the condition of the mind is related to the occupants' psychological factors and mental state.

Therefore, in this study, the author has identified two notable scaling methods: Emojis/ expressions, and colour from Visual Analogue Scale (VAS) to perceive Thermal Sensation Votes (TSV) from the occupants of different age groups. (Fig. 1) shows the methodology flow chart.

The questionnaire survey is divided into two sections, the first includes personal information such as location, age, gender, and educational level, and the second contains questions about thermal sensations. The respondents were asked to match the colours scale and emojis scale (Fig. 2a & b) with the appropriate thermal sensation verbal anchors. The questions related to the level of difficulty in understanding the scales were also present in the questionnaire form. The authors gave proper instructions and a brief about the topic were given in prior to the respondents.

The survey was conducted in both online mode (through the internet) and offline mode (face to face interviews) for the period of 8 months (October 2022 till June 2021). After the survey, the collected data were consolidated and analysed through Microsoft Excel and SPSS- IBM software packages to investigate the research objectives.

Table 1: Respondents' characteristics

Total number of respondents	**323**
Gender- wise	
Male	169
Female	154
Age- wise	
Younger (below 60 years)	123
Male	61
Female	62
Elder (above 60 years)	200
Male	108
Female	92
Educational qualification- wise	
Primary & Secondary Education (1&2)	159
Younger	24
Elder	135
Technical college/ University education (3&4)	164
Younger	109
Elder	55

3. RESULTS AND DISCUSSION

3.1 Descriptives

The survey had a total of 323 participants. Out of which, 123 people were under the age of 60 and 200 people beyond the age of 60, referred to as elderly population. The characteristics of respondents are shown in (Table. 1). The questionnaire was given to those staying indoors for at least 30 minutes, primarily in their residences. The bar charts (Fig. 3 & 4) below show the percentage of people's votes who have effectively matched the relevant thermal sensation scale with the appropriate colours/emojis.

Among all the age groups, the percentage of votes to match the extremities (i.e., "Hot" and "Cold") of the Thermal sensation scale with its corresponding colours are significantly higher than the other verbal anchors.

As demonstrated in the colours bar graph (Fig. 3), female respondents were more likely than male respondents to match the colour representation with its TSV verbal anchors. Young and elderly people (95 percent and 93.5 percent, respectively) were more likely to associate the neutral Sensation with its colour scale than other intermediate verbal anchors like "slightly warm," "warm," "slightly cool," and "cool."

Like the younger group, the elderly female respondents were more appropriate in matching the colour scale with Thermal sensation verbal anchors than elderly males.

In the elderly population, there was much ambiguity about which colour scale to use, especially for verbal anchors like "slightly warm" (43.5 percent men and 60 percent females) and "warm" (43.5 percent males and 60 percent females) when contrasted to the cooler side (70.1 percent males and 76.4 percent females in "slightly cool" and 64.1 percent and 80.4 percent in "cool") verbal anchors.

The younger population identified the emojis/expressions scale with its verbal anchors more than the older population, as shown in (Fig. 4). It's worth noticing that, in both age groups, the percentage of votes acquired to match the extreme ends was significantly lower than the other intermediate verbal anchors.

The percentage of people selecting appropriate emojis was high when it comes to identifying "slightly warm" (87 percent, 77.4 percent younger male and female whereas 67.2 percent and 64.1 percent elder male and female respectively) and "neutral" sensation (87 percent, 77.4 percent younger male and female however 67.2 percent and 64.1 percent elder male and female respectively). Overall, the elderly population voted far less on the emojis scale than on the colours scale than appropriate thermal sensation verbal anchors.

3.2 Relationships

Fig. 5 depicts the relationship between thermal sensation votes and the participants' ages. The data suggests that participants of all ages comprehend and choose the proper answers for the thermal Sensation verbal anchors on the colour scale rather than the expression/ emoji scale. Female participants are better

at interpreting the colours scale than the emoji scale in all age categories. Only 52.2 percent and 29.5 percent of male respondents in the age group of 40-59 years accurately matched the colours scale and

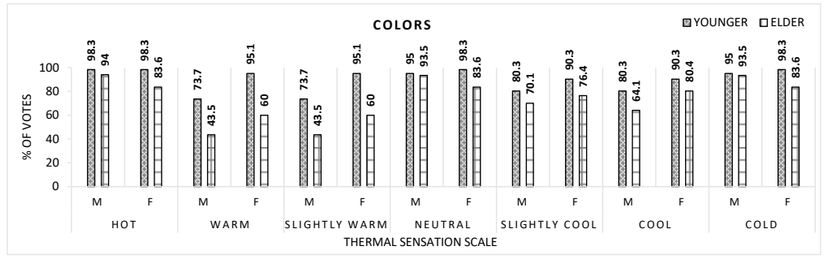

Figure 3: Percentage of matching appropriate colours with its thermal sensation verbal anchors

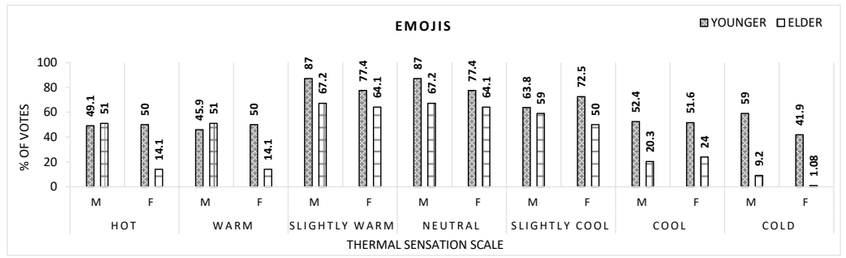

Figure 4: Percentage of matching appropriate emojis with its thermal sensation verbal anchors

emojis/expressions scale with their thermal Sensation verbal anchors, whereas 88.2 percent and 82.3 percent of male respondents in the age group of 20-39 years accurately matched the colours scale and emojis/expressions scale with their thermal sensation verbal anchors, respectively.

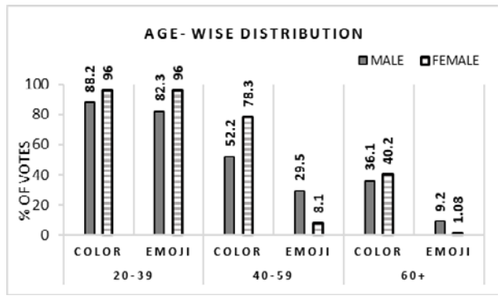

Figure 5: Percentage of votes based on age- wise distribution

The elderly men had a lower matching rate than the other two age groups (36.1 percent valid colour matches and just 9.2 percent valid emoji/expression matches). With increasing age, the participant's ability to match with the appropriate verbal anchors became less. Female participants in the 20–39-year age group comprehended both colours and emojis scales (96 percent of colour scale & 96 percent of emojis scale), but this trend declined as age progressed. This could be because the use of mobile phones and messaging applications among younger people are higher than the elders.

The respondents' educational profiles were divided into four groups. Primary and secondary education are represented by 1 & 2, while technical college and university education are represented by 3 & 4.

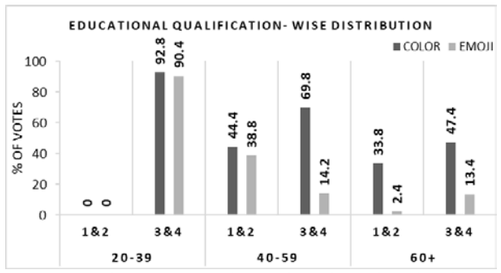

Figure 6: Percentage of votes based on educational qualification wise distribution

The results (Fig. 6) show that younger responders (20-30 years old) with 3 & 4 educational qualification had a greater matching rate (92.8 percent appropriate verbal anchors with colour scale & 90.4 percent suitable verbal anchors with emoji scale). The age group of 40-59 years old with the 3 & 4 year educational levels had a better knowledge of the colour scale than the emojis scale. Regarding the colour scale, the older people with educational levels of 1 & 2 gave less accurate answers (33.8%) than the 3 & 4 groups (47.4%). In the older population, however, the emojis scale was less grasped by all educational levels (2.4 percent in 1 & 2 and 13.4 percent in 3 & 4).

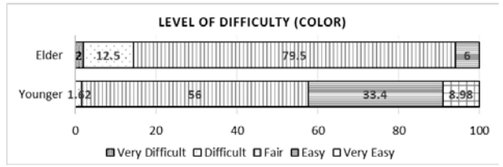

Figure 7: Level of difficulty to understand colours scale

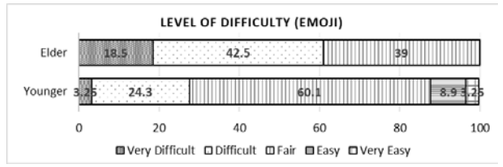

Figure 8: Level of difficulty to understand emojis scale

The level of difficulty (from very difficult to very easy) in relating the thermal sensation scale to colours and emoji representations was determined and shown in a stacked bar chart (Fig. 7 & 8). It is apparent that the elderly people voted 79.5 percent as fair in colour representation, but only 39 percent in emojis, which is almost half the number of votes than the colour representation.

In the colour representation, only 14.5 percent of the elderly's votes were in the very difficult zone, but it is significantly higher in the emojis representation (57.62 percent in the zone of very difficult and difficult). When it comes to understanding emojis, it's worth noting that the elderly did not vote in the zones of very easy and easy, but 12.5 percent of the younger people did.

Overall, both younger and elderly people had less difficulty in deciphering colour representations, but the elderly had more difficulty comprehending emoji representations than the young.

4. CONCLUSION

Before commencing the substantive study, it is always necessary to do a preliminary investigation.

Based on the results of this investigation, it is evident that the elderly population requires a unique questionnaire design to understand the thermal Sensation in thermal comfort studies. This study is a preliminary attempt to investigate the possibilities and difficulties to find a suitable scaling representation to understand the thermal sensation votes.

The following are the conclusions arrived:

- There are two types of scaling methods used to perceive Thermal sensation verbal anchors in this study: 1. Colors and 2. Emojis/ expressions. Out of which, the color scale was recognised and understood by the elderly population more than the emoji scale.
- It was easy for the younger people to match the emoji scale w.r.t its verbal anchors may be because of mobile phone usage and frequent texting applications, which is quite less in the elderly population.
- Female participants are better at interpreting the colours scale than the emoji scale in all age categories.
- Educational qualification plays a major role in perceiving the scales with its verbal anchors. The younger responders (20-30 years old) with 3 & 4 educational qualification had a greater matching rate (92.8 percent appropriate verbal anchors with colour scale & 90.4 percent appropriate verbal anchors with emoji scale). In terms of colour scale, the older people with educational levels of 1 & 2 gave less accurate answers (33.8%) than the 3 & 4 groups (47.4%).

Thermal comfort research focusing on the elderly are in their early phases in India. Therefore, this research will pave the way to determine the preferable survey instrument for older adults. The thermal Sensation is always subjective to the occupants. Hence there is a need to find a precise method to obtain accurate results to evaluate thermal comfort. This study currently considers only two approaches to assess the thermal sensation scales and it is particular to warm and humid climate type. Thus, it is subject to further improvement with different scaling methods such as images, numbers etc., in different climates as well as different regions of India.

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Thermal performance evaluation of perforated solar screen for office buildings in the hot and humid climate

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ABSTRACT: This study aims to evaluate the perforated solar screen as shading devices for office buildings. These devices are used worldwide in architecture, showing aesthetical values, and valorizing the buildings. Nevertheless, perforated screens are usually made of steel, which is a highly conductive material that could at the same time block direct solar radiation and emit longwave radiation to the inside through the window. Thermal simulations were carried out in EnergyPlus for an office room in São Paulo/Brazil, in the hot and humid climate ASHRAE 2A classification. The model represents an existing building with low rise height with windows facing north and east. Shading screens were added to evaluate the feasibility of reducing cooling load energy and check whether it may cause local discomfort for occupants sitting near the wall, especially when considering natural ventilation. The results showed that perforated solar screen might decrease the transmitted radiation through the window surface. However, the device is not as efficient to low indoor air temperature when coupled with passive ventilation strategies.
KEYWORDS: Building simulation, perforated solar screen, thermal performance, thermal comfort

1. INTRODUCTION

The design of building envelopes and openings are relevant for thermal comfort and energy performance. Shading elements on the building facade are traditional in Brazilian architecture, as the climate presents high mean outdoor air temperatures and high direct solar incidence rate during most of the year.

The civil construction is one of the most polluting sectors and, following the Paris Agreement, urge to reduce energy consumption in buildings and increase thermal performance. In Brazil, commercial and public buildings consume 25.9% of the energy produced [1]. Air conditioning represents 47% and lighting 22% of total energy consumption in the commercial sector [2].

Gonçalves [3] analyzed the guidelines for the bioclimatic design in São Paulo city according to the ASHRAE comfort parameters. The study found that the natural ventilation of buildings is favorable in São Paulo climate. Temperatures are mild during approximately 70% of the year, with a monthly average between 18°C and 33°C. Thus, the potential of natural ventilation would be 89% per year. The study recommends natural ventilation with passive thermal mass and vertical surface shading.

In this context, perforated solar screens (PSS) have gained attention in institutional and commercial buildings in Brazil. This solution seeks to aesthetically update the shading solutions widely present in Brazilian architecture. However, the aesthetic use of PSS without understanding the building operation may conflict with other thermo-energetic performance solutions, such as natural ventilation. The metal sheet heat transmission can cause discomfort to the occupants and discourages the window operation.

Studies on PSS are recent and meet many relevant aspects, highlighting experimental works concerning material composition, orientation, geometry [4-5], and model validation [5-6]. Other studies approached the simulation tools, software, methods, and limitations [6-12]. Also, many authors [7-9, 12-13] conducted parametric simulations with different perforation rates, shapes and holes arrangement, sheet thickness, the distance between building and PSS to meet daylight and thermal comfort thresholds with feasible energy balance.

To analyze PSS performance, it is important to check its properties, physical parameters and predict thermal behavior facing different applications. Building Energy Simulation (BES) is the most adequate method for parametric analysis. In Kirimtat et al [10] review, it was found that the main available tools for building shadowing device evaluation were Energy Plus, DesignBuilder, DoE-2, Ecotect, DIVA for Rhino, IES–VE, Radiance, ESP-r, and Tas.

It is worthwhile to mention that computational simulation implies some constraints concerning data availability limitations and tools calculation methods. In this way, inputs such as field-measured databases and deep knowledge of software are essential to a well-successful simulation analysis. However, such

data is not always easy to obtain due to the variability of PSS types. Minoli [4] made an important contribution, presenting experimental results of solar and visual transmittance. The results were based on different solar incident angles in metallic perforated, expanded, and ceiling tiles screens.

Blanco et al [5-6] conducted an experimental work and further validation with BES for parametric analysis using EnergyPlus and Matlab. They collected data from galvanized steel-aluminum PSS with 0 to 35% perforation rates and natural or black-painted finishes. Results showed that PSS reduced 45% of energy consumption for the hottest areas in Spain.

Chi, Moreno, and Navarro [7-9] developed a method to optimize daylight and energy consumption for early design stage coupling EnergyPlus and Diva. They raised many variables to evaluate thermal balance. LAVIN and FIORITO [13] employed genetic algorithms for optimization in an office building in Australia using Grasshopper. Srisamranrungruang and Hiyama [11] investigated ideal perforation rates regarding daylight and natural ventilation in Japan, using Rhinoceros, Radiance, and DesignBuilder. The perforated percentage of 50% provided the best scenario for natural ventilation.

This article proposes the thermal analysis of perforated solar screens comprising natural ventilation in an office room of an existing building in São Paulo, Brazil. Four scenarios were run in EnergyPlus, two with PSS and two without PSS. The model had glazing facing north and east, enabling natural ventilation by window opening. The objective was to check the effect of perforated solar screens on shading, mainly in the hot climate, where ventilation is a great ally to passive cooling. The PSS is widely used in architecture, and many studies pointed to visual comfort, but there is a lack of an effective analysis between ventilation and shading's effect on thermal performance.

2. MATERIALS AND METHODS

This section contains de case study and modeling description with detailed inputs.

2.1 Case study

The object of this study is a medium-sized commercial building, located in the southern area of the city of São Paulo, Brazil. The building consists of a ground floor with pilotis, a mezzanine, and three main commercial floors.

The external façade of the building has a large glazing area with metallic rails acting as shading devices. The masonry sills have a metallic coating with a white thermal insulation layer. External awning windows and doors located on the balconies in all offices provide natural ventilation. The atrium is approximately 22 meters high and promotes a chimney effect. It has permanent ventilation through slats next to the floor and on the roof.

Since its opening in 2003, this building has become a reference in architecture publications because of passive cooling strategies for ventilation and daylighting. The analyzed room is on the second floor; it has external walls facing north, east, and south. This room has more influence of solar radiation on the façade in comparison to other rooms in the building.

2.2 Building modeling

The building was modeled in SketchUp and initially set up in Open Studio. Then, the IDF was exported to EnergyPlus 9.3, where advanced data for the PSS were inputted. Fig. 1 shows the whole building model, and Fig. 2, the simulated office room.

Figure 1:
Building Energy Model

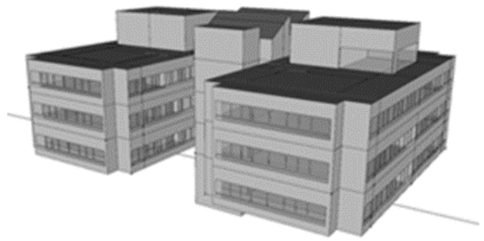
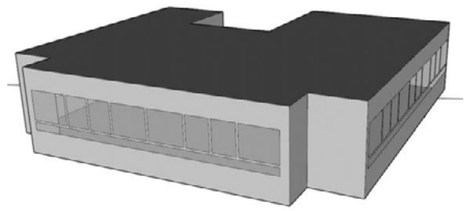


Figure 2:
Simulated thermal zone



The object of this study comprises an office room with 17 m x 17 m x 4 m (length x width x height), presenting laminated glass windows in the external façades with a window to wall ratio (WWR) of 52.1%, as shown in Figure 2. Internal walls were adiabatic, so the heat flux from the other zones was not contemplated in thermal balance. Other existing shading systems in the actual building were not considered in the model because it would affect PSS analysis.

The opaque walls were of 19 cm concrete block masonry, with mortar and acrylic painting from the inside and polyurethane insulation and aluminum coating on the outside. The slabs were of 10 cm concrete, and the floor has an elevated deck with a 5 cm air gap and laminated melamine. Table 1 describes the constructive components and associated U-factors of the compositions.

Table 1:
Thermal properties of construction elements

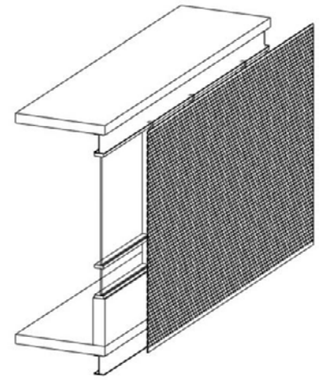
Construction component	Materials	U-factor (W/m².°C)
Opaque wall	Aluminum (1 mm) Insulation (PUR - 2 mm) Concrete block (19 cm) Mortar (1.5 cm) Acrylic painting (0,5 mm)	1.01
Floors and slabs	Laminated melamine (3 cm) Air gap (5 cm) Concrete (10 cm)	1.81
Windows	Laminated glass (8 mm)	5.70

Internal loads such as lighting, electrical equipment, and occupation were not considered within the models to reduce the variable quantities of the analysis.

The perforated solar screen was modeled similarly as described in Blanco et al [5]. The PSS material had an 0.84 emissivity and a 52 W/m.K conductivity, representing an anodized aluminum material. The screen was placed at a distance of 1.0 m from the window, on the north and east façades, with a 24% of perforation rate.

Energy Plus's Window Screen object simulated the specific properties of the external screen material. The window screen model assumes an orthogonal cylinder's mesh that intersects each other. The cylinder diameter was 3 mm, admitting a perforation with 0.5 mm of spacing. The diffuse solar reflectance is 0.16. The appearance of the PSS reproduces circular holes, and the screens have the same size as the window, projected 1.0 m ahead, with no closures in the top and the bottom. Fig. 3 illustrates the PSS modeling.

Figure 3:
Isometric view from the PSS in front of the window



The simulations were run for the winter and summer design days, on Feb 21st and July 21st, respectively. São Paulo is at -23.62° latitude/ 46.65° longitude and has a humid subtropical climate characterized by mild winter (2A in ASHRAE Classification). Natural ventilation was modeled with the Airflow Network (AFN) module. AFN describes a flow path through a group of zones bounded by doors and windows. A total of four scenarios were simulated, as follow:

Case 1: without the PSS and without natural ventilation.

Case 2: with PSS and without natural ventilation.

Case 3: without PSS and with natural ventilation.

Case 4: with PSS and with natural ventilation.

The simulation outputs included the thermal zone's indoor air dry-bulb temperatures, the surface temperature on the front and the back face of the window, and the surface window transmitted solar radiation, including the amount of beam and diffuse solar radiation.

3. RESULTS AND DISCUSSION

Preliminarily, the scenarios with and without the PSS were compared, analyzing the window transmitted radiation through the window and the mean radiant temperature. The objective was to evaluate the impact of the shading element on the transmitted radiation.

Subsequently, the window surface temperature was obtained on the external and internal surfaces. The window surfaces temperature difference was verified to check the perforated solar screen influence. Finally, we compared the results from the four cases mentioned in section 2.2, analyzing the impact of PSS application on thermal comfort, especially when coupling natural ventilation.

The results show that PSS reduces the energy transmission by radiation through the window. Fig. 4 and Fig. 5 display window transmitted radiation rate in Watts (W) and mean radiant temperature (°C) for the summer and the winter design day. It can be observed

that the radiation dropped about 90% concerning the cases without the PSS. However, on the morning of the winter's day (Fig. 5), this difference decreases because of the lower solar altitude at this season compared to the summer design day. It reduces the PSS shading effect as more direct incident radiation reaches the window surface.

The perforated solar screen also changes the mean radiant temperature measured at the center of the room. In the scenario with PSS, there is an average reduction of 2°C compared to the scenario without the PSS. Similar behavior is noted in the winter.

Figure 4:
Window transmitted radiation and mean radiant temperature for the summer design day

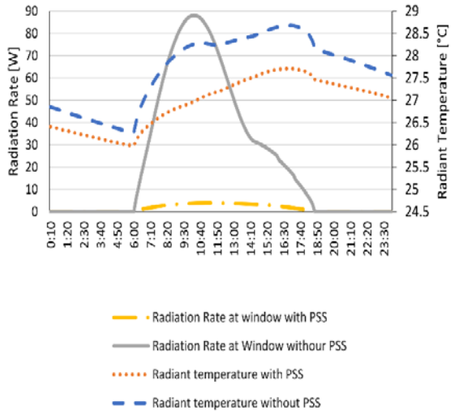


Figure 5:
Window transmitted radiation and mean radiant temperature for the winter design day

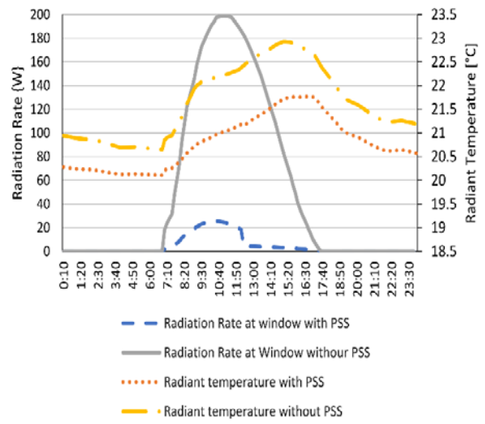


Fig. 6 and Fig. 7 show the window surfaces temperatures of Case 1 and 2. When comparing the temperature differences between the front and rear face of the window in the cases with and without PSS, it is observed that the PSS causes a temperature difference between the glazing surfaces, while there is no difference in the temperature in the scenario without the perforated solar screen.

The laminated glazing usually presents no difference in the temperature surfaces because the heat conduction occurs with lower resistance. When adding the PSS, the back face of the glazing showed a temperature up to 10°C lower, which decreases local discomfort due to radiant temperature asymmetry.

Figure 6:
Surface window temperatures for the summer design day

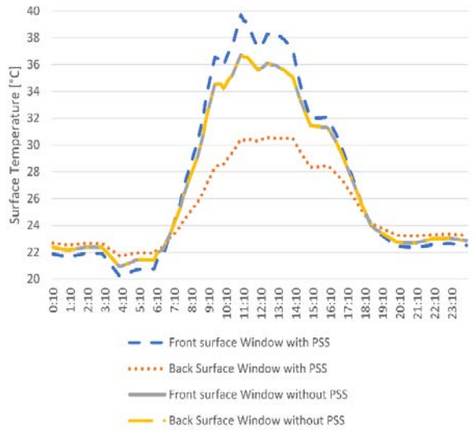


Figure 7:
Surface window temperatures for the winter design day

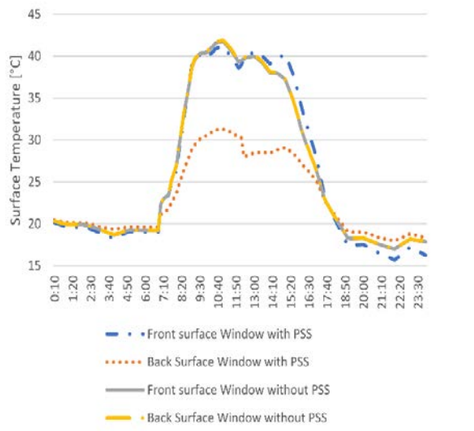


Fig. 8 and Fig. 9 show the results with the natural ventilation in cases 3 and 4. In the scenario without ventilation, the zone operative temperatures with the perforated solar screen were lower, both in the summer and on the winter design day. It suggests that the PSS reduces the contribution of the envelope to the thermal load, which may ensure energy savings in HVAC systems operation.

For the models with natural ventilation, the perforated solar screen had little impact on the operative temperature, showing a slight decrease since natural ventilation plays a major influence than the PSS in the indoor thermal conditions. In the cases without natural ventilation, the simulation results indicate that the shading element reduced the operative temperature by 1°C on average. Considering ASHRAE 55 adaptive comfort model [15], the São Paulo operative temperature limits are from 19.1°C to 26.1°C throughout the year. In the summer, the operative temperature is below the upper limit in part of the day with natural ventilation, but it clearly demands a climatization system to guarantee thermal comfort. In the winter, all the scenarios with natural ventilation attend to adaptive comfort limits, although the perforated solar screen without natural ventilation scenario supports higher energy savings.

Figure 8:
Operative Temperature for the summer design day

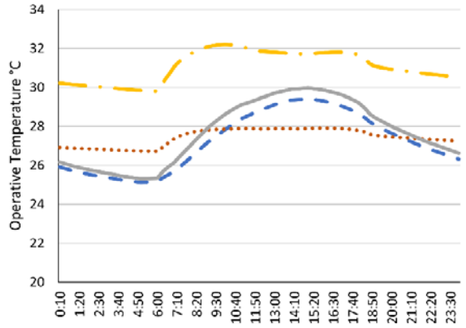
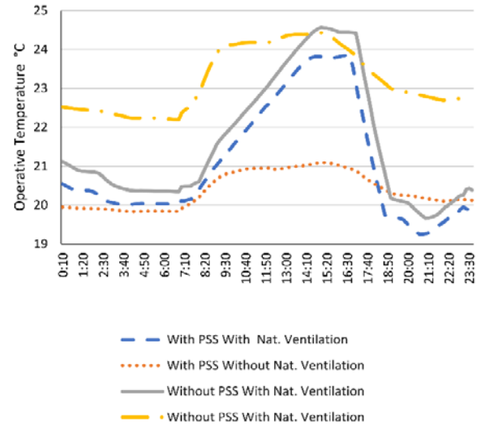


Figure 9:
Operative temperature for the winter design day



4. CONCLUSION

The perforated solar screen (PSS) is a relevant shading element in buildings but may conflict with other energy efficiency strategies. In this work, building energy simulations were carried out for an office room in São Paulo, Brazil, combining scenarios with and without the PSS and natural ventilation.

The results showed that the PSS can reduce the transmitted radiation through the windows, generating a difference between the temperatures of the front and rear surfaces of the windows. It may avoid local discomfort and ensure energy saving with cooling systems.

When the perforated solar screen is integrated to natural ventilation, it is clear that natural ventilation is more efficient in removing heat load when the outdoor air temperature conditions are favorable, i.e., when the air temperature is lower than the zone temperature. For a humid subtropical climate like São Paulo, it is necessary to design shading devices to reduce thermal load envelope's contribution and allow natural ventilation in specific situations

The perforated solar screen showed a low resistance in natural ventilation, as the results indicated a 1°C difference between the scenarios with and without the PSS. Lower distances (< 1.0 m) between PSS and window may affect natural ventilation and should be further investigated.

EnergyPlus showed some limitations in PSS modeling: the orthogonal mesh defined the perforation geometry, and the window-screen distance is up to 1.0 m. Considering higher lengths might cause inaccuracies in thermal balance. One might contemplate other tools for a detailed study in heat convection near the PSS and windows surfaces.

Future works may consider running an annual simulation to analyze the effect of the PSS in the autumn and spring seasons. Also, one can run parametric simulations changing perforation rate, and PSS material. The glazing type might be changed as

well, contemplating an insulated glass unit with low-E in the inner layer. An integrated study accomplishing visual comfort and thermal comfort might enrich the discussion.

ACKNOWLEDGEMENTS

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Interior courtyards and vegetation: impact on users' comfort and energy efficiency in heritage housing

Expansions In Cité Housing In Santiago, Chile

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ABSTRACT: Heritage buildings are an opportunity to satisfy the increasing housing demand in cities, but many occupants have altered the original conditions to satisfy their living needs. This research develops a comparative analysis of comfort and energy efficiency in "cité" housing to assess the effects of covering their interior courtyards. The methodology considers energy performance simulations of both the original design and current situation, and on-site data collection for three housing units located in downtown Santiago, Chile.
Results show that the courtyard is a key element to achieve comfort and energy efficiency. Homes with covered courtyards do not reach levels of light comfort and occupants depend on artificial lighting increasing the energy demand. Courtyard ventilation in the original design performs as an efficient passive strategy but, in the current scenario, living spaces show air tightness. However, CO_2 measurements show acceptable levels as unintended air gaps in the new construction result in uncontrolled air changes. Thermal simulations show that modified homes do not achieve comfort levels in winter and could result in overheating in summer. Nevertheless, on-site measurements found that vegetation in courtyards is a feasible and effective passive strategy that creates microclimates in summer, reducing the interior temperature through evapotranspiration processes.
KEYWORDS: Energy efficiency, habitability standards, comfort, vegetation, heritage buildings.

1. INTRODUCTION

Housing deficit in downtown areas of cities has been a growing concern due to the rise in population [1]. According to the latest census, the population of Santiago de Chile increased from 6,094,118 inhabitants in 2002 to 7,112,808 in 2017 [2]. Heritage buildings have become one of the main opportunities to accommodate this housing demand. Occupants of traditional houses, workers' housing, and cité housing have built expansions to satisfy the lack of livable area. However, these expansions have deteriorated their homes' habitability conditions affecting the residents' health condition, as well as, reducing the building's lifespan.

Habitability conditions in dwellings comprehend, among others, thermal comfort, daylighting comfort, acoustic comfort and indoor air quality. These factors are directly related to weather conditions, building design and orientation, building materials, as well as user behavior [3]. These conditions may be altered in buildings with expansions or renovations, as new rooms may lack adequate thermal insulation, lighting and ventilation. Consequently, these buildings incur in higher energy loads due to increased artificial lighting and heating requirements.

In heritage housing buildings, this is a complex issue, as regulation codes are restrictive in order to preserve its architectural attributes and values [4]. These codes limit intervention in facades, but allow renovation of interior spaces. Thus, many users of these buildings have chosen to cover interior courtyards to compensate for the lack of a proper built area. Additionally, these courtyards are often used as spaces where residents grow plants. Studies have shown that the presence of vegetation in buildings may reduce glare, improve the air quality, deflect prevailing winds in winter and protect the building's envelope from solar radiation in summer. Their contribution to regulate the temperature during the year can result in energy savings [5-6-7] and built expansions might alter this performance.

This research analyzes the habitability conditions in heritage houses in order to develop a diagnosis as input for retrofit strategies to mitigate energy poverty issues and, therefore, improve the user's quality of life. The study of physical parameters that affect indoor environment conditions —such as Carbon Dioxide (CO_2) levels, ventilation, thermal and lighting performances— is fundamental to evaluate the impact of self-built expansions and prevent a permanent deterioration. Furthermore, this study analyses the thermal performance impact of vegetation located in an enclosed courtyard.

Downtown Santiago has the country's largest housing deficit, so the balance between the protection of heritage buildings and improving their habitability standards is essential for their resilience. For that reason, this research focuses on traditional cité housing located in this area.

2. CASE STUDY: THE "CITÉ" HERITAGE HOUSING TYPE

The cité building was the first social housing type developed in Chile as response to the migration from the countryside to the city in the 19th century. They were massively built and today are still occupied after surviving earthquakes, real estate pressure and gentrification. In Downtown Santiago alone, there are 178 housing complexes and many of them count with a Heritage Buildings designation [8] (Fig.1).

The cité consists of a group of 1 or 2 story attached houses ranging from 6 to 30 units facing a narrow alley, usually no more than 5 m wide, that serves as public space. [9-10]. Each unit's original layout has a built area between 50m^2 and 80m^2. Homes can hold from 1 to 3 bedrooms, as well as a living/dining room, kitchen, bathroom and an interior open courtyard [9]. Architectural layouts can be O, L or C-shaped, depending on the building's orientation and courtyard location to allow natural ventilation and sunlight in all rooms. However, due to the narrow common space, these homes usually lack proper sunlight.

Currently, these buildings do not fit the living requirements of the families and users have adapted the interior courtyards into covered spaces leaving some rooms with no windows and affecting the interior environmental conditions (Fig. 2). These houses show high deterioration that needs to be updated to improve wellbeing conditions.

This study analyses three units from housing complexes with a linear distribution. The units have a similar built area, height and massing. These houses are built according to Chilean local standards from the early 20th century with masonry and adobe walls; wooden floors; wooden roof trusses with steel sheet roofing and mud insulation; and single glazed wooden windows. Plan layouts differ according to the location of the interior courtyard. All three units have been renovated by their users covering the interior courtyard (Table 1). The courtyard plan distribution of these houses is representative of the cité housing type and implies a methodological replicability of the study to other houses with similar features, as well as a contribution to the recovery of heritage neighborhoods.

3. METHODOLOGY

This research consists of a comparative analysis of the physical factors that determine the indoor environment quality, users' comfort levels and energy efficiency for three cité-type housing units. Measurements consider both on-site data collection and environmental/energy simulations to evaluate the impact of the interior courtyard on the building's performance. The analysis also assesses pathologies and alterations that could be originated from covering the courtyard.

Figure 1:
Location of cités in Downtown Santiago

Figure 2:
Cité located in García Reyes 333, Santiago (covered interior courtyards are in red).

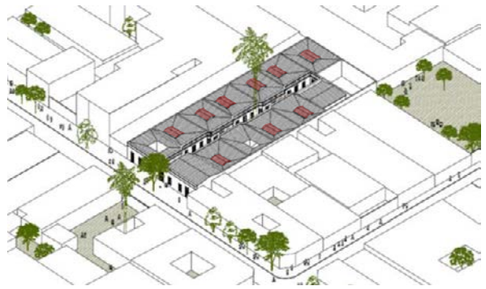
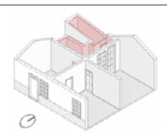
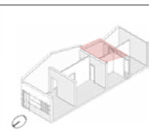
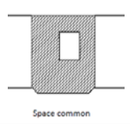
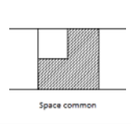
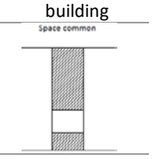


Table 1:
Case Studies

Case A	Case B	Case C
		
García Reyes 333 Unit 3	Gral. Bulnes 1411 Unit 13	Gral. Bulnes 1411 Unit 8.
Orientation: S	Orientation: S	Orientation: N
one-story building	one-story building	one-story building
		
Total plan area: 103.2m^2	Total plan area: 78.8m^2	Total plan area: 68.5m^2
Courtyard Floor area: 12m^2	Courtyard Floor area: 11.6m^2	Courtyard Floor area: 13m^2

3.1 On-site Data Collection

On-site data collection gathered information about interior room temperature, walls and ceilings surface temperature, illuminance and CO_2 levels. The data collection period for temperature and illuminance levels was from March 15th to March 31st, i.e. end of summer in the Southern Hemisphere. CO_2 levels were recorded between May 27th and June 2nd, when temperatures drop and natural ventilation problems are more common. Details about the equipment used, location of the devices and data collection frequency are shown in Table 2.

Table 2:
On-site data collection.

Variable	Data	Location	Device
Indoor temperature	Temperature & Humidity every 10 min	Courtyard Bedroom	HOBOS U10 Temp/RH
	Thermographic Camera	Courtyard	RayCAm
Natural Lighting	Lighting (lux) every 10 min	Courtyard Bedroom	HOBO Pendant®/ Light,64K
CO_2 concentrations	CO_2 levels every 5 min	Courtyard Bedroom	HOBO MX CO_2

3.2 Computer Simulations and Wind Tunnel Test

Interior temperature and illuminance levels simulations were modelled to compare the performance of the original building´s design —open interior courtyard— with the current scenario —covered courtyard. Tests were carried out using the DesignBuilder software for one week in the summer season (January 1st-5th), and one week in the winter season (July 1st-5th). Simulations were also performed for the summer-autumn transition period (March 15th to March 31st) to compare with data collected on-site.

Standards for buildings' thermal and energy performance were defined according to the requirements for the City of Santiago in the current Chilean Building Code [3]. For this type of buildings, the Code establishes the number of users, air infiltrations (1.5 ACH) and a temperature range of 18°C – 27°C to determine heating/cooling demands.

Daylighting intensity levels for each house activity were considered to define the minimum requirements for each room and visual comfort standards [3]. To analyze natural ventilation performance, air flow was replicated using 1:50 scale models in a wind tunnel.

4. RESULTS

4.1 Thermal performance analysis

Results based on simulations and on-site data collection demonstrate various design aspects affecting the thermal performance of covered courtyards, but also assesses the impact of indoor vegetation on the building's performance.

4.1.1 Computer Simulations

None of the analyzed building envelopes meet the thermal transmittance standards required by the current Chilean Building Code. Only 30 cm-thick adobe walls (1.94 W/m^{2}K) perform close to current requirements. Brick masonry walls (2.89 W/m^{2}K) and roof assemblies (3.45 W/m^{2}K) do not meet Chilean Building Code standards. The window/wall ratio meets the Code requirements as adobe construction systems demand small openings due to structural considerations [11] (Table 3).

Table 3:
Building Assemblies' U-values and Chilean Building Code requirements

	Roof	Wall	Floor	Window
Unit	U-value (W/m2K)	U-value (W/m^{2}K)	U-Value (W/m^{2}K)	Single glazing (%)
CASE A	3,45	1,94 adobe 2,89 masonry	1,68	22%
CASE B	3,45	1,94 adobe	1,85	14,23%
CASE C	3,45	1,94 adobe	1,68	11,09%
Chilean Building Code	0,47	1,9	0,7	25%

Annual thermal performance simulations were carried out for both the original design and its current situation. Results for the winter period showed that no cases achieve thermal comfort levels. In the current scenario, significant heat losses occur in covered courtyards as their roofs are built with zinc or polycarbonate sheets with no insulation and a poor finish with unintended openings up to 5 cm wide. However, in summer, these buildings reach comfort standards as both the thermal mass of walls and a significant height from floor to ceiling of 3.20m contribute to prevent overheating [11].

On the other hand, covered interior courtyards with a reduced surface area of translucent elements have a positive impact on the conditions of thermal comfort of the house, due to the fact that direct solar radiation is limited resulting in lower interior temperatures. However, the current case study scenario still requires higher heating and cooling loads than the original cases, due to uncontrolled ventilation and roof overheating. (Table 4).

Table 4:
Hours of thermal comfort in covered patios, cooling and heating loads analysis.

	Case Study	Roofing finishing materials	Translucent Roofing Area (%)	Winter period	Summer period	Cooling demand (kWh/m² year)	Heating demand (kWh/m² year)
A	Original Case	198,2	-	31% comfortable 19% too hot 50% too cold	100% too cold	29,2	198,2
	Original Original	209,0	100%	50% comfortable 38% too hot 12% too cold	100% too cold	14,5	209,0
B	Original Case	Open courtyard	-	31% comfortable 19% too hot 50% too cold	100% too cold	3,0	123,8
	Original Original	Covered courtyard: Policarnonate OSB bords & zinc	11%	90% comfortable 10% too hot	100% too cold	21,6	171,9
C	Original Case	Open courtyard	-	31% comfortable 19% too hot 50% too cold	100% too cold	5,4	86,4
	Original Original	Covered courtyard: Policarnonate OSB bords & zinc	22%	60% comfortable 37% too hot 3% too cold	5% comfortable 95% too cold	17,0	121,4

4.1.2 On-site Data Recollection – Covered Courtyards

For the data collection period, covered courtyards of CASES B and C show discomfort levels of 45% and 57%, respectively. CASE A covered courtyard has a 100% translucent roofing so overheating and high discomfort levels would be expected to be recorded, but, surprisingly, it performs with comfort levels of 87%. This is the only courtyard that features considerable interior vegetation generating shade and avoiding direct solar radiation on the walls while its evapotranspiration process controls the interior temperature (Table 5) (Fig.3).

The DesignBuilder software simulates shade conditions for the vegetation but does not consider the effects of the evapotranspiration processes carried out by the plants. Therefore, results show that summer period exterior temperatures from the computer model match data collected on-site. However, hours of thermal comfort levels for Case A courtyard reach only 50% according to simulation results when on-site data registered 87% (refer to Tables 4 and 5).

Table 5:
Hours of thermal comfort in covered patios (on-site data collection).

Thermal Sensation	Comfortable	Too hot	Too cold
Case A (S)	**87%**	0%	13%
Case B (S)	55%	3%	42%
Case C (N)	43%	27%	30%

Figure 3:
Vegetation in covered courtyard - CASE A

4.1.3 Vegetation as a Temperature Regulator Strategy in Cité Housing

The strategic addition of vegetation in interior courtyard of cité-type housing contribute to energy savings as plants block solar radiation and have evaporative cooling features.

A thermal image from the covered courtyard in CASE A was captured on May 23 at 1:00 pm using a RayCAm thermal camera. The courtyard has abundant vegetation (14 pots) while the width of its foliage ranges from 0.3m. to 1m. Figure 4 shows that the temperature for the vegetation is between 16°C and 17°C, while the roof reaches temperatures over 41°C.

Figure 4:
Thermal image from the underside of the vegetation (CASE A)

Vegetation has a positive impact in interior courtyards, as they regulate the air temperature and provide shade, shortening discomfort hours in summer periods. Vegetation acts as "natural umbrellas" that reflect up to 30% of the solar radiation [5]. While the exterior temperature is 20°C, the temperature of the courtyard walls is 12.4°C due to the shade.

For the purposes of this research, a comparative analysis of the temperature performance for covered courtyards from CASES A and B was carried out for the 3 days with the higher thermal oscillations within the data collection period, i.e., March 21st-23rd.

Results show that CASE A presents lower temperature fluctuations than CASE B. CASE A shows more constant temperatures ranging between comfort levels from 20°C to 25°C. CASE A's courtyard vegetation regulates the interior ambient temperature through evapotranspiration and the density of its foliage acts as an insulator and barrier against uncontrolled ventilation. The courtyard reaches peak temperatures of 24.1°C during the day and 20°C at night, whilst the exterior temperature fluctuates from 29.4°C (day) to 13.6°C (night) (Fig.5). Thermal simulations show that in the absence of vegetation from CASE A, the interior courtyard would overheat reaching 30°C when the exterior temperature is 29°C (Fig.6).

4.2. Daylighting analysis

Spatial Daylight Autonomy (sDA) simulations were carried out using the DesignBuilder software to assess daylight conditions on an annual basis. The analysis considered sDA 300/50% -i.e. 300 lux for 50% of standard operating hours- to evaluate lighting levels of

Figure 5:
3-day Temperature Record (Courtyard CASE A, Courtyard CASE B, Exterior)

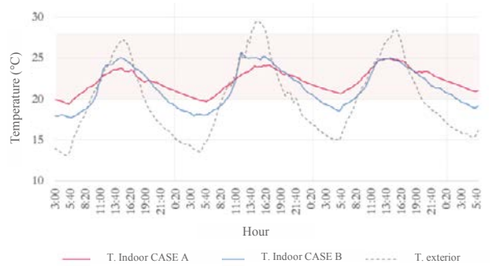
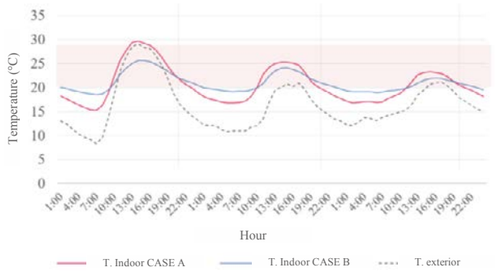
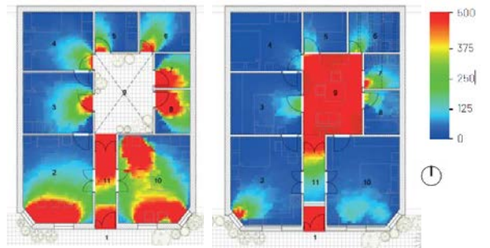


Figure 6:
3-day Temperature Simulation (Courtyard CASE A, Courtyard CASE B, Exterior)



the rooms adjacent to the courtyard both in the original and current scenarios. Light simulations consider external conditions of 8500 lux for cloudy skies in Santiago. All three study cases show similar results where the original units' layout achieves acceptable light comfort levels with 80 to 300 lux for bedrooms and living rooms [12]. The scenario with the covered interior courtyard does not reach standards of light comfort and rooms adjacent to the courtyard are almost in complete darkness (0-30lux). Users mostly depend on artificial lighting impacting their energy demand and increasing the cost of electricity bills from 50USD to 75USD/month (Fig. 7). Both computer simulations and on-site data present a negative impact of all extensions and renovations resulting in poor light comfort standards.

Figure 7:
Case A comparative light analysis for original layout (left) vs. current situation with the covered courtyard (right)



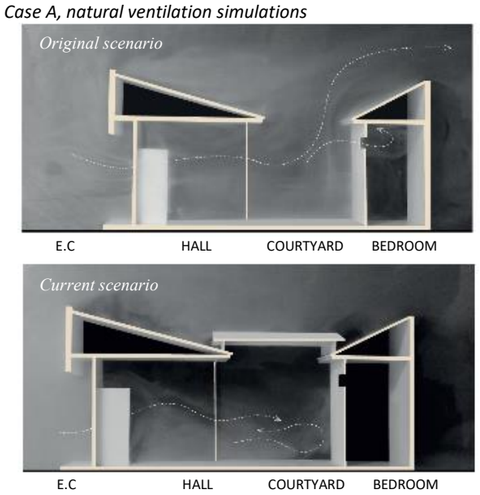
4.3. Natural ventilation and CO_2 levels analysis

Wind tunnel simulations show the cross ventilation through the courtyard in the original house design as an efficient passive strategy. In the expanded scenario, living spaces have one-sided ventilation resulting in air tightness and lack of air renovation (Fig. 8).

Additionally, the on-site survey detected mold on walls and ceilings of bedrooms and bathrooms. This pathology is caused by high humidity levels and lack of ventilation that could result in building deterioration.

In winter, CO_2 on-site measurements show that expansions with covered courtyards have acceptable levels of air quality not exceeding 1000ppm [12,13,14]. A possible cause is the poor execution of the new roof with gaps that result in uncontrolled air changes. On the other hand, results confirm a significant increase of CO_2 concentration in rooms with no windows that are heated using gas stoves. In these cases, the acceptable CO_2 concentration reaches only 46% of the total hours.

Figure 8:
Case A, natural ventilation simulations



5. CONCLUSION

This study shows that the courtyard is a key element to achieve comfort and energy efficiency in cité housing in Santiago. The design and orientation of the interior courtyard has a significant impact in thermal comfort, lighting comfort and air quality in these dwellings. Thus, alterations covering these courtyards affect these situations. Covering the courtyard may reduce thermal oscillations in winter compared to the original design but may result in overheating in summer. Air infiltrations due to an inappropriate roof construction also impact the building's performance negatively affecting its thermal performance, but unintentionally contributing with natural ventilation and reducing CO_2 levels during the winter period.

However, and more importantly, these expansions could negatively impact natural lighting. Currently, altered homes depend on artificial lighting which increase energy demands.

Also, it was found that vegetation in courtyards is a feasible and effective passive strategy that creates microclimates in summer reducing the interior temperature through evapotranspiration processes. Its performance could reduce heating loads but will vary according to the foliage and plant species used.

ACKNOWLEDGMENTS

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PLEA SANTIAGO 2022
Will Cities Survive?

From the rise of open-plan office HQ to working anywhere post-2020

How Australian academics rate workplaces

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ABSTRACT: Before the pandemic, Australian workplaces were fast-changing. Open-plan offices were on the rise, aligned with a push towards more collaboration. As the pandemic restrictions ease, it is critical to look back to understand the benefits and drawbacks of recent shifts. This paper discusses findings from surveys (n=73), interviews (n=6), and floor plan analysis of eleven case study buildings, providing insights into the changes in the design, performance, and experience of academics before, during and after 2020 focusing on the millennial workforce. Floor plan analysis shows an increase in the uptake of a variety of collaborative meeting and shared spaces, along with the emergence of 'deep work' spaces and a move towards smaller individual offices. Survey data demonstrate the desire to continue embracing remote working and choosing where, when, and how individuals work. Despite the sense of belonging and identity in their offices, collaborating and meeting other colleagues is the primary driver to returning to HQ. Millennials and younger academics were more likely to continue to work remotely post-2020. The indicated preference for 2 to 3 days on campus and other days elsewhere will likely bring a new wave of change in occupancy in the post-2020 era.
KEYWORDS: Workplaces, Millennials, Academia, Remote working, post-Covid

1. INTRODUCTION

Before the COVID-19 pandemic, academic workplaces were changing at a fast pace with many institutions moving away from traditional, individual offices towards semi or open-plan designs, with a view of maximising opportunities for collaboration and innovation. Some universities went as far as to fully embrace open-plan offices, with or without desk ownership in place, facing several issues related to the physical work environment, academic identity and interpersonal relations and communication (1). These physical environment changes posed challenges in providing academics with spaces supporting their need to concentrate and collaborate (2). Further, anecdotal evidence shows that open plan offices also challenge deep-rooted hierarchal cultures (3), work practices (3, 4), a sense of belonging (5), concerns about academic identity (1, 6), and ownership of space (especially if removing desk-ownership) (3, 6). Studies of more open plan designs showed academics beginning to adapt to these new environments. Occupants' complaints about lack of concentration (7,8), privacy, storage space and personalisation (8) in a more open plan environment made working from home an option for academics to undertake individual and more concentrated tasks that needed a quieter space (3, 4, 7, 8, 9).

Once pandemic-imposed restrictions started, digital work modes enabled geographical and temporal flexibility (10), allowing academics to perform their duties away from campus. This move appeared to have increased the appetite for working away from campus - a recent industry report looking into academic workplaces shows a decline in reported preference to work from the on-campus office from 4 to 3 days a week post-pandemic (11). On the other hand, 49% of the surveyed academics reported an inclination to share a desk/office if they do not need to be on campus often (11).

Although welcoming of the increased workplace flexibility, recent Australian studies of academics' experiences have revealed a serious concern over work intensification. This intensification has included a rapid shift to mixed modes of online and in-person (hybrid) teaching as universities struggle to maintain student

numbers. Furthermore, the financial impacts of COVID have led to a fear of staff job losses. These factors have culminated in increased work-related stress, digital fatigue, and overall adverse effects on wellbeing (12). For example, one study shows that self-isolation during the pandemic has led to higher levels of stress for academics (13). Although, until now, the gold standard has been individual offices (14) in terms of better supporting deep work (15), privacy, storage space, personalisation (8) and noise (16), this is at odds with increased calls for a more collaborative work environment (17).

Since office space accounts for approximately 22% of universities' real estate (18), attracting 20% of capital and operational expenditures (19), it is not sustainable for assets to remain empty in the long run. As a result, the pull (or lack thereof) of the campus-based office and the impact of flexible working arrangements prompted by the onset of COVID-19 have become discussion foci. This paper adds to this conversation by mapping changes in office space to illustrate the trend in Australia before the pandemic alongside views from the millennial academic workforce about their remote working experiences since the onset of COVID-19 and their preferences post-pandemic. To this end, this paper discusses findings from surveys (n=73), interviews (n=6) with academics, and floor plan analysis of eleven case study buildings.

2. METHODOLOGY AND PROCEDURES

This study used a combination of Post-Occupancy Evaluation (POE) surveys, floorplan analysis and structured interviews to map changes in the physical configuration of spaces, workers' remote working experiences and directions post-2020.

2.1 Floor plan analyses and site visits

The eleven case studies cover heritage buildings that have gone through a fit-out renovation to recently completed building projects, ranging from small to large in square meters, comprising many activities apart from academic offices. This study only considered academic offices. Basic descriptive methods identified changes in size, room type and layout configurations implemented through time.

2.2 SHE Post-occupancy evaluation (POE) survey

This study used the SHE remote working survey, developed to understand workers' experiences in remote working arrangements during the pandemic. The questionnaire asks about different aspects of remote working, such as satisfaction with Indoor Environmental Quality (IEQ), perceived mental and physical health, challenges, and best aspects, along with some questions about work arrangement before COVID-19 and people's expectations of the post-pandemic workplace. In addition, background questions recorded the respondents' age, gender, type of work and employment arrangements.

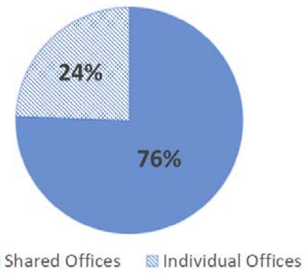
2.3 Structured interviews

Structured interviews were conducted with six millennial academic staff to understand the main drivers for returning to campus-based offices, the negative and positive perceptions about working from campus/elsewhere and the strategies to maintain productivity. Thematic analysis used individual questions and spatially related terms to filter the transcripts. All responses relating to the terms 'Space', 'Office', 'Workspace', 'Physical', 'Rooms', or 'Environment' were grouped, and then themes were identified based on frequency results. Interview transcripts were analysed by word frequency and thematically to draw out essential sentiments and experiences. NVivo 12 was used to perform the analysis and generate word clouds.

3. RESULTS AND DISCUSSION

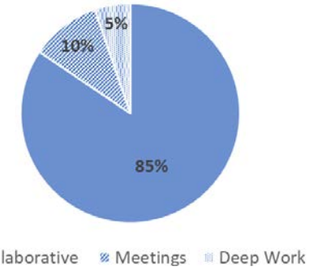
Floor plan analysis shows how workplaces evolved to incorporate a variety of zones intended to support work activities and, ultimately, the intended change in ways of working. The number of individual, private office spaces reduced, while the number of open plan offices or shared offices increased. Furthermore, the shared, open offices had a highly increase implementation, achieving a total of 76% of offices spaces (Figure 1). Shared office spaces mainly were designed to accommodate early career researchers, with or without desk ownership.

***Figure 1**:*
Percentage breakdown of shared versus individual offices



To have a better view of spaces implemented through years, rooms with similar functioning were grouped into different zones, giving it a wider view towards changes occurring in the use of space. **Figure 2** shows the percentage breakdown of each group zone. Activities that once occurred within individual offices are now taking place around the building which in turns creates opportunities for incidental collaboration while at the same time being a more efficient use of space. As depicted on **Figure 2**, spaces for collaboration more recently started to take a significant portion of buildings, amounting for approximately 85% of the remaining office space, because of the reduction of individual offices.

***Figure 2**:*
Percentage breakdown of each group zone



Meeting rooms, which comprises formal (enclosed) and informal (open) areas with a total area of 10% is taking place as a way to support meetings that once were held in individual offices (now with a reduced footprint). Figure 2 also illustrates the emergence of spaces designed to undertake 'deep work`, a space designed to accommodate only one person at a time, representing 5% of spaces.

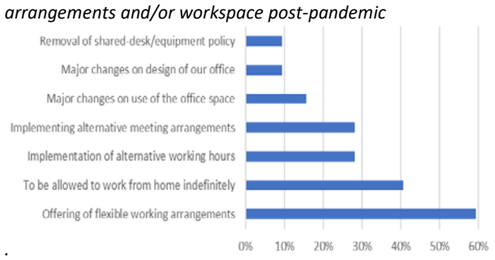
Combined, these changes illustrate the move towards a smaller number of individual offices, more shared offices and a significant increase in collaborative, meeting and informal spaces. It is also important to highlight the emergence of 'deep work` rooms, designed specifically to attend concentrated and cognitive tasks, a must-have space for academics (15) to undertake concentrated tasks.

3.2. Remote working experiences during the pandemic - Survey findings

In general, millennial academics were keen to embrace the flexible/remote working post-pandemic, with 6 in 10 workers indicating that they would like to see "increased offering of flexible working", 4 in 10 wanting to be allowed to work from home indefinitely, and 3 in 10 reporting they wanted implementation of alternative working hours and meeting arrangements. Following the trend observed in other sectors (20), survey data from the Australian academic workforce demonstrates the desire and inclination to continue to embrace remote working, keeping control over where, when, and how individuals work in the post-2020. Considering that only 1% of academic workers from this study stated that they had worked from home consistently before the pandemic, with 49% working in an open-plan office and 48% working in a private office pre-pandemic, it is fair to say that remote working has been a new experience for the academic workforce studied here.

Increased workload (63%), isolation from colleagues (63%), stress and burnout (59%), internet connectivity (50%), difficulty in connecting/engaging with colleagues (41%) and furniture ergonomics (41%) are the top challenges that Australian millennial academics have faced in remote working. When comparing millennials' work-from-home challenges with all other age groups in the academic workforce, isolation from colleagues, difficulty in concentration and inability to establish a consistent routine were reported by a higher percentage of millennial workers (difference was 21-23%). These struggles might be related to a lack of support from the organisation (9% of respondents) or the challenges with child-caring responsibilities (31% of the respondents).

Figure 3:
Changes academic millennials like to see in their work arrangements and/or workspace post-pandemic



When looking at the best aspects of this new work arrangement for academic millennials, the top five are no commute (72%), more time with family (72%), more focused work (56%), control over where/when to perform work (53%), and less stress at the start of the workday (50%). Work-life balance was considered a benefit from work from arrangements by less than half (44%) yet was a positive aspect for the majority of other age groups (61%). Conversely, control over where and when to perform work was stated as the top benefit by the majority (53%) of academic millennials whereas only 27% of other age groups reported it as a benefit in remote working.

Despite all challenges associated with work-from-home arrangements for millennial academics, benefits

seem to outweigh the negatives, and this workforce acknowledges the flexibility and choice presented to them. Academics are not prone to fully getting back on campus, while the everyday commute seems like a waste of time, with the majority (63%) having to travel 30-75minutes (one way). As the side effects of remote working, mental health has suffered more than physical health in millennial academic remote workers. However, this might be related to the broader impacts of the pandemic on people rather than remote working. Whether the removal of COVID stressors might mitigate this effect is not clear yet.

3.3. Remote working experiences during the pandemic - Structured Interviews

Interviewees' responses to the main prompts and reasons for their return to campus reinforced the key challenges found in our survey results. Adequate workspace setup and space within the home to maintain work-life balance was a major driver, though this went two ways. Whilst many confirmed the benefit of flexibility to be able to manage family or life and personal commitments, many also simply did not have the adequate spaces, set up or configurations possible to create productive long-term working conditions in their homes. The prolonged lockdown periods prompted and forced some academics to make permanent adjustment to their home arrangements. Optimising their home office spaces to best suit their individual needs, they found returning to their campus workspace that it was inferior for concentrated individual work. This factor took on importance in instances where participants had diverse/special needs:

> *"we bought a COVID house…we were in quite a small two bedroom townhouse and so one of us worked from the spare room and the other one had to work from the kitchen…the place wasn't small for eight years but during that time it became small…But (now) my setup at home is a lot better than my setup in the office because I'm visually impaired and so I've got a much larger screen and stuff like that at home….so my setup at home is actually preferable to being in the office now." Participant D*

Many academics also simply did not feel ready to return given the continued public health risk with many unsure what strategies were in place to ensure the safety of the workplace environments.

> *"they're encouraging windows to be open, and they're doing this about the air and all that kind of stuff…unless you're going to make the windows open, we're not forcing anyone to come back in a minute!" Participant D*

Unexpected (or forgotten about) distractions within shared office and open plan office spaces was another key issue which came up in the conversations. Given the extended two-year period of working from home, this finding would support that these academics have also adjusted their work styles, expectations and needs in this regard. As our survey data also found, focused work was done much more successfully from home and many acknowledge that they had more control over and overall, less distractions, from work colleagues at least.

> *"I would leave the office more stressed in that I didn't actually achieve any of those things because I didn't account for the 'Oh, can I just ask you this one thing?' You know? Or an impromptu counselling session with someone and that kind of stuff." Participant D*

Heightened awareness of the use of a diversity of work settings or locations was also evident, with many academics finding this to have been an existing or newly formed work habit and strategy for maintaining their personal sense of productivity. Whilst not always a strong reason to return to the campus office space, the need for a mix of spatial settings for different tasks was clear to many:

> *"extended periods of working in one location meant I became less focused, less productive, and definitely less mentally stable… the change of environment just helped on all of those fronts, and we were still a bit constricted, but we were able to go back into the office a little bit, so I did some work from home, some in the office, and when cafes opened back up I added that into the mix and gradually felt good on all fronts I think "Participant B*

Much like other knowledge worker's experiences, the choice factor was and is a critical expectation moving forward. Despite previously having an implied flexibility in the way they work, for academics the pandemic has given rise to tangible opportunity and expectation that this be formally recognised. Consistent with findings from global studies, no-one wants to be back to the campus office on full-time:

> *"I don't wanna go back full time so we're all moaning about working from home I think we appreciate the balance but it has to be on our terms…Like no one wants to work five days at home and they don't want to work five days in the office. So it's about having a bit more flexibility in the workplace." Participant E*

Linked to this was the overwhelming sense of burnout and fatigue, most particularly felt by those with family or caring responsibilities. Whilst academics' immediate managers and teams were understanding, the situation forced many academics to reduce and manage their workload on an essential needs basis.

> *"the only bit that I felt maybe not distrusted but not understood was difficulties of working and caring for children and home schooling at the same time. I felt there was a lack of appreciation or a lack of understanding from the university." Participant B*

The physical separation of the office and campus offered many a welcome return to segregation and compartmentalisation of their work-life balance. Routine and incidental activities like exercise or the mental transition a commute can offer were highlighted as positive outcomes. All respondents acknowledged the importance of choice, control and flexibility to get the best out of individual work patterns. Also, setting their own work schedules to be able to use the time gained back for their own wellbeing.

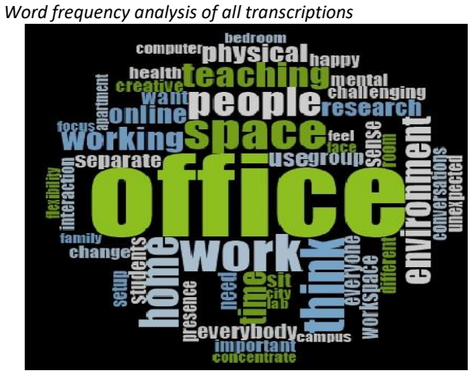
> *"Getting out of the house…I have young children, so certainly commuting to work and working and commuting home, that just gives another dimension to your day that we really haven't had for two years…I think that's important because many working parents haven't had any headspace away from the family home or to concentrate fully on work or family or self or exercise, you know?" Participant A*

An unexpected experience for many academics was the social connection and community building that occurred through the shared experience of working/ studying from home with students. It illuminated the meaning which face-to-face connection holds in terms of how valued and valuable academics feel – particularly with regards to their teaching roles, and their connections within their wider teams or faculties. Research activity is often done in different settings or in isolation, so did not come up in the conversations. However, the connections and sense of value that academics could bring to students and their work contributions were enhanced by the ability to return to campus and have incidental physical encounters and conversations.

> *"And then I think there were some nice social connections that happened there as well that had been lost due to being online, not close friendships, but just social connections that were I felt, good for my mental health." Participant B*

Word frequency analysis of all transcriptions were performed with top 50 results shown in the word cloud below (**Figure 4**). The findings suggest that academic workplaces are also following a more global transformation of purpose, moving towards a place of collaboration and people interaction dependent activities, like teaching, rather than focused work which may better perform in various other locations and ways by different individuals.

Figure 4:
Word frequency analysis of all transcriptions



When coupled with interview data, findings suggest that although academics draw a strong sense of belonging and identity from their offices on campus, the main driver for returning to the physical workplace is to collaborate with and meet other colleagues. That said, millennial academics were more likely to express the desire to retain more control over remote versus in-person work interactions gained in 2020 when compared to other groups. Millennials were also likely to better navigate online tools and hybrid ways of communicating and interacting synchronously and asynchronously, which helped them to generate and preserve opportunities for mentoring and collaboration in Australia and overseas.

4. CONCLUSION

With many campus workspaces sitting empty, questions remain about how people see themselves working post-2020 and the kind of physical workspace they wish to return to. The combination of how, when and where seems to be front and centre in academics. Millennials reported that balancing workloads with demands from personal and family life makes commuting to work a poor use of time. At the same time, millennial academics are also mindful of missing out on career development opportunities by not being physically on campus. Dissatisfaction with the physical configuration of workplaces was a pull-off when going back to the campus HQ for some, especially those sharing an office. Combined, these results suggest that workplaces need to continue to provide workers with flexibility and control over when and where they work while at the same time improving leadership practices and cultures inclusive enough to provide the hybrid workforce with mentoring and career advancement opportunities. The indicated preference for 2 to 3 days on campus and other days elsewhere is likely to bring a new wave of change in occupancy and the need to revisit workplace accommodation in the post-2020 era.

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Building integrated photovoltaics' impact in urban microclimate

A case study of two Brazilian cities

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ABSTRACT: In an urban context of the growing implementation of solar energy and rising concerns related to the urban heat island effect, this article aimed to contribute to the topic of evaluating the influence of building integrated photovoltaics in urban microclimate. The goal was to evaluate if the use of this material in the building envelope could lead to an increase in surface or surrounding air temperatures, hence negatively impacting the thermal comfort, or even if a temperature reduction could be achieved. The proposed method used building simulation to calculate a hypothetical commercial building in the cities of Rio de Janeiro and Curitiba. Monocrystalline photovoltaic panels with a 10cm ventilation gap were integrated into the façades and a baseline with traditional construction materials was established. The simulations were performed considering both the full year and the hottest week, the latter giving a better insight during a critical period to the pedestrians' thermal comfort. Results have shown that overall building integrated photovoltaics could not cause heat in the surrounding microclimate. The reduction of the surface and air temperature, especially during the afternoon—the most critical period of the day for users' thermal comfort—was also likely.
KEYWORDS: Urban Microclimate, Photovoltaic, Simulation.

1. INTRODUCTION

Renewables are considered the backbone of the energy transition to achieve decarbonization in multiple sectors [1]. Buildings are among one of the most power-demanding sectors, being responsible for over one-third of global final energy consumption [1]. Due to both factors, Building Integrated Photovoltaics (BIPV) has grown in popularity and adoption. This constructive system is characterized by the replacement of traditional building elements—such as shading devices, façades, and skylights—with photovoltaic panels. One of its main benefits is on-site clean energy generation, providing energy directly to the location of the demand. It has also been shown to be a useful tool to help achieve Nearly Zero Energy Buildings (NZEB) [2].

One of the biggest concerns in cities and urban microclimates is the Urban Heat Island effect (UHI). The urban heat island effect happens when air temperatures are higher in dense urban areas compared to surrounding suburban or rural zones [3]. Factors such as fast urbanization and climate change have been aggravating this phenomenon, which could lead to a series of impacts on humans, such as dehydration, heat stroke, and heat exhaustion [4]. When combined with poverty, poor housing conditions, and little access to cooling options, the UHI can be an even more serious health threat to people, already being an issue in Latin American cities like Sao Paulo and Mexico City [5]. It can affect cities regardless of their climate (temperate, cold) and the season of the year [6].

Buildings have a tremendous influence on the urban microclimate and the UHI effect since their envelopes emit heat to the urban microclimate. Most of the studies have tried to reduce the UHI effect by changing the materials of buildings, such as green or cool roofs, phase change materials (PCM), and others [7]. Since Building Integrated Photovoltaics (BIPV) is considered primarily an energy generator, the vast existing bibliography emphasizes its benefits exclusively via this perspective, and little is known about its impact on the urban microclimate [8]. The few articles found on the topic only investigate the influence of roofs. However, considering that the façade/roof ratio increases in the context of urban densification, it is crucial to assess the influence of BIPV vertical elements of the building envelope in the urban microclimate and the urban heat island effect.

With such factors in mind, this study aimed to contribute to the topic of evaluating the influence of building integrated photovoltaics—more specifically those in façades— in the urban microclimate. An evaluation was required since using BIPV as an envelope material will change how the urban microclimate functions, therefore leading to benefits or drawbacks to thermal comfort. Although the benefits of using BIPV from an energy perspective are clear, comprehending their impact on the urban microclimate is crucial to creating future cities with high-quality urban environments. An increase in temperature caused by BIPV could, for instance, decrease the photovoltaic panel's efficiency, aggravate the urban heat island effect, reduce the pedestrians' thermal comfort, and lead to an increased energy demand for cooling by surrounding buildings [2]. On the other hand, a decrease in temperature would have the opposite effect.

2. METHOD

The proposed method used building simulation as a tool to calculate the influence of building integrated photovoltaics in the urban microclimate. The goal was to explore whether this building material when used in façades, can intensify the UHI effect or even mitigate it. Considering the current growing adoption of BIPV and its potential large-scale future implementation, comprehending its impacts on the urban microclimate is crucial.

Since the performance of photovoltaics and the building envelope are highly dependent on their climate, this study aimed to investigate diverse conditions. Brazil, the biggest country in Latin America, is currently divided into eight bioclimatic zones (ZB) listed from the coldest to the hottest [9]. Two cities were used as a case study in this article: Curitiba, located in the coldest Brazilian bioclimatic zone (ZB1), and Rio de Janeiro, in the hottest (ZB8). The criteria to choose these cities was their size, being the most populated in their bioclimatic zone.

2.1 Software used and validation

There are currently multiple building energy simulation tools, ranging from simple spreadsheets to software, but the most popular tools are TRNSYS, ENVI-met, and Energy Plus.

TRNSYS (Transient System Simulation Program) has a modular structure based on components [10]. It can calculate a series of simulations, such as the performance of photovoltaic panels and the energy demand of HVAC. ENVI-met allows the user to analyze the impacts of design decisions on the local environment and help mitigate factors such as urban heat stress [11]. It has, however, some drawbacks, such as large grid cells (0.5-10m) and high CPU time to achieve the results [10].

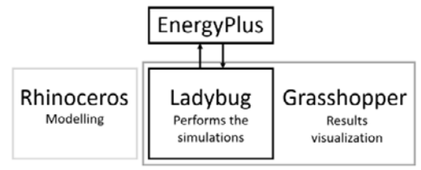
EnergyPlus is a free energy simulation program used to calculate heat transfer between surfaces, air temperature, thermal comfort, heating and cooling demand of buildings, and other factors [12]. It is capable of not only accounting for radiant and convective effects that produce surface temperatures but also creating heat and mass transfer models [12]. EnergyPlus' analyses are based on local climate, requiring an Energy Plus Weather File (.epw) to be performed. There are currently more than 13,000 .epw files available, allowing simulations to be replicated worldwide.

Considering the available options, four factors led to EnergyPlus being the chosen software: it takes less time to run the simulations compared to the alternatives; its accessibility due to being free-to-use; its wide use among architects, engineers, and researchers; and, consequently, its wide use in publications related to the urban microclimate. in publications related to the urban microclimate. A few relevant articles that used EnergyPlus to evaluate the urban microclimate are [13], which calculated the impact of reflective materials on urban canyon albedo, outdoor, and indoor microclimate. [14] investigated the effects of urban configuration and density on urban climate and building energy consumption. [15] mapped the building overheating risk and air conditioning use due to the urban heat island effect.

Some computer programs such as DesignBuilder and Ladybug Tools are an easier-to-use and more comprehensive interface to several validated simulation engines, EnergyPlus being one of them [16]. This means both pieces of software share the same source code as EnergyPlus (and other simulation engines) and therefore are just as validated [16]. The benefits compared to simulating using Ladybug Tools or DesignBuilder are purely for being more user-friendly and do not affect the results obtained for the simulations. Since both computer programs have comparable simulation outputs for the scope of this work, Ladybug Tools was chosen due to the author's familiarity.

Ladybug Tools requires 3D-modeling software to run, in this case, Rhinoceros and Grasshopper. By combining these programs, it was possible to create the geometry, run the desired simulations, and visualize the results within one interface via an integrated workflow. Rhinoceros facilitates geometry modeling, Ladybug Tools performs the simulations, by running EnergyPlus source code, and Grasshopper visualizes the results. The latter is also where Ladybug Tools' components are installed. The summarized workflow can be seen in Fig. 1.

Figure 1:
Summarized workflow for the simulation performed.



Multiple publications that combine Ladybug Tools, Energy Plus, Rhinoceros, and Grasshopper to

simulate urban microclimate were found. For instance, [17] created a workflow to model outdoor thermal comfort considering the Egyptian climate. [18] also created a workflow, but additionally evaluated the energy demand and the scope of the research was urban canyons. [19] assessed the localized climate change mitigation potential of building façades.

2.2 Building geometry and materials used

In Brazil, photovoltaic systems are more frequently installed in commercial buildings. Therefore, a typical commercial Brazilian building archetype whose dimensions are 20 x 20 x 30m (W x L x H) [20] and 50% window-to-wall ratio (WWR) was used as a case study for the simulations [21]. Regarding the technology of photovoltaic panels, monocrystalline silicon cells are the most widely used ones worldwide, hence were used in this article. A 10cm ventilation gap between the panels and the façade was considered on all façades of the building since it is a common practice in BIPV, which helps to avoid overheating [22].

A baseline was established and simulated, consisting of a building using traditional construction materials rather than photovoltaic panels on its envelope. By comparing the performance of both buildings, the influence of BIPV on the microclimate is more clearly assessed. Considering the Brazilian architecture and construction industry, the material considered more suitable was a 9cm masonry brick with 2.5cm of inner and outer grout (total of 14cm width) [21]. All definitions required to run the simulations are summarized in Table 1.

Table 1:
Definitions of building properties and materials for the BIPV case and baseline

Property	BIPV case	Baseline
Building size	20 x 20 x 30m	20 x 20 x 30m
WWR	50%	50%
Façade material	Monocrystalline silicon panels	Masonry brick + grout
Ventilation gap	10cm	Non-existent

2.3 Simulations performed

Two parameters were simulated, the surface temperature and the air temperature, the latter at a 0.50m distance from the building façade and in the middle of the building height [23]. Since orientation influences the radiation levels, these parameters were calculated for the north, east, west, and south façades. The simulations ran for both the BIPV case and the baseline and the difference between the values is highlighted.

Two parameters were simulated: the surface temperature and the air temperature, the latter at a 0.50m distance from the building façade and in the middle of the building height [23]. Since the orientation influences the radiation levels, these parameters were calculated for the north, east, west, and south façades. The simulations ran for both the BIPV case and the baseline, and the difference between the values is highlighted.

Two sets of simulations were performed. The first set aimed to assess the average yearly air and surface temperatures. This step was crucial since it allowed the comparison between the orientations and cities and to detect those with the highest and lowest potential. While the first simulations gave a bigger overview of the impacts of BIPV in the urban microclimate, the second round considered a smaller and more important time frame: the hottest week of the year. This period is relevant since, due to the higher temperatures, the pedestrians' thermal comfort is more critical, and it would be even more damaging if BIPV caused heating during the hottest hours of the day. An hourly profile considering the average values was constructed, allowing the detection of the temperature difference behaviors through 24 hours. These simulations ran considering all façades and both cities.

The weather data required to run the simulations was extracted from EnergyPlus Weather Files (.epw). This article used the Curitiba weather station, BRA_PR_Curitiba.838420_INMET, for the city of Curitiba. Since no file is available for the whole city of Rio de Janeiro, Galeao Airport was used since it is the city's international and most known airport.

The hottest week for Rio de Janeiro is from February 19th to 25th and for Curitiba, from February 10th to 16th. Such dates were extracted from the previously mentioned weather stations, via a .stat file that automatically provides several periods of interest for the location, such as the hottest week, design day for cooling/heating, and many more.

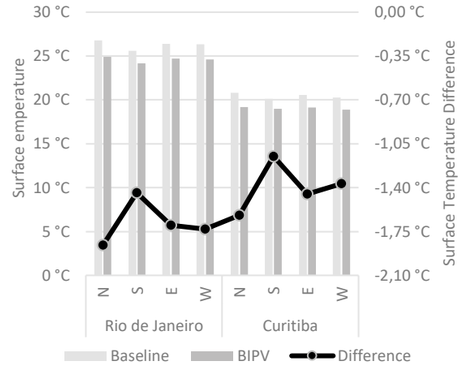
3. RESULTS AND DISCUSSION

3.1 Average yearly temperatures

The simulation results have shown a reduction in surface temperature in all cities and orientations, ranging from -0.93°C up to -1.86°C. The integration of photovoltaic panels into the North orientation has shown a higher impact, while panels in south-facing façades had the least significant impact on surface temperature among all the simulation results. It's important to highlight that both Curitiba and Rio de Janeiro are in the southern hemisphere and therefore the north façade has the most incident solar radiation. This behavior would very likely change if this study was undertaken considering cities in the northern hemisphere.

The results obtained for the surface temperature are plotted in a two-axis graph. The results of the simulation obtained for the baseline and the BIPV case were plotted on the main axis, while the difference between both values is highlighted on the secondary axis. Such a chart is plotted in Fig. 2.

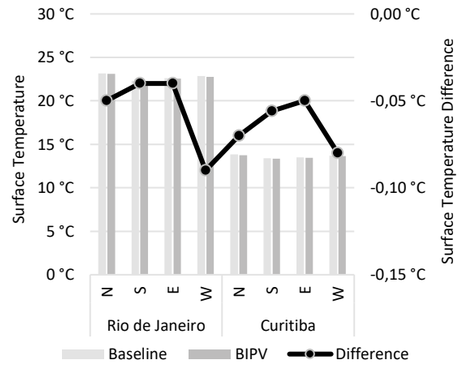
Figure 2:
Surface temperature for the baseline, the BIPV case, and the difference between both per façade and city.



Note: N = north façade; S = south façade; W = west façade; E = east façade.

Regarding the air temperature, the integration of photovoltaic panels on the façades of buildings could also potentially lead to a decrease in all orientations and cities. Yet, the reduction detected in air temperature simulations was lower than the one observed in the surface temperature ones. The results for the air temperature simulations follow a similar plot to the previous graph, having a two-axis visualization. It can be seen in Fig. 3.

Figure 3:
Air temperature for the baseline, the BIPV case, and the difference between both simulations per façade and city.



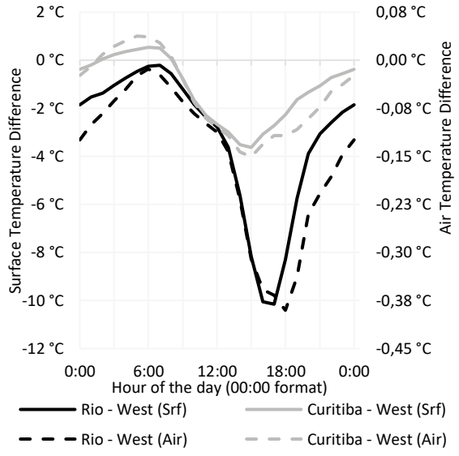
Note: N = north façade; S = south façade; W = west façade; E = east façade.

3.2 Hourly profiles

The previous simulations gave a yearly overview of the influence of building integrated photovoltaics in the urban microclimate. The results plotted in this section aimed to give a clearer insight into the influence of building integrated photovoltaics in the hottest week, which is a critical period of the year for thermal comfort. The results obtained for these simulations were also plotted in an hourly two-axis chart. The surface temperature difference is shown on the main vertical axis, while the air temperature difference is plotted on the secondary vertical axis. The horizontal axis shows the hour of the day.

In the city of Curitiba, simulation results pointed to an increase in air and surface temperature from 02:00 to 09:00 (2am to 9am). This heating, although minimum, was detected in all four orientations. However, for the remainder of the day, a decrease in temperatures was detected, especially during the afternoon (around 14:00/2pm). When assessing the influence of building integrated photovoltaics in the city of Rio de Janeiro, a similar pattern was detected. Yet, the main difference is that in this city, both the air and the surface temperature would potentially not create a heating effect during the late-night period, but rather a constant cooling one. Investigating each orientation yielded a significant variation in the results. The West façade has the biggest influence on both the surrounding air and surface temperatures from all the simulations, hence potentially in the urban microclimate in real-life applications. The results of the simulations obtained for the West façade can be seen in Fig. 4.

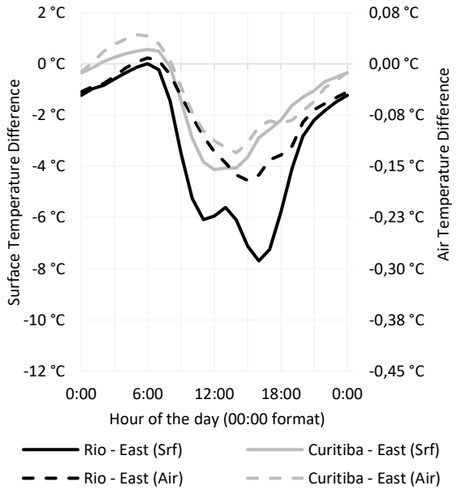
Figure 4:
Hourly profile of the surface and air temperature difference for the West façade.



Considering the results obtained by the simulations, the East orientation also showed a relevant impact in the cities of Rio de Janeiro and

Curitiba, as shown in Fig 5. But this influence was lower than the one achieved by the West orientation.

Figure 5:
Hourly profile of the surface and air temperature difference for the East façade.



The North and South façades showed the lowest potential from all the hourly profiles simulated in this subsection. Yet, they still had very similar behavior to the previous ones, only on a smaller scale. The hourly profiles for the North and South façades are plotted in Fig. 6-7.

Figure 6:
Hourly profile of the surface and air temperature difference for the North façade.

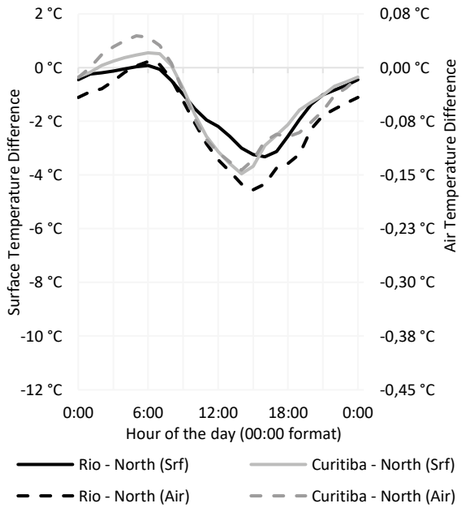
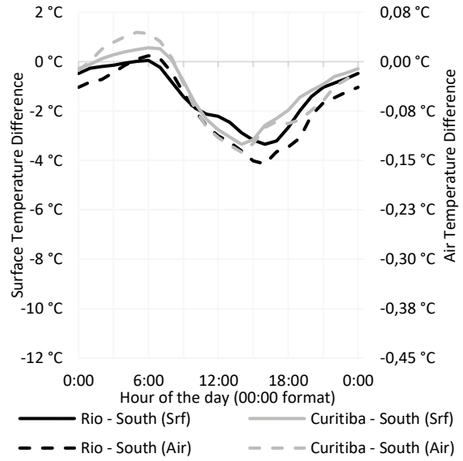


Figure 7:
Hourly profile of the surface and air temperature difference for the South façade.



Results have shown that the use of BIPV could cause a positive impact on the urban microclimate of Rio de Janeiro considering all orientations. Although there were temperature variations during the day, heating during the hottest week of the year was unlikely. In Curitiba, however, there is likely to be an increase in air and surface temperatures during the late night/early morning period. Yet, it is important to highlight that the heating detected by the simulations was caused in a lower magnitude than the cooling, with the latter happening especially during the afternoon. It's also worth mentioning that the heating likely happens at a time when temperatures are considerably lower and people are less active, leading to a lower impact on people's thermal comfort. The use of BIPV could lead to a positive influence on the urban microclimate during the afternoon when temperatures are higher — and consequently, the most critical time of the day for pedestrians' thermal comfort.

4. CONCLUSION

Comprehending the behavior of BIPV in cities is relevant considering the growing use of photovoltaic panels in the building envelope and the concerns regarding the urban heat island effect. This article investigated the influence of building integrated photovoltaics by simulating the variation in surface and air temperatures during the year and the hottest week. The performance of a BIPV façade system with monocrystalline panels and a 10cm ventilation gap was compared to widely used materials in the Brazilian construction industry. The cities of Curitiba and Rio de Janeiro were analyzed, but the proposed method can be replicated worldwide.

Overall results have shown that BIPV would likely not cause an increase in surface or air temperature, only a slight increase during the late night/early morning period. Yet, during the hottest and most critical period of the day, the use of BIPV could decrease the air and surface temperature in both cities and all orientations assessed. This influence could be considered positive in the urban microclimate since it could reduce the urban heat island effect, increase the outdoor thermal comfort, and improve the solar panels' efficiency in the most critical period of the day.

Future works should further investigate the influence of building integrated photovoltaics in the surrounding microclimate. One key aspect to be explored is how such façade material will behave considering the remaining six Brazilian climate zones or even other heavily populated cities worldwide, like Sao Paulo or Mexico City. The proposed method should also contemplate the surrounding building geometry. The temperature at different building heights, as well as at the pedestrian level, ought to be assessed.

ACKNOWLEDGEMENTS

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WILL CITIES SURVIVE?

November 22 - 25, 2022

ANALYSIS AND METHODS

DAY 01
10:15 — 11:45

CHAIR
JOEY MICHELLE HUTCHISON

PAPERS
1154 / 1602 / 1649 / 1650 / 1563 /
1454

10TH PARALEL SESSION / ONLINE

Urban climate recommendations for urban planning in Phnom Penh, Cambodia

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ABSTRACT: Urban climatic analysis is one of the tools for climate adaptation in urban planning research within the framework of studies for the Build4People project in Phnom Penh, Cambodia. We use various disciplines to understand the well-being of people. Urban climatic maps and urban climate measurements are used to integrate it in a planning system. In particular, urban climatic maps provide recommendations for urban development strategies to reduce heat stress using ventilation and shading devices. Using a mesoscale evaluation and existing literature concerning urban climate, especially the climate in Phnom Penh, including air temperature measurements to analyze the urban heat island, knowledge was acquired for urban design purposes. The methodology based on the urban climatic mapping method will be used within the city of Phnom Penh in order to demonstrate a climatic urban design following sustainability criteria.
KEYWORDS: Climate change, Phnom Penh, Urban climate, Urban planning

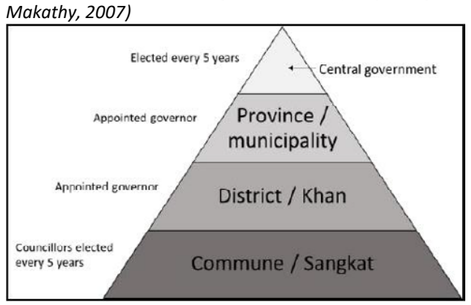
1. INTRODUCTION

Climate change has demonstrably strong impacts on urban life. Cities are exposed to various threats including increasing temperatures during the day and at night. These increases are accompanied by health problems that decrease the quality of urban life. Climate and air quality are also important factors that need to be considered in the context of climate change and urban planning.

Urban and neighborhood planning need more information about climate functions and climate change to develop climate adaptation processes. This is mainly done at mesoscale level for a city and locally at microscale level for urban and zoning plans. Figure 1 describes the planning hierarchy in Cambodia compared to international processes, and this is similar to most countries worldwide. Therefore, Table 1 can be used for developing a similar methodology for urban climate studies in Phnom Penh, the capital of Cambodia.

Phnom Penh population is expected to increase from 2 million to 6 million by 2035 due to rural to urban migration (NCSD et al., 2018). With its high population density, Phnom Penh is more urbanization than other cities in Cambodia (NIS, 2019; WBG, 2017). New high-rise buildings including malls, casinos, residential apartments, and gated communities have appeared to make the capital expanded rapidly. 8,000 hectares, equal to 12% of the whole city's land area are covered by seven satellite city projects for the next 10-15 years (NCSD *et al*., 2018). With experiencing rapid urbanization and increasing very quickly the urban construction, the urban area has increased from 40 km^2 in 1990 (Mialhe *et al*., 2019) to 678.47 km^2 in 2017 (NCSD et al., 2018; Yen et al., 2017), and the urban impervious surface has the largest area in the various underlying surfaces.

Figure 1:
Government structures of Cambodia (adapted from Makathy, 2007)

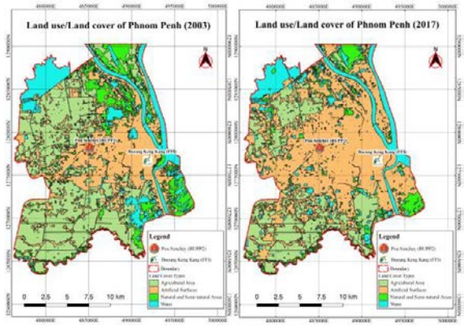


Phnom Penh is the largest and fastest growing city in the country and serves as the gateway to the world economy (Baker et al., 2017). The capital plays an important role as transportation hub, business centre, and comprehensive industrial base in Cambodia. It also plays a centre of urbanization and economic development that have transformed natural landscape into impervious surfaces that might lead to increase the absorption of solar radiation, decrease evapotranspiration, increase runoff, increase surface friction, and release anthropogenic heat, and these phenomena will influence the urban climate. Land use/land cover of Phnom Penh capital has been changed with reducing and converting agricultural areas and natural and semi-natural areas to be artificial surfaces (Figure 2). The lack of management on uncontrolled development of private sectors will be negatively impact on the city's functioning. Thus, the right urban planning is very crucial to sustainably develop the city in order to increase the quality of life of urban people.

Table 1:
Planning and climate scales (VDI, 2015)

Instruments and plans		Scale, spatial resolution of the maps	Climate analysis contributions (air quality and human biometeorology)
Regional planning	Regional land-use plan	1:50.000 - 1:100.000 > 100 m	Mesoclimate Climate analysis maps: comprehensive pollution control maps, themal stress areas (overheated areas), ventilation lanes, cold air production areas Planning recommendation map
Urban land-use planning	Preliminary urban land-use planning: land-use plan	1:5.000 - 1:10.000 25 – 100 m	Mesoclimate Climate analysis maps: area-related air pollution maps, air exchange, thermal stress areas (overheated areas) Planning recommendation map
	Mandatory urban land-use planning; local development plan, planning permission procedure	1:1.000 2 – 10 m	Microclimate Climate analysis maps: local air pollution for „most severely affected areas", neighbourhood considerations, air exchange, human-biometeorological suitability tests for "highly relevant areas" Planning recommendation map

Figure 2:
Land use/land cover change of Phnom Penh in 2003 and 2017 (Source: World Bank, 2021)



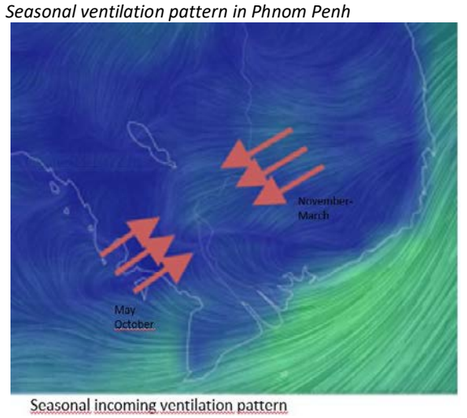
2. REGIONAL AND URBAN CLIMATE UNDER A PLANNING PERSPECTIVE

To proceed an urban climatic analysis, it is important to understand the regional climatic pattern. Any planning recommendation needs to understand the influence of ventilation and radiation conditions for thermal heat load.

To derive practical recommendations for a climatical oriented urban design input parameters are needed to drive calculations for ventilation and thermal conditions. Any microscale analysis needs input forces for radiation and wind direction.

In the case of Phnom Penh, the monsoon effect with seasonal differences must be respected. So, incoming winds must be considered with northeast for wet periods and for southwest in combination to dry hot conditions (Figure 3). In Figure 4, also, this principal structure can be seen with wind distribution and wind channeling effects, which show air paths within urbanized areas.

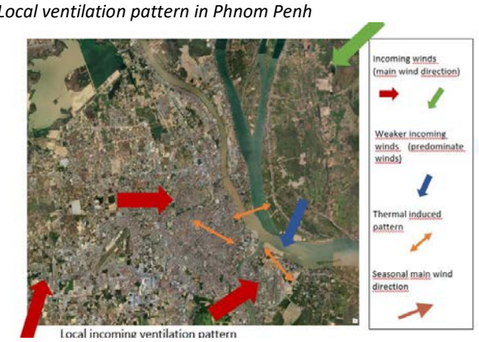
Figure 3:
Seasonal ventilation pattern in Phnom Penh



Seasonal incoming ventilation pattern

In a next step for urban planning in the case study site at Chbar Ampov, also, thermal-induced circulation is analysed (Section 5). To understand the influence of the seasonal effects for more detailed analysis of roughness according to buildings and open spaces and the thermal behaviour are needed. According to that in Figure 4 main incoming wind turns to westerly direction in Phnom Penh city centre using air paths, while in the investigation site, which is described in section 5 southwesterly direction is dominated. Inside the urban areas, only thermal-induced circulation occurs. The blue arrows in Figure 4 show the conditions during north wind directions. Here the river has high channelling effects and direct ventilation towards the investigation site of Chbar Ampov.

Figure 4:
Local ventilation pattern in Phnom Penh



Local incoming ventilation pattern

3. URBAN HEAT ISLAND

The Urban heat island (UHI) has become a serious concern for the quality of densely urban built environments worldwide, especially tropical cities. Phnom Penh, as one of the most rapidly urbanizing cities in Cambodia, has been chosen as a case study for looking at the UHI, which are strongly connected to urbanization and climate change. Two automatic weather stations (AWSs) were installed within Phnom Penh city. One AWS was installed in the central business districts (CBDs), Boeung Keng Kang (FFI) and another AWS was installed in the suburban area, Pou Senchey (RUPP2) (Figure 2). These two AWSs have been measuring necessary weather parameters such as temperature, humidity, wind speed and direction, and precipitation on a 15-minute basis and continuously for a period of January to December 2021. These parameters have been observed and used to analyse differently based on their indications and characteristics. The UHI intensity and rate and wind velocity were calculated due to equations stated by Ma *et al*. (2009), Oke (1973), and Wolberg (2006).

Almost on a daily basis, the morphology and land use of Phnom Penh city becomes changed with high-rise buildings and narrow streets which reduce urban ventilation leading to an increased UHI intensity at the city scale. The CBDs, with high and dense buildings, may inhibit the inflow of wind leading to an increased UHI intensity in Phnom Penh. The UHI intensity in the city differs from area to area depending on the various stages of urban development for each area. According to data observation and analysis, we found that maximum and minimum temperature difference at CBDs is 15.1°C and 2.9°C while those at suburban area is 13.1°C and 2.2°C. The difference in the increased intensity and rate of the UHI between CBDs and suburban area in Phnom Penh were 1.3°C and 0.15% on average.

Phnom Penh is dominated by the monsoon circulation [cf. Figure 3] and therefore, important for the city ventilation in different seasons. Southwesterly winds may play a crucial role in reducing the UHI intensity as they create a cooling effect that can decrease the temperature in urban areas. We found that wind velocity at CBDs ranged from 0.4 m s^{-1} to 3.1 m s^{-1} whereas that at suburban area ranged from 1.4 m s^{-1} to 7.8 m s^{-1}. So, the wind velocity in suburban area was higher than in the CBDs. The difference in wind velocity rate was 1.8 m s^{-1} on average. This effect may be responsible for the UHI intensity in suburban area, being lower than that in CBDs.

4. NEIGHBOURHOOD DESIGN

For the Build4People case study area, situated within the dynamically growing Chbar Ampov district at the urban–rural edge of the Southeast section of Phnom Penh, an integrated urban design approach was applied to develop an Ecocity demonstration project (Messerschmidt, 2005). This case study considered the importance of addressing local climate conditions to enhance the urban quality of life.

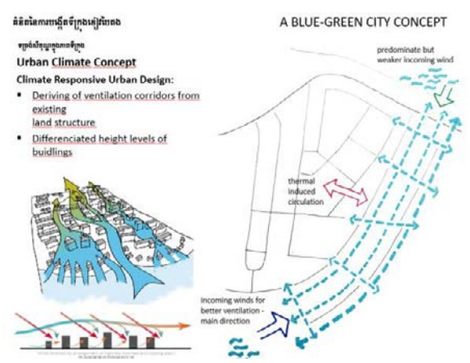
The concept development was undertaken during the first Ecocity Transition Lab held in March 2020 as a transdisciplinary and participatory design workshop. After presentations including international best-practice strategies on urban climate, one of the hands-on-planning sessions with experts, local administrations, and university professors and students on the topic of “Water, Green & Climate” led to initial ideas for a climate-sensitive neighborhood.

In the subsequent collaborative planning week (Messerschmidt & von Zadow, 2019), a design methodology with a multi-layered approach and a “graphical overlapping” of all relevant layers of urban development, including urban climate, was used. The results of an urban climatic analysis with local wind directions were projected onto the site. Based on this, an urban grid was developed, providing ventilation corridors for the incoming southwesterly winds and the weaker, but predominant, winds from the northeast across the Mekong River. These southwest to northeast corridors should feature wide boulevard-type streetscapes. In addition, the perpendicular orientation of the corridors plays a role in the thermally induced circulation between the existing already built-up area in the northwest and the surrounding green area in the southeast, which will be maintained as a biodiversity and wetland corridor with an urban climatic function. Within the new neighborhood, the ventilation corridors have been integrated into the urban fabric with an alley, green canals, and green fingers connecting the urban area with the natural landscape. Furthermore, the urban green system of the neighborhood also encompasses larger parks and smaller pocket parks with a high green volume, which contributes to reducing the UHI effect for the neighborhood. A proposed guideline for the development of urban blocks is to implement differential height levels in the building structures to link and draw down the air flow to the ground level in outdoor areas to create climatological benefits from the local wind system.

This forms a basic urban climate concept, which has been integrated into a first land use plan and the so-called “Blue Green City” neighborhood planning approach, which illustrates the mutual integration of the urban climate and green corridors into an urban design (see Figure 5). The motto “Let the nature flow” that was conceived by one of the hands-on-planning working groups, based on the underlying wetland and landscape structure of the site, and comprehensive neighborhood planning reflecting this motto should foster outdoor comfort in an exemplary way and make a major contribution to the urban quality of life.

These strategies will be the further developed during the already initiated research and development phase of the Build4People project to create an exemplary neighborhood development for climate responsive urban environments and serve to develop valid guidelines and criteria for sustainable, resilient, and healthy neighborhoods in Phnom Penh and Cambodia in general.

Figure 5:
Climate-orientated urban design. Sources: Suzhou Eco-Town, China (JTP, Joachim Eble Architektur, Yen-Yi Li 2010), and the Build4People Ecocity Transition Lab



5. CLIMATOLOGICAL ORIENTED PLANNING FOR PHNOM PENH

5.1. Work in progress

In consideration of the above-described matter, it is essential to formulate guidelines for urban climate studies as they have to fulfil comparable criteria of evaluation. As Phnom Penh and most cities have a comparable planning hierarchy urban climate study should follow this hierarchy in order to give direct recommendations for each level.

Table 2:
Planning recommendations according to climatic scales.

Administrative level	Planning scale	Climate scale	Climate measures	Climate adaptation
	Regional plan scale: 1:100 000 accuracy: 100-500m	**Regional climate pattern** thermal and topographical circulations, land use climates	Climate zone, regional climate analysis (air mass exchange, heat)	Definition of areas for climate protections and climate adaptation (air mass exchange, areal distribution)
	Masterplan scale: 1:10 000 accuracy: 20-100m	**Urban Climate** climatopes, urban structure types, „local climate zones“	Interaction surface - atmosphere, urban climatic maps (urban heat island, ventilation)	Enhancing ventilation with air paths, avoiding building volume and densities, roughness, barriers, connecting green open spaces
	Zoning plan / neighbourhood scale: 1:5 000 accuracy: 10-20m	**Open space climate** surface sealing, building effects, vegetation	Urban climate analysis, modelling (meso- and microscale), local air exchange, thermal induced circulations	Enhancing ventilation and cooling, building orientation and materials, connecting green open spaces
	Open space planning scale: 1:2 000 accuracy: 5-10m	**Local climate** street canyon, courtyard and open spaces	Microclimate analysis (human-biometeorology, temperature, radiation, wind)	Open space planning, Building position, shadow design, cooling materials, surface cooling, vegetation, vegetation distribution
	Building design scale: 1:500 accuracy: 2-5m	**Building climate** single objects	Microclimate analysis (human-biometeorology, radiation balance, outside building ventilation)	Analysis of thermal effects (shadow, surfaces, facades, sealing)

Mesoclimate ⟷ Microclimate

The scope of a climate analysis map should cover the areas of regional, urban planning and local planning. A guideline aids the evaluation of the thermal and air quality situation and impacts of surfaces, densification, conversion measures, and urban renewal as well as individual buildings. Consideration of climate within regional and urban planning requires detailed knowledge of the reciprocal process between the urban factors and the atmosphere. Results are illustrated in maps of different spatial resolutions depending on the scale of urban planning. In this respect, climatologically following aspects should be considered (Katzschner, 2010):

- regional occurrence and frequency of air masses exchange (ventilation) and their frequencies.
- regional seasonal occurrence of the thermal and air quality aspects of urban climate (stress areas, insolation rates, shading conditions).
- regional presentation and evaluation of the impact area and stress areas.
- energy optimization of location based on the urban climate analysis with regard to areas with heat load and cold air areas, building density.

5.2. Outlook

For further studies and climatical oriented urban development, the tools of urban climatic maps are used. Many countries take advantage of these methods (Ren, 2010). For Phnom Penh, next steps are to collect data and bring them in the right layer order for a modular geographic information system (modGIS) (see Figure 6) calculation. Finally, planning recommendations follow the structure of Figure 3 (Katzschner, 2007).

Figure 6:
Input data for an urban climate analysis

Developing an urban climate 'Site Risk Assessment' toolkit

City of Birmingham pilot study

JULIE FUTCHER[1]; EMMA FERRANTI[2]; LEE CHAPMAN

[1] Urban Generation
[2] University of Birmingham

ABSTRACT: Here we report on the initial development of a city wide prototype 'Urban Climate Site Risk Assessment Toolkit' for Birmingham (UK). The toolkit sets out to provide an early design stage site analysis framework where a number of urban climate and environmental risks and benefits can be identified at the pre-design stage. The toolkit is designed specifically to support built environment practitioners, and is accompanied by a CPD series which includes an urban climate walk. The toolkit translates geographically based information of built form at the urban; neighbourhood; street and building scale, allowing us to generate a standardised way to profile urban climate 'risks' and 'benefits', for any given site within the city limits. The aim here is to highlight the long-term benefits of adopting a 'local and neighbourhood climate' approach towards sustainable urban development. The project integrates Birmingham's extensive body of urban climate research into city plans to support Climate Resilient Planning
KEYWORDS: Urban Heat Island; Climate Resilient Planning; Urban 'Form and Function'; Urban Morphology

1. INTRODUCTION

Climate projections indicate that the global warming that will take place over the next 100 years will be associated with higher night-time temperatures and more frequent heat wave events. In addition, it is projected that there will be changes in precipitation receipt, including more intense rainfall events. The impacts of these changes will be accentuated in urban areas, which are characterised by impervious surface cover, high building density and intense anthropogenic emissions of heat. These attributes will give rise to higher urban surface and air temperatures and increased flooding owing to water pooling (pluvial) and rapid runoff (fluvial). Building resilience to climate change at urban scales means altering the attributes of the urban landscape to mitigate urban climate risks, whilst promoting urban climate benefits. Mapping the spatial and temporal patterns of urban climates and identifying its drivers can be an effective way of diagnosing urban neighbourhoods that (will) have undesirable climate effects and how best to overcome these.

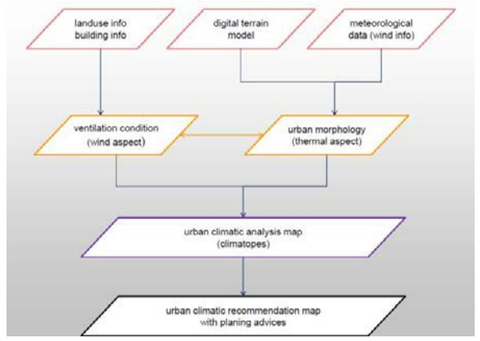
Here we report on the ongoing development of a prototype 'Urban Climate Site Risk Assessment Toolkit' for Birmingham, the UK's second largest city. The toolkit has been designed to assist decision makers, planners, and design teams (built environment practitioners) to evaluate a range of climate and environmental site risks and benefits at the pre design stage.

2. BACKGROUND

As global temperatures and climate driven risks increase, understanding urban climate resilience, particularly risks associated with overheating, are becoming increasingly critical. A first step in understanding these risks is to understand how cities receive, store and release heat. And whilst a full description of the various urban climate effects, their scale, causes and consequences are outside the scope of the study presented here, understanding when and where these effects occur is critical to understanding how they can be optimised towards climate resilient planning.

Cities are known for their sheltering effects, their characteristic warmth and lower wind speeds when compared to their non-urban, often rural, surroundings. These urban rural differences, are found to be complex, occur on an infinite number of levels and are both spatial and temporal in nature. The intensity[1] of these effects is shown to be dependent on the background climate conditions, alongside the form (Land Cover) and function (Land Use) of the underlying surface[2] (fig 1).

[1] The UHI intensity refers to the temperature differences between an urban site and its surrounding non or semi urban site (△T).
[2] form' describes the morphology (Land Cover), and 'function' describes the activities (Land Use).The form refers to both the built and organic elements whereby their proximity to each other, will influence both levels of radiation (i.e., availability, direct, diffused or reflected) and airflow (i.e., channelling, turbulence or buoyancy). The fabric refers to the climatically



In Figure 7, the principle method to calculate the urban climatic map is shown. Here the different input data get an weighting factor to translate all layers into an atmospheric classification which can be integrated into an geographical information system and calculate the urban climatic map.

Figure 7:
Modular Geographic Information system

6. CONCLUSION

It is fundamental for any urban climate study, which has the challenge for assessment, to follow the planning a political decision process. As this is different in cities and national laws, climate evaluation and climate recommendation need to have guidelines and if possible strict criteria for ventilation, the thermal aspect and urban heat load occur.

This paper indicates how climate analysis maps can contribute to an enhanced understanding of urban climate phenomena and urban planning quality by using a qualitative approach, which can be later evaluated by measurements to get quantitative data to enrich results and planning competence.

ACKNOWLEDGEMENTS

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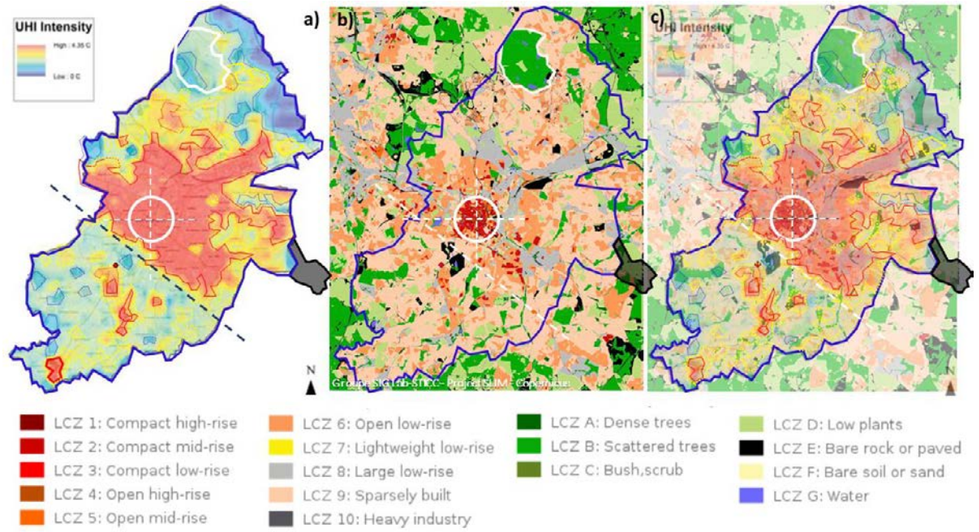
At the urban scale these climate effects have been categorised into; 1) the Boundary Layer urban heat island (UHI), the >1km deep layer of atmosphere above and downwind of the city; 2) the Canopy Layer UHI (CLUHI), the lower layer of the atmosphere, i.e., the spaces between buildings and below roof level; 3) the Surface Layer UHI (SLUHI), the 'instantaneous' surface temperature between a solid surface and the air; and 4) the Substrate or Ground UHI, the temperature held in the ground below the city. For this study we focus on the canopy and surface UHI's.

Figure 1:



The City of Birmingham, a) Nocturnal Canopy Layer (CL) UHI under heatwave conditions (1PM July 2006) [1] b) Birmingham's Local Climate Zones (LCZ)[3] after Bocher 2021 [2], and c) the isotherms overlaying the LCZs. These images show a clear correlation between the underlying form (LCZ) of the urban surface and the overlying intensity of the urban climate. It is worth noting the significant difference in air temperature either side of the dashed line; this cliff effect results from differences in land cover where to the south LCZ 6 & B dominate, and to the north LCZ 4,5, 6 & 8 dominate

Understanding the timing of these various UHI intensities (△T) are also critical parameters towards achieving urban climate resilience. For example, whilst night time urban air temperatures (CLUHI) are often found to be several degrees warmer than the surrounding area (due to slower rates of cooling) reaching maximum △T several hours after sunset, daytime air temperatures are found to be lower or equal to those of the surrounding area (slower rates of heating). These air temperature effects are typically measured through Urban Meteorological Networks. On the other hand surface temperatures (SLUHI) are found to be warmer than the surrounding area, reaching their maximum after the solar noon before cooling later in the day. These effects are typically measured through remote sensing [3] (fig 2), and often represent a 2D view of the horizontal plane.

It is important to note the UHI is not always associated with negative outcomes. For example, in the UK, cities like Birmingham benefit from the city scale UHI by lowering heating loads, reducing cold related mortality, improving thermal comfort, and in turn improving health and wellbeing [4]. Nevertheless, care needs to be taken to limit the overheating risks associated with the UHI.

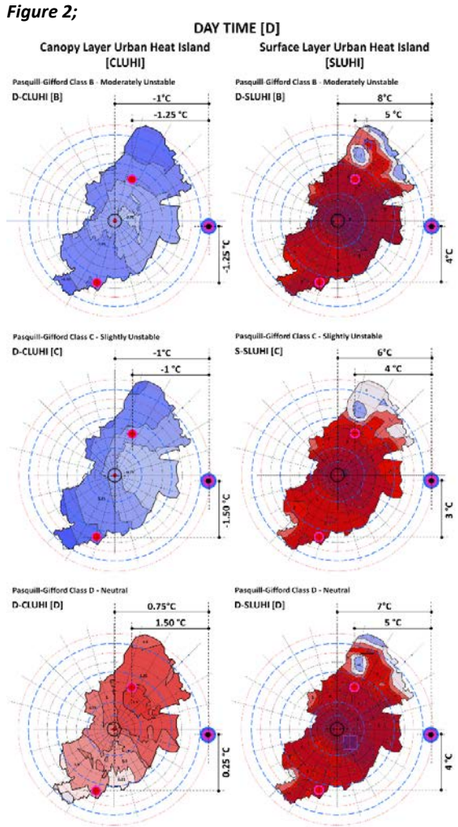
Both risks and benefits of the UHI are shown to be directly linked to the urban 'form and function' of the underlying surface [5]; and can be managed at various scales through urban planning strategies [6]. Nonetheless despite the vast volumes of research on the drivers, risks and benefits associated with a range of urban climate outcomes, urban climate phenomena such as UHI type (surface or air), timing (daytime or night-time) and cause (natural energy exchanges or anthropogenic heating) are poorly represented in the non-specific urban climate literature [8]; and clear and accurate guidance is limited [9].

The overall aim of this project is to develop a 'site risk assessment toolkit' that provides an early design stage site analysis framework for built environment practitioners to explore a range of urban climate and environmental risks and benefits, and to embed urban climate knowledge into built environment practice.

active surfaces i.e., radiative; thermal; moisture and aerodynamic properties.

[3] The Local Climate Zone (LCZ) indicates a series of site conditions and have been derived on their 'approximate ability to modify local climates' [7]

Figure 2;

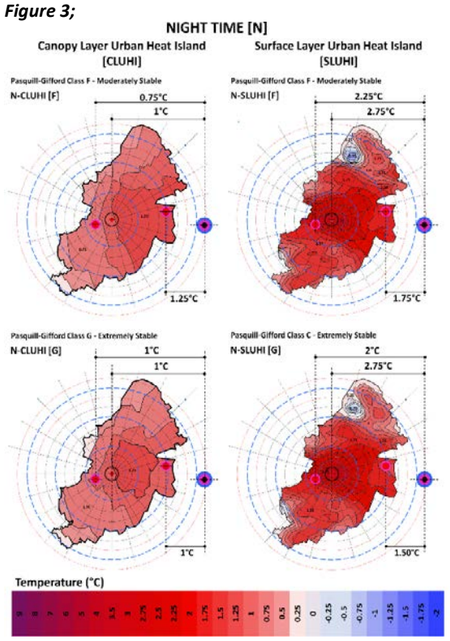


Both figure 2 & 3 have been modified after Azevedo et al., 2016 [10] and show the averaged summer time (June, July, August 2013) UHI intensity (△T) against Coleshill (the rural refence site) for both 1) the CLUHI (taken from the BUO dataset), and 2) the SLUHI from the MODIS Aqua land Surface Temperature (LST) data. Under prevailing South Westerly conditions. Figure 2 shows 'daytime' for Pasquill-Gifford Stability Classes B; C & D; A full description of the methodology used for these data sets can be found at Azevedo et al., 2016. The figure highlights the range of temperature differences that can occur as a result of the background weather conditions, and should be viewed alongside table 1

3. THE TOOLKIT

The toolkit discussed here builds on the University of Birmingham's extensive body of urban climate research (both empirically and through modelling) [10, 11 & 12]; and utilises data from the Birmingham Urban Observatory (BUO)[4] [13] a high resolution Urban Meteorological Network, which along with remote sensing, identifies the dynamic nature of Birmingham's Canopy and Surface UHI's.

Figure 3;



As to figure 2 this figure shows averaged summer △T night time against Coleshill for Pasquill-Gifford Stability Classes G & F, after Azevedo et al., 2016

The toolkit considers; 1) The background climate conditions (fig 2 & 3); 2) The site specific spatial and temporal UHIs including intensity and range (maximum, minimum, average and mode), alongside the timing of these effects; e.g. day and/or night (table 1); 3) Land Cover; i.e., low density, green or compact high-rise; 4) Land Use i.e., commercial or residential, and the timing of the activity associated with these functions; 5) a range of risks, i.e., flood, air quality and heatwaves; 6) benefits, i.e., green and/or blue infrastructure (figs 5 & 6).

Here a range of Birmingham's built environment parameters (Fig 5 & 6) are explored through a series of 3 interconnected grids (Fig 4). The first is an 'Urban Scale' radial grid, which is divided into ❶ central; ❷ inner; ❸ middle; and ❹ outer zones (Blue Dashed Lines) which corresponds to the underlying urban layout, i.e., dense central urban area and so on. The second is the 'local scale' 1km2 grid (pink squares) which corresponds to a number of existing data sets such as the LST data [10]. Finally the hexagonal grid, at the 'neighbourhood' or 'street scale', which represents the typical site

[4] The BUO provides high quality data on a wide range of urban effects, including, heat waves, flooding and air quality, alongside weather and climate impacts on health and wellbeing. A full description can be found at birminghamurbanobservatory.com

scale of a development[5]. Together these grids help us to identify the hierarchy of urban climate scales, and their interdependencies with urban form and function.

Table 1:

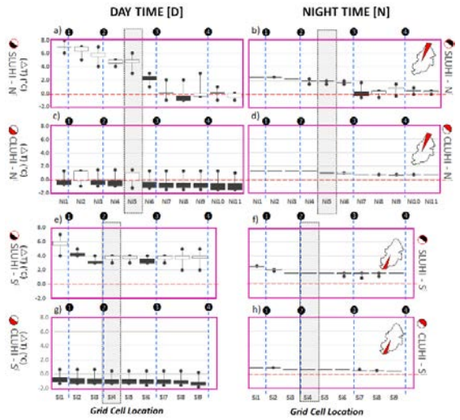


Table 1 shows the dynamic nature of Birmingham's summer time SLUHI and CLUHI (as identified in figure 2 and 3), for our 2 case study areas N[i] the north and S[i] in the south of the city. The Figure focuses on both the night and day time temperature differences (△T) between Coleshill and the 2 sites. The box and whisker plots show 1) the max and min temp range of △T, 2) the △T average (indicated by the top of the black box and the bottom of the white box) and 3) the frequency of △T. Here the black box indicates △T is more likely to be lower than the average UHI temperature (lower risk of maximum temperatures), and the white bar indicates△T more likely to be higher than the average UHI temperature (higher risk of maximum temperatures). In addition the numbers ❶ to ❹ and the blue dashed lines represent distance from city centre (2, 4, 8.5 & 12.5 km respectively) (figure 4)

For the site assessment proposed here, both risks and benefits are assessed in terms of; site location within the city wide UHI (Fig 1, 2, & 3); the strength and timing of these climate effects i.e., night time heat island or daytime cool island (Fig 2 and 3); along with any conflicts or tensions between the timing of the proposed function (Fig 6) and the timing of the dominant climate effect (Table 1).

3.1 Site Risk Assessment

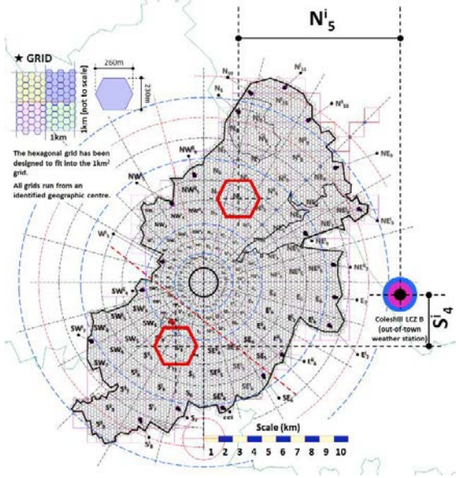
Here we present an overview of the prototype toolkit through 2 case study sites (N[i]5 the north and S[i]4 in the south of the city) examples.

The framework leads practitioners through a range of different site analysis to evaluate both the positive and/or negative risks associated with the proposed site. The tool does not attempt to relate the impact of the development on the UHI.

The first step is to identify any tensions or conflicts between the timing of the UHI at the site; i.e., day or night (or both), the type i.e., surface or air (or both); and the underlying form for example low or high density. The next step is to identify Land Use. Whilst the LCZ protocol provides a good indication of a range of built form parameters, it only implies building function. Research shows matching the timing of a buildings (or area) function against the timing of a specific urban climate effect increases efficiency [9]. For example a low daytime CLUHI lowers cooling loads for a commercial office buildings (daytime activity) compared to a residential function where a nocturnal summertime overheating risk is linked to 'the quality of a night's sleep'. The toolkit also considers urban function outcomes such as those associated with traffic, poor air quality and/or noise as reasons not to open the window (Fig 5 & 6).

In addition the toolkit is supported by an urban climate walk methodology [14] designed to install a deep understanding of the dynamic and interdependent relationships between buildings and outdoor spaces[6].

***Figure 4:** 3 interconnected grids*



The grids are based on the city's climate, geography and morphology and are set out from Birmingham's geographical centre. The blue dashed circles represent distance from city centre (2, 4, 8.5 & 12.5 km respectively) The figure also shows the location of Ni5 and Si4.

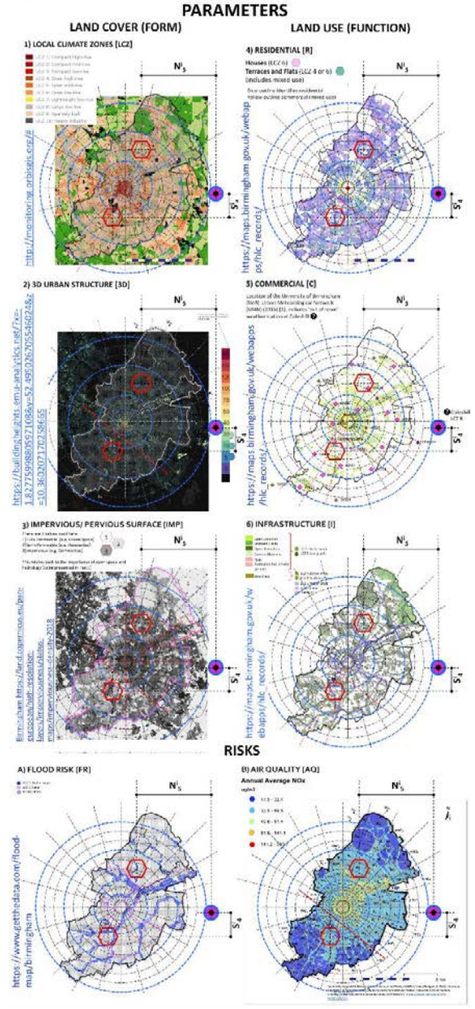
[5] This neighbourhood scale is useful as not only does it allow us to directly link the form and function of the underlying surface to the UHI's; but links to other urban climate resilience research designed to assist built environment practitioners, for example the LCZ protocol [15], TDAG's 'First Steps' series [16] and the Albedo Calculator [17]

[6] Reporting on the impact of Birmingham's urban climate walk (which forms part of this project) is outside the scope of this article

4. RESULTS

To demonstrate the framework, we examine two areas (Ni5 and Si4) and briefly discuss outcomes. **Ni5** represents a residential area to the north of the city centre; **Si4**, an area of mixed use to the south.

***Figure 5**: Urban Parameters*



LAND COVER 1) LCZ [2]; 2) 3D Urban Structure; i.e., building height & open space [19]; 3) Surface Permeability, which along with levels of tree cover are key drivers of daytime SLUHI [20 & 5]; LAND USE; 4) residential (semi) detached, terraces & flats [21]; & 5) commercial (office & industry) [21]; 6) Urban Infrastructure, & the opportunity to 'open the window' i.,e air quality; noise; cooling; risks associated with A) flood risks [21] and B) Air Quality (AQ) [22].

At the city scale figs 2 and 3 and Table 1 show **Ni5** to sit within a high summertime daytime SLUHI; but to have a low CLUHI risk; and by comparison, whilst **Si4** experiences a much lower daytime range it sits in an area with a high nocturnal heat wave risk (Fig 6/C);

At this point it is worth considering the function of these two areas. Whilst **Si4** has a high nocturnal heat wave risk it is an area of mixed use with a significant level of LCZ 8 (large low rise industrial buildings), typically a daytime commercial function, making the function well suited to its lower daytime UHI, lower cooling loads. Where any nocturnal overheating risk will have less of an impact and may be easily mitigated. In addition whilst at the local scale **Si4** has a low level of permeability (fig 6/3); at the neighbourhood scale the site is close to the canal. Close proximity (<30m) to waterbodies is shown to lower daytime overheating by 1°C [18]. The area has good air quality. In part this could result from its varying building hight and street width ratio (fig 6/2) where increased surface roughness is shown to increase surface mixing for pollution and heat dispersal [5]. Nonetheless the area might be less suitable for a residential function.

On the other hand **Ni5** (a low rise residential area) is generally open to sky (promoting nocturnal terrestrial radiation loss); which together with high levels of blue and green infrastructure; and a medium level of permeability (both identified as beneficial to the built environment, and to have a positive impact on the thermal comfort), we can say that the residential function of **Ni5** is suited to its low summertime nocturnal UHI, although it is advisable to consider winter conditions. In addition the area suffers with air quality and flood risks (fig 6/A), which need to be accounted for. Nonetheless if designed with care (as with **Si4**) varying building hight and street width can have positive outcomes.

Finally whilst the summertime nocturnal △T range of both sites sits between the average 1 & 2°C; at the higher temperature range (i.e., heat wave conditions) an increase of 1°C is shown to impact significantly on health and wellbeing [4].

These outcomes show that whilst these 2 areas might be suitable for their current function, care needs to be taken when considering the tensions between increasing urban density and the wider environment and climate impacts

5. CONCLUSION

The paper presented here describes the early stage development of a site risk assessment tool that considers a range of urban climate and environmental risks and benefits. Crucially the tool addresses a key implementation gap; namely, a scientific understanding of UHI is not incorporated within city planning and design documents, and many practitioner resources poorly represent the complexity and indeed the benefits of the UHI. It is becoming increasingly clear that overheating risks must be incorporated within the planning and design processes.

Urban geometry and microclimate effects on building energy performance

The case of Mediterranean climate districts in Turkey

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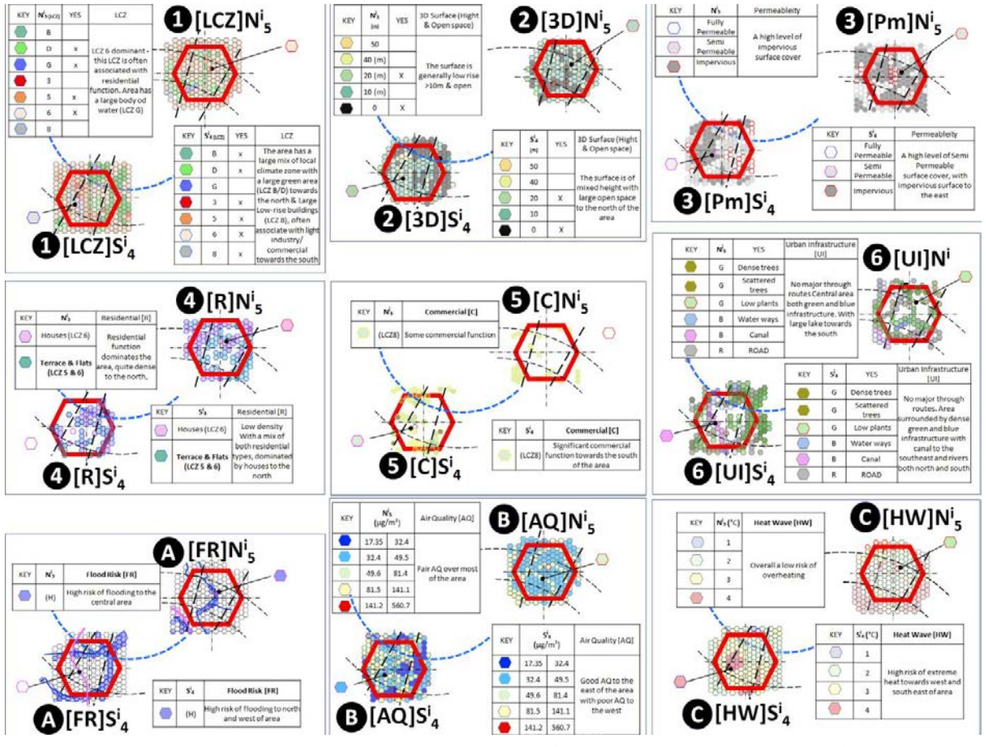
ABSTRACT: Considering the fact that the arrangement of the built form and urban morphology have a significant impact on building energy consumption, a favourable adaptation of urban form should be prioritised at an early stage of urban planning and design. However, there are few studies that have focused on urban morphology and microclimate related to heating and cooling energy consumption in the context of the Mediterranean climate with distinctive urban morphology features. This study will explore the interrelationship between the impacts of urban form and microclimate on the energy consumption of buildings in the climatic context of Gaziantep by coupling Envi- met results with the Design-Builder. Three different urban forms were defined as traditional and regular formal urban areas. The aim of the research is to make energy consumption comparisons between traditional and formal urban forms. The results show the influence of urban morphology on the cooling performance of the structure and provide ideas for future planning and building design.
KEYWORDS: Microclimate, Urban Form, Envi-met, Building Cooling Energy Consumption

1. INTRODUCTION

The world's population is anticipated to reach 9.7 billion by 2050, with metropolitan regions housing 70% of the population (Ibrahim et al., 2021). Rapid urbanisation has resulted in increasingly complex urban morphologies that include a wide range of constructed densities, layouts, and forms. The variety of urban morphologies has caused various building design and energy issues. Cities now consume 76% of the world's primary energy and emit 43% of CO2 emissions (Ibrahim et al., 2021). Furthermore, the building industry accounts for roughly 30% of worldwide final energy consumption, 70% of which is shared by the residential sector(Energy Technol. Perspect. 2020). As a result of cities' complicated microclimate circumstances, the majority of this is driven by building industry demands. It is obvious that urban scale studies are an essential element of the discussion regarding the future of built environments.

Numerous geometrical components that make up the urban fabric individually contribute to the creation of the building microclimates. Previous studies also have shown that the urban microclimate environment has a significant influence on building energy consumption (Boccalatte et al., 2020; López-Cabeza et al., 2018; Salvati et al., 2019). According to Liu et al. (Liu et al., 2015), the local microclimate, as defined by the external surface convective heat transfer coefficients (CHTCs), can impact overall cooling energy usage by 4%. Morero et al. (2020) focused on analysing the energy usage at the district level while accounting for the microclimatic impacts brought on by the planning of open and constructed space and taking into account the local climatic trends, the space cooling requirement of the various buildings ranged between -5 and +14 percent on the chosen day. Taleghani et al. (2015) evaluated three typologies within two orientations and concluded that courtyard and NS slab typologies are better for reduced air temperatures, MRT, and PET in a temperate environment. Despite being in a comparable environment, Allegrini et al. (2012) criticised the two typologies for their inferior convective cooling. Natanian and Auer (2020) recently conducted parametric research of four FARs, three widths, and four window-to-wall ratios in a Mediterranean environment to assess the thermal comfort, daylighting, and load match of four distinct typologies (192 total cases). Courtyard typologies outperformed other typologies in thermal comfort and average load match when lower FAR were employed (Natanian & Auer, 2020). As a result, analysing, evaluating, and optimising the geometry of urban form provides the opportunity to create a sustainable built environment with preferable thermal performance and comfort, which will be a positive impact on energy demand. The goal of this research is to investigate the impact of real-world urban geometries and local microclimate on summertime traditional and modern residential buildings' cooling energy consumption in Mediterranean climate.

Figure 6: *Detailed investigation of Form & Function of the 2 local scale grid cells N^i_5 (north of the city centre) and S^i_4 (south). 1) Local Climate Zone (LCZ); 2) 3D urban structure (3D); 3) Permeability (Pm). 4) Residential (R); 5) Commercial (C); 6) Urban Infrastructure [UI]; The figure also shows RISKS A) Flood [FR]; B) Air Quality [AQ] & C) heatwave [HW] risks.*



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2. CASE STUDY DESCRIPTION

Gaziantep is located at 37.0585 °N, 37.3510 °E, in the southeast region of Turkey (Fig. 1). The area of the city is 6803 km². According to the 2021 Turkish Statistical Institute report, the city has a population of 2.130.432 (Turkiye Statistical Institute, 2021). Gaziantep is the largest city in the South-eastern Anatolia area and the sixth-largest city in Turkey. Gaziantep has a hot-summer Mediterranean climate (Köppen climate classification, Csa).

Figure 1: Location of Gaziantep

Gaziantep, according to Kurian (2001), is one of the world's oldest inhabited cities. The city's location between Mesopotamia and the Mediterranean, where the first civilisation born, being at the crossroads of the roads leading from the south and the Mediterranean to the east, north and west has shaped the history of civilization and today. For this reason, Gaziantep has been the settlement and haunt of human communities since

is presented, and it is used to assess the energy performance of traditional and formal neighbourhoods in Gaziantep. As the city developed, both the cultural and structural texture began to become cosmopolitan. Unplanned and adjacent regular buildings, devoid of aesthetic concerns, took the place of traditional buildings. Morphologically four different textures were chosen to show these changes and to understand the cooling energy performance of these structures, each neighbourhood has a reference building. The first one is the traditional texture that has formed around streets developing organically, and around streets and dead-end streets. A courtyard completely disconnected from the street is common in traditional houses in accordance with the Mesopotamian tradition. The materials and construction components of traditional Gaziantep dwellings that line narrow streets stand out. The second area includes adjacent and low-height structures. The narrow street concept was also applied; however, the material of the buildings was changed in this area. The third and fourth areas are modern structures. They have wide streets and concrete structures. The only difference is the height of them (Fig. 2). It was modelled by selecting an area with a diameter of 100 meters.

The paper provides a comparative and comprehensive assessment considering the influence of the surrounding urban morphology on the canyon microclimate to evaluate the relationship between urban geometries and building cooling demand.

3.1 Simulation Tools

Two software tools were utilised in this study to better analyse the influence of urban microclimate

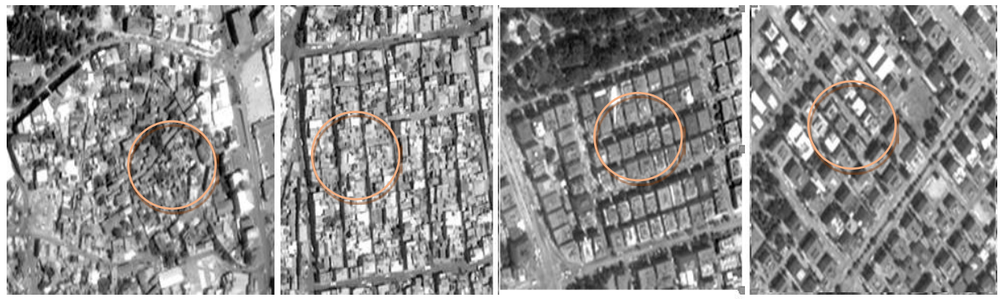


Figure 2: Case study areas (Traditional area(A) and Formal areas (B,C,D)

3. METHODOLOGY

In this research, an approach for integrating urban microclimate, form and building energy simulations on energy performance: Envi-met and Design-Builder. Envi-met outputs for energy modelling created a microclimatic EPW weather file for the day having the highest temperature. The ENVI-met simulation tool was used to create a three-dimensional spatial model that included the footprint and height of the buildings for the selected areas. Air temperature, relative humidity, direct radiation, diffused radiation, and wind speed are the meteorological parameters that were adjusted. The simulation was carried out on the highest temperature day (13/08/2019) to calculate the cooling energy performance of the structures. According to the data used in the METAR annual weather report taken hourly weather station (Oguzeli International Airport), the highest temperature day was defined for the simulation. In the first step, the geographic model for the chosen case study is created in ENVI-met (4.4.6), and simulations are run using the basic forcing approach with meteorological data from the chosen day. In the second stage, ENVI-met is utilised to produce meteorological parameters that are then used to adjust each of the EPW files sent to Design-Builder to simulate the energy usage for each area. To assist inform and guiding design decisions, Design Builder gives realistic energy, comfort, cost, and daylighting performance statistics. To execute a cooling energy simulation of the test residence using Energy Plus, the simplified textures were designed in Design Builder.

Table 1: Input data for Envi-met simulation and Urban geometry features

Date of Simulation	13/08/2019
Time of Start of Simulation	08:00am
Simulation Period	24 hours
Wind Direction	West-270°
Wind Speed at 10m	8 m/s
Relative Humidity	30%
Min. and Max. Air Temp.	24-43 °C

4. RESULT

4.1. Comparison of Microclimate Data

Geometric Features	Site T1	Site T2	Site F1	Site F2
Building Heights	6-12m	3-12m	12-18m	51-55m
Aspect Ratio(H/W)	1.4-2.6	0.6-1.6	1.6-3	1.4-1.7
Skyview Factor	0.65	0.72	0.48	0.6
Distance between buildings	Courtyards	Adjacent	5m	30m

This section looks into the site-specific climatic data for Gaziantep. The receptor points are defined for each model. The microclimate data for each point are compared.

The comparisons for air temperature, wind speed, relative humidity and mean radiant temperature data are shown in Fig.4. On the hottest day, the air temperature surrounding the building units shows a significant difference between day and night. According to these results, there are no big differences between traditional1 (T1), traditional2 (T2), formal1 (F1) and formal 2 (F2) case areas. However, when the air temperature is compared, the maximum difference is 2 °C between F1 and T2. In formal areas 1 and 2, older structures had a stronger reaction to microclimate impacts, whereas newer, fully insulated buildings exhibited considerably less effect.

To account for the influence of a street canyon's microclimate on the cooling and heating energy consumption of a building, the microclimate output from the ENVI-met simulation is utilised to modify the original EPW file before the Energy Plus simulation is performed.

Table 2: Building Coverage Ratio and Energy demand in the hottest day

Urban Texture	Building Coverage Ratio	Heating Demand kWh/m2	Cooling Demand kWh/m2	Annual Demand kWh/m2
Traditional 1	0.64	16.18	-18.18	34.36
Traditional 2	0.80	13.36	-16.51	29.87
Formal 1	0.40	17.77	-19.26	37.03
Formal 2	0.15	16.92	-20.72	37.64

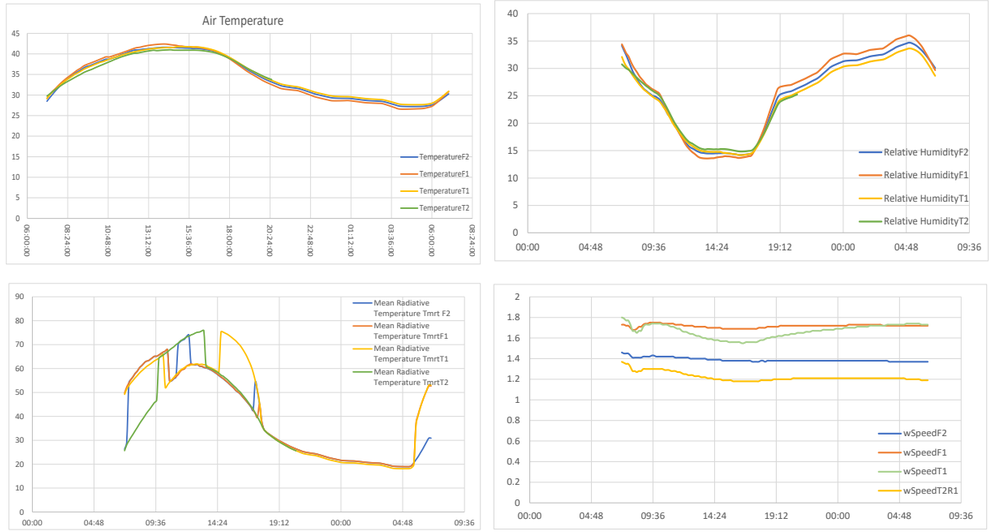


Figure 4: Comparison of the air temperature relative humidity (top), and mean radiant temperature, wind speed (bottom) from average air temperature around the buildings from ENVI-met for the hottest day

The trend lines in Figure 5 depict the variation in the average apartment heating and cooling needs as a function of urban density in the hottest day in Gaziantep. The red line represents the energy use of the same unit in a rural setting. The variance in demand resulting from an increase in the site coverage ratio is thus the consequence of a decrease in solar radiation and indicates the overall effect of urban density on energy demand.

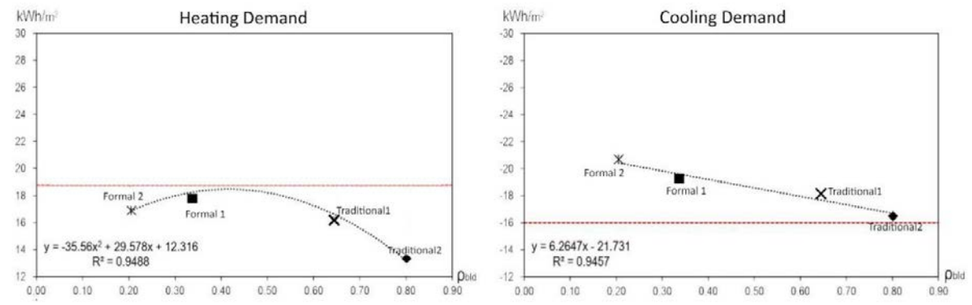


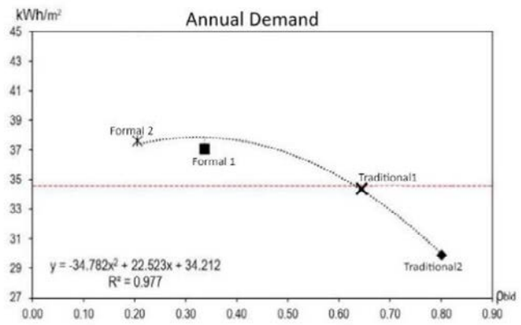
Fig.5: Relationships between the texture's site coverage ratio and the apartment's heating demand and cooling demand for four case studies

There is a strong linear correlation between urban density and cooling demand, with R2 equal to 0.95. The reduction in cooling demand for the test apartment is related to the rise in urban density. According to these results, a high degree of compactness is advantageous during the summer in a Mediterranean environment, since the decreased solar radiation is more important than the increased heat island.

Concerning the heating requirement, a nonlinear connection has been discovered in relation to the compactness of the material (R2=0.95). Even in the urban texturing with the lowest value of site coverage ratio, the heating demand is often lower in urban environments than rural ones, as a result of the favourable impact of the UHI intensity. Due to the gradual reduction of solar radiation, a rise in the texture's compactness initially results in a proportional increase in the heating requirement. There is, however, a threshold value of the texture's coverage ratio (bcr=0.40) above which the heating need begins to decrease again.

Figure 6 depicts the evolution of the yearly energy consumption in response to the ratio of site covered by the texture; the annual demand is the total of the heating and cooling needs. These findings imply that a dispersed urban layout negatively impacts the energy efficiency of buildings. For low values of site coverage ratio, the apartment's energy usage exceeds that of a rural setting. Furthermore, in particularly dense urban textures (bcr approximately 0.64), the conflicting consequences of urban compactness on energy demand balance themselves, defining the same energy demand as a rural environment. Even less energy is used annually in Traditional 2, bcr=0.8, the most compact urban texture in the example studies. Therefore, this research proves that in a Mediterranean environment, compact urban textures (bld > 0.5) are preferable to dispersed and discontinuous urban patterns in terms of energy efficiency.

Fig.6: The correlation between the ratio of the



texture's site covering and the apartment's heating and cooling needs across four case studies

5. DISCUSSION & CONCLUSION

Recent research has demonstrated that urban compactness and aspect ratio have an essential effect on regulating the microclimate at the street level [8-9]. The study describes a method for quantitatively analysing district-scale energy consumption while accounting for microclimatic effects. In a case study where urban development processes are expected to change microclimatic conditions and, as a result, the energy performance of buildings, a coupling approach that links the simulation tools ENVI-met and Design Builder is used.

The case study in this paper represents traditional and formal areas in Gaziantep with different urban characteristic features. Increasing H/W ratio associated with the reduction of Tmrt. The traditional site has a low aspect ratio, but high Tmrt values can be seen simulation result in Fig.3. However, Sharmin and Steemers highlighted that the relationship between the two parameters should refer to the presence or lack of shade . The shadow of the structures affects the cooling performance of the buildings. The traditional area has the biggest advantage in the summer regarding cooling performance.

By comparing the performance of an isolated building to that of a cluster of buildings in a Mediterranean environment, the findings demonstrate that dense urban texturing with a Building coverage ratio over 0.5 contribute to lowering energy consumption. Based on these findings, it seems that dense and compact urban textures, like the traditional fabric of many city centres, are more energy efficient than the more spread out and modern urban patterns.

Using a standard density metric, such the' building coverage ratio' the connections discovered in this research provide a rough estimate of the energy performance of urban textures. Facilitating the work of designers, planners, and decision makers in establishing a priority of interventions on the built environment would be the capacity to undertake fast evaluations at the district size and provide maps of the energy vulnerability inside the city.

ACKNOWLEDGEMENTS

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PLEA SANTIAGO 2022
Will Cities Survive?

BIM and EnerPHit-assisted energy efficient refurbishment

A case study of a UK Georgian terrace house

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ABSTRACT: The existing UK building stock contributes significantly to high energy consumption and carbon emissions. Accordingly, the UK government proposed net-zero targets by 2050 as a solution for this environmental issue. Although there is a growing interest in the construction industry in meeting low carbon standards for new buildings, there has been a low uptake of building refurbishment due to poor refurbishment strategies, cost overruns and unsatisfactory refurbishment outcomes. This study aims to set a new refurbishment model by implementing Building Information Modelling (BIM) tools and the EnerPHit standard, which is the refurbishment version of the German Passivhaus standard, for energy-efficient housing refurbishment in the UK. The indoor thermal data of a Georgian terrace house in Liverpool has been recorded since November 2021. A semantically enriched BIM model of the selected house was then created in ArchiCAD with a proposed 24-day refurbishment timeline activities. Then, to offer organisational priority for the key refurbishment phases and better coordination in selecting building material, and for energy assessment, DesignBuilder (DB) and Passivhaus Planning Package (PHPP) tools were applied. The final simulation results indicate that the EnerPHit standard is achievable with less than 25 kWh/m2 of heating energy demand annually for the proposed case study.
KEYWORDS: refurbishment, energy efficiency, EnerPHit standard, BIM, UK housing stock

1. INTRODUCTION

The impact of climate change, sustainability challenges, and resource scarcity on the built environment motivate the Architecture, Engineering and Construction (AEC) industry and governmental policies globally to manage resources more efficiently. For example, the UK government committed to achieving net-zero carbon emissions by 2050 (BEIS, 2021). The existing UK building stock is a major consumer of the UK's energy production and contribute to 22% of total carbon emissions (Committee on Climate Change, 2019). If the UK government is to achieve the 2050 net-zero targets then one effective solution is the sustainable refurbishment of buildings, which has enormous potential for improving energy efficiency and mitigating environmental impacts (Juan, Gao, & Wang, 2010).

The conventional building refurbishment process has been examined in recent literature, which identified examples of ambiguous refurbishment strategies, extra costs and effort, and unsatisfactory refurbishment outcomes (Okakpu et al., 2018; Ustinovichius et al., 2018; Wang & Cho, 2015). Due to these issues, homeowners have been quite reluctant to support housing refurbishment projects to meet the 2050 targets in the UK. To deal with this, a novel refurbishment model should be discussed as a holistic approach to sustainable and energy-efficient building refurbishment (Alwan, 2016; Juan et al., 2010; Volk, Stengel, & Schultmann, 2014). This approach can be categorised into three key phases (Ma, Cooper, Daly, & Ledo, 2012):

- Assessment Phase: project setup and data collection
- Method & Strategy Phase: data analysis, strategy formulation, and implementation
- Validation & Verification Phase: post-measurement and post-occupancy survey

The Method & Strategy phase is investigated within the scope of this study.

To cope with the conventional refurbishment-related issues, Building Information Modelling (BIM) has the potential to develop new ways of predicting, managing, and monitoring the impacts of the built environment regarding energy efficiency. Another important approach to energy-efficient refurbishment is EnerPHit, which is the refurbishment version of the German Passivhaus standard. This paper aims to develop a new conceptual framework for implementing BIM tools and the EnerPHit standard to apply to the energy-efficient building refurbishment of the UK residential building sector. With its further dimensions - 4D BIM (time schedule) and 5D BIM (cost estimation) - BIM implementation will be discussed for a real-world case study of a typical 19th century Georgian terrace house in Liverpool.

2. LITERATURE REVIEW

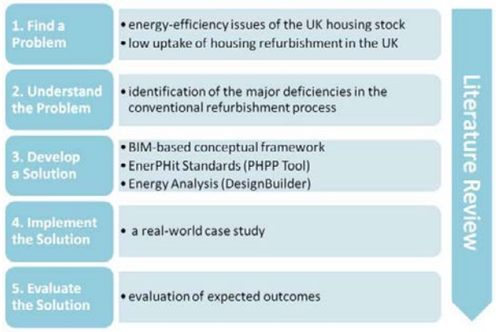
Energy Performance Certificates (EPCs) indicate the energy efficiency of buildings in the UK. They were introduced in 2007 and are based on data about a building's energy features, for example, the building's materials, the heating systems, and insulation. EPCs, measures the energy efficiency on a rating scale from A (most efficient) to G (least efficient). Out of the 27 million homes in the UK, over 19 million have EPC ratings below C (Deasley & Thornhill, 2017). Moreover, approximately 20 per cent of these dwellings were built before 1919 and need to be refurbished for energy efficiency if the UK is to move towards its 2050 net zero target (Piddington, Nicol, Garrett, & Custard, 2020). The Passivhaus EnerPHit standard has been proposed and tested internationally as an energy-efficient refurbishment approach (Bastian et al., 2022). The EnerPHit standard sets performance criteria in terms of fabric U-values, building envelope airtightness, and heating and cooling energy demand. Over 65,000 Passivhaus-certified projects have now been completed all around the world, including 1,300 in the UK (Mitchell & Natarajan, 2020). It is acknowledged that for heritage dwellings, such as this Georgian terrace house, a single retrofit approach, such as EnerPHit, might not always be feasible or acceptable (Wise, Moncaster, & Jones, 2021).

3. METHODOLOGY

The key objective of this study was to evaluate the BIM and EnerPHit-assisted energy-efficient refurbishment of a typical Georgian terrace house within the UK housing context. The approach to the research methodology focussed on solution-oriented research to provide valid knowledge that enables practitioners to solve problems(Saunders, Lewis, & Thornhill, 2016) – see Fig. 1. The purpose of this evaluative methodology was to critically appraise how BIM tools and the EnerPHit standard could develop a novel refurbishment model for the retrofit case study. Models such as this might encourage the housing sector to accelerate demand for an energy-efficient refurbishment programme amongst homeowners in the UK. This study mainly discusses developing and implementing solutions to some of the conventional building refurbishment issues.

A baseline scenario was modelled in a BIM tool, with the geometric and non-geometric features of the real-world case study, a 3-storey Georgian terrace house with a basement located in Liverpool. A potential benefit of the BIM tool for the generated house model was that it provided better coordination with its clash detection feature at the pre-refurbishment stage. Moreover, using 4D BIM offered the virtual environment to simulate 24-day refurbishment project activities with improving time management and avoiding overlapping construction areas. Furthermore, with its cost estimation benefit, 5D BIM had an economically feasible opportunity for the refurbishment project, considering the quantity take-off throughout the refurbishment processes regarding the chosen Passivhaus-certified building components.

Figure 1:
Research Design



As one of the main criteria of the EnerPHit standard, it is important to consider the concept of 'fabric first' approach to defining the refurbishment measures and implementing them step-by-step for heat retention and airtightness regarding building material selection.

To evaluate the proposed BIM-based refurbishment energy performance outcomes, predicted energy demands were compared using the Passive House Planning Package (PHPP) software – an Excel-based Passivhaus tool – and the dynamic thermal simulation modelling software DesignBuilder (DB).

3.1 Case Study Model

This study investigated a 3-storey Georgian terrace house with a basement in Liverpool, built with a brickwork structure and insufficient insulation in terms of energy performance. Liverpool is in a temperate maritime climate of warm, wet summers and cool, wet winters, with temperatures peaking around 20°C in summer and dropping to around 2°C in winter.

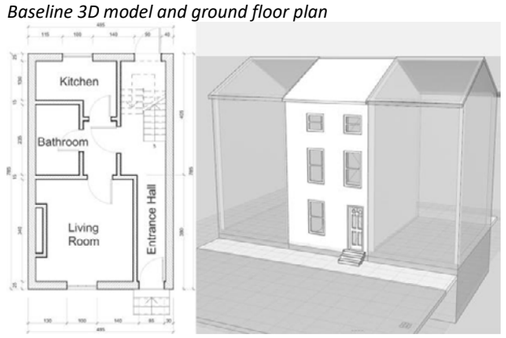
The baseline case study was modelled in ArchiCAD, one of several convenient BIM tools used worldwide. All three floors of the case study are for residential use, each having a similar layout, with a below-ground basement acting as a plant room. The building has 100 m^2 total treated floor area, 2.85 m floor-to-ceiling height, 12.6 m^2 total glazing area, and 221 m^3 net volume (Fig. 2).

Figure 2:
View of the case building in Liverpool

With its geometric and non-geometric details, the baseline model of the property was generated in ArchiCAD (Fig. 3). The potential benefits of BIM in the developed refurbishment model can be categorised as:

- The 3D BIM model can enable the project stakeholders to ensure better coordination to avoid remedial works and clash detection in advance of implementing the proposed refurbishment measures for the building.
- The 4D BIM can offer a virtual environment for simulating and visualising the housing refurbishment process with consideration of construction site coordination and time scheduling throughout the refurbishment project.
- The 5D BIM can provide a cost estimation opportunity to the refurbishment project, performing the quantity take-off from the pre-refurbishment to the post-refurbishment processes related to the selected Passivhaus-certified building components.

Figure 3:
Baseline 3D model and ground floor plan



The EnerPHit standards guide the refurbishment of existing buildings to achieve specified Passivhaus standards. The anticipated energy demand within the context of the Liverpool climate is limited to 25 kWh/m^2 for heating. The EnerPHit criteria demand the same thermal comfort as the Passivhaus criteria i.e. 20°C to 25°C, with no more than 10% of the hours in a year outside of this range (Passive House Institute, 2016).

4. RESULTS AND DISCUSSION

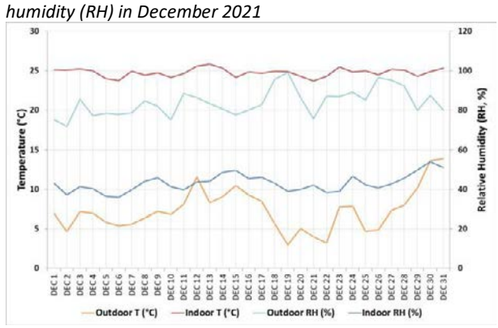
4.1 Field Measurements

The indoor temperature and humidity data have been recorded at 15-minute intervals using HOBO UX100-003 Temperature and Humidity Data Loggers in the house's living room. The outdoor weather data condition was obtained from the University of Liverpool Weather Station (weather.liv.ac.uk). Fig. 4 compares the recorded outdoor and indoor air temperature (T_a) and humidity (RH) data for in December, 2021.

The outdoor temperatures changed from 13.9°C to 3°C. The indoor temperatures changed from 25.8°C to 23.7°C. The occupant's higher preferred temperature due to his Mediterranean background can explain the higher than the UK average indoor temperature.

The outdoor RH levels fluctuated more than the indoor levels, between 71% and 99%. The indoor RH levels changed between 36% and 54%.

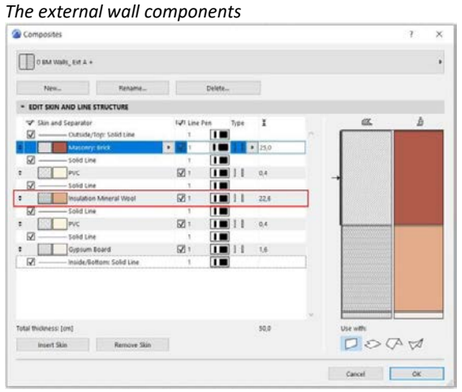
Figure 4:
Recorded indoor and outdoor temperature (T_a) and relative humidity (RH) in December 2021



4.2 BIM Model

A semantically enriched BIM model of the selected Georgian terrace house was created in ArchiCAD considering some key criteria: 3D coordination, time schedule and planning, cost estimation, and building refurbishment material selection. Moreover, all relevant building components were defined as different groups and layers in the model: external walls, internal walls, floors, roof, windows, and doors (Fig. 5).

Figure 5:
The external wall components

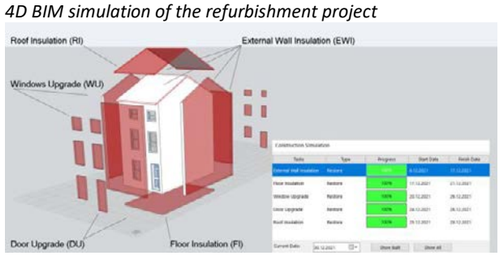


Furthermore, the geometric and non-geometric data were acquired from the BIM model to investigate the property's current condition and improve effective refurbishment strategies. Based on the BIM model calculation, 38 m^2, 238 m^2 and 46 m^2 surface areas of insulation materials were applied to the floor, external walls and roof within the scope of the proposed refurbishment model.

Next, PHPP's material inventory was used to select Passivhaus certified insulation materials. The same materials were modelled in DesignBuilder for energy analysis.

In order to manage the implementation process of the EnerPHit standards, the 4D BIM simulation of the case study was created, including the definition of the refurbishment activities' sequences. The proposed simulation demonstrates 24-day refurbishment project activities, describing the sequences of external wall, floor and roof insulation, as well as windows and doors upgrades (Fig. 6).

Figure 6:
4D BIM simulation of the refurbishment project



4.3 Energy Analysis

After generating the selected case study's BIM model, the EnerPHit-based insulation materials and upgrades were applied step-by-step on the PHPP tool, starting with the exterior walls, floor, and roof to improve the case building's energy performance. Moreover, the double glazed windows were replaced with triple-glazed windows and the doors were upgraded with consideration of energy efficiency too. Table 1 summarises the thermal properties of the existing building and the proposed refurbishment alterations. Table 2 shows the improvements at each stage.

In addition to this, the airtightness assumed at 1.0 ach to meet EnerPHit criteria.

Table 1:
Thermal properties and U-values of the model before and after the refurbishment

	Wall	Floor	Roof	Window
Main material	250 mm brickwork	100 mm concrete	20 mm slate	Double glazing
Insulation material	Mineral wool	Mineral wool	Mineral wool	Triple glazing
Insulation thickness	225mm	150mm	250mm	-
U-value pre-refurbishment	1.69 W/m²K	1.80 W/m²K	1.04 W/m²K	2.90 W/m²K
U-value post-refurbishment	0.15 W/m²K	0.15 W/m²K	0.14 W/m²K	0.75 W/m²K

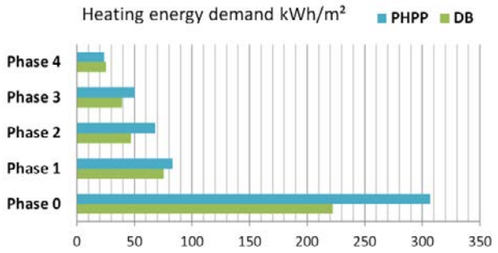
The main focus of the proposed refurbishment was improving the energy performance of the case study. Heating is the primary source of energy consumption in houses in Liverpool, and therefore the aim was to reduce the heating consumption.

Fig. 7 demonstrates step-by-step heating energy demand reduction and compares the results for the PHPP and DesignBuilder models. With regards to this, Phase 0 represents the baseline heating energy demand of the case study and each of the following phases represents the thermal improvements of the building components phase-by-phase;

- Phase 0 baseline model
- Phase 1 external wall insulation,
- Phase 2 floor insulation
- Phase 3 windows upgrade
- Phase 4 roof insulation

The baseline PHPP model's energy demand was 307 kWh/m^2 for heating, much higher than the EnerPHit standard.

Figure 7:
Comparison of modelled heating energy demand between pre-refurbishment and post-refurbishment



The following alterations (also, see Table 2) were implemented phase-by-phase in DB and PHPP to improve the case study's heating energy performance:
The refurbishment started with external wall insulation and decreased the heating energy demand from 307 kWh/m^2 to 83.2 kWh/m^2. Although Phase 1 was the most effective step of this refurbishment project, it was essential to focus on the whole-house refurbishment approach and to meet EnerPHit standard. In this regard, floor insulation, windows upgrade and roof insulation followed the first phase. The PHPP tool implied how the inadequately insulated baseline model could be refurbished systematically to achieve the EnerPHit heating demand criteria of less than 25 kWh/m^2 annually. As a result of this, the PHPP-based phase-by-phase refurbishment model could achieve 23.7 kWh/m^2 of annual heating energy demand. According to the obtained results, each step of the refurbishment remarkably contributed to high thermal performance.

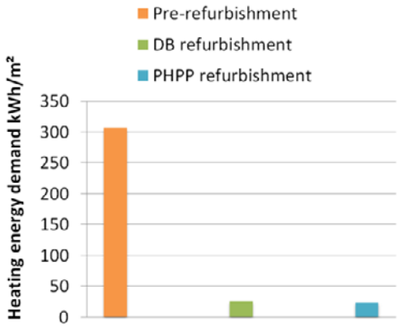
Table 2:
Refurbishment phases, including a summary of U-values (W/m²K), used for each element of the building envelope

Upgrade	External Wall U-value W/m²K	Floor U-value W/m²K	Window U-value W/m²K	Roof U-value W/m²K
Phase 0	1.69	1.80	2.90	1.04
Phase 1	**0.15**	1.80	2.90	1.04
Phase 2		**0.15**	2.90	1.04
Phase 3			**0.75**	1.04
Phase 4				**0.14**

After developing the BIM and PHPP models of the case study, the DB model was generated phase-by-phase considering the EnerPHit standard for heating energy demand. The pre-refurbishment energy use results of the baseline model in the DB differed from the heating energy demand in the PHPP simulation results, as shown in Figure 7. The obtained heating energy demands for the first four phases (Phase 0-3) in the PHPP results were greater than that in DB results. This might be due to the different weather profiles as PHPP, Excel-based software, carries out static simulations. DB tool performs dynamic simulations and is more effective in the feasibility studies to evaluate the performance improvements of buildings in terms of energy efficiency. Accordingly, DB uses hourly weather files to run the thermal simulation while PHPP uses the monthly average weather data. However, the same conclusion could be drawn from both tools regarding the effectiveness of the refurbishment phases.

The external wall insulation was the most effective measure in both DB and PHPP results. The following phases, floor and roof insulation and windows upgrade, supported the proposed refurbishment model to meet the EnerPHit heating demand criteria. The correlation between static and dynamic simulations results is noteworthy that the same building components were assessed in the PHPP and DB tools and achieved the targeted heating energy demand score of less than 25 kWh/m^2. The baseline model had 307 kWh/m^2 of heating energy demand. The PHPP and DB refurbishment results had 23.7 kWh/m^2 and 25 kWh/m^2, respectively (Fig. 8). The results had the potential to evaluate the different energy efficiency gains amongst the refurbishment phases regarding various building components.

Figure 8:
Comparison of monthly heating demand (kWh/m²) of the phase-by-phase refurbishment of the base case model



The proposed refurbishment model of the Georgian terrace house could meet the real needs of the UK housing stock as solution-oriented research to provide useful knowledge that guides practitioners to solve the issues related to the conventional refurbishment process. Utilising a BIM tool for this study provided better coordination in building material selection, organisational priority for the key refurbishment phases, and collective decision making for the project stakeholders with consideration of the EnerPHit standard. Moreover, 4D BIM offered the virtual environment to simulate the 24-day refurbishment project activities, improving time management and avoiding overlapping areas throughout the refurbishment project. The cost estimation benefits of 5D BIM discussed the economic feasibility of the presented refurbishment model as a solution for the conventional refurbishment issues such as cost overruns and unsatisfactory outcomes. Applying static and dynamic energy simulation tools, PHPP and DB, offered a different perspective on the analysis of energy performance of the selected case study. Although some parameters for energy analysis were assessed with slight nuances, both of the results of PHPP and DB energy models achieved 25 kWh/m^2 of heating energy demand for the Passivhaus EnerPHit criteria.

5. CONCLUSION

This paper examines how energy efficiency can be achieved by implementing the BIM and EnerPHit-assisted refurbishment model for the UK housing stock.

A BIM model for a typical Georgian terraced house type was generated and simulated with consideration of the further dimensions of BIM, 4D BIM (time schedule), and 5D BIM (cost estimation). Using PHPP and DB, the energy demand of the baseline model and proposed refurbished model were investigated phase-by-phase. Based on the examined findings, the proposed model shows how the case study building can be refurbished to achieve the EnerPHit criteria by comparatively assessing the PHPP and DB results.

Briefly, the proposed housing refurbishment model has potential as a solution for the conventional refurbishment projects with utilising BIM tools and EnerPHit standards for the energy-efficient housing refurbishment in the UK to meet the UK's 2050 net-zero targets.

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Living roofs for cooling in hot dry climates

Effects of temperature and swing

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ABSTRACT: This paper discusses the cooling potential of three types of green roofs, insulated, uninsulated, radiant-evaporative. Different rules and schedules were tested for irrigation, water movement through the radiant pipes, fan operation, and cooling with outside air. A total of three monitoring series are discussed in this paper between November of 2017, and June and July of 2018, The three-series developed had different conditions, in terms of outside temperature and swing. Results indicates the uninsulated living roof works best in hot days with high daily swings, the insulated living roof works best on warm days with lower daily swings, and the radiant/evaporative living roof works best in very hot-dry days with high daily swings. Optimum zones for the green roofs are plotted on the Building Bioclimatic Chart.
KEYWORDS: Living Roofs, Cooling, Temperature, Swing, Hot Dry

1. INTRODUCTION

Green roofs have well-known positive effects on buildings such as reducing thermal stress on the roof surface, reducing noise transmission into the building, reducing the urban heat island effect, reducing storm water runoff, and providing habitat for living organisms and generating new ecosystems. In addition, a green roof can also help with the cooling of the building underneath. [1]

Recent studies indicate that the green roof has significant contributions in reducing thermal stress inside, achieving a reduction in temperature from 2.5 ºC to 3.5 ºC, in the summer. [2]. Green roofs can effectively block solar radiation by functioning as a good passive cooling technique, and that these also have the potential to reduce the high surface temperature presented by conventional roofs due to the thermal resistance of the substrate, evapotranspiration, and by effects of foliage shading. Decreasing the amount of flow on the roof, improving the interior thermal conditions and energy demand of the building. [3]

This paper discusses the cooling potential of different types of living roof configurations during summer and fall: A) An insulated living roof with insulation under the planting material, which is the most common configuration; B) An uninsulated living roof thermally coupled to the internal space; and C) A radiant-evaporative cooled living roof with pipes embedded in it and connected to a radiator inside the test cell. These configurations were tested through experiments to establish the most appropriate option for different temperature ranges during the testing period.

All configurations were developed by the authors from previous prototypes [4][5] and tested over the fall of 2017 and the summer of 2018.

2. METHODOLOGY

2.1. Experimental set up

Figure 1: View of the Test Cells with Shade

The test cells are located at the Lyle Center for Regenerative Studies at Cal Poly Pomona University, 40km east of Los Angeles, in California. The climate is hot and dry with an average high August temperature of 31.5˚C and an average low in January of 5.3 ˚C.

All modules are 1.35 m. × 1.35 m. × 1.35 m. with south facing windows and similar envelope characteristics (Fig 1). The design of the roof is the only difference between the cells. All series had night ventilation and shade.

2.1 Monitoring System and Schedule

HOBO type data loggers by Onset computer were used for data collection (Model: U12-012, UX 120-006 M, TMC6-HD). These sensors were installed in the middle of the indoor cells space to monitor dry bulb temperature. Outdoor Dry Bulb Temperature and Relative Humidity were also collected on site. [6] A total of three monitoring series are discussed in this paper between November of 2017, and June and July of 2018.

3. LIVING ROOF SYSTEMS

3.1. Radiant-Evaporative cooled living roof

The radiant-evaporative cooled living roof consisted of a radiant water pipe, water pump, and sprinkler (mist type) on the green roof. (See Fig: 2). The water flow in the pipe and the sprinklers could operate on different schedules, based on their different functions. The sprinkler was typically scheduled to operate during the daytime and reduced the soil temperature with the evaporatively cooled water. The U value of the radiant-evaporative living roof was also 0.282 W/m^2 K. (See Fig: 3).

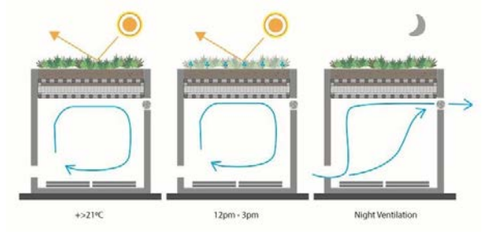
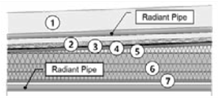


Figure 2: Radiant- Evaporative Living Roof



#	Material	mm	W/mK	U-Value (W/m^{2}K)
1	Soil	130	0.610	0.282
2	Gravel	20	2.000	
3	Water Proofing Liner	1	0.210	
4	Metal Pan	2	44.000	
5	OSB	11	0.130	
6	Glass Wool	21	0.044	
7	XPS	127	0.043	
8	Dry Wall	11	0.180	

Figure 3: Radiant- Evaporative Living Roof U-Value

3.2. Insulated living roof

This living roof had insulation underneath the planting material (See Fig. 4). The U value of the insulated green roof including the wood structure was 0.282 W/m^2 K (See Fig: 5). The conditions inside the insulated living roof are affected by the thermal mass inside the space, the ventilation rates, and the amount of shade in the window.

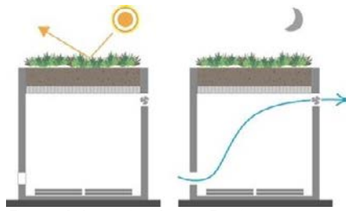
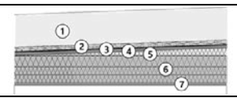


Figure 4: Insulated Living Roof



#	Material	mm	W/mK	U-Value (W/m^{2}K)
1	Soil	130	0.610	0.282
2	Gravel	20	2.000	
3	Water Proofing Liner	1	0.210	
4	Metal Pan	2	44.000	
5	OSB	11	0.130	
6	Glass Wool	21	0.044	
7	XPS	127	0.043	
8	Dry Wall	11	0.180	

Figure 5: Insulated Living Roof U- Value

3.3. Uninsulated living roof

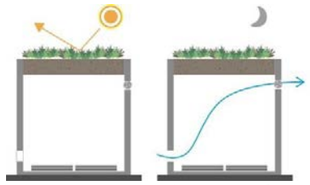
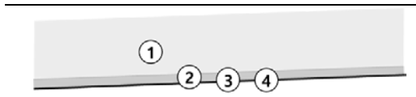


Figure 6: Uninsulated Green Roof



#	Material	mm	W/mK	U-Value (W/m^{2}K)
1	Soil	130	0.610	2.534
2	Gravel	20	2.000	
3	Water Proofing Liner	1	0.210	
4	Metal Pan	1	44.000	

Figure 7: Uninsulated Green Roof U- Value

The uninsulated living roof, the planting material is thermally coupled with the interior of the space via a metal plate under the green roof. There is no insulation between the living roof and the space below. An uninsulated living roof combined with night ventilation cools a space in two ways: during the daytime, the vegetated canopy layer reduces solar gains through shade while the growth medium acts as a heat sink. During the night, the cell is night ventilated and cooled with outside air (See Fig: 6). The U value of the insulated living roof was 2.534 W/m^2 K (See Fig: 7).

4. RESULTS AND DISCUSSION

The three-series developed had different conditions, in terms of outside temperature and swing. The results indicate that each of the three types of living roofs performed best under different conditions. Figure 8 shows the outdoor maximum and minimum temperature values and the swing, together with the best performance of each evaluated green roofs (overlaid in color rectangles. Blue for the radiant-evaporative living roof, green for insulated living roof and fuchsia for uninsulated living roof).

Figure 8: Outdoor maximum and minimum Temperature and swing with the best performing living roof

The length of each rectangle corresponds to the number of days on which the series was made and the width of each rectangle corresponds to the record of minimum-maximum temperature and maximum-maximum temperature inside the cells for each series (the color corresponds to the cell that worked best for each series).

The uninsulated living roof (See Fig. 9) performs best when the outdoor swing is between 11˚C and 26˚C with the outdoor maximum temperature below 40 ˚C, (22˚C to 40˚C), with indoor maximum temperatures between 19˚C and 31˚C. In this series, the insulated green roof performance is worse.

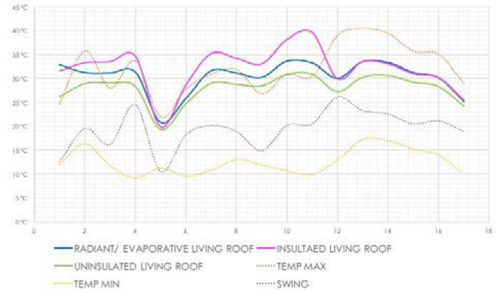


Figure 9: Outdoor maximum and minimum Temperature and swing with the best performing for uninsulated living roof

The insulated green roof (See Fig. 10) performs best when the outdoor swing is lower, between 4˚C and 13˚C, and outdoor maximum temperatures are between 24˚C and 37˚C, with indoor maximum temperatures between 25˚C and 36˚C. However, in this series temperatures inside all cells are very close together. The uninsulated green roof performance, in general, is slightly worse.

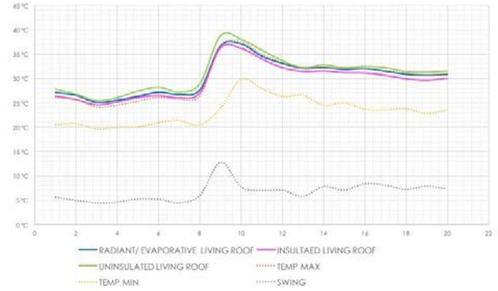


Figure 10: Outdoor maximum and minimum Temperature and swing with the best performing for uninsulated living roof

The radiant- evaporative green roof (See Fig. 11) performs best when the outdoor swing is high, between 8˚C and 24˚C and outdoor maximum temperatures are high between 30˚C and 44˚C, with indoor maximum temperatures between 27˚C and 31˚C, in which thermal comfort can be achieved with air movement. In this series, the uninsulated green roof performance is worse.

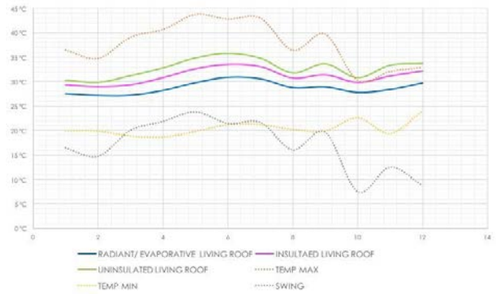


Figure 11: Outdoor maximum and minimum Temperature and swing with the best performing for uninsulated living roof

5. APPLICABILITY OF LIVING ROOF SYSTEMS WITH THE EFFECTS OF OUTSIDE TEMPERATURE AND SWING

To see the results in a more graphical way and understand the performance of the evaluated systems, daily recorded outdoor and indoor maximum temperature and minimum relative humidity were plotted on the Building Bioclimatic Chart superimposed on the psychrometric diagram.

A lower indoor maximum temperature indicates a better cooling performance. The limits of outdoor optimum performance for each system are determined by the relationship between the indoor temperature and the comfort zone for a given exterior maximum temperature. If the indoor conditions are inside the comfort zone, the strategy is assumed as effective for those given conditions of exterior temperature and relative humidity. [4]

The goal of this analysis was to determine the applicability of the different living roof strategies with the effects of outside temperature and swing. Colors were used to represent each option (blue for the radiant-evaporative living roof, green for insulated living roof and magenta for uninsulated living roof), if the indoor temperature was inside the comfort zone (up to 27 °C) when the outdoor temperature was above the comfort zone, the strategy was assumed to be effective to achieve thermal comfort. If the maximum temperature inside the cell was between 27°C and 31 °C this indicated that the strategy was “somewhat effective to achieve thermal comfort”. [4]

Data for the maximum temperature and minimum relative humidity outside and compared with the interior data, were then plotted on the psychometric chart. A total of 49 usable data points was plotted for 49 selected days tested under different conditions taking into account the outside temperature and swing.

5.1 Insulated Living roof

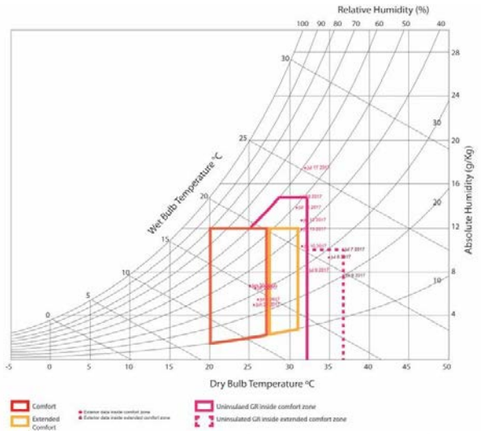


Figure 12: Psychrometric Chart for insulated green roof

Fig. 12 shows the Building Bioclimatic Chart with the data for the cell with the insulated living roof. The area in which the insulated green roof is effective to achieve thermal comfort is indicated by a green line, between 20 °C and 35°C Dry Bulb Temperature, and below 12 g/ Kg of Absolute Humidity. The green dotted line defines the period during which this design strategy is somewhat effective, between 35 °C and 40°C Dry Bulb Temperature, and 12 g/ Kg of Absolute Humidity.

5.2 Uninsulated Living roof

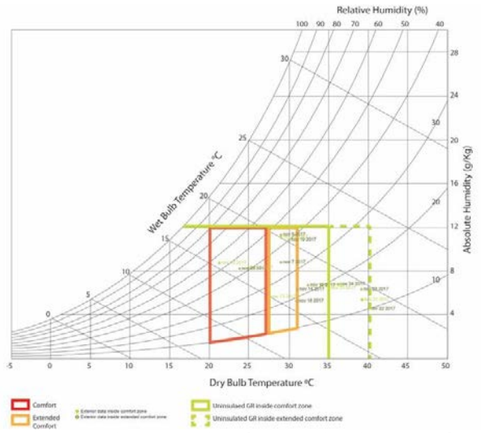


Figure 13: Psychrometric Chart for uninsulated green roof

Fig. 13 shows the Building Bioclimatic Chart with the data for the cell with the uninsulated living roof. The area in which the uninsulated green roof is effective to achieve thermal comfort is indicated by a magenta line, between 25 °C and 32°C Dry Bulb Temperature, below the 60% Relative Humidity curved line and 15 g/ Kg of Absolute Humidity. The magenta dotted line defines the period during which this design strategy is somewhat effective, between 32 °C and 36°C Dry Bulb Temperature and 10 g/ Kg of Absolute Humidity.

5.3 Radiant- Evaporative Living roof

Fig. 14 shows the psychrometric Chart with the data for the cell with the living roof with radiant- evaporative cooling and the lines that define this design strategy in blue. The area in which the radiant- evaporative cooling strategy is effective to achieve indoor thermal comfort is between 25°C and 41°C Dry Bulb Temperature; below the 60% Relative Humidity curved line and 23 g/ Kg of Absolute Humidity. The blue dotted line defines the period during which this design strategy is somewhat effective, between 41 °C and 44°C Dry Bulb Temperature; below the 60% Relative Humidity curved line and 27 g/ Kg of Absolute Humidity.

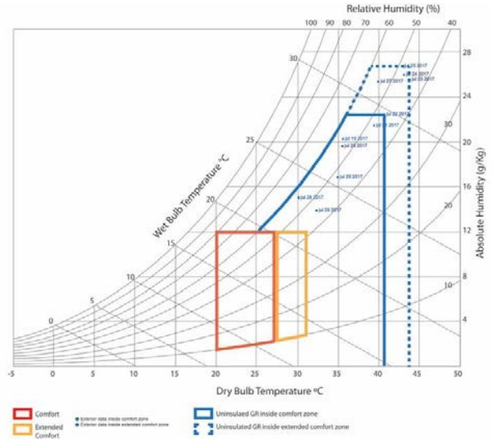


Figure 14: Psychrometric Chart for radiant –evaporative cooling green roof

6. CONCLUSION

Some experiments have been done to establish which configuration is the most appropriate for each temperature range during the analysis period, testing night ventilation, evaporative cooling, radiant cooling, with and without insulation. Figure 15 shows the combination of maximum temperatures and daily swings under which of the different types of living roofs performs best, using the maximum-minimum and maximum-maximum values of the outside temperature in the Y axis and the values of the swing in the X axis.

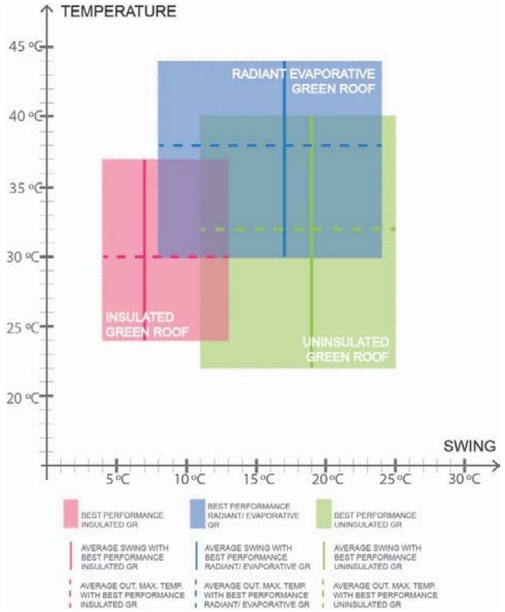


Figure 15: Effects of maximum temperature outdoor and the average swing in the performance for each evaluated living roof

Results indicate that there is no green roof configuration that works best under all outdoor conditions tested. The performance of the living roofs varies as a function of temperature and daily swing which is affected by relative humidity. The uninsulated living roof works best in hot days (32°C average, horizontal dotted green line) with high daily swings (19°C average, vertical green line), the insulated living roof works best on warm days (30°C average, horizontal magenta dotted line) with lower daily swings (7°C average, vertical magenta line), and the radiant/evaporative living roof works best in very hot-dry days (38°C average, horizontal blue line) with high daily swings (17°C average, vertical blue line).

The conditions under which these three green roofs are most effective are defined on the psychometric chart (See Fig. 16). This is a first approximation of what could be a useful design guide to select the most effective living roof for cooling taking to account the outside maximum temperatures and daily swings.

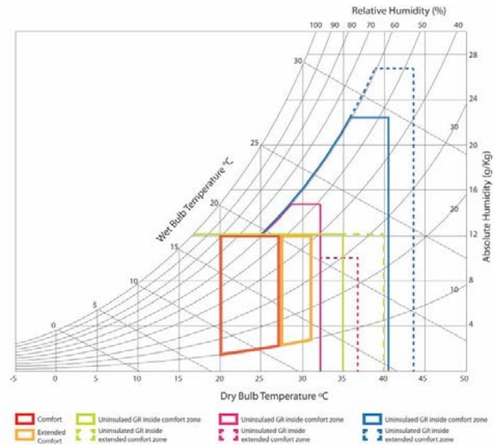


Figure 16: Psychrometric Chart for each evaluated living roof

The "insulated living roof" (See Fig. 12) works best between 20 °C and 35°C DBT, and below 12 g/ Kg of Absolute Humidity. The somewhat effectiveness area is from 35 °C to 40 °C DBT, and below 12g/ Kg of Absolute Humidity.

The "uninsulated living roof" (See Fig. 13) works best between 25°C and 32 °C DBT; below the 60% Relative Humidity and 15 g/ Kg of Absolute Humidity. The somewhat effectiveness area is between 32 °C and 36 °C for DBT and below 10 g / Kg of Absolute Humidity.

The "living roof with radiant- evaporative cooling" (See Fig. 14) works best between 25°C and 41 °C DBT; below the 60% Relative Humidity and 23 g/ Kg of Absolute Humidity. The somewhat effectiveness area is between 41 °C and 44 °C DBT; below the 60% Relative Humidity and 27g/ Kg of Absolute Humidity.

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Glare metrics for a glazed façade with a side view in restaurants

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ABSTRACT: This research examines the visual comfort of daylighting in restaurants with highly glazed windows. Out of 94 restaurants surveyed in Spain, 47% have outside vision problems. Glare indexes are useful to assess this disturbance. The daylight glare probability (DGP) and the daylight glare index (DGI) were chosen. In bright scenes with illuminance high level, the saturation effect of DGP is considerable, and the luminance average is relevant. A modelled scene of a table with two diners and a side view at a hypothetical restaurant was chosen to test the view. The radiance-based tool, Evalglare, was used to set the glare source detection. The results show that the Front View and Out View are sensitive planes for daylight for DGP. In these scenes, the contrast effect is not considerable, but the vertical illuminance is higher than 5000 lux, so the DGP result is somewhat overestimate according to the real perception. A complex fenestration system (CFS) increases glare, but if the side light is controlled and the illuminance is not very high, the DGP works. DGI works only by contrast. For the Out View it is 28%, but the glare source detection is set at 3450 cd/m², which is just uncomfortable.
KEYWORDS: daylight, discomfort glare, visual comfort, radiance, restaurants

1. INTRODUCTION

Daylight is one of the passive resources that we can find in buildings. In addition to energy efficiency advantages, the health benefits of daylighting are well known. For instance, daylight helps to regulate circadian rhythm, reduce stress, improve mood and increase immunological power [1].

Consequently, this study addresses daylighting to enhance the quality of indoor atmospheres, considering building skins. In the hotel industry, lighting accounts for over 10% of energy consumption [2]. Many highly glazed façades create visual comfort problems, which results in increased electric lighting consumption. A total of 94 restaurants were studied in Spain. Almost all the cases have a window with outside views and more than half of the cases have tables adjacent to the outside views, which are the tables in most demand [3]. In addition, 47% have outside vision problems due to direct solar radiation. Under outdoor midday high luminance a large out view can cause visual discomfort [4].

In research on glare metrics, current discomfort glare prediction metrics consider at least the saturation and contrast effects that cause discomfort glare. In laboratory studies, hybrid metrics such as DGP performed best in both investigated ranges of dimmer and brighter scenes. However, further research is needed to extend their applicability to a larger variety of lighting conditions that can be observed in work environments [5].

A literature review revealed that there are few studies on daylighting performance in hotels and restaurants. However, we consider that advanced daylighting systems could be used in this sector.

In a review on sustainable design of renewable energy systems written by Shi and Yit Lin Chew, they explain that in complex fenestration systems (CFS) with prismatic glazing, higher efficiency seasonal shading can be achieved [6]. In the study of Energy Efficient Lighting Strategies in Buildings [7], Tsangrassoulis and Li mentioned that innovative daylighting devices can effectively block solar heat gain but still allow certain amounts of daylight to penetrate the building.

Therefore, this paper discusses the use of glare metrics to enhance the quality of indoor atmospheres, considering a building side view, particularly at restaurants with large, glazed façades [8]. It is considered that a higher glare source luminance is tolerated more in a view direction parallel to windows than in a view facing the windows [9].

2. MATERIAL AND METHODS

Simulation methodology was selected to examine glare indexes. The simulation tools that were used were based on Radiance [10].

After an analysis of all the selected restaurants, the most common pattern of distribution was detected, and two restaurants were chosen to assess the glazed façade system. Various vision tests were carried out, on site and on models (Fig. 1).

Figure 1: The two restaurants selected: left, restaurant in Barcelona; right, restaurant in Bilbao

However, it was not very useful to add a complex fenestration system (CFS) to redirect direct daylight in either of the restaurants. The restaurant in Barcelona has an overhang and the restaurant in Bilbao is oriented to north. Furthermore, if the façade and space composition vary in each restaurant, the daylight effect of the complex fenestration system is difficult to determine (Fig. 2). Therefore, a virtual restaurant prototype was proposed, for simulation and only proposed façade light performance. For the façade, a highly glazed façade system was selected as in most cases, but with an overhang integrated with a prismatic film complex fenestration system (CFS) to balance the shading system, side view and light distribution.

Figure 2: Virtual models of the two restaurants: left, restaurant of Barcelona; right, restaurant of Bilbao

2.1 Glare indexes

Two glare indexes were selected for this purpose: daylight glare probability (DGP) and daylight glare index (DGI) [11]. The DGI is defined [12] as the following Equation (1):

$$DGI = 10 \log_{10} 0.48 \Sigma((L_s^{1.6} \Omega_s^{0.8})/(L_b + 0.07 w_s^{0.5} L_s)) \quad (1)$$

where DGI – daylight glare index (-);

L_s - luminance of source (cd/m²);

Ω_s - solid angle subtended by the source, modified for the effect of the observer's position in relation to the source (sr);

L_b - average background luminance (cd/m²);

w_s - angular size of the source as seen by the eye (sr).

Regarding DGI scaling, when the DGI result is less than 22, it is in the comfort zone; when it is greater than 22, it is in the discomfort zone; and when it is greater than 28, it is intolerable.

In addition, the DGP was defined as the following Equation (2):

$$DGP = c_1 E_v + c_2 \text{Log}(1+ (\Sigma((L_{s,i}^2 w_{s,i})/(E_v^{a1} P_i^2)))) + c_3 \quad (2)$$

where DGP – daylight glare probability index (-);

E_v - vertical eye illuminance (lux);

$L_{s,i}$ - luminance of source (cd/m²);

w_s - solid angle of source (-);

P – position index (-);

c_1 – 5.87 10^{-5}; c_2 – 9.18 10^{-2}; c_3 – 0.16; a_1 – 1.87.

Vertical eye illuminance (E_v) is considered the saturation effect, as the overall illuminance on the eye, and the logarithmic part, the contrast effect, as the adaptation aspect [11].

Regarding DGP scaling, when the DGP result is less than 0.40, it is classified as perceptible or imperceptible. When it is greater than 0.40 it is disturbing, and when it is greater than 0.45 it is intolerable.

The DGP and DGI of the simulated pictures were calculated by Evalglare [13,14]. In addition, a spreadsheet was written to adjust the variables. The DGP works for interior environments with the factor method. In contrast, the DGI works with the threshold method [13,15]. The dimension of the outside view is large, so the surface with high luminance is large [16]. A suitable index should be chosen to obtain acceptable results.

To control this large glare source, "–b", a glare source detection parameter of the Evalglare program was used. There are three options: average luminance detection mode or factor method; task luminance detection mode; or fixed luminance detection mode or threshold method [11]. The pixels that come out as the glare source appear to be coloured. If there is more than one source they will be of different colours, but the type of colour has no meaning. Furthermore, the influence of the "–r" parameter, the diameter for combining glare pixels with a glare source, was checked, and the "-G" parameter for field of view type, as a total or for both eyes.

2.2 Image processing

The "rpict" Radiance program was used to create pictures with fisheye projection. Moreover, for high quality pictures [17], with 4 diffuse reflections and 2048 rays, the "rtrace" parameters used were: -ps 2 -pt .05 -pj .9 -dj .7 -ds .15 -dt .05 -dc .75 -dr 3 -dp 512 -st .15 -ab 4 -aa .1 -ar 512 -ad 2048 -as 1024 -lr 8 -lw .005. In addition, the "falsecolor" Radiance program was used to obtain a false colour image with the parameters of: scale value "-s" 3000 cd/m²; 10 number of contours "-n"; and a logarithmic scale with 3 decades "-log".

Additionally, the "pvalue" Radiance program was used to obtain luminance values of the pictures from the RGB values of each pixel. To achieve this, the following equation (3) had to be applied:

$$L_{px} = 179 (0.213 R + 0.715 G + 0.072 B) \quad (3)$$

where, L_{px} – Luminance of each pixel (cd/m²);

luminous efficacy - 179 (lm/w);

R – radiance in Red wavelength (w/m²·sr);

G–radiance in Green wavelength (w/m²·sr);

B – radiance in Blue wavelength (w/m²·sr).

2.3 Model of the virtual prototype

The virtual prototype was built by the Rhinoceros program to obtain an accurate façade system light contribution [18]. The virtual prototype is a simple room. The façade to be intervened on has a southern orientation. The module was proposed according to a common layout of real restaurants. Therefore, it had a width of 2 m, a depth of 5 m and a height of 2.7 m. It contained a table of 0.7 m x 0.7 m and two chairs of 0.5 m x 0.4 m. There was a person seated at the table, and some food on it. Inside there was a white and highly reflective ceiling; medium reflective plain grey walls; and a low reflective plain grey floor (Fig. 3).

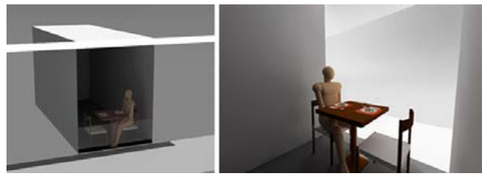

Figure 3: Scene description of a table with 2 diners and a side view at a hypothetical restaurant.

As described in the article entitled Transition Planes for Visual Comfort: Out View with Complex Fenestration System Design at Restaurants in Spain [19], glare is assessed in three work planes, according to one point of view: that of a seated person adjacent to the glazed façade, who is eating with a companion. In the field of view, there are three relevant work planes: Down View, towards table; Front View, towards the person in front; and Out View, towards the outside. These three views were defined because each of them requires concentration and a different view direction, although the concentration level for each is different. To obtain the glare perception of the global field of view (FOV), the geometric mean of three view directions was proposed.

3M™ Daylight Redirecting Film is added to move excess light close to the window and redirect it deeper into the building to increase daylight penetration. However, this material can become a source of glare.

In the simulation, the bidirectional scattering distribution function (BSDF) material type loads an XML (eXtensible Markup Language) file to describe this type of reflection of 3M™. Real arguments on this material may define additional diffuse components that augment the BSDF data. String arguments are used to define the thickness of proxied surfaces and the "up" orientation for the material. The BSDF file was obtained from Chantal Basurto Dávila's PhD as Film3M_145x145_9142012_t.xml [20].

The simulations and the review with the spreadsheet were carried out under CIE Clear Sky with Sun at Barcelona location and Weather Data from EnergyPlus. The simulations were run on 22 July at 10:00 Solar Time and lat. 41.3 N long. 2 E with the "gensky" Radiance program (parameters: 07 22 11 +s -a 41 -o -2 -m -15).

3. RESULTS

The results of the indexes are described below (Fig. 4). The DGP shows that at the selected point of view there is >0.50, intolerable glare. However, the DGI results with about 2000 cd/m² threshold shows 22, acceptable glare (Table 1).

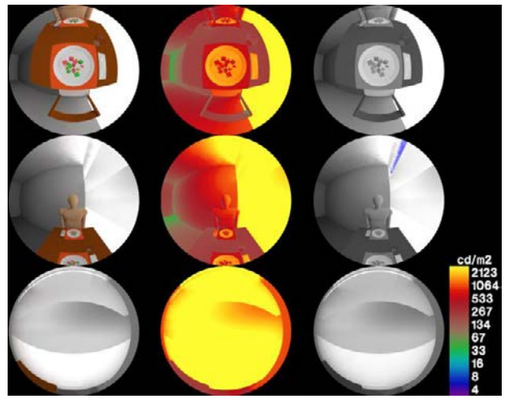

Figure 4: Luminance distributions of view planes of the selected common visual field.

Table 1: DGP and DGI results according to the view planes.

Glare Metrics	Down View (Table)	Front View (Person)	Out View (Outside)	Geometric Mean
Illuminance (lux)	3756	5722	11320	6243
DGP	0.38	0.49	>>0.50	>0.50
Luminance (cd/m²)	2000	2000	3000	2289
DGI	19	21	28	22
Luminance (cd/m²)	6000	6000	6000	6000
DGI	16	15	15	15

The DGP results were obtained by the average luminance or factor method. Every pixel showing a luminance greater than 7 times of the average luminance of the full image is treated as a glare source pixel. This is a default factor. The DGI results were obtained by fixed luminance detection. For the Down View and Front View, every pixel showing a luminance larger than 2000 cd/m² was treated as a

glare source pixel. For the Out View, a pixel larger than 3000 cd/m² was treated as a glare source pixel [11].

According to the results (Table 1), the DGP results for Front View and Out View were overestimated when compared to the real perception, because the perception was not intolerable. In the DGI results, the Front View result was close to the real perception, an acceptable condition. However, the result of the Out View remained high, at just intolerable. Therefore, a test was carried out with 6000 cd/m² limit luminance to reduce the solid angle of the glare source, and then to reduce the DGI result.

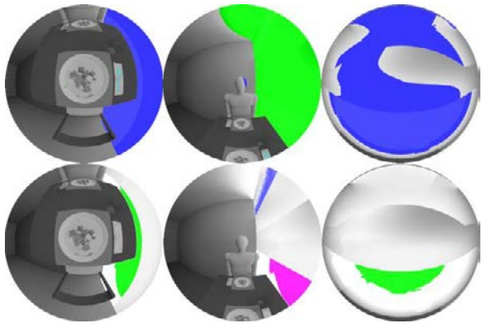

Figure 5: Glare source results with threshold luminance: 3000 cd/m² at the top; and 6000 cd/m² at the bottom. Different colours are only used for detected glare sources.

With fixed luminance for detection glare source (Fig. 5) pixels above 6000 cd/m² (Table 1), the DGI result for the Out View was reduced to just perceptible. This value was closer to the real perception. However, it is strange that the DGI Out View value was a little lower than the Down View value.

Another test was carried out in the task luminance detection mode. The three work planes were related in a different way. In the same view direction, the Front View, the table with a glare source and the Out View with a glare source were compared by task luminance detection (Fig. 6). This mode of glare source detection only makes sense with average luminance mode or the factor method, because the fixed luminance detection does not relate. Therefore, the DGP index was tested.

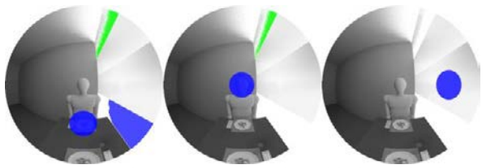

Figure 6: Task Luminance detection with the table, the person in front and the Out View. The tasks are the blue circumferences.

Table 2: Front View with three work planes, table, person in front and Out View, by task luminance detection mode

Glare Metrics	Front View			
	table	person	out	Geometric Mean
Illuminance (lux)	5672	5672	5672	5672
DGP	0.50	0.49	0.49	0.49

The DGP results obtained in the Front View with three work planes, table, person in front and Out View, in task luminance detection mode (Table 2), show that: with the task at the table, the value was higher than for the Down View; with the task at the person in front, the value was the same as for the Front View; and with the task at out, the value was lower than for the Out View. This task luminance detection mode was carried out with the default factor method with luminance greater than 7 times the average luminance of the defined task.

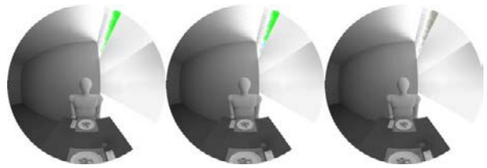

Figure 7: Glare source detection with different diameter "-r" parameter: left, default value, –r 0.2; middle, -r 0.015; and right, -r 0.001.

The results of DGP with different glare source diameters (Fig. 7) were the same, 0.49, the number of detected glare pixels were the same, and the value was also the same. When "-r" was smaller, plus glare sources, the values were a third decimal point higher, but the difference was inconsiderable.

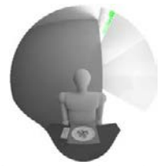

Figure 8: Default glare source detection of Front View with field of view seen by both eyes "-G 2" [21].

The DGP results obtained by default glare source detection of the Front View with a field of view seen by both eyes "-G 2" (Fig. 8) were very similar, 0.49, to the default total field of view: total FOV, 0.494965; and FOV for both eyes, 0.494911. In this situation, the type of view is not relevant.

4. DISCUSSION

In the default DGP results (Fig. 4), in the Down View and in the Out View, the glare source was not detected. This is because the average luminance was not 7 times lower (Table 3). Note that, for this Out View, the DGP index is not the most accurate.

Table 3: Luminance values of three work planes.

Luminance	Down View (tablet)	Front View (person)	Out View (out)
Average	1350	1912	3412
Maximum	6451	18831	6435
Minimum	1426	34	2899
Background	1196	1740	3603

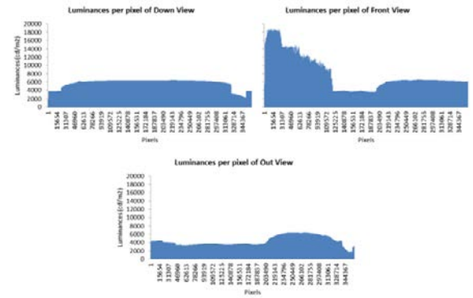

Figure 9: Luminance results per pixel of: left, Down View; centre, Front View; right, Out View.

In Out View the DGP value is very high because, although the contrast effect is low, the vertical illuminance, E_v, is very high. In addition, if the glare source is not detected in the scene, the DGP results are always the same. Therefore, for very bright work planes, it is noted that, according to the activity, for instance in the Out View, the DGP does not work properly, with only a high saturation effect. However, the CFS increases glare with 0.49 under 5722 lux illuminance, but, with only a highly glazed façade and an overhang, the DGP is 0.44 with 4803 lux [19]. Therefore, if the vertical illuminance of this Front View decreases up to 5000 lux the DGP decreases up to 0.45, which is a more reliable result. In this context, with a glare source above 6000 cd/m², the DGI index falls sharply, because the Out View does not have many pixels above this threshold. With this threshold, the Down View DGI result (Table 1) is a point higher, because the L_s of the Down View is slightly higher, at 6279 cd/m² against 6225 cd/m². The solid angle is a bit higher in the Out View, at 0.48 against 0.29, and the Index Position is a little lower, at 2.05 against 2.50.

DGP tends to be higher with less factor "–b" because the solid angle is higher. However, if the mean L_s decreases considerably, DGP does not have to be much higher. This result also depends on the position index. For the variation of luminance threshold "-b" the position index is the same. This is because all the glare source area is in the same position index.

According to the task luminance detection mode, there are differences in the Down View and Out View (Table 2). The result of the Front View is the same (Fig. 6) because the average luminance of the task to detect the glare source is similar to the average luminance of the global scene. However, the average luminance of the table is lower, and consequently 2 glare sources are detected. As the contrast effect is higher, the DGP increases considerably. Increasing the factor "-b" to 8.5, the result decreases, to obtain a fine result. In contrast, in the Out View, the average luminance of the task is higher than the average luminance of the picture. Thus, the glare source is not detected, so the DGP result is similar to the global scene result. This is because in the global scene the contrast effect is small, at 0.000740 (Fig. 6).

Therefore, the possibilities for each work plane are as follows. In the Down View, the perception is that the outside pavement is a bit disturbing, because its luminance is around 6000 cd/m². This light condition is acceptable for both indexes (Table 1). For DGP, perceptible 0.38 is a little low. Decreasing the factor to detect the glare source at "-b 3", the result increases to 0.40, which is on the borderline between perceptible and disturbing. For DGI, the result can also be a bit low, so by reducing the threshold of luminance to 1800 cd/m², the result increases a point to reach just acceptable with 20 to noticeable with 19.

In the Front View is a scene that is borderline for the DGP (Fig. 4) as it has a lot of vision from the outside and CFS contribution. The result is quite high compared to the perception. Increasing the factor "-b" up to 10, the result decreases, but only by a little, to the third decimal place. From this threshold, only the saturation effect applies and the result remains at 0.49. However, the DGI result is fine, at just acceptable with 21. If it were a little higher, setting the threshold at 1200 cd/m², the DGI would reach a higher level of acceptable with 22.

In the Out View with the parameters and conditions used, the DGP result is unlikely to be able to go down. However, it fits better with DGI, with the threshold set between 3000 and 6000 cd/m² (Table 1), and it can be adapted to all levels. With a threshold of 3450 cd/m², best suited for such adaptation, the DGI result is just uncomfortable at 24, and this is closer to the real perception.

5. CONCLUSION

In conclusion, glare indexes can be adjusted considerably. When the parameters of the Radiance-based Evalglare program are set, the results of DGP and DGI can approach real perception.

Front View and Out View are planes that are sensitive to daylight for DGP. In these scenes, the contrast effect is not considerable, but the vertical

illuminance is higher than 5000 lux, so the DGP result is somewhat overestimated compared to real perception. CFS increases glare, but if the side light is controlled and the illuminance is not very high, the DGP works. Nevertheless, for the Down View the vertical illuminance is lower and the contrast is higher by the solid angle of the glare source. In this atmosphere, the DGP results are reasonable. To set the results, glare source detection helps. DGI only works by contrast and the glare source can be adjusted by setting any luminance threshold. However, the effect by level is not detected. Therefore, the parameters of glare indexes should be set and checked according to real glare perception.

The task luminance detection mode was used to test whether it is possible to work on the three defined directions of views at the same time: the Down View, the Out View and the Front View (Fig. 6). However, it allows adjusting, but they do not follow a very logical pattern, since it is compared to the glare source of this view.

In the future, it might be interesting to test whether it is reasonable to compare different glare sources using the same view direction.

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WILL CITIES SURVIVE?

Perceived environmental qualities, satisfaction and mental health in outdoor public spaces of university campus

A survey of university students in China

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ABSTRACT: If there is the association between perceived environmental qualities of campus public spaces and overall satisfaction or mental health among current Chinese university students? To answer this question, an online survey with a structured questionnaire was recently implemented. The survey instrument included five components: perceived environmental qualities, place attachment, overall satisfaction, mental health, and background (socioeconomic & demographic). Two types of campus public space were studied, such as centre and normal public spaces. A multiple mediation analysis was first conducted on the surveyed data. Several findings were achieved as: 1) For both centre and normal public spaces, effects of environmental satisfaction on the overall satisfaction and students' mental health were positive. 2) The effect on the overall satisfaction was partially mediated by the place attachment, while the place attachment can fully mediate the effect on students' mental health. In addition, a paired t-test exposed that the mean scores on facilities in normal public spaces were significantly higher than those of centre public spaces. This study can provide guidance for the design of more psychologically sustainable university campus in China.
KEYWORDS: Environmental Qualities, Mental Health, Students' Satisfaction, Public Spaces, Chinese Universities

1. INTRODUCTION

The World Health Organization (WHO) defines the quality of life (QOL) as "individuals' perceptions of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns" [1]. The QOL among young people is a complex combination of physical health, psychological state, and the relationship with environmental impact, and cultural and social backgrounds [1, 2]. Globally, there are rising rates of mental disorders among university students, such as attention fatigue, anxiety, stress, depression, bad sleep quality, etc [2, 3].

Over the past 10 years, it has been proved that there are significant effects of environmental features of the university campus on the satisfaction and mental health among students and staffs, including greenery, visual qualities, accessibilities, environmental pollution, facilities and maintenance, and safety [4-12]. The greenspace in university campus has been recognized as the most important environmental factor to provide students and/or staffs with a space to relax and conduct social activities [4, 5]. The association between the greenness of campus environment and students' quality of life was well identified by some studies among university students [4, 5, 6, 7]. A cross-region investigation also exposed that there is significant impact of greenspace location on the restoration potential of university campus [6]. A study in Hong Kong [7] explored the application of healing gardens to a compact campus environment and produced suggestions for the improvement of both the existing campus natural space and possible new design in terms of providing a healthier environment for study and leisure. The campus healing garden could also be planned to enhance visual connections between urban and natural environment and facilitate natural ventilation and daylighting utilization [7]. In addition to the effect of greenery, a public space in a university campus with colourful visual arts and seats had a higher restoration effect on the students than the standard setting with basic facilities [8]. Several investigations pointed out facilities and maintenance, and perceived safety can take clear effects on satisfaction in a university campus [9, 10], whilst the level of environmental pollution (e.g., noise, litter) was closely related to dissatisfaction in an outdoor campus area [10]. Similar to a normal urban neighbourhood [11], the accessibility of campus public space has been commonly used as one of critical indicators to justify environmental qualities and students' satisfaction [12].

In addition, the place attachment has been identified as an important social factor affecting satisfaction and mental health among university students [13, 14]. The homesickness can affect students during their studies at university or college, which will receive direct impact from the multiple place attachment [14].

In current China, university students can receive high pressure from their routine life and studies, especially when approaching the end of each semester [15]. However, current design theories and practices of such campuses do not have substantial strategies to address issues relating to students' mental health and wellbeing [12]. Thus, this article aims to conduct an online survey to examine the association of perceived environmental qualities in university campus public spaces, and satisfaction and mental health among current university students.

2. METHODS AND MATERIALS

2.1 Survey design and instrument

This online survey has been approved by the University of Liverpool Ethics Committee (no. 10368). It was conducted through a self-reported questionnaire (Fig. 1), with a total of 76 items. This questionnaire included five components, such as the background information of participants (university students), perceived environmental qualities in campus outdoor public spaces, place attachment at the university location, overall satisfaction for university campus, and students' mental health. The dependent variables were 'Overall Satisfaction' and 'Mental Health', while independent variables included 'Perceived Environmental Qualities', 'Place Attachment', and 'Background'.

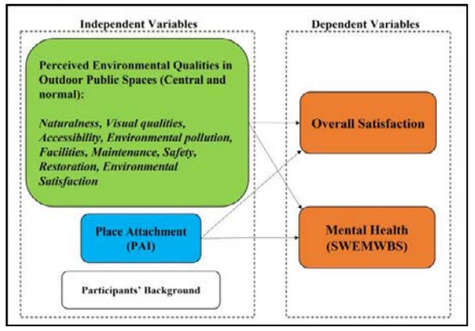

Figure 1: *Research design: independent and dependent variables in the survey.*

'Perceived Environmental Qualities', the largest part, has nine sub sections (domain), including Naturalness (4 Items) visual qualities (5 items), accessibility (4 items), environmental pollution (4 items), facilities (2 items), maintenance (2 items), safety (2 items), restoration (4 items: being away and fascination), and environmental satisfaction (1 item). As the most important instrument, it aimed to collect participants' perceptions on the environment in their campus public spaces. Two typical types of campus public spaces are investigated as: (1) Centre – located at campus centre, with the most important social and cultural status in this university (CPE); (2) Normal – others used for leisure activities (NPE). A 5-item instrument for 'Place Attachment' was developed from the Placement Attachment Inventory (PAI) [16], which was applied to test participants' affective or emotional response to the locations of their universities.

The component of 'Overall Satisfaction' includes three items, such as 'I like this campus; I prefer to walk around in this campus when I feel bored; I would invite friend to visit here'.

The 'Mental Health' was tested using a professional instrument of Short Warwick-Edinburgh Mental Well-being Scale (SWEMWBS) (https://warwick.ac.uk/fac/sci/med/research/platform/wemwbs/about), with seven items to express the status of human mental wellbeing.

The 'Background' has eight questions to gather socioeconomic & demographic information.

2.2 Participants

There were 97 participants who have attended the survey (until 24th January 2022). Three completed questionnaires have been discarded due to the missing information. All valid feedback (n=92; female: 62) was given by undergraduate and postgraduate students who are currently studying in a university (age: 21±3.81). They come from 11 programmes, three of which are engineering (55.43%), art (16.30%) and literature (15.22%). 96.74% of students live in campus accommodations.

2.3 Data analysis

Data description, correlation, mediating analyses, and multiple regression were used to test the association between environmental qualities, overall satisfaction, and mental health (significance level: 0.05) [17]. Statistical analyses were performed using IBM-SPSS (v27).

3. RESULTS

3.1 Correlation analyses

A Pearson correlation analysis was conducted to assess the relationship between the perceived environmental qualities, place attachment, overall satisfaction, and mental health.

In the centre public space, there were positive correlations between nine domains of perceived environmental qualities, and overall satisfaction or mental health:

1). For the overall satisfaction, naturalness (r = 0.537, p<0.01); visual qualities (r = 0.480, p<0.01); accessibility (r = 0.473, p<0.01); environmental pollution (r = 0.498, p<0.01); facilities (r = 0.450, p<0.01); maintenance (r = 0.384, p<0.01); safety (r = 0.415, p<0.01); restoration (r = 0.584, p<0.01); environmental satisfaction (r = 0.603, p<0.01).

2). For the mental health, naturalness (r = 0.200, p>0.05); visual qualities (r = 0.218, p<0.05); accessibility (r = 0.185, p>0.05); environmental pollution (r = 0.268, p<0.01); facilities (r = 0.234, p<0.05); maintenance (r = 0.174, p>0.05); safety (r = 0.199, p>0.05); restoration (r = 0.245, p<0.05); environmental satisfaction (r = 0.283, p<0.01.

In the normal public space, similarly, the positive correlations were found between nine domains of perceived environmental qualities and overall satisfaction or mental health:

1). For the overall satisfaction, restoration (r = 0.437, p<0.01); accessibility (r = 0.488, p<0.01); environmental pollution (r = 0.507, p<0.01); visual qualities (r = 0.614, p<0.01); facilities (r = 0.516, p<0.01); maintenance (r = 0.477, p<0.01); safety (r = 0.328, p<0.01); naturalness (r = 0.585, p<0.01); environmental satisfaction (r = 0.656, p<0.01).

2). For the mental health, restoration (r = 0.279, p<0.01); accessibility (r = 0.328, p<0.01); environmental pollution (r = 0.224, p<0.05); visual qualities (r = 0.281, p<0.01); facilities (r = 0.284, p<0.01); maintenance (r = 0.334, p<0.01); safety (r = 0.215, p<0.05); naturalness (r = 0.232, p<0.05); environmental satisfaction (r = 0.332, p<0.01).

In addition, there were positive correlations between place attachment and overall satisfaction or mental health as: overall satisfaction (r = 0.627, p<0.01); mental health (r = 0.412, p<0.01). Positive correlation was found between overall satisfaction and mental health, (r = 0.393, p<0.01).

Overall, there were strong positive correlations between perceived environmental qualities, place attachment, overall satisfaction, and mental health.

3.2 Effect of perceived environmental qualities on the overall satisfaction

When analysing the surveyed data, the environmental satisfaction for the public spaces was assumed to be an individual predictor for the overall satisfaction, while other perceived environmental qualities (8 domains) and the place attachment were tested as the mediators. Respondent characteristics were controlled for in the mediating analysis.

Table 1 & 2 show the multiple regression analysis in centre and normal public spaces, respectively.

In Table 1, the model 1 indicates that the predicting role of environmental satisfaction for the overall satisfaction in centre public spaces of university campuses was significant (p<0.01). When the nine mediators were entered into the regression (model 2), the direct effect of environmental satisfaction on overall satisfaction decreased, but still presented as significant (p<0.01), while the effect of place attachment was significant (p<0.01). Thus, the indirect effect (95% bias-corrected Confidence Interval) was achieved (INDIRECT, 5000 boot-strapped samples). The analysis expressed that there was partial mediating effect of place attachment (0.0591 0.3663) on the overall satisfaction, with the environmental satisfaction as the predictor.

Table 1: *Multiple regression with overall satisfaction as outcome variable (centre public space).*

Predictors	Model 1		Model 2	
	B	SE	B	SE
constant	-2.00	1.13	-2.99**	1.08
Gender	-0.27	0.13	-0.17	0.13
Age	0.10**	0.04	0.09*	0.03
University status	0.31**	0.09	0.23*	0.09
Programme	0.09**	0.03	0.08**	0.03
Year of study	-0.16*	0.05	-0.11*	0.05
University location	0.13	0.09	0.14	0.09
Hometown	0.14	0.11	0.19	0.11
Environmental Satisfaction	**0.64****	**0.08**	**0.41****	**0.11**
Naturalness			0.02	0.13
Visual qualities			-0.16	0.14
Accessibility			-0.10	0.13
Environment pollution			0.22	0.15
Facilities			-0.12	0.09
Maintenance			-0.11	0.12
Safety			0.23	0.13
Restoration			0.26	0.14
Place Attachment			0.30**	0.09
R^2	0.53		0.66	

*Significant: *. p≤0.05, **. p<0.01*

Table 2 displays that the predicting role of environmental satisfaction for the overall satisfaction in normal public spaces of university campuses was significant (p<0.01) (see model 1). When the nine mediators were entered into the regression (model 2), the direct effect of environmental satisfaction on overall satisfaction tended to go down, but still presented as significant (p<0.01). Meanwhile, the effect of place attachment was significant (p<0.01). The indirect effect (95% bias-corrected Confidence Interval) was achieved (INDIRECT, 5000 boot-strapped samples). Thus, it can be found that there were partial mediating effects of place attachment (0.0178 0.3590) on the overall satisfaction, with the environmental satisfaction as the predictor.

Table 2: *Multiple regression with overall satisfaction as outcome variable (normal public space).*

Predictors	Model 1		Model 2	
	B	SE	B	SE
Constant	-1.79	1.08	-1.87	1.06
Gender	-0.20	0.13	-0.17	0.13
Age	0.13**	0.04	0.10*	0.04
University status	0.24**	0.09	0.20*	0.08
Programme	0.08**	0.03	0.06*	0.03
Year of study	-0.19**	0.05	-0.16**	0.05
University location	-0.01	0.08	0.01	0.08
Hometown	0.08	0.11	0.13	0.11
Environmental Satisfaction	**0.64****	**0.07**	**0.42****	**0.11**
Restoration			-0.11	0.10
Accessibility			0.07	0.12
Environment pollution			0.07	0.12
Visual qualities			0.18	0.17
Facilities			0.04	0.10
Maintenance			0.04	0.14
Safety			-0.12	0.14
Naturalness			-0.08	0.15
Place Attachment			0.29**	0.09
R^2	0.56		0.66	

*Significant: *. p≤0.05, **. p≤0.01*

Furthermore, it is worth noting the role some participants' characteristics played for the overall satisfaction. According to the regression analysis, independent, significant, and predictive effects of age (B=0.10, p<0.01), university status (B=0.31, p<0.01), programme (B=0.09, p<0.01), and year of study (B=-0.16, p<0.05) for overall satisfaction were found in centre public spaces. The same results were achieved in normal public spaces as age (B=0.13, p<0.01), university status (B=0.24, p<0.01), programme (B=0.08, p<0.01), and year of study (B=-0.19, p<0.01).

3.3 Effect of perceived environmental qualities on the mental health

During the analysis of the surveyed data, the environmental satisfaction for the public spaces was assumed to be an individual predictor for the mental health, while other perceived environmental qualities and place attachment were tested as the mediators. Respondent characteristics were controlled for in the mediating analysis.

In Table 3 & 4, the multiple regression with mental health as outcome variable was conducted to test if the environmental qualities can predict the mental health in centre public spaces and normal public spaces, respectively.

Table 3: *Multiple regression with mental health as outcome variable (centre public space).*

Predictors	Model 1		Model 2	
	B	SE	B	SE
Constant	1.99	1.08	1.51	1.11
Gender	-0.10	0.12	-0.04	0.13
Age	0.06	0.04	0.05	0.04
University status	0.17	0,09	0.13	0.09
Programme	0.00	0.03	-0.01	0.03
Year of study	-0.06	0.05	-0.02	0.05
University location	-0.01	0.09	-0.00	0.09
Hometown	-0.11	0.11	-0.06	0.12
Environmental Satisfaction	**0.20***	**0.08**	**0.06**	**0.11**
Naturalness			-0.18	0.13
Visual qualities			0.07	0.15
Accessibility			-0.11	0.14
Environment pollution			0.31*	0.15
Facilities			0.04	0.09
Maintenance			-0.18	0.12
Safety			0.10	0.13
Restoration			-0.00	0.14
Place Attachment			0.25**	0.09
R^2	0.17		0.30	

*Significant: *. p≤0.05, **. p<≤0.01*

In Table 3 (centre public space), Model 1 supports that the predicting role of environmental satisfaction for mental health was significant (p<0.01). When the nine mediators were entered into the regression as mentioned in Model 2, the direct effect of environmental satisfaction on the mental health was proved as insignificant (p>0.05), while the effects of environmental pollution and place attachment were tested as significant (p<0.01). The indirect effect (95% bias-corrected Confidence Interval) was achieved (INDIRECT, 5000 bootstrapped samples). Thus, a full mediating effect was found for the place attachment (0.0386 0.3334), with the environmental satisfaction as the predictor.

Similar regression analysis was presented in Table 4 (normal public space). For Model1, insignificant effect of environmental satisfaction was found on the mental health (p<0.01). When the nine mediators were entered into the regression (Model 2), the direct effect of environmental satisfaction on the mental health was insignificant (p>0.05), while effects of maintenance and place attachment were significant (p<0.01). The indirect effect (95% bias-corrected Confidence Interval) was achieved (INDIRECT, 5000 bootstrapped samples). It can be found that the place attachment can fully mediate the effect of environmental satisfaction on the mental health, with the bias-corrected Confidence Interval of (0.0034 0.2866).

Table 4: *Multiple regression with mental health as outcome variable (normal public space).*

Predictors	Model 1		Model 2	
	B	SE	B	SE
Constant	1.73	1.03	1.91	1.06
Gender	-0.07	0.12	-0.00	0.13
Age	0.07	0.04	0.03	0.04
University status	0.15	0.08	0.12	0.08
Programme	0.00	0.03	-0.02	0.03
Year of study	-0.07	0.05	-0.03	0.05
University location	-0.04	0.08	-0.06	0.08
Hometown	-0.12	0.10	-0.07	0.11
Environmental Satisfaction	**0.24****	**0.07**	**0.18**	**0.11**
Restoration			0.04	0.10
Accessibility			0.07	0.12
Environment pollution			-0.04	0.12
Visual qualities			0.03	0.17
Facilities			-0.03	0.10
Maintenance			0.28*	0.14
Safety			-0.14	0.14
Naturalness			-0.24	0.15
Place Attachment			0.20*	0.09
R^2	0.22		0.33	

*Significant: *. p≤0.05, **. p≤0.01*

3.4 Comparisons of effects of environmental satisfaction in centre & normal public spaces

Table 5 & 6 presents the multiple regression analysis of the predicting effects from CPE-environmental satisfaction, NPE-environmental satisfaction, place attachment and other participants' characteristics for the overall satisfaction and the mental health, respectively.

Table 5: *Multiple regression with overall satisfaction as outcome variable (two types of public spaces).*

Predictors	B	SE	95% CI	
			Lower	Upper
Constant	-2.48*	1.01	-4.48	-0.47
CPE-Environmental Satisfaction	**0.19**	**0.12**	**-0.05**	**0.42**
NPE-Environmental Satisfaction	**0.32****	**0.11**	**0.10**	**0.54**
Place attachment	0.29**	0.08	0.13	0.46
Gender	-0.19	0.12	-0.42	0.04
Age	0.10**	0.04	0.03	0.17
University status	0.26**	0.08	0.10	0.41
Programme	0.08**	0.03	0.02	0.13
Year of study	-0.15**	0.05	-0.24	-0.06
University location	0.08	0.08	-0.09	0.24
Accommodation	0.17	0.21	-0.24	0.57
Hometown	0.18	0.10	-0.02	0.38
R^2	0.60			

*Significant: *. p≤0.05, **. p<0.01*

Table 5 explained a statically significant amount of variance in overall satisfaction, F (11,80) = 13.37, R^2=0.60. NPE-environmental satisfaction and place attachment were significant predictors of the overall satisfaction, (B=0.32, p=0.01 and B=0.29, p=0.00). The same results were achieved at age (B=0.10, p=0.01), university status (B=0.26, p=0.00), programme (B=0.08, p=0.01), and year of study (B=-0.15, p=0.00). However, the predicting role of CPE-environmental satisfaction was found as insignificant for the overall satisfaction, B=0.19, p=0.12, 95%CI [-0.05,0.42].

Table 6: *Multiple regression with mental health as outcome variable (two types of public spaces).*

Predictors	B	SE	95% CI	
			Lower	Upper
Constant	1.66	1.03	-0.39	3.71
CPE-Environmental Satisfaction	**-0.09**	**0.12**	**-0.33**	**0.15**
NPE-Environmental Satisfaction	**0.17**	**0.11**	**-0.05**	**0.40**
Place attachment	0.22*	0.09	0.05	0.39
Gender	-0.05	0.12	-0.28	0.19
Age	0.05	0.04	-0.03	0.12
University status	0.13	0.08	-0.04	0.29
Programme	-0.01	0.03	-0.07	0.04
Year of study	-0.05	0.05	-0.14	0.05
University location	-0.04	0.08	-0.21	0.12
Accommodation	0.24	0.21	-0.18	0.66
Hometown	-0.06	0.10	-0.27	0.15
R^2	0.18			

*Significant: *. p≤0.05, **. p<0.01*

In Table 6, similarly, a multiple regression indicated that this model explained 18.3% of the variance and that there was a significant effect on the mental health, F (11,80) = 2.85, p=0.00. The place attachment was identified as an effective predictor of the mental health (B=0.22, p=0.01), while the effects of environmental satisfaction (CPE and NPE) were insignificant (p=0.45 and p=0.13).

Table 7: *Comparison of perceived environmental qualities between two public spaces (paired t-test, sig. p≤0.05).*

Items	Mean difference (CPE-NPE)	SE	t	p
Restoration	0.09	0.07	1.31	0.19
Environmental satisfaction	-0.03	0.06	-0.52	0.60
Naturalness	0.02	0.08	0.21	0.83
Visual qualities	0.05	0.09	0.55	0.58
Accessibility	0.01	0.09	0.16	0.88
Environmental pollution	-0.05	0.07	-0.75	0.46
Facilities	**-0.16**	**0.07**	**-2.09**	**0.04**
Maintenance	0.04	0.06	0.67	0.51
Safety	-0.09	0.06	-1.39	0.17

A paired-samples t-test (Table 7) was conducted to compare nine domains of environmental quality in centre and normal public spaces. There was significant difference only found between the scores for facilities [mean difference (CPE-NPE) = -0.16, t (92) =-2.09, p=0.04]. Specifically, this could expose that the facility qualities in centre public spaces were lower than those in normal public spaces. There were no significant differences noticed at other environmental features.

4. CONCLUSION

Based on an online survey among current Chinese university students, this article examined the association between the perceived environmental qualities and overall satisfaction or mental health in university campuses, and a possible mediating role of the place attachment.

First, the effect of environmental satisfaction of centre and normal public spaces on students' overall satisfaction has been proved as significantly positive. This effect can be partially mediated by the place attachment, which may be linked to students' affective or emotional response to their university locations. However, other environmental features have no effect on the overall satisfaction.

Second, students' mental health in universities can receive positive effect from the environmental satisfaction of centre and normal public spaces, which can be fully mediated by the place attachment. Except for the environmental pollution and maintenance, other environmental features have no effects on students' mental health.

Third, some confounding variables, such as age, university status, programme, and year of study, can also have a positive effect on the overall satisfaction, but not students' mental health.

Finally, except for the feedback on facilities, there were no significant differences of other environmental qualities (eight domains) between centre and normal public spaces.

As a pilot study, this research has some limitations. Due to the delay of ethics process, the number of participants has not achieved a level as expected (e.g. 200 samples). In addition, it seems that the survey period could be considered as effective factor. These aspects will be further studied in the future work.

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Influence of pavement materials on pedestrians

Extent of impact on simulated, measured and perceived parameters

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ABSTRACT: One of the most common components in an outdoor setting is pavements. Due to its large surface area, the materials covering the ground significantly impact its surroundings. This study will focus on how it affects pedestrian comfort and explore its potential to improve it. A site with different types of pavement materials was selected and various parameters surrounding these pavements were simulated, measured and surveyed. Individual material properties were compared to determine their influence on surface temperature and their surroundings. The study was carried out in Chennai, Tamil Nadu, India which has a Warm & Humid climate. Based on the results, pavement materials have a measurable influence on their surroundings. Although there is a measurable difference in thermal comfort surrounding different pavements, pedestrians don't always perceive the difference. The conditions around each pavement varied with its albedo. The grass had a significantly lower surrounding Air Temperature and Mean Radiant Temperature. Shading reduced surface temperature and improved surrounding thermal comfort.
KEYWORDS: Pavement Material, Albedo, Surface Temperature, Thermal Comfort, User Perception.

1. INTRODUCTION

Pavements have an impact on their users due to the large area they occupy. According to many existing studies, factors such as Thermal & Visual comfort can be improved by careful selection of pavement materials.

The influence of pavements is mainly determined by the way the material absorbs and radiates solar radiation. The properties of surface materials, such as the reflective capacity of solar radiation (albedo), emissivity and heat absorption capacity, affect the surface temperature and consequently the air temperature surrounding. [6]

Various material factors such as albedo, thermal emittance, conductivity, heat capacity, colour and texture affect the extent to which heat is absorbed and radiated. Many studies concluded that the selection of high albedo pavements should be followed as a general rule of thumb. However, certain studies debate the practical efficiency of this concept due to uncertainty on its thermal performance, and the lack of studies on radiant gains due to solar reflectance. Moreover, it was also observed that an increase in albedo and light colours had adverse effects on visual comfort.

2. SCOPE FOR THE STUDY

The potential of pavement materials as a tool to improve overall pedestrian comfort can be explored. Individual material properties need to be studied to determine their extent of influence. This data can be used to design composite pavements. It may also help mitigate Urban heat islands. Knowledge about pavement materials' positive, negative, and negligible effects will help establish better design guidelines. The general lack of focus on user perception needs to be addressed and correlated with measured values to check its practicality. A study in Indian Context for a Warm & Humid climate can help improve the outdoor microclimate and pedestrian comfort.

3. AIM & OBJECTIVES

This research aims to explore the potential of pavement materials as a means to improve pedestrian comfort in Warm & Humid climates, by comparing comfort aspects surrounding different pavement materials in an urban setting.

3.1 Objectives

- To correlate simulations, field studies, and user surveys to determine the extent of the materials' influence on pedestrians.
- To compare each material and its properties and determine which is most suited in terms of thermal, visual and user comfort.
- To determine the positive, negative and negligible effects of pavements.
- Attempt to address uncertainties over the efficiency of high albedo pavements in an urban setting.

3.2 Research Questions

- To what extent do pavements hold an influence on their surroundings and pedestrians? Is the influence positive, negative or negligible?
- Is the effect sufficient enough for pedestrians to perceive it?
- Does high albedo positively or negatively influence pedestrian comfort?

4. LITERATURE REVIEW

Different studies carried out in different regions, climate zones and seasons gave several inferences.

4.1 Studies reporting high influence on thermal comfort by pavement materials

Many studies indicate that pavement materials contribute to modifying air temperature to a good extent. It was stressed that High albedo, light coloured materials maintained low surrounding air temperature. It was also found that roughness had an impact on surface temperature as it decreases albedo compared to that of a smooth texture thus increasing the possibility that a reflected beam strikes the same surface again and is absorbed [1-3, 9].

4.2 Factors affecting the influence of pavements

The extent of their influence depends on the amount of radiation it receives. It holds the most influence in warm climates (high solar radiation). The difference in temperature surrounding pavements is highest in summer and not very significant on rainy days (high cloud cover). When there is no radiation to reflect, the conditions around all pavements are mostly similar [3, 7].

4.3 Pedestrian comfort as perceived by users

Perception studies indicated that users perceive the temperature variations to a certain extent but the difference needs to be significant. High albedo and light materials tend to cause visual discomfort and glare. Most users prefer lower reflectance and are regarded as visually more comfortable [2].

4.4 Studies challenging the existing reports on pavement influence

Conflicting studies suggest that although the use of high-albedo materials may lower air temperature, the reduction is not enough to offset increased radiant loads. As a result, pedestrian thermal comfort may in fact be compromised as the side effect counterbalances the positive effects and worsens the outdoor thermal comfort conditions. The extent of influence is very modest and does not affect pedestrian comfort [4]

Increasing the albedo changes the composition of the total environmental load: reflected sunlight (Shortwave) contributes more to the overall heat flux on a pedestrian, while the longwave component decreases. The reflected radiation falls back on pedestrians/ building facades and worsens their comfort conditions. [5, 8].

4.5 Effect of vegetation on its surroundings

It was accepted by most researchers that vegetation and grass pavements are the best means of achieving pedestrian comfort [1-3, 5-9].

5. SITE SELECTION

An office complex with different pavements & ground cover materials was selected. City: Chennai, Tamil Nadu, India - Warm and humid climate (according to Indian climate zones).

Figure 1, 2, 3, 4 & 5:
Interlocking – grey, Concrete pavement, Interlocking – red, Asphalt & Grass respectively

Table 1:
Properties of the pavements

Properties / Materials	Albedo	Emissivity	Specific Heat Capacity (J/m^3K)	Thermal Conductivity (W/mK)	Density (kg/m^3)
Interlocking grey	0.70	0.90	2.11×10^6	1.51	2100
Interlocking grey - Shaded	0.70	0.90	2.11×10^6	1.51	2100
Concrete	0.40	0.90	2.11×10^6	1.51	2100
Concrete - Shaded	0.40	0.90	2.11×10^6	1.51	2100
Interlocking Dark red	0.30	0.90	2.11×10^6	1.51	2100
Interlocking Dark red - Shaded	0.30	0.90	2.11×10^6	1.51	2100
Asphalt	0.20	0.91	1.94×10^6	0.75	1700
Asphalt - Shaded	0.20	0.91	1.94×10^6	0.75	1700
Grass	0.15	0.95	2.8×10^6	1.1	1400
Grass - Shaded	0.15	0.95	2.8×10^6	1.1	1400

6. METHODOLOGY

The methodology includes simulation analysis (ENVIMET 4.4.5), field studies and a questionnaire survey. The simulated results and field measurements are compared to determine the accuracy of the software. The simulated, measured and survey results for user comfort are compared to determine how pedestrians perceive the effect of different pavements. The detailed steps are shown in Figure 6.

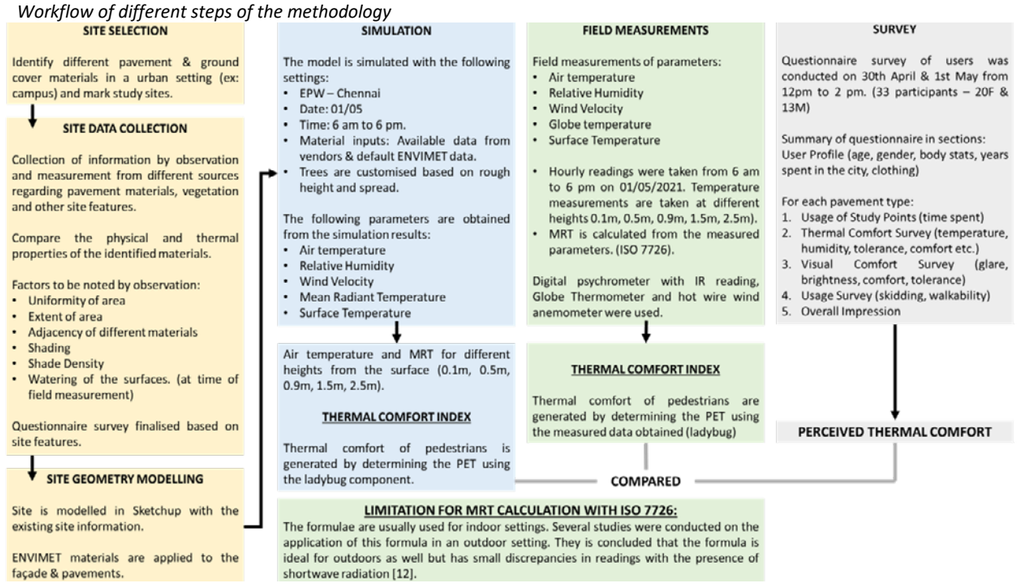
6.1 MRT calculation for measured data

The MRT was mathematically calculated using Equation (1) from the measured parameters.

$$MRT = [(GT+273)^4 + (1.1 .10^8 . v_a^{0.6} / \varepsilon . D^{0.4}) (GT - Ta)^{1/4}] - 273 \quad (1)$$

where *MRT* – Mean radiant temperature (◦C);
T_a - air temperature (◦C);
GT - globe temperature (◦C);
v_a - air speed at the level of globe (m/s).
ε = emissivity of the globe (no dimension);
D = diameter of the globe (m)

Figure 6:
Workflow of different steps of the methodology



7. RESULTS & DISCUSSIONS

Simulation results and field measurements determined the thermal comfort surrounding each pavement numerically. The correlation between measured thermal comfort and perceived pedestrian comfort was determined. The comparison between surface temperature, air temperature and MRT at different heights above the surface for each pavement showed how thermal conditions varied with an increasing distance from the surface. Data obtained from different heights help determine how human activity is affected by reflected shortwave radiation (upper body/ lower body).

7.1 Variation of surface temperature with time

The surface temperature decreases with an increase in albedo. As the day progresses, the low albedo materials heat up faster than others.

Figure 7:
Simulated surface temperature from 6 am to 6 pm

	6AM	7AM	8AM	9AM	10AM	11AM	12PM	1PM	2PM	3PM	4PM	5PM	6PM
Interlocking pavers - grey	26.5	27.6	28.9	31.4	34.0	34.6	34.7	36.5	37.5	36.0	34.8	31.0	27.8
Interlocking pavers grey - Shaded	26.6	26.6	29.2	28.8	29.7	30.8	32.2	31.5	32.0	31.8	28.7	27.5	25.5
Concrete	26.5	27.1	29.0	32.6	34.5	35.2	36.2	38.2	39.0	34.7	34.4	33.1	30.9
Concrete - Shaded	26.4	26.2	27.7	29.3	31.6	32.7	33.1	34.5	35.4	33.0	32.9	31.0	28.1
Interlocking Dark red	27.3	29.3	29.8	33.5	35.3	37.4	38.3	40	42.0	37.8	35.9	34.5	33.0
Interlocking Dark red - Shaded	26.9	27.0	29.3	29.8	31.5	33.5	34.5	35.2	36.0	35.3	32.5	31.9	31.0
Asphalt	27.4	30.0	31.0	34.3	35	35.6	41.1	45.0	45.5	39.7	38.4	37.2	36.0
Asphalt - Shaded	26.7	27.3	30.2	31.2	33.1	34.6	38.7	39.7	42.7	37.7	37	35	33.9
Grass	26.5	26.9	27.1	29.1	34.1	35.2	35.6	36.1	36.7	37.5	31.5	27.3	26.0
Grass - Shaded	26.0	25.5	27.2	27.0	27.3	26.4	25.8	26.9	28.2	29.1	27.2	26.5	25.0

Figure 8:
Measured surface temperature from 6 am to 6 pm

	6AM	7AM	8AM	9AM	10AM	11AM	12PM	1PM	2PM	3PM	4PM	5PM	6PM
Interlocking pavers - grey	29.5	31	34.7	35.8	35.8	36.5	37.1	38	38	38.2	36	35.1	34.4
Interlocking pavers grey - Shaded	28.2	28.8	29.6	29.1	30.5	32.1	33.5	35	35	34.7	31.2	30.4	29.8
Concrete	32	32.7	34.7	36	36.4	37.3	38	39	39	38.5	37.9	36.3	35
Concrete - Shaded	28.9	29.5	29.8	30.8	31.1	32.6	34.2	35	36	35.3	33.3	31.9	30.5
Interlocking Dark red	32	33.1	35	35.6	37	37.6	38.2	39	40	39	38.5	37.3	36.2
Interlocking Dark red - Shaded	31.2	31.5	31.8	33.9	34.4	35.9	36.2	36	37	35.5	34.6	34	32.1
Asphalt	31.5	34.5	35.3	36.5	37.1	37.8	38.5	39	42	39.5	38.5	36.9	36.2
Asphalt - Shaded	31.2	31.3	31.8	32.2	34.5	36.2	36.2	37	37	36.1	34.8	33.4	32.1
Grass	27.6	28	33.6	34	35.2	35.6	36.1	37	38	36.2	33.9	32.9	29.5
Grass - Shaded	27.8	28.6	29.3	29.7	30	30.3	30.8	34	34	34	33.6	30.3	28.2

Asphalt has the highest temperature followed by dark interlocking pavers. For all pavements, the peak temperature is reached at around 2 pm and then starts to drop after 3 pm. High albedo materials get cooler faster compared to asphalt. Overall, the simulated values are slightly lower than that of the measured values except during the peak noon hours. This is likely due to the overestimation of solar radiation for those hours. Shading has a major effect on cooling the surface temperature. Grass is cooler compared to all other pavements.

7.2 Analysing the influence of Surface Temperature

The average and peak surface temperatures are compared to the average and peak air temperature, MRT and PET.

Table 2:
Legend for graphs with their albedo values

1	2	3	4	5	6	7	8	9	10
Interlocking grey	Interlocking grey - Shaded	Concrete	Concrete - Shaded	Interlocking Dark red	Interlocking Dark red - Shaded	Asphalt	Asphalt - Shaded	Grass	Grass - Shaded
0.70	0.70	0.40	0.40	0.30	0.30	0.20	0.20	0.15	0.15

In case of simulated values:

For peak time (2 pm), the air temperature is lower than the surface temperature on most pavements. Average air temperature is almost constant but during the time of peak radiation, the difference in air temperature is much more prominent. The effect of shade is seen at noontime.

Figure 9:
Graph comparing surface temperature, air temperature, MRT and PET. (Simulation – Day Average)

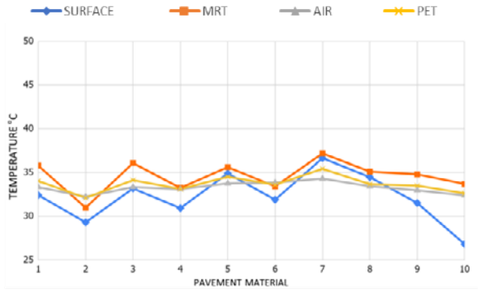
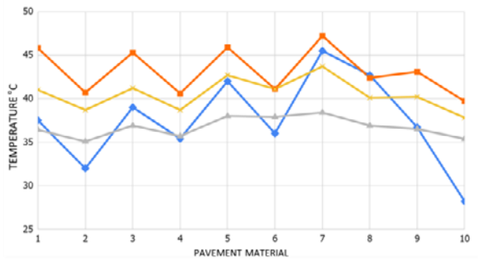


Figure 10:
Graph comparing surface temperature, air temperature, MRT and PET. (Simulation – 2 PM peak time)



In case of field measurement values:

The effect of shade on air temperatures is more prominently seen in the measured values.

Figure 11:
Graph comparing surface temperature, air temperature, MRT and PET. (Measured – Day Average)

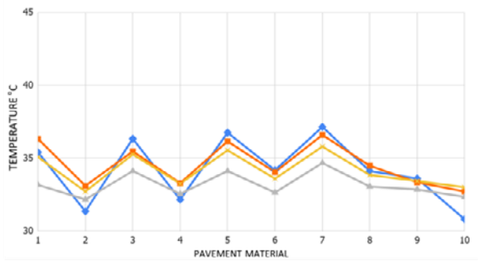
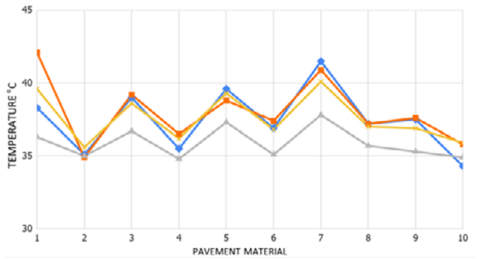


Figure 12:
Graph comparing surface temperature, air temperature, MRT and PET. (Measured – 2 PM peak time)



Overall:

The surroundings are highly influenced by the surface temperature. The influence is most prominent at noontime. Despite having a lower surface temperature, high albedo pavements have a high MRT in both simulated and measured data.

7.3 Variation of Air Temperature and MRT

The variation with time helps determine the rate at which each material absorbs and radiates heat. The variation of values with height helps determine which pavement is ideal for thermal comfort at a pedestrian level – near the shoulder and upper body.

7.3.1 Variation of Air Temperature and MRT with the time of measurement:

Figure 13:
Chart showing the variation of the Measured Air temperature from 6 am to 6 pm.

	Interlocking pavers - grey	Interlocking pavers grey - Shaded	Concrete	Concrete - Shaded	Interlocking Dark red	Interlocking Dark red - Shaded	Asphalt	Asphalt - Shaded	Grass	Grass - Shaded
6:00 AM	27.9	28.5	28.9	29.1	28.8	29.1	29.2	29.2	28.6	28.6
7:00 AM	29.3	29.1	31.0	30.4	29.6	29.9	31.2	30.1	29.5	29.4
8:00 AM	31.6	31.1	33.0	31.6	32.8	31.8	33.7	31.3	32.3	31.5
9:00 AM	33.7	31.5	34.5	32.7	33.9	33.0	34.2	33.3	32.8	32.1
10:00 AM	34.0	32.6	35.0	33.0	34.2	32.8	35.2	33.6	33.4	32.8
11:00 AM	34.4	32.6	35.3	33.2	35.3	33.5	35.7	34.6	34.1	33.7
12:00 PM	34.9	33.9	35.9	34.3	36.2	34.2	36.2	34.8	34.5	33.8
1:00 PM	36.3	34.1	36.5	34.8	36.4	34.8	36.6	35.4	35.0	34.0
2:00 PM	36.3	35.0	36.7	34.8	37.3	35.1	37.8	35.7	35.3	34.9
3:00 PM	35.4	33.9	36.2	34.5	36.6	34.0	37.3	34.4	34.6	33.7
4:00 PM	33.5	33.0	35.2	32.6	35.6	33.4	35.6	33.2	33.5	32.8
5:00 PM	32.6	31.9	33.4	31.2	34.0	31.6	34.5	32.2	33.0	31.8
6:00 PM	31.2	30.8	31.8	31.0	32.9	31.2	33.4	32.1	30.5	31.3

Figure 14:
Chart showing the variation of the Measured MRT from 6 am to 6 pm.

	Interlocking pavers - grey	Interlocking pavers grey - Shaded	Concrete	Concrete - Shaded	Interlocking Dark red	Interlocking Dark red - Shaded	Asphalt	Asphalt - Shaded	Grass	Grass - Shaded
6:00 AM	29.7	29.8	29.9	29.5	29.8	30.2	28.8	29.9	28.0	28.8
7:00 AM	30.8	29.9	30.4	30.8	34.5	31.6	30.7	31.8	31.0	29.6
8:00 AM	33.1	32.0	34.8	33.4	35.4	33.3	34.4	34.1	31.7	31.3
9:00 AM	34.8	33.1	32.4	32.6	33.7	33.2	35.7	32.2	31.8	32.4
10:00 AM	37.6	34.8	33.7	34.5	35.3	35.0	36.7	33.7	34.1	32.7
11:00 AM	36.8	35.7	36.2	35.1	37.5	35.1	35.8	34.9	34.8	33.5
12:00 PM	39.0	32.8	37.4	35.1	34.9	35.4	37.7	35.6	34.8	34.1
1:00 PM	40.4	34.6	39.1	35.8	37.6	36.1	38.9	36.5	34.6	35.0
2:00 PM	42.1	34.9	39.2	36.5	38.8	37.4	40.9	37.2	37.6	35.8
3:00 PM	38.8	35.0	39.1	31.5	41.0	34.9	41.4	37.2	36.9	34.6
4:00 PM	37.1	34.4	37.7	33.1	38.3	35.1	40.3	36.5	35.2	34.2
5:00 PM	37.2	32.3	37.2	33.0	37.6	34.5	37.5	35.9	32.8	33.1
6:00 PM	34.7	31.0	34.2	31.9	35.4	30.6	37.1	32.7	30.2	30.0

All pavements have almost constant surrounding conditions during the early hours of the day due to the absence of radiation. Air temperature and MRT increase in the morning and reaches their peak at noon 2 PM. There are a few inconsistencies in the variation of MRT with time because of fluctuating winds and RH. Asphalt has the highest air temperature as well as MRT. Low albedo materials have high air temperature during evening hours likely due to the diffuse radiation of heat absorbed. It is observed that high albedo materials have a low MRT when there is lesser solar radiation (early morning and evening). It absorbs lesser heat hence there is reduced diffuse radiation. High albedo caused high surrounding MRT during noon. Grass has the lowest surrounding air temperature as well as MRT. Shading improves the surrounding air temperature and MRT. Similar results were found in the simulated data.

7.3.2 Variation of Air Temperature and MRT with the height of measurement:

The general observation is that in this case of high albedo materials, the air temperature gradually increases by 0.1°C with the increasing height. (The temperature would be slightly higher near the upper body). In the case of low albedo materials, the air temperature and MRT decrease with measurement height. (The temperature would be slightly higher near the lower body). The measured globe temperature was highly influenced by the prevailing wind. Hence the MRT also varied. These trends were found in both the simulated and measured data.

Figure 15:
Shows for a select time (2 pm) how measured air temperature varies with height.

	Interlocking pavers - grey	Interlocking pavers grey - Shaded	Concrete	Concrete - Shaded	Interlocking Dark red	Interlocking Dark red - Shaded	Asphalt	Asphalt - Shaded	Grass	Grass - Shaded
0.1 m	36.1	35.0	36.8	34.9	37.5	35.2	38.0	35.7	35.3	34.9
0.5 m	36.2	35.0	36.8	34.9	37.4	35.2	38.0	35.7	35.3	34.9
0.9 m	36.2	35.0	36.8	34.9	37.4	35.0	37.8	35.7	35.3	34.9
1.5 m	36.3	35.0	36.6	34.7	37.2	35.0	37.8	35.7	35.2	34.9
2.5 m	36.5	35.0	36.4	34.6	37.1	34.9	37.6	35.7	35.2	34.9

Figure 16:
Shows for a select time (2 pm) how measured MRT varies with height.

	Interlocking pavers - grey	Interlocking pavers grey - Shaded	Concrete	Concrete - Shaded	Interlocking Dark red	Interlocking Dark red - Shaded	Asphalt	Asphalt - Shaded	Grass	Grass - Shaded
0.1 m	42.0	33.9	39.3	36.6	37.9	37.2	41.3	37.3	37.5	35.8
0.5 m	42.1	33.9	39.3	36.6	38.1	37.4	41.3	37.3	37.5	35.8
0.9 m	42.1	35.4	39.3	36.4	39.4	37.5	41.2	37.2	37.5	35.8
1.5 m	42.2	35.7	39.2	36.6	39.5	37.1	41.0	37.2	37.7	35.8
2.5 m	42.2	35.7	39.1	36.4	39.4	37.6	39.8	37.0	37.7	35.9

8. PHYSIOLOGICAL EQUIVALENT TEMPERATURE

The users were categorised into 5 ensembles based on gender, age, body characteristics and clothing insulation.

8.1 Observations from PETs:

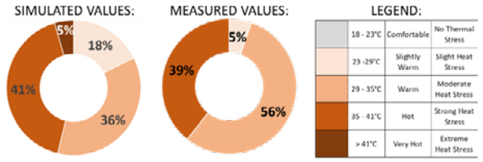
<u>In case of simulated values:</u>

Only slight heat stress is present during the early hours of the day. There is extreme heat stress in certain pavements at noontime. This is likely due to the very high MRT simulated. There are more hours with strong and extreme heat stress when compared to the measured values.

<u>In case of measured values:</u>

The majority of the day including the early hours of the day indicates moderate heat stress. No extreme heat stress is present including during the noon hours.

Figure 17:
Chart showing the distribution of heat stress by percentage hours. (Ex: slight heat stress for 5% of hours)



The variation of PETs with time is similar to the variation of MRT & Air Temperature with time for both simulated and measured PETs. Shading helps reduce the hours of strong heat stress thus improving user comfort. High albedo pavements with shade and Grass pavements have the least hours of strong heat stress.

9. PERCEPTION SURVEY:

Refer to figure 6 for details about the survey.

9.1 Thermal Perception Survey:

Most users indicated that they perceived the temperature to be very hot and intolerable when unshaded. The responses showed similarity to the simulated and measured data but pedestrians seem to be slightly more tolerable towards the heat stress than what was predicted by the PETs. All scenarios were described as very humid. Shaded high albedo pavement and grass were found to be most tolerable with the least thermal stress. However, small temperature differences were not perceived by users.

Figure 18:
Perceived temperature for different pavements

	Very Cool	Cool	Moderate	Hot	Very Hot
Interlocking pavers - grey	0%	0%	0%	21%	79%
Interlocking pavers grey - Shaded	0%	9%	61%	15%	15%
Concrete	0%	0%	0%	27%	73%
Concrete - Shaded	0%	0%	52%	24%	24%
Interlocking Dark red	0%	0%	0%	18%	82%
Interlocking Dark red - Shaded	0%	0%	33%	45%	21%
Asphalt	0%	0%	0%	11%	89%
Asphalt - Shaded	0%	0%	26%	21%	53%
Grass	0%	0%	32%	53%	16%
Grass - Shaded	0%	26%	32%	26%	16%

9.2 Visual Perception Survey:

In terms of visual comfort, the results indicate that high albedo pavements cause most glare and visual discomfort. Dark pavers and grass were visually (aesthetically & comfort) more preferred by users. As expected, shading drastically reduces glare. Users also stated that visual discomfort was more manageable than thermal discomfort.

Figure 19:
Perceived level of glare

	Very low glare				Very high glare
	1	2	3	4	5
Interlocking pavers - grey	0%	0%	3%	26%	71%
Interlocking pavers grey - Shaded	0%	58%	42%	0%	0%
Concrete	0%	0%	0%	50%	50%
Concrete - Shaded	8%	76%	16%	0%	0%
Interlocking Dark red	0%	0%	26%	55%	18%
Interlocking Dark red - Shaded	16%	53%	32%	0%	0%
Asphalt	0%	0%	0%	52%	48%
Asphalt - Shaded	0%	14%	52%	33%	0%
Grass	0%	0%	18%	11%	71%
Grass - Shaded	0%	13%	48%	21%	18%

9.3 Usability Survey:

In terms of usability, all pavements except grass were comfortable to use and did not cause any skidding. 52% of users felt that the grass was uneven and irregular and worsens during rains.

10. CONCLUSION

Based on the results, it can be inferred that pavements influence the surroundings to a high extent when there is high radiation present. In terms of thermal comfort, shaded pavements and grass are most comfortable. For visual comfort, shaded pavements, asphalt and grass are most preferred. For usability, all uniform surface pavements were preferred.

<u>Positive effects of high albedo pavements:</u>

It reduced longwave radiation and cool surroundings when no direct solar radiation. It cools faster than the other pavements and is an ideal pavement with the incorporation of shading.

<u>Negative effects of high albedo pavements:</u>

Caused higher MRT near the upper body away from the ground surface due to reflected shortwave radiation. The reflected shortwave radiation may come in contact with surrounding buildings and add a further increase in heat. It also caused high glare and visual discomfort.

<u>Negligible effects of pavements:</u>

A small reduction in temperature does not impact pedestrian comfort as they don't perceive it. The difference in temperature needs to be prominent for user comfort to improve.

<u>Material Properties:</u>

Asphalt has the lowest specific heat capacity and as expected tends to heat faster than the other materials. Although concrete-based pavements seem to have higher density and conductivity, because of their ability to reflect radiation more, they are cooler compared to asphalt. Hence albedo and surface finish hold more influence compared to other physical properties. Roughness tends to increase the surface temperature as the irregular surface may cause the radiation to reflect back to the surface.

For improving thermal comfort, reducing direct solar radiation seems to be the most effective solution. Surfaces tend to lose their ability to reflect solar radiation over time. Hence the effects are not always long-term as the pavement surfaces are highly prone to wearing off and damage.

The simulations, field measurements and survey results are closely correlated with a few exceptions. ENVIMET tends to underestimate temperatures during the early hours of the day and overestimate the temperature during noontime. In a few instances, ENVIMET tends to underestimate the effect of shading. There are differences in values due to external factors such as vehicles. Survey results indicate that users cannot perceive small variations lesser than 2°C. It is also noted that when compared to PET, users seem more tolerable to heat stress as they have acclimatised to the city's climate.

11. RECOMMENDATIONS

High albedo pavements coupled with good shading are recommended. Concrete pavers can be used with the incorporation of grass while making sure that walking surfaces are regular. This tends to require more maintenance. Shading employing trees and green shelters can cut off direct radiation on pavements.

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Indicators to evaluate the introduction of telework

Post-COVID-19 flexible work arrangements

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ABSTRACT: Although some companies have already discontinued telework, it is expected to have various effects such as the realization of diversified working styles and part of Business Continuity Planning (BCP). Companies need to correctly understand the impact of telework and introduce it in a way that suits their employees. In corporate activities, small INPUT and large OUTPUT are better. It is assumed that telework directly affects energy consumption as the INPUT and workers' performance as the OUTPUT; therefore, these two points can be used as indicators to evaluate the efficiency of telework. This study aimed to determine the impact of telework from the perspective of these two indicators with the help of a case study.
KEYWORDS: Telework, Corporate Activities, Energy, Work Efficiency, Work Environment

1. BACKGROUND AND PURPOSE OF RESEARCH

The percentage of companies implementing telework in Japan increased substantially from 20% or less to 55% or more by April 2020, as shown by the "Questionnaire on COVID-19" survey conducted by Tokyo Shoko Research, Ltd., as described in Fig. 1 [1]. However, the current situation is that approximately 36% of the companies that had introduced telework have already discontinued it. In total, 26% of companies cited productivity reasons for discontinuation of telework.

It is still unclear whether telework is advantageous or disadvantageous for corporate activities, but the introduction of telework is expected to have various effects, as listed in Table 1 [2], and should be utilized even after the COVID-19 pandemic stabilizes. To that end, companies need to correctly understand the impact of telework and introduce it in a way that suits them.

In corporate activities, a small INPUT and large OUTPUT are considered beneficial. It is assumed that telework directly affects energy consumption as the INPUT and workers' performance as the OUTPUT; therefore, these two points can be used as indicators to evaluate the introduction of telework.

Therefore, this study aimed to determine the impact of telework on corporate activities, to find the ingenuity of a hybrid work system with the combined use of office work and telework, and to give specific indicators from these two perspectives through a case study.

In Japan, approximately 90% of people who have experience with telework have worked from home [3]; therefore, in this paper the location of telework is limited to the home.

Figure 1:
Fluctuations in the rate of companies introducing telework in Japan

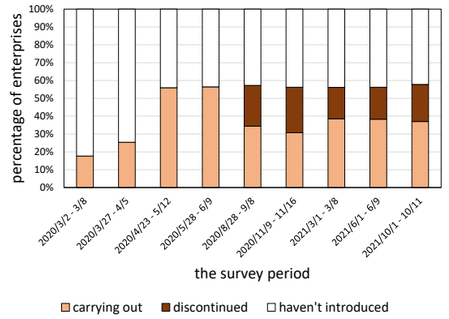


Table 1:
Effects of telework suggested by the Ministry of Internal Affairs and Communications

For society	Work system reform Securing the workforce Improvement in productivity Regional revitalization
For companies	Part of BCP Securing human resources/Preventing employee turnover Part of Business Process Re-engineering (BPR) or Digital Transformation (DX) Cost reduction in offices Improvement in productivity
For workers	Realization of diversified working styles Saving of commuting time

Note: The declining birth rate and the centralization in Tokyo are severe problems in Japan.

2. COLLECTION OF NECESSARY DATA

The case study involves two office buildings of a company engaged in insurance business in Tokyo. The industry has the third highest introduction rate of telework among all sectors [4]. The collected Building Energy Management Systems (BEMS) data, Scope3 data, and Human Resources (HR) data are listed in Table 3. Moreover, a questionnaire was presented to workers, and 82 responses were received from September to December 2021. The details of the questions are listed in Table 4.

In the questionnaire, subjective work efficiency (a method of self-evaluating efficiency of the last month from 0 to 10 points) was used in order to grasp workers' performance. It is Question B11 in the Health and Work Performance Questionnaire (HPQ) Short Form [5]. Considering that the motivation of workers is important, self-evaluation is assumed to have reliability.

To understand the office environment, we used the Comprehensive Assessment System for Built Environment Efficiency - Office Health Checklist (CASBEE-OHC) [6]. It is a subjective evaluation tool focused on the office environment. In contrast, since there is no tool for evaluating the home environment for telework, we extracted and rewrote the questions of CASBEE-OHC that can be applied to the home. To this extent, we made a connection with CASBEE - Wellness Office (CASBEE-WO), which was the source of CASBEE-OHC (Fig. 2).

Figure 2:
An example of creating questions for telework environment

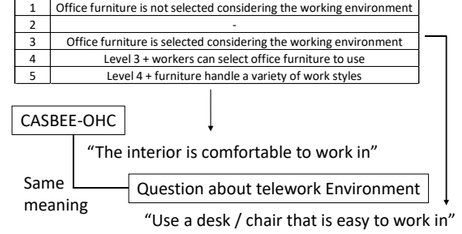


Fig. 3 shows the personal attributes and the status of telework implementation of respondents. Majority of the respondents conducted telework more than three times a week, which was higher than the national average.

3. INPUT: ENERGY CONSUMPTION

Here, we analyze energy consumption in Office D as the indicator of the INPUT. The relationship between telework implementation rate and CO_2 emissions was calculated separately for Office D, commuting, and the workers' homes, and then summed up. It is assumed that the number of workers is 2500, the work is 8 hours a day, and there are 104 days off a year (twice a week).

Table 2:
Overview of Survey Case Study

	Office D	Office T
Place	Chiyoda Ward	Koto Ward
Completion year	1995	2011
Stories	26	15
Total floor area	97 966 m^2	98 805 m^2
Target floor area	59 760 m^2	-

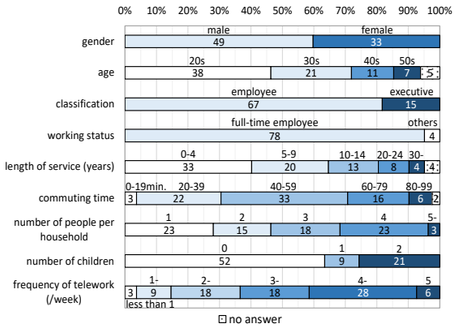
Table 3:
Data obtained in this study

Data to collect	Contents	Target	Term
BEMS	Energy consumption	Office D	2019.4 - 2021.3
Scope3	CO_2 emissions from commute		
HR	Number of workers	Office D, Office T	2021.9 - 12
Questionnaire for workers	Actual teleworking conditions		

Table 4:
Items in the questionnaire

Basic	Gender/occupation/employment status/ office location/length of service/ means of commute/commuting time/ amount of sleep/about family
Office work	Frequency of work/working hours/ working hours per task/ work efficiency/CASBEE-OHC (31 items)
Telework at home	Frequency of work/working hours/ working hours per task/ work efficiency/CASBEE-OHC (23 items)

Figure 3:
personal attributes and the status of telework implementation of respondents



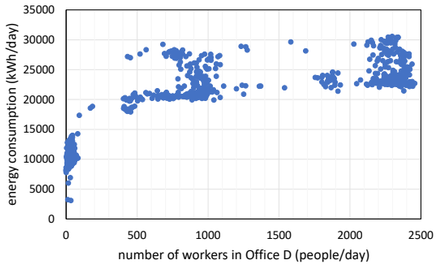
3.1 CO_2 emissions attributable to Office D

The relationship shown in Fig. 4 was obtained by comparing the daily number of workers in Office D obtained from HR data with the daily power

consumption obtained from BEMS data. It can be seen that the transition is logarithmic.

However, since the variation was large, we recounted them into the intermediate period, cooling period, and heating period before approximating each of them using logarithmic functions. In addition, the power consumption when the number of workers was 0, was linearly approximated separately by extracting the data for 100 or fewer workers. Finally, the results shown in Table 5 were obtained.

Figure 4:
Number of workers and energy consumption per day



3.2 CO_2 emissions attributable to commute

Using Scope3 data, CO_2 emissions were calculated by the following Equation (1):

$$E_c = M_t * I_e \qquad (1)$$

where E_c - CO_2 emissions attributable to commute ($kgCO_2$);

M_t - the transportation expenses of commuter passes (yen);

I_e - the emission intensity of each traffic classification ($kgCO_2$/yen).

Table 6 shows the result. By comparing this with HR data, we calculated the annual CO_2 emissions per person.

3.3 CO_2 emissions attributable to homes of workers

We used a trial calculation because only energy directly consumed by doing work is included, although the increased time spent at home associated with telework may result in more energy being consumed by cooking, leisure time usage and so on. The items to be included were decided concerning previous studies, and the daily CO_2 emissions per person were calculated as shown in Table 7 in consideration of individual power consumption and usage rate of each item.

3.4 Relationship between the rate of telework and CO_2 emissions

Table 5:
Rate of telework and CO_2 emissions

Rate of telework	Energy consumption (kWh/year)	CO_2 emissions (tCO_2/year)
0%	7,632,169.12	3,487.90
10%	7,545,053.32	3,448.09
20%	7,447,666.14	3,403.58
30%	7,337,257.65	3,353.13
40%	7,209,800.41	3,294.88
50%	7,059,050.50	3,225.99
60%	6,874,547.51	3,141.67
70%	6,636,681.79	3,032.96
80%	6,301,428.88	2,879.75
90%	5,728,310.26	2,617.84
100%	3,489,798.70	1,594.84

Table 6:
Annual CO_2 emissions attributable to commute

way	I_e (kg CO_2/yen)	E_c (kg CO_2) FY2019	FY2020
train	0.00185	331,900	330,571
bus	0.00471	46,091	46,739
car	0.00331	319	283
summary		378,310	377,594

Table 7:
CO_2 emissions per person due to telework at home

Item/date	Electric power (W)	Kerosene usage (L/h)	CO_2 emissions (kgCO2/day)
PC	41.2	0	
monitor	22.8	0	0.24
printer	4.0	0	
light	19.3	0	0.07
air conditioner	139.0	0	0.56
fan	18.1	0	
heater	208.8	0.099	1.14
4/17 - 5/22	87.3	0	0.31
5/23 - 10/4	244.4	0	0.87
11/8 - 4/16	296.1	0.16	1.45

Figure 5:
Rate of telework and annual CO_2 emissions

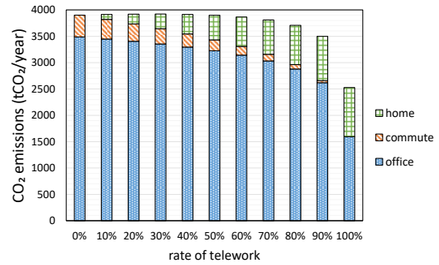


Fig. 5 summarizes the above calculation results. Unless the rate of telework is 50% or more, the emission amount does not fall below the amount at 0%, and even if it is raised to 90%, the reduction effect is only approximately 400 t CO_2/year.

To connect telework to energy consumption reduction, the review of zoning for floor closure, the area reduction, and the introduction of clean energy should also be considered for urban companies with few car commuters.

4. OUTPUT: WORKERS' PERFORMANCE

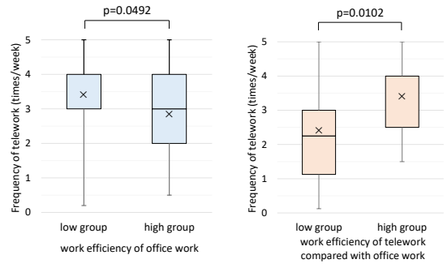
Here, we analyze the relationship between the implementation of telework and workers' performance based on the questionnaire.

4.1 Frequency of telework and work efficiency

First, Fig. 6 shows the difference in the frequency of teleworking. In the graph on the left, those who answered low subjective work efficiency in the office (Less than 5 out of 10 points) comprise the low group, and those who answered high (6 or more out of 10 points) are the high groups. From the figure, the frequency of telework was lower in the high group. On the right side, the group in which the subjective work efficiency at home is lower than that in the office is the low group, and that with high subjective work efficiency is the high group. Contrary to the left graph, here, the high group had a higher frequency of telework. Both differences are 5% significance level.

Therefore, when introducing telework, it is better to prepare an office-like environment that can fully demonstrate high performance and then increase the frequency of telework.

Figure 6:
Work efficiency and frequency of telework



4.2 Work description and work efficiency

Next, we analyzed the work contents. The relationship between the frequency of going to an office and the percentage of time spent on "communication" in Fig. 7 and "knowledge creation" in Fig. 8 is explored. Here, "communication" includes meetings, telephone calls, emails, etc., and "knowledge creation" includes browsing or creating materials and thinking and making decisions.

From these figures, it can be observed that workers who frequently go to an office tend to spend more time on "communication" and those who go to an office less frequently, on "knowledge creation." Therefore, considering the results in Fig. 6, it is necessary to secure sufficient time for "communication" to demonstrate high performance when using office work and telework together. For the same purpose, it is necessary to promote the digitization of work to ensure that the work of "knowledge creation" that can only be done in an office is reduced.

Figure 7:
Frequency of going to an office and the rate of time toward "Communication" in office work

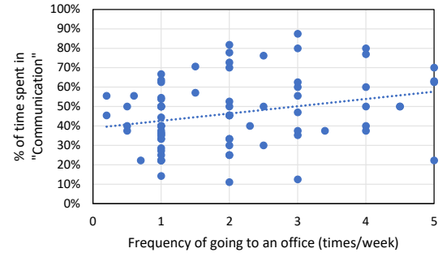
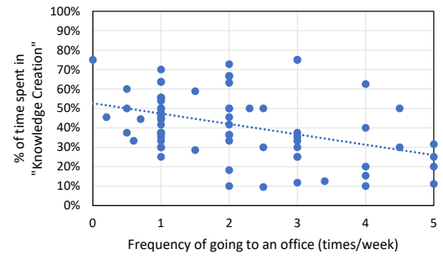


Figure 8:
Frequency of going to an office and the rate of time toward "Knowledge Creation" in office work



4.3 Office environment and work efficiency

Previous study has shown that the total score of the 16 items of the simplified-CASBEE-OHC positively correlate with subjective work efficiency [7], but that trend could not be confirmed this time.

Thereafter, we hypothesized that telework might have changed what workers want in the office environment. We compared between the "low OHC group," the group with the score of 0 to 27 points in the CASBEE-OHC simplified version and the "high OHC group," the group with the score of 28 to 48 points in the CASBEE-OHC simplified version. At this time those with less than 5 points of subjective work efficiency in the office are extracted.

The score of "whether or not there is a refresh lounge" shown in Fig. 9 and "whether or not there is a space to promote conversation" shown in Fig. 10 have differences of 1% significance level, which proved that these two do not contribute to the

improvement of subjective work efficiency. It is assumed that this is because the influence of COVID-19 and the decrease in the frequency of going to an office have made the work to be done in the office clearer, and the need for a space where people can take a break has decreased. It could also be said that they no longer have the luxury of time to take a relaxing break at the office. However, as shown in the previous section, "communication" is important in the office; therefore, instead of reducing such space, the work itself should be devised to ensure that one can work calmly in the office.

Figure 9:
The score of "whether or not there is a refresh lounge" in the office

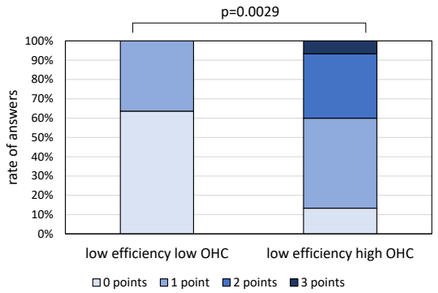
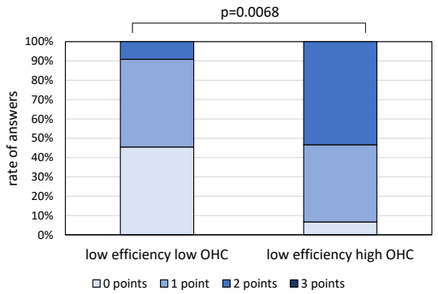


Figure 10:
The score of "whether or not there is a space to promote conversation" in the office

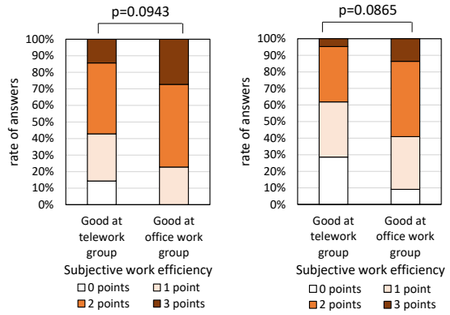


4.4 Home environment and work efficiency

To know the characteristics of workers who are suitable for telework, we grouped them into two: "Good at telework group" those who rated higher subjective work efficiency for telework and "Good at office work group" those who rated higher for office work. Then we compared personal attributes such as age, gender, position, family structure and work environments.

As a result, a 10% significant difference was found with regard to certain items of the home environment such as "uneven brightness" and "outdoor noise," as shown in Fig. 11. It shows that the home environment plays more crucial role in telework than personal attributes such as the presence or absence of children.

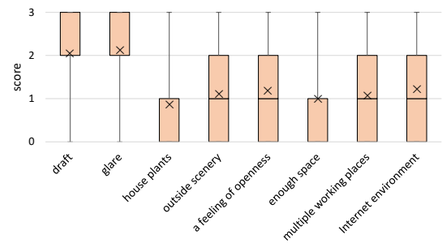
Figure 11:
Work efficiency of telework and home environment (Left: Uneven brightness, Right: Outdoor noise)



In response to this, we conducted a more detailed analysis of the home environment.

Fig. 12 shows the current state of the worker's home environment. Satisfaction with "draft" and "glare" that one could handle was high. In contrast, the low scores were those for factors such as "house plants," "outside scenery," "a feeling of openness," "enough space for work and storage," "multiple working places," and "internet environment." From this, it was found that there was a problem in securing a workspace at home, and that there are few people who voluntarily devise refreshment ideas.

Figure 12:
Each score of the OHC home version (excerpt)



Here, to clarify the elements of the home environment that are particularly important for telework performance, a hypothetical model was created as shown in Fig. 13 based on the items asked in the OHC home version, and covariance structure analysis was performed. First, "physical comfort," " securing workspace," "refresh," and "ICT environment" were given as latent variables that can affect the subjective work efficiency of telework.

Figure 13:
Hypothetical model of home environmental factors and work efficiency of telework

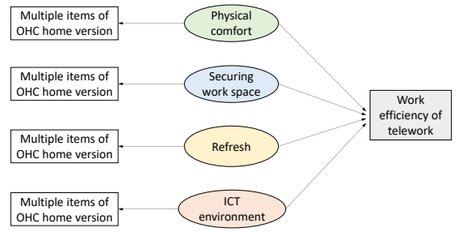


Fig. 14 shows the final model. It proves that for subjective work efficiency of telework, it is important to improve the environment for "physical comfort" such as light, heat, and air environment and "refreshment" such as a feeling of openness and outside scenery.

5. CONCLUSION

We analyzed the degree of impact of working and corporate activities on energy consumption and workers' performance, which can be used as indicators to evaluate the introduction of telework.

In terms of energy consumption, the emission amount at a 50% telework introduction rate falls below those at a 0% rate for the first time. Even if the rate is raised to 90%, the reduction is only about 400 t CO_2/year. From the performance point of view, the subjective work efficiency at home improves when the frequency of telework is high, but it decreases in the office. Therefore, both the office and home environments are important. At home, "physical comfort" and "refreshment" affect subjective work efficiency.

In general, it is difficult to have a positive impact on corporate activities just by introducing telework, but it can be fully utilized depending on the ingenuity.

Since this is a case study of one company, a more comprehensive survey is necessary. Nevertheless, suppose companies determine the purpose and initial costs for telework and consider these two indicators. In that case, it is possible for them to set the rate of introduction of telework and the number of days that each employee can work at home appropriately. It allows them to move forward from the blind abolition of the idea and actually implement telework.

ACKNOWLEDGEMENTS

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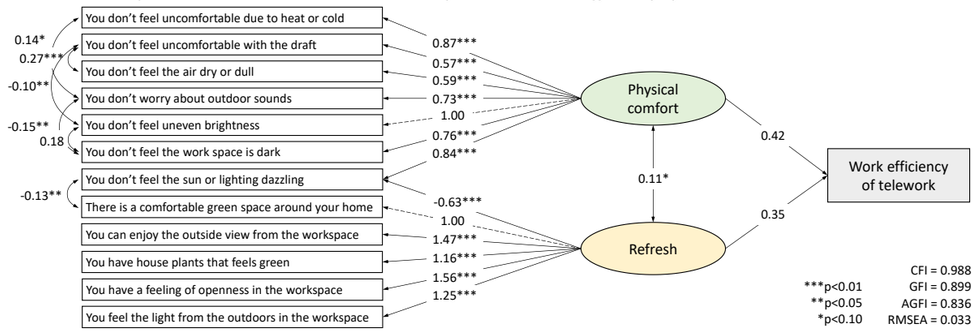
Figure 14:
Causal relationship model between home environmental factors and work efficiency of telework



Natural ventilation as sustainable response to Covid-19
Designing an airborne disease treatment centre in Burkina Faso

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ABSTRACT: Climate, pandemic and energy have often shaped and characterised the transformations of our built environment. Today, under the current pandemic conditions, we are witnessing the ability (or not) of the built environment in responding to such emergency through changes and adaptation. Among many approaches to such changes and emergencies, we are presenting the idea of relying on passive design as a medium to manage and prevent pandemic events. In particular, this paper will focus on the tight relation between natural ventilation and architectural design as a sustainable response to Covid-19. To do so, the work focus on the design of a Severe Acute Respiratory Infection (SARI) Treatment Centre in Dori, Burkina Faso, in collaboration with an International humanitarian Institution. This experience shows the ability of passive design and natural ventilation to deliver a sustainable and resilient health facility able to engage the local community and optimise resources in a context of scarcity. The importance of this work is to inform design guidelines for further health facilities in the same climatic area, as well as to set the example of passive design support the prevention of the spread of air borne diseases.
KEYWORDS: Natural Ventilation, Thermal Comfort, Covid-19, Health Facilities Design, Passive Architecture, Pandemic

1. INTRODUCTION

This work presents a study conducted by a research team from Full: Future Urban Legacy Lab and Denerg - Energy Department from the Polytechnic of Turin in support of Techne Team, the Helpdesk of an International Humanitarian Institution. The relation between natural ventilation and architectural design as a sustainable response to Covid-19 is explored by presenting the work carried out on the design of a Severe Acute Respiratory Infection (SARI) Treatment Center in the city of Dori in Burkina Faso. The work carried out was aimed at providing compositional, technological and environmental solutions to respond to the need to adapt the ventilation health parameters required by World Health Organization (WHO) in a context of energy and material scarcity, by reviewing and modifying a preliminary existing building layout.

2. THE DESIGN CHALLENGES

The team at work was called to design a covid-19 hospital in a context of resource scarcity and hot climate. In Dori, Burkina Faso, the wet season is oppressive and mostly cloudy, the dry season is partly cloudy, and it is sweltering year round. Over the course of the year, the temperature typically varies from 60°F to 107°F and is rarely below 55°F or above 111°F, with a diurnal swing of about 50°F. Moreover, the months of December and January are characterized by important sandstorms.

The context of resource scarcity led the team to rely on the idea to apply passive design approach with a substantial focus on natural ventilation in order to limit, control, and prevent the covid-19 spread. Yet, the air flow rate parameters required for a covid-19 hospital was very demanding, setting the standard of air flow rate for critical patients at 160 l/s. Previous to covid-19, the parameter utilised for air flow rate in case of airborne disease was the of the guideline of tuberculosis transmission setting the ACH between 6 and 12 (Escombe, et.al. 2007).

Alongside this fundamental requirement, other design challenges were:

- To design the patients and medical staff flow layout organization, as it was important to ensure that infected patients, medical staff and untested patients had different and independent paths and circulation within the hospital.
- To review an existing layout design defined by the SARI Manual edited by World Health Organization. A pre-defined layout was produced to ensure that all the medical operational needs were ensured, which set some design boundaries in terms of layout.
- To ensure the satisfaction of the need for a significant thermal control, as relying on natural ventilation called for the thermal control due to the hot temperature throughout the year.
- To embed in the design cultural aspects related to the local people belief, based on the idea that negative presence of bad spirits might enter through the open windows at night time, limiting the ability of ensuring the required air flow change from opening the windows.

3. METHODOLOGY AND DESIGN PROCESS

The methodological approach utilised was to verify the design layout through a number of simulations to ensure natural ventilation throughout the building, as well guarantee thermal comfort and that functional and social needs were met.

Overall Layout and ventilation strategy

The preliminary building layout set by the WHO SARI guidelines was organized in three identical blocks placed perpendicularly among them and containing ten patient rooms each. Each room was divided into three environments: a bedroom hosting the patient, a private bathroom and a small room filtering the access from/to the corridor.

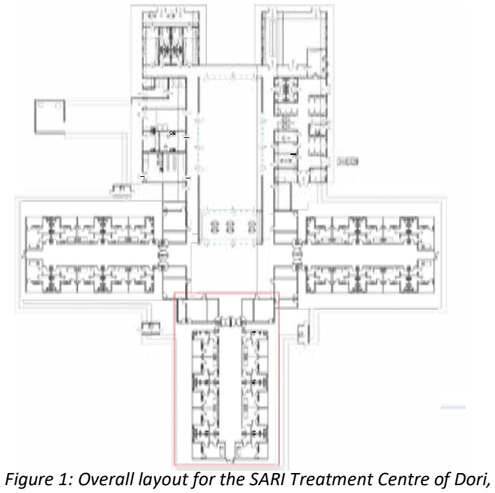


Figure 1: Overall layout for the SARI Treatment Centre of Dori, Burkina Faso (North as oriented)

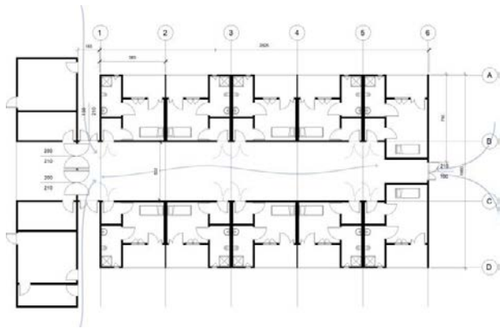
In this context, natural ventilation approach was very critical in terms of resource management, costs savings, and reduction of both energy and maintenance costs. Nevertheless, the design of the natural ventilation strategy was challenging to fulfil the 160 l/s requirements. This fact was particularly valid as it was not possible to exploit the orientation of the building according to primary wind directions, as the predefined layout designed set the overall layout. Indeed, the three blocks were perpendicular to each other and optimizing one orientation would disadvantage another block.

To overcome these limitations, a building adopting a mixed-mode natural ventilation strategy was therefore designed. Some mechanical fans were have been envisioned to ensure the satisfaction of the strict performance limits and to reduce the risk of contaminants infection from the room to the corridor. M0oreover, each of the room environment was then designed with ad-hoc ventilation strategy:

The bedroom environment was envisioned as a cross-ventilation strategy with large openings oriented outdoor and a window over the upper part of the internal wall. The opening over the internal wall was not to communicate with the corridor but with the space under the roof. The different window heights allowed the stack effect to be exploited.

The bathroom was envisioned to be ventilated by a one-sided ventilation strategy, i.e. a unique window over the external wall. The ventilation of this environment was considered not crucial since the time spent by patients and operators within this environment is limited.

The room filtering the access from/to the corridor relied on mechanical ventilation. In detail, a fan was placed in the ceiling to extract exhaust air directly to the outdoor. This solution allowed the environment to have a negative pressure compared to the corridor and avoiding the dispersion of contaminants from the room to the corridor.



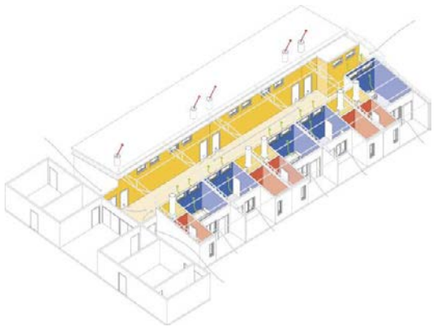


Figure 2: Overall dimensions and ventilation scheme for the SARI Treatment Centre of Dori, Burkina Faso

The patient waiting rooms at the treatment centre entrance was designed in order to decrease the risk of spreading the infection, by proposing a solution based on a punctual ventilation strategy that removes the exhaust air nearby the infection source. The proposed system consists of an air duct connected to the outdoors with air supply holes under the benches used by waiting patients. An exhaust fan is placed above the patient at the ceiling level. It extracts exhaust air directly to the outdoors, removing the infected air from the environment, and helping to decrease the risk of infection.

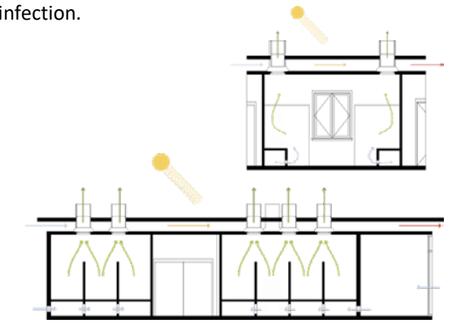


Figure 3 : Ventilation scheme for the patients waiting rooms

Thermal Comfort

The construction system was envisioned with the characteristics of ease construction, modular and easy to maintain. Regardless of the selection of the specific construction system, the proposed design was double roof system to prevent and decrease overheating, supported by a sequence of truss elements to improve the air collection and expulsion. This structural system envisioned, was not the only possible to be utilised, but it was essential to choose a system without structural elements, bearing walls, or other partitions that could block or alter the airflow intake or expulsion, as envisioned in this proposal.

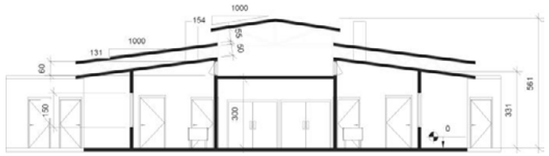


Figure 4: Double system roof and overall dimensions in section

In order to contribute to the thermal control of the building, the proposal suggested to rely on local natural materials such as adobe blocks isolated with natural fibres such as either kenaf (*Hibiscus altissima*), earth blocks and cow-dung, or fonio (*Digitaria exilis*) straw**.** These strategies were put in place during the preliminary design phase as suggestion to contribute to thermal control via passive design. Yet, further test and simulation need to be undertaken in the due course of the architectural and construction design phase.

Social Needs

In the area of Dori, Burkina Faso, there is the belief among the local people that negative spirits might enter into the house at night if windows are left opened. This belief added one more challenge to the ability of designing a space that can be naturally ventilated night and day, through window opening. To overcome this challenge, the team at work designed a system composed by a window and a ventilation vent that could be used at different time of day at night. During the day widows could be opened, while at night window were closed, but vent remained open. This strategy allowed to maintain a minimum airflow at night too, as well as respecting at the same time the social need of protection from bad spirits by having windows closed. The shape and dimensions of the vent have neem simulated and tested to find the optimal option, as it will be presented in the next section 4.

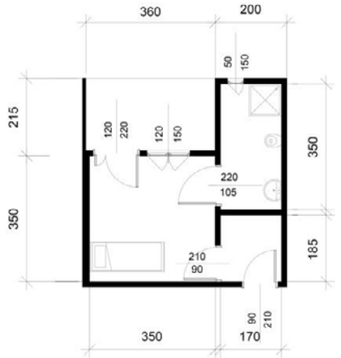


Figure 5: dimension of single room

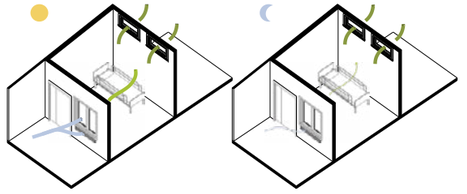


Figure 6: Ventilation system of single room

Natural Ventilation methodology

Natural ventilation is strongly influenced by stochastic processes that can modify the boundary conditions affecting the effective ventilation rate. In particular, two processes were individuated as much critical: the variation of wind intensity and direction and occupant behaviour. On the one hand, Weather conditions can be simulated using the Typical Meteorological Year (TMY) of the selected location, i.e. Dori in Burkina Faso. On the other hand, the occupant behaviour can be forecasted considering the worst condition that is represented by a manual closing of openings during night time (10:00pm to 7:00am) and during dust storm (occurring when wind velocity > 5 m/s) (Nigra, Simonetti, Galleano, Gentile 2022).

To assess the performance of the proposed building design, simulations were undertaken through Energy Plus - Design Builder. This software allowed the ACR of every single environment of the healthcare structure to be calculated on an hourly basis. The software was preferred over CFD due to the dimension of the single room and the time span of analysis. The TMY of Dori airport weather station were used as reference to simulate the climatic boundary conditions. Each room was listed as a single zone (e.g. room 1, room 2…), plus the corridor and the unconditioned environment under the roof were considered as standalone zones. Rooms were further segmented into bedroom, bathroom and divider filtering the access to/from the corridor. Each bedroom was considered occupied by a single patient 7/7 days and 24/24 hours (Nigra, Simonetti, Galleano, Gentile 2022).

Simulations were performed for the entire building. It was necessary to estimate the trend of airborne infection diffusion to further assess the effectiveness of the ventilation strategy. The formula used for calculate the concentration of virus quanta in the room is the following:

$$N_t = \frac{q \cdot I}{n} + \left(N_0 - \frac{q \cdot I}{n}\right) e^{-n \cdot t}$$

Where Nt is the quanta concentration at time t, q is the quanta/hour emitted by an infected person (for our simulations a value of 100 quanta/hour was considered), I is the number of infected people in the room (in this case 1 patient per bedroom), n is the ACR hourly profile resulting from the simulations of Design Builder, N0 is the initial concentration of airborne infection in the room and t is the time in hour. This formula is applied recursively updating the time-varying terms (Nigra, Simonetti, Galleano, Gentile 2022).

Once the quanta of infection in the room is known it was possible to estimate the risk of contagion of a person accessing the room. In this case the formula is:

$$Risk = 1 - e\left(-\frac{p \cdot q \cdot I}{V} \cdot \frac{N_i \cdot t + e^{-N_i \cdot t} - 1 - \left(\frac{N_i \cdot n}{q \cdot I}\right) e^{-N_i \cdot t} + \left(\frac{N_i \cdot n}{q \cdot I}\right)}{N^2}\right)$$

Where Risk is an indicator ranging between 0 (minimum risk) and 1 (maximum risk), p is the infected person respiration rate (0.6 m3/h is a typical value for sedentary activity), V is the volume in m3 and N is the concentration of airborne infection calculated with the formula above mentioned (Nigra, Simonetti, Galleano, Gentile 2022).

The risk increases according to the time spent with an infected subject. In the healthcare facility the major risk involves sanitary personnel taking care of the patient. It is reasonable that the time spent by the sanitary staff into the room is always less or equal than 1 hour. Thus, periods of 1 hour were considered as the most dangerous case. Therefore, the calculation is repeated recursively by varying the boundary condition and setting t = 1 hour (Nigra, Simonetti, Galleano, Gentile 2022).

4. RESULTS

The night time was outlined as the more critical moment for ensuring the required ventilation rate, withstanding, night time is also a moment when the room is occupied by the patient only, not representing a source of risk for the healthcare personnel. For this reason, the trend of contaminant in the environment was simulated to understand the variation of the airborne infection quanta in the room. The calculation was repeated on an hourly basis for the day of the year having the median value of ACR (in TMY occurred on 13-14 September) and the day of the year having the mini- mum value of ACR (in TMY occurred on 03-04 July). Since the night time is the most challenging period the simulation started at 10:00pm when the windows are closed.

After the simulation of the ventilation for the proposed the design, it was possible to see that at night window closure mode the limit of 160 l/s was not respected for the very majority of time, especially in the ward room, mostly due to the need of closing windows at night.

To overcome this limitation and improve the performance of the building, a ventilation vent was introduced, as mentioned in section 3 '*Social Need*'. This vent remains always open even during night time with the exception of the insect screen. Several dimensions of the vent were studied (minimum size with a circular 20 cm diameter and maximum dimension of rectangular 45*120 cm). The latter is a vent with the same width of the outdoor window and the height necessary to ensure minimum ventilation requirement for a significant majority of time. Specifically, even the minimum vent allowed the fresh air flow-rate to be in- creased in the more critical moments, i.e. nights with no wind and windows closed. However, the strict threshold of 160 l/s is overtaken very seldom during night time, especially in the leeward bedroom. This fact is a clear consequence of the stochastic variable affecting natural ventilation design (e.g. human behaviour closing windows and weather conditions causing low wind speed). On the contrary the wider vent solution ensures the respect of the threshold for the very majority of time. Nevertheless, a big opening vent on the outdoor wall may cause dissatisfaction of the patient's expectation (e.g. patient might not appreciate sleeping with low sense of security due to a large opening in the wall).

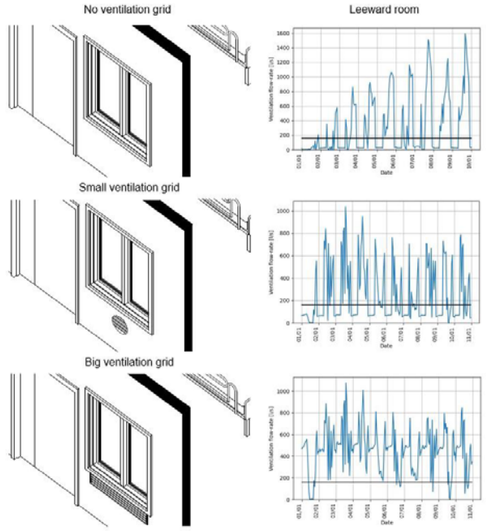


Figure 7: Airflow rate with different types and dimensions of ventilation vents

The different simulation studies prove that natural ventilation results to be efficient for SARI treatment centres in combination with mechanical systems, but design and operational precautions have to be taken.

As previously said, the ward presented in the preliminary project was based on a typical mechanical served facility, and modifications at the plan could be introduced to improve natural airflow by detaching the ward with a filter space. Furthermore, using a symmetric double-shell sloped roof enhances the thermal behaviour of the hospital by preventing excessive indoor heat gain and improving the collection of more fresh air for both the rooms and corridor thanks to the stack effect.

Using double top windows instead of a singular one can facilitate operations and leave a higher degree of airflow control while introducing a grid for night ventilation when the windows are closed can reduce the concentration of viruses in the air. In this case, operational precautions must be taken to prevent the risk of potential staff members infections. Indeed, we suggest that staff should enter the room in the morning for opening the windows only within a limited time span, and then exit before entering again 10 minutes later for visiting the patients.

The limitations of this work are that some of the design assumptions done during this preliminary study (i.e. stack height, materials, natural ventilation performance) will need to be confirmed during the design and construction phase.

5. THE RELEVANCE OF THIS WORK

The relevance of this work is multi-fold. This project has allowed to refine the ventilation and spatial scheme parameters for all SARI Treatment Centres in similar climatic zones and has stimulated interest in the relationship between engineering, architecture and health. Moreover, the designing process undertaken allowed to discuss the passive approach and the importance of natural ventilation in contrasting and managing the pandemic emergency of covid-19. Moreover, the work demonstrated the importance of include the participation of the users in the correct procedure of naturally ventilating the interior spaces, in order to avoid contamination. In this work the user participation was taken into consideration during the design phase in two ways: firstly, by collaorating with a local cultural mediator, and secondly by calculating during the simulation the optimal behaviour of the room occupants in terms of reducing time of exposure to contaminant in a non-ventilated room for a period of time.

The importance of natural ventilation demonstrated on this project allowed to set design and use guidelines also for other context such as school, public buildings, commercial premises, and housing.

6. CONCLUSION

Although the importance of natural ventilation for the health of buildings is not a new concept, the covid-19 pandemic has pushed many sectors – such as the architectural and the health one – to re-discover and re-apply principle of passive design in order to create resilient solutions to emergent problems. In doing so, guidelines for natural ventilation as a medium to manage and prevent airborne diseases have been presented and discussed in this work.

ACKNOWLEDGEMENTS

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The Post-COVID-19 cities. A field study on pedestrian thermal comfort in outdoor urban spaces

The case of the esplanade la Bréche, Constantine, Algeria

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ABSTRACT: Since the outbreak of the COVID-19 pandemic, the daily life that we were used to has changed and many countries around the world still struggling with the effects of the COVID-19 crisis. Therefore, this study, was set out to assess the pedestrian thermal comfort and the usage of outdoor urban spaces in the post-COVID-19 pandemic conditions. To this end, a field study was carried out in the esplanade/terrace la Bréche on a typical hot summer day in the semi-arid climate of Constantine, Algeria. Thus, the micro-meteorological parameters were recorded simultaneously with a questionnaire survey, the respondents were selected randomly in the study area, and then the collected data were statistically analysed and interpreted. The results indicated that summer conditions are less pleasant for pedestrians only 22.5% were satisfied; a strong correlation was found between thermal sensation and thermal satisfaction votes. 75% preferred a change in their thermal environment (lower air temperature), and 90% voted for higher shade. According to the Chi-square test the visiting frequency was statistically independent of the COVID-19 pandemic. Meanwhile, the pedestrian thermal comfort and the planned activities were affected by the pandemic restrictions (face mask and social distancing).
KEYWORDS: COVID-19 pandemic, outdoor urban spaces, Thermal comfort, Thermal perception, Pedestrian

1. INTRODUCTION

21st century is the era of challenges; the inevitable impacts of climate change on the built environment combined with the rapid urbanization growth and high energy consumption affect severely people's life in cities. Furthermore, the unexpected spread of the COVID-19 pandemic has worsened the situation, and become a global issue. Where governments all throughout the world have addressed the public health threat by imposing emergency strategies and new protocols like: hygiene procedures, wearing face masks, social distancing, and extensive quarantine.

According to the review paper of (Sharifi and Khavarian-Garmsir, 2020), early scientific research on the impacts of COVID-19 on cities can be categorised on four main subjects: (1) the environmental aspect (2) socio-economic influences (3) management and governance (4) transportation and urban design. Besides, other papers accentuated on the effects of corona-virus disease 2019 on tourism and hospitality industry (Khan and Hashim, 2020). Moreover, numerous studies (Bhadra et al., 2020; Kadi and Khelfaoui, 2020) have shown the rapid propagation of the COVID-19 pandemic in cities with high population density, the number of infected people increased in crowded urban settlements. Whereas, the findings of a recent paper (Barak et al., 2021) indicated that; the population density was not a key determinant in the spread of the COVID-19 pandemic. Rather the socio-cultural makeup, lifestyle and the urban political conditions have a significant impact on the infection rates in cities. As a result, the outdoor urban spaces which play a vital role in urban life, as an essential environment for human well-being, are now facing new requirements in order to adapt and mitigate the transmission of the corona-virus infection, and remain functional and comfortable at the same time. It has been hypothesised that the new measures enforced by the COVID-19 outbreak have affected the interaction between humans and outdoors urban spaces, in terms of thermal perception and usage. In this regard, the research aimed to explore from a pedestrians perspective, the attitudes in which human behaviour, thermal perception and usage of outdoor urban spaces may have changed during the post-pandemic period. In addition, the study assessed human thermal sensations and preferences and in turn pedestrians comfort in a semi-arid climate to elicit constructive insights for urban design enhancement.

1.1 Context of study

This study represents a part of ongoing research; it was conducted in the old city of Constantine, Algeria, located at (36.17 North and 07.23 East), and characterized by a semi-arid climate. The study area is a part of the open public space the 1st November place, it's an esplanade/terrace commonly known as: *la Bréche,* situated in the central part of the old city (Fig. 1) and (Fig. 2).

Figure 1:
View of the study area esplanade la Bréche.

Figure 2:
Fish-eye photo of the study area esplanade la Bréche.

Note: the image was taken using Canon EOS 5D SLR camera with Canon EF 8-15mm f/4L USM fish-eye lens, upward from a height of 1.1 m at a representative location of the study area.

2. MATERIALS AND METHODS

The study was based on objective measurements (micro-meteorological monitoring) and subjective assessments (questionnaire survey), carried out concurrently in a typical hot summer day 22 August 2021 from 7 a.m. to 7 p.m. (12 hours in a row), to account for the changing climatic conditions during the survey day. Though, we weren't allowed to go beyond 7 p.m. when the climate was supposed to be more cool and comfortable, because of the COVID-19 curfew (8 p.m. – 6 a.m.). To sum up, the collected data were analysed, visualized and interpreted, the following steps explain the adopted approaches in more details.

2.1 Microclimate measurements

The microclimate parameters such as air temperature T_a (°C), relative humidity RH (%), wind speed V_a (m/s), globe temperature T_g (°C) were measured simultaneously using Delta OHM HD 32.3 instrument, The frequency for data recording was set to one hour (1h) interval, the characteristics of the instrument are described in (Table 1). In comply with the technical specifications of (ISO 7726, 1998) and (ANSI/ASHRAE Standard 55, 2010), the measurement instrument was set at 1.1 m above the ground. In order, to evaluate the outdoor thermal comfort the mean radiant temperature T_{mrt} is an essential parameter, it was calculated by means of the recorded data T_a, T_g, and V_a and based on the Equation (1) (Thorsson et al., 2007):

$$T_{mrt} = [(T_g + 273.15)^4 + (1.1 \times 10^8 \times V_a^{0.6}) / (\varepsilon \times D^{0.4}) \times (T_g - T_a)]^{0.25} - 273.15 \qquad (1)$$

where T_{mrt}- mean radiant temperature (◦C);
T_g- globe temperature (◦C);
T_a - air temperature (◦C);
v - air speed (m/s);
ε - globe emissivity (normally 0.95);
D- globe thermometer diameter (50 mm).

Table 1:
Technical characteristics of the Delta OHM HD 32.3 instrument.

Climatic factors	Probe type	accuracy	Range
Air Tempera-ture	Combined probe TP3207.2R, thin film Pt100	Class 1/3 DIN ± 0.1 °C	−40°C to 80°C
Relative humidity	Combined probe HP3217.2R, capacitive sensor	±1.5% (0…90% RH) ±2% (90…100%)	0% to 100%
Wind speed	AP3203.2 Omnidirectional hot wire probe, NTC 10Kohm	±0.2 m/s (0.1÷1 m/s) ±0.3 m/s (1÷5 m/s)	0.1 m/s to 5 m/s
Globe Tempera-ture	TP3276.2 globe thermometer probe (Ø = 50 mm) Pt100	Class 1/3 DIN ± 0.1 °C	−10°C to 100°C

2.2 Questionnaire survey

A questionnaire was conducted to obtain data about subjective thermal perception; and the usage of the outdoor urban spaces in the post-pandemic period. Furthermore, to verify the clarity and feasibility of the survey a pre-investigation was accomplished on 19 August 2021 between (10 a.m.

to 4 p.m.). Ten copies were distributed at the esplanade *la Bréche*, and based on the respondents feedbacks a few corrections were made mainly in the length of the questionnaire to simplify the collect of data and to avoid the dropouts. Thus, this questionnaire is structured in three sections consisted of close-ended questions to finish the survey within 8-10 minutes. It was created based on previous studies (Pantavou et al., 2013; Wang et al., 2017).

In the first section, personal questions such as gender, age, height, weight, type of clothing, and place of residence were requested. Similarly, the survey gathered information about the reasons of the visit in the study site, the sun exposure (under the shade, exposed to sun, and cloudy weather), thermal history (related to outdoor/indoor thermal conditions prior to the survey), and the activity level in the last 15-30 minutes (seating, standing relaxed, walking, and other).

Followed by, enquiry about thermal sensation, and thermal satisfaction developed according to the (ANSI/ASHRAE Standard 55, 2010). In which respondents were asked to rate their current thermal sensation vote (TSV) and thermal satisfaction vote on a seven-point scale (from −3) cold; (-2) cool; (-1) slightly cool; (0) neutral; (1) slightly warm; (2) warm; to (3) hot), and (from −3) very dissatisfied; (-2) dissatisfied; (-1) slightly dissatisfied; (0) neutral; (1) slightly satisfied; (2) satisfied; to (+3) very satisfied) severally. Sensation about humidity (HSV) and wind speed (WSV) were also assessed on a 7 point scale from (−3) very dry; (0) neither dry nor humid to (+3) very humid and from (−3) very low; (0) neither low nor high to (3) very high in turn. In addition, the thermal preferences to different climatic variables (air temperature (T_a), relative humidity (RH), wind speed (V_a), and shade) was reported on the MacIntyre (1980) three-point scale ranging from lower (-1); no change (0); and (+1) higher.

Finally, the third section included questions about the visiting frequency, the planned activities (resting, social and cultural interactions, walking, and other) in the outdoor urban space *la Bréche*, and the effects of wearing face mask during the post pandemic. In order to highlight the effects of COVID-19 restrictions (such us curfew; social distancing; wearing face mask) on the overall usage and the pedestrians' thermal comfort.

2.3 Sample

In this study, the targeted population was pedestrians and visitors of the outdoor urban space *la Bréche*. Forty (40) participants were randomly selected at different survey points and asked to fill out the two-sided questionnaire. It was impossible to asses all the visitors during the survey for several constraints: the hot weather, the time limitation, and people precaution because of the pandemic.

2.4 Data processing

The datasets were inserted and coded in the SPSS software (Statistical Package for the Social Sciences), version 25.0, to perform statistical analysis. However, in this paper the analysis focused on the second section of the survey were the interviewees indicated their thermal sensation/satisfaction/preference votes and the last section about the COVID-19 pandemic effects.

Therefore, descriptive statistics were used to summarise and measure the variability of the micrometeorological data. Then, a nonparametric Spearman correlation was used to determine the relationship between ordinal variables which are: the thermal sensation vote (TSV), humidity sensation vote (HSV), wind sensation vote (WSV), and thermal satisfaction vote. In addition, a simple linear regression was applied to measure the proportion of the variance in the subjective thermal responses (TSV) (dependant variable) that can be explained by air and globe temperature (T_a), (T_g) (independent variables). While a Chi-Square test was applied for nominal variables such as visiting frequency, planned activities, etc. to assess if the COVID-19 pandemic influenced both the pedestrian's thermal comfort and the use of the outdoor urban space *la Bréche*.

3. RESULTS AND DISCUSSION

3.1 Micrometeorological data

The minimum, maximum, mean values, and the standard deviation of the recorded microclimate parameters during one representative day of hot summer conditions are given in (Table 2). The air temperature T_a and the mean radiant temperature T_{mrt} through the field measurements were high 40.9 °C (SD = 6.02) and 79.2 °C (SD = 17.29) respectively, due to the high globe temperature T_g 47.2 °C (SD = 7.98). Regarding the relative humidity RH, the peak was 35.4% and the minimum record was 10.6%. While the average wind speed V_a was relatively high 2.31 m/s (SD = 1.13 m/s), and the highest recorded wind speed was 5.26 m/s, perhaps due to the urban geometry of the esplanade *la Bréche* (open outdoor space with low/mid-rise buildings).

Table 2:
Descriptive statistics of the micrometeorological data.

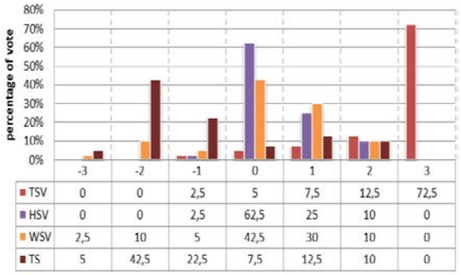
	Minimum	Maximum	Mean	Std. Deviation
T_a (°C)	21.5	40.9	34.7	6.02
T_g (°C)	21.6	47.2	38.26	7.98
RH (%)	10.6	35.4	17.73	7.71
V_a (m/s)	0.98	5.20	2.31	1.13
T_{mrt} (°C)	22.2	79.2	54.06	17.29

3.2 Thermal responses vote

(Fig. 3) displays the percentage distribution of thermal sensation vote (TSV), humidity sensation vote (HSV), wind sensation vote (WSV) and thermal satisfaction vote (TS) of all interviewees. For (TSV) hot (+3), warm (+2) and slightly warm (+1) were prevalent with 72.5%, 12.5%, and 7.5% votes, 5% felt neutral and the rest 2.5% were slightly cool. Though, in terms of humidity (HSV) and wind (WSV) sensation votes, the majority expressed neutrality (0) with 62.5% for neither dry nor humid and 42.5% for neither low nor high. Followed by, slightly high wind speeds (+1) with 30% votes and 25% for slightly humid (+1). Otherwise, a total of 70% votes (including very dissatisfied, dissatisfied and slightly dissatisfied) were conveyed by the respondents, only 10% were satisfied (+2) and 12.5% slightly satisfied (+1) with their thermal conditions. It was expected to detect a high level of thermal stress, since the study area was exposed to intensive solar radiation, merely few respondents were resting under tree shade.

Considering the result of the Spearmen's correlation test between TSV, HSV, WSV, and thermal satisfaction TS shown in (Table 3). It can be concluded that a strong negative relationship at the level of significant 1% between the variables TSV-HSV and TSV-TS with a coefficient of correlation r_s= -0.833 (*p*-value=0.000) and r_s= -0.815 (*p*-value=0.000) correspondingly.
This indicates that the two variables TSV-HSV tended to change in inverse directions. Likewise, the thermal sensation vote TSV decreased when the thermal satisfaction TS increased, and vice versa. It can be explained by the fact that the majority of the respondents were thermally dissatisfied, whereas only 10% were satisfied and 7.5% voted for neutral (Fig. 3). Yet, there's a moderate correlation of r_s=0.455 (*p-value*=0.003) between the thermal satisfaction TS and WSV, reveals that when wind sensation vote WSV increased the thermal satisfaction increased too. Furthermore, at the level of significance 5% the Spearman's correlation test expressed a weak association between WSV-HSV with a coefficient of r_s= 0.344 (*p*-value=0.0300).

Figure 3:
Percentage distribution of TSV, HSV, WSV, TS.



Note: thermal sensation vote (TSV), humidity sensation vote (HSV), wind sensation vote (WSV), and thermal satisfaction vote (TS).

Figure 4:
Scatter plot of (TSV) versus Ta and Tg.

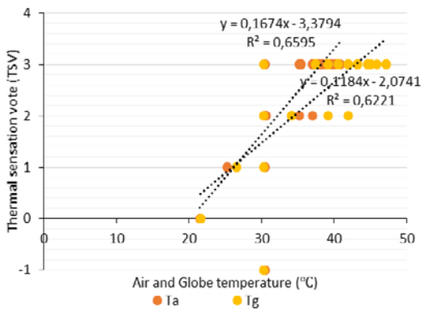


Table 3:
Spearman's correlation test of thermal responses votes.

			TSV	WSV	HSV	TS
Spearman's rho	TSV	Correlation Coefficient	1.000	-0.526**	-0.833**	-0.815**
		Sig. (2-tailed)	.	0.000	0.000	0.000
		N	40	40	40	40
	WSV	Correlation Coefficient	-0.526**	1.000	0.344*	0.455**
		Sig. (2-tailed)	0.000	.	0.030	0.003
		N	40	40	40	40
	HSV	Correlation Coefficient	-0.833**	0.344*	1.000	0.657**
		Sig. (2-tailed)	0.000	0.030	.	0.000
		N	40	40	40	40
	TS	Correlation Coefficient	-0.815**	0.455**	0.657**	1.000
		Sig. (2-tailed)	0.000	0.003	0.000	.
		N	40	40	40	40

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

A simple linear regression was used to define the equations that relate the thermal conditions of the respondents and the measured Ta and Tg. (Fig. 4) illustrates the scatter diagrams of TSV versus T_a and T_g, where the simple linear regression equations are expressed as:

$$y = 0.1674x - 3.3794 \quad (R^2 = 0.6595) \qquad (2)$$
$$y = 0.1184x - 2.0741 \quad (R^2 = 0.6221) \qquad (3)$$

where R^2 - the coefficient of determination.

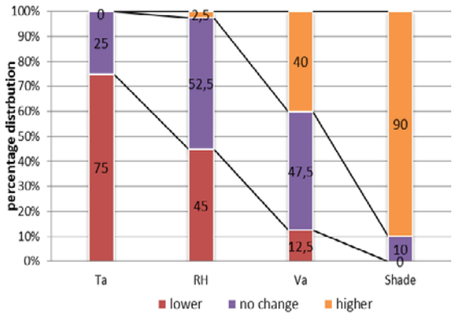
The coefficient of determination (R^2 = 0.6595) from equation (2) indicate that 66% of the variance in subjective thermal sensation was predicted by air temperature, while 62% of the variance in thermal sensation can be explained by globe temperature. The results are in agreements with a previous study conducted in Mediterranean environment (Nikolopoulou & Lykoudis, 2007). Where air temperature was the most significant microclimate parameter that influences thermal sensation and consequently the use of the outdoor open spaces.

3.3 Thermal preferences vote

The percentage distribution of thermal preferences (TPV) (Fig. 5), was based on the MacIntyre (1980) three-point scale, ranged from (-1) lower, (0) no change and (+1) higher. The respondents were asked to give their opinion on thermal preferences for the 4 variables (T_a, RH, V_a, and shade).

Around 75% preferred lower T_a, and 90% favoured higher shade, a minority 10% voted for no change in shade. Whereas 52.5% voted for no change in RH, and 40% preferred higher wind speed V_a. This indicates that summer conditions especially during heat waves are less pleasant for pedestrians; almost all preferred a change in their thermal environment and favoured a stay under tree shade or urban shelters.

Figure 5:
Percentage distribution of pedestrian's thermal preferences TPV.



3.4 The COVID-19 pandemic effects

In the study area, over the half of those surveyed (65.0%) reported that they are no longer visiting the esplanade *la Bréche* as before the curfew and social restrictions. Then again, 72.5% responded that the social distancing during the post pandemic period influenced their planned activities. Only 22.5% of the interviewees conveyed that they feel thermally comfortable wearing the face mask in the outdoor space *la Bréche*. Whereas 77.5% contemplated that wearing a face mask contributed to thermal discomfort as conveyed in (Table 4).

Table 4:
Frequency and percentage distribution of the visiting frequency, planned activities and pedestrian's thermal comfort.

		Frequency	Percent
Visiting frequency	Yes	14	35.0
	No	26	65.0
	Total	40	100.0
Planned activities' adjustment	Yes	29	72.5
	No	11	27.5
	Total	40	100.0
Pedestrian's thermal comfort	Yes	9	22.5
	No	31	77.5
	Total	40	100.0

Table 5:
Chi-square test for the visiting frequency, planned activities and pedestrian's thermal comfort.

	Visiting frequency	Planned activities	Pedestrian's thermal comfort
Chi-Square	3.600[a]	8.100[a]	12.100[a]
df	1	1	1
Asymp. Sig.	0.058	0.004	0.001

a. 0 cells (0.0%) have expected frequencies less than 5. The minimum expected cell frequency is 20.0.

In order to test if there is a significant difference between the proportions of responses, the Chi-Square test has been used. The results mentioned in (Table 5) showed that the proportions of responses are statistically different according to their chi-Square values: X^2=8.100 (*p-values*=0.004), X^2=12.100 (*p-values*=0.001), respectively for the planned activities, and pedestrians' thermal comfort. Unlike the visiting frequency, the difference is statistically not significant with X^2=3,600 (*p-values*=0.058). Overall, the COVID-19 pandemic affected two variables (planned activities, and pedestrians' thermal comfort) so has a highly probable influence on the pedestrian's thermal comfort and the usage of the outdoor urban space *la Bréche*.

These results concur with a recent study (Morabito et al., 2020), who reported that in hot environment, the thermal discomfort due to the use of protective face mask won't be local but it will affect the whole body, and consequently the human thermal sensation and body heat stress.

4. CONCLUSION

The present study tried to shed light on the effect of COVID-19 pandemic on pedestrian's thermal comfort and the usage of outdoor spaces. To this end, a field investigation was carried out in a typical hot summer day in the semi-arid climate of Constantine. Meanwhile, coupled methods such as microclimatic measurements and 'the point in time' questionnaire were used to comprehend and quantify the effects of objective weather parameters and subjective thermal sensations on pedestrian's thermal comfort. The obtained data at the esplanade *la Bréche* deliver essential information on human thermal perception and the usage of the outdoor urban spaces during the COVID-19 pandemic in 2021.

The results showed that the thermal response votes of pedestrians were in accordance with the microclimate measurements, when TSV increased the actual recorded Ta around the surveyors was high too. Moreover, the sensation of hot was dominant 72.5%, lower air temperature (T_a) was preferred by almost 75% of the respondents, and 90% desired a higher shade. While over half of the interviewees preferred no change in relative humidity and 40% favoured a higher wind speed (V_a). Only 22.5% of the participants were satisfied with their thermal conditions. Summing up the results, it can be concluded that pedestrians in the outdoor urban spaces are more stringent in thermal sensation and summer conditions especially heat waves are less pleasant for them.

The COVID-19 pandemic and the consequent use of face masks altered human thermal comfort and social distancing shaped the pedestrian's attitude in the study area. Hence, urban planners and architects need to reconsider the role of outdoor spaces (street parks, squares, esplanades … etc.) in order to adapt to the new challenges and prevent the transmission of the virus. For instance, encouraging small initiatives yet not expensive such as temporary sidewalks, mobile gardens, improving outdoor urban spaces by increasing shade using extendable devices or planting more vegetation could reduce significantly the thermal dissatisfaction especially in hot environments.

Regarding the limitations, it should be noted that the outdoor comfort analysis seems to fit the sample size (40) better than the post-COVID section. For the former, since it is site-specific, it can be presumed that a small sample is representative enough. The results of the latter, which is a much larger hypothesis, are constrained by the size sample, future work should involve different outdoor urban spaces with a wider sample to make the results more robust.

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Development of tree planting rules for urban spaces based on expert systems and fuzzy logic

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ABSTRACT: This work proposes a rule-based expert method to plant trees in urban spaces like streets, considering thermal comfort criteria. The methodology incorporates the conclusions and assumptions from some experiments on the analysis of temperatures and the estimation of thermal comfort in urban streets with trees and puts them together in the form of planting rules to apply the proposed method. The approach is based on the domain of expert rules; on the syntax of propositional logic and the deductive method, the concept of fuzzy logic and the concept of "Expert Systems". We obtained 56 observation rules in if-then form based on the concept of expert systems. and 8 rules represent the best thermal comfort conditions (matrix rules) with a degree of certainty from 80% to 100%. The results show that the proposed approach can be used to integrate knowledge for the development of tree planting rules useful for architects, town planners, and landscapers.

1. INTRODUCTION

This work proposes a rule-based expert method to plant trees in urban spaces like streets, considering thermal comfort criteria. The results show that the proposed approach can be used to integrate knowledge for the development of tree planting rules useful for architects, town planners, and landscapers.

2. METHODOLOGY

The methodology incorporates the conclusions and assumptions from some experiments on the analysis of temperatures and the estimation of thermal comfort in urban streets with trees and puts them together in the form of planting rules to apply the proposed method. The approach is based on the domain of expert rules; on the syntax of propositional logic and the deductive method, the concept of fuzzy logic and the concept of "Expert Systems". The combinations of planting parameters are valued by their degree of certainty.

This work was developed as follows:

-Formalization of the results of microclimatic measures [6], which includes: a classification of the cases studied related to their planting parameters and associated with their degree of thermal comfort; a summary of the results obtained during the measurement campaigns at the urban area of Aix-en-Provence city in France (43°27 latitude north, 5°14 longitude east and 6 m of altitude) (Fig. 1); and the prepositive hypotheses that will be used to create new rules.

-Development rules: Developing rules from all possible combinations of parameters and validated by observations, hypotheses, and the studied bibliography.

-Representation of rules or how they are interpreted. They are written in the form "*If-then*", from the field of expert systems, and illustrated. The rules with the best thermal comfort conditions will be presented.

Figure 1 : Measurement site map Aix-en-Provence

In the microclimatic study, air temperature (°C), relative humidity-RH (%) and Wind Speed – WS (m/s) measurements were taken at several streets of Aix-en-Provence with trees canopy coverage and others without trees canopy coverage (Fig. 2). There are a medium-sized buildings on each side of the street with concrete and brick walls and the pedestrian walk-through has paved floor.

All the rules presented in this work are intended for the study site but can be applied in urban areas with similar climatic and urban conditions with street geometry H/W from 0.4 to 0.5.

Figure 2: Installation of measuring devices in Place Albertas, in Aix-en-Provence

2.2 Parameter values of tree planting

Distance from trees to buildings (da)

The parameter Da is a scaled value that relates the width of the street (W) to the gap between the crown of the tree and the building. The width of the street has been divided by 0.5 to consider only half its width (this would also avoid having Da approaching the opposite facade). In this logic, two extreme situations are revealed: Da = 0, where the tree is against the wall; and Da = 1, where the tree would be on the axis of the street. Thus, consider that a tree is far from the facade when Da>0.5, and that a tree is closer to the facade when Da<0.5. (Fig. 3)

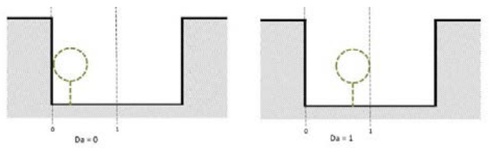

Figure 3: Distance from trees to buildings (da)

Foliage spreading (fs)

The foliage spreading is also a scaled value that relates the width of the street (W) to the crown of the tree. The crown of the tree was multiplied by two in order to consider the trees on the two facades of the street. (Fig. 4)

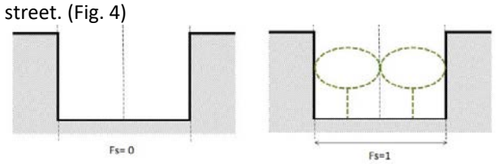

Figure 4: Foliage spreading (fs)

Foliage (F)

The quantification of the percentage of foliage of trees uses fisheye lens photos to estimate the leaf factor and the cover factor of the tree. This work considers that sparse foliage is represented by a value <45%, that dense foliage is >55% and that regular foliage is between 45 and 55%. (Fig. 5)

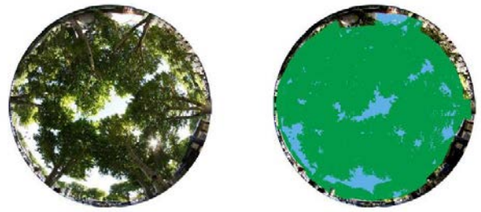

Figure 5: Fisheye lens photos to calculate percentage of foliage

Orientation of the centerline of the street (o)

The street orientation parameter can change the microclimatic conditions and comfort due to North-South (N-S), East-West (E-W), North-East/South-West (NE-SW) or North-West/South-East (NO-SE) solar radiation blocking, windbreak, etc.

Geometry (H/W)

For a typical street, the relevant geometric parameters are the average building height (H), the street width (W) and the street length (L). The relationship between building height (H) and street width (W) gives coefficients which make it possible to categorize the urban configurations which are very varied, and which have influences on the thermal conditions of the urban microclimate (Fig. 6).

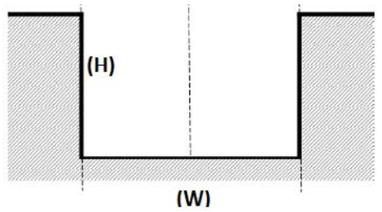

Figure 6: Geometry (H/W)

2.3 The expert systems

Research on Expert Systems (ES) is a subfield of Artificial Intelligence (AI) and has been one of the longest-running and most successful areas of ongoing research within the AI field since the 1980s, having many applications on functional areas and problem domains [1]. ES are characterized by the representation of knowledge about a use case specific problem area (knowledge base) and the processing of this knowledge (knowledge processing) [Cited in 2].

ES is based on databases of facts and knowledge, on an inference or deduction engine to solve complex problems that needs high expertise and essentially uses empirical rules or expert rules of the field of heuristics [3, 4].

Knowledge of limited domains in an expert system is often represented in the form of "*If-then*" rules for their simplicity, implementation, validity and very powerful form of expression [3, 4].

The general form of an *If-then* rule is:

If condition 1 and condition 2 and condition 3 ...
Then, action 1, action 2 ...

Where,
Conditions are antecedents
Actions are consequences

In this work the form if-then will be presented as in the figure below (Fig. 7)

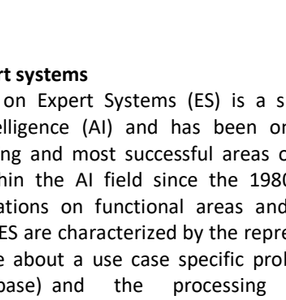

Figure 7: Presentation of the rules

2.4 The fuzzy logic

Fuzzy logic is a system that formalizes valid reasoning that contains sentences called fuzzy terms, very commonly used in natural language, reasoning that classical logic cannot address [5].

Since the values or responses are not precisely determined or completely reliable, we use fuzzy logic for the parameter values of tree planting, like foliage (f), distance from buildings (d), and foliage spreading (fs) (Table 1), and for the degree of certainty (Table 2).

Table 1: Equivalence of parameter values in linguistic labels. Data from [6].

	f	d	fs
NONE	0	0	0
WEAK	<39 %	< 0.39	< 0.39
AVERAGE	40 - 59 %	0.4 – 0.59	0.4 – 0.59
STRONG	> 79 %	0.6 - 0.79	0.6 - 0.79

Table 2: Certainty rules.

Certainty rules	
CONFIRMED (BY MEASUREMENTS **AND** BIBLIOGRAPHY)	100% certainty
CORROBORATED (BY MEASUREMENTS **OR** THE BIBLIOGRAPHY **OR** VALIDATED HYPOTHESES)	80% certainty
TO BE CONFIRMED (SINGLE CASE)	50% certainty

3. RESULTS

3.1 The matrix rules

For the first part of the construction of rules, the cases which present different situations have been retained and classified according to the thermal sensation experienced. We have synthesized our results in a grid that brings together all the parameters according to orientation and façade. These parameters are validated by other research results. This reasoning resulted in eight (8) rules that we will call matrix rules.

The matrix rules are our original rules and express the maximum comfort. We observe that matrix rules 1, 4, 7 and 8 are used for all orientations. We varied each parameter for each matrix rule, and this new combination of parameters allowed us to create new rules that we called derived rules. This logic gave us 27 possible combinations, which represent the number of rules per orientation. An additional rule (rule N° 28) has also been added; its values are null or zero (no tree).

They were constructed from the classification of cases studied, the summary of results, the bibliography and matrix rules (RM). All rules have been associated with a degree of certainty, and matrix rules have been highlighted. We present below, by way of examples, the rules which express maximum comfort conditions in the streets. The street orientations are N (North), S (South) E (East) W (West). The rules use the *if-then* form and the degree of certainty.

-Matrix rule 1. IF N-S street, East facade AND strong foliage AND Average distance AND Strong vegetal, THEN very good comfort 100% certainty

-Matrix rule 2. IF N-S street, West facade AND medium foliage AND medium distance AND strong vegetal, THEN very good comfort 80% certainty

-Matrix rule 3. IF N-S street, East facade AND strong foliage AND Average distance AND Strong vegetal, THEN very good comfort 80% certainty

-Matrix rule 4. IF N-S street, West facade AND strong foliage AND low distance AND strong vegetal, THEN very good comfort 80% certainty

-Matrix rule 5. IF E-W street, north facade AND strong foliage AND strong distance AND strong vegetal, THEN very good comfort 80% certainty

-Matrix rule 6. IF E-W street, North facade AND average foliage AND Average distance AND Average vegetable, THEN very good comfort 100% certainty

-Matrix rule 7. IF E-W street, South facade AND strong foliage AND short distance AND strong vegetal, THEN very good comfort 80% certainty

-Matrix rule 8. IF E-W street, south facade AND strong foliage AND medium distance AND strong vegetal, THEN very good comfort 80% certainty

We have illustrated the Matrix rule one and two to shows how rules can be presented for informative purposes (Fig. 8).

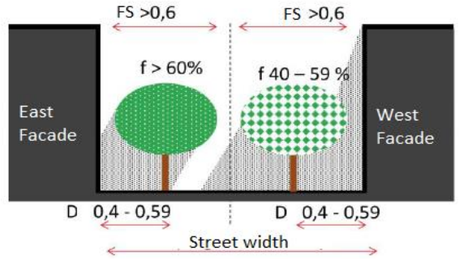

Figure 8: Example of matrix rules one and two.

3.2 The Derived Rules

The parameters of Foliage spreading (fs), Distance from trees to buildings (da) and Foliage (F) have been combined with each other in all possible ways to offer the maximum number of rules, they have been called derived rules. The combination was made as in figure 9, where A, B and C represent the parameters fs, da and f and 1, 2 and 3 the degrees of intensity of strong, average and weak values. This logic gave us 27 possible combinations which represent the number of rules per street orientation. A rule N° 28, without tree has also been added.

Figure 9: Parameter combination method

The resulting derived rules were examined and related to the results to the summary of results of the microclimate study, to the bibliography and to the matrix rules (RM). We have also considered the observations made for certain rules. All rules were associated with a degree of certainty

3.3 Application of the tree planting rules

The planting rules may apply in landscaping projects in the following cases:

1. Diagnosis: Estimation of comfort conditions according to the characteristics observed.
2. Vegetation of built places: In a planting or replanting project of an existing street.
3. Design of new urban projects with trees.

The steps to follow are:

- Identify the orientation of the street and the facade exposed to the sun.
- Obtain the following information: Street width, distance from buildings (d), diameters of the crowns, which represent the foliage spreading (fs) and the percentage of foliage (f) which can be calculated by using fisheye lens photos.
- To calculate the coefficients, relate the distance and the diameters of the crowns to the width of the street. The coefficients and percentages obtained are translated into linguistic labels (strong, medium, weak, etc.)
- Depending on the orientation and the facade, look for the corresponding rule in the grid (Fig. 8). An estimate of comfort is given, which will allow decision-making.

Example: We have a street has an East-West orientation (Fig. 10). It is necessary to consider a planting distance (X2) of at least 2.0 m and the height of the buildings (Y1), which will determine the choice of the type of tree. We must follow the way of calculating the parameter values of tree planting, as we explain previously.

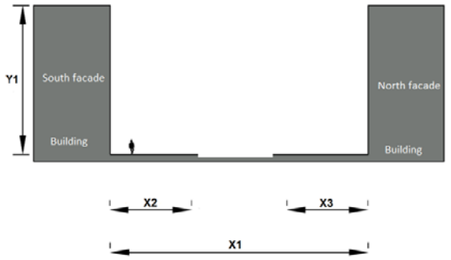

Figure 10: Example of an east-west orientation street

Depending on the orientation and the facade, look for the corresponding rule in the grid (Fig. 11), in this case we choose rules 1 and 45. If it is a new project where you have more design freedom, it is in your interest to choose the rules that offer the best comfort.

Rule	F	Da	Fs	Comfort
1	●	●	●	☺
2	●	⊙	●	☺
3	●	○	●	☺
4	⊙	●	●	☺
5	⊙	⊙	●	☺
6	⊙	○	●	☺
7	○	●	●	☺
8	○	⊙	●	☺
9	○	○	●	☺
10	●	●	⊙	☺
11	●	⊙	⊙	☺
12	●	○	⊙	☺
13	⊙	●	⊙	☹
14	⊙	⊙	⊙	☺
15	⊙	○	⊙	☺
16	○	●	⊙	😐
17	○	⊙	⊙	☺
18	○	○	⊙	☺
19	●	●	○	😐
20	●	⊙	○	😐
21	●	○	○	😐
22	⊙	●	○	😐
23	⊙	⊙	○	😐
24	⊙	○	○	😐
25	○	●	○	😐
26	○	⊙	○	☹
27	○	○	○	😐
28	⊗	⊗	⊗	☹

Rule	F	Da	Fs	Comfort
29	●	●	●	☹
30	●	⊙	●	☺
31	●	○	●	☺
32	⊙	●	●	☹
33	⊙	⊙	●	😐/☺
34	⊙	○	●	☺
35	○	●	●	☹
36	○	⊙	●	☺
37	○	○	●	😐
38	●	●	⊙	☹
39	●	⊙	⊙	☺
40	●	○	⊙	☺
41	⊙	●	⊙	☹
42	⊙	⊙	⊙	😐
43	⊙	○	⊙	☺
44	○	●	⊙	☹
45	○	⊙	⊙	😐
46	○	○	⊙	😐
47	●	●	○	☹
48	●	⊙	○	😐
49	●	○	○	😐
50	⊙	●	○	☹
51	⊙	⊙	○	😐
52	⊙	○	○	😐
53	○	●	○	☹
54	○	⊙	○	😐
55	○	○	○	☹
56	⊗	⊗	⊗	☹

Figure 11: The tree planting rules

Since facades with a North-South orientation behave differently due to exposure to solar radiation, we have a different rule for each facade. You can have asymmetrical street profiles with different tree species, with different sizes and layouts (Fig. 12).

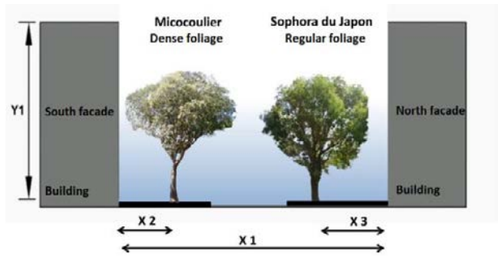

Figure 12: Section of the street with the application of the rules

5. CONCLUSION

Results obtained:

-56 tree planting rules in *if-then* form based on the concept of expert systems. By its degree of certainty, they are divided into confirmed, corroborated and to be confirmed.

-Among the 56 rules, 8 represent the best thermal comfort conditions (matrix rules) with a degree of certainty from 80% to 100%.

We consider that planting rules seek to guide decisions during urban projects and that their use should not be systematic. Rather, it should be subject to evaluation to make the most appropriate decisions. It is also important to remember that these rules should be sufficiently tested and validated before considering their use. We consider that the computer simulation tool can be quite reliable for such purpose

In the professional context, it is necessary to carry out a future work of conveying these rules for their understanding.

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November 22 - 25, 2022

SUSTAINABLE BUILDINGS AND TECHNOLOGY

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12:00 — 13:30

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PAPERS
1197 / 1286 / 1296 / 1485 / 1675 /
1115

12TH PARALEL SESSION / ONLINE

WILL CITIES SURVIVE?

Retrofit of heavy mass buildings in Mediterranean climates

A method for optimizing insulation and solar control strategies

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ABSTRACT: In temperate climates, the need to limit both winter heat losses of the buildings and their overheating in other periods is present. The second requirement is particularly relevant in the presence of high internal and solar gains. In these climates, it is not convenient to exceed the insulation thickness. Moreover, in warmer Mediterranean climates the convenience of insulation against the thermal inertia of the building must also be evaluated. Therefore, when the energy renovation of an old building with heavy masonry is performed it is a question of optimizing the position and the thickness of the insulation. If extended glazed surfaces are presents, another question is the choice of a solar control strategy. Both problems are present in many Italian public buildings. This paper presents a computerized methodology for optimizing these choices. The case study consists in a typical school building from the early 1900s. The thermal behavior of the building was simulated in three Italian climates, those of Bologna, Roma and Palermo. The effects on energy demand and comfort of various types of insulation and of various solar control devices were compared. The possible effects of different types of masonry, different orientations and various intended uses were also explored.
KEYWORDS: Retrofit, Solar Control, Energy, Comfort

1. INTRODUCTION

In temperate climates, such as most Italian ones, the need to limit both winter heat losses of buildings and their overheating in other periods is present. The second requirement is particularly relevant in the presence of high internal and solar gains. It is well known that, in these climates, it is not convenient to exceed the insulation thickness. In addition, in warmer Mediterranean climates it is to be evaluated the convenience of insulation in comparison to the thermal inertia of the building.

When the energy renovation of an old building with heavy masonry is performed, it is a question of optimizing the position and the thickness of the additional insulation according to the intended use (Sami et al., 2011; Deng et al., 2019; Stazi et al., 2015; Tzoulis et al., 2017). The usefulness of a certain insulation depends on a number of factors, such as:

- local climate, in particular the presence in it of significant day-night temperature ranges,
- building's thermal inertia,
- building's thermal balance,
- building's time profile of use.

Moreover, in the case of old public buildings, large glazed surfaces are often present, which involve the well-known problems and requires an appropriate solar control strategy (Buvik et al., 2015).

This work presents a computerized methodology for the optimization of these choices.

The various retrofit strategies are evaluated in relation to the total primary energy demand, and the effects on thermal and light comfort.

The primary energy demand considered is that for heating, ventilation, air conditioning (HVAC) and artificial lighting, since insulation and solar control strategies influence these end uses of energy. Furthermore, these final uses of energy are linked to each other, so analyzing them separately can lead to misleading results. Therefore, a specific homemade software has been used here that allows simulating within each calculation step the effects of solar control actions on comfort and energy demand.

Figure 1:
The examined building, in the centre of the picture.

The case study consists in two classrooms of a typical school building from the early 1900s with a heavy structure and large glass surfaces (Fig. 1) in a city of Northern Italy: Bologna. The climate of the town (2259 base 20°C heating degree-days) is temperate with cold winter and warm summer with daily temperature ranges not negligible in all the seasons.

The building has structural internal and external brick walls (0.25 m thick) with plaster on both sides (total thickness 0.3 m), its U-value is 2.06 $W \cdot m^{-2} \cdot K^{-1}$ and front thermal capacity (C) is 481 $kJ \cdot m^{-2} \cdot K^{-1}$, the floors are made in wood, with superimposed lime mortar and bricks. Vertical wide windows are present. The two classrooms are identical, with the windows facing approximately east (76° East azimuth), for a classroom this is the most critical orientation. They are located at the second and the third floor respectively; therefore, the influence of surrounding urban obstruction is different.

The hypothesized retrofit intervention includes additional insulation and more sophisticated solar control devices. In order to assess the influence of internal gains, time profile of use and solar radiation, other possible uses of the building, i.e. offices and dwelling, and a south orientation of the outer wall were considered. In addition, to evaluate the influence of thermal inertia, some different masonry, both heavier and lighter, were simulated. Given the diffusion of this type of building in the Italian territory, its thermal and light behavior has also been simulated in the climates of Rome and Palermo (1415 and 751 heating degree-days respectively).

It was assumed that in Bologna the retrofit intervention involves the installation of a triple glazing (overall U-value: 1 $W \cdot m^{-2} \cdot K^{-1}$), its external air gap can contains movable and packable slats (Fig. 2). In Rome and Palermo, windows with only two glasses and U-values close to the limit values (1.8 $W \cdot m^{-2} \cdot K^{-1}$ and 3 $W \cdot m^{-2} \cdot K^{-1}$ respectively) have been hypothesized, with the same solar control devices. The hypothesized light system consists of fluorescent lamps. In the case of the offices, six occupants with the related equipment have been assumed in the same space as the previous single classroom, and a more localized light system always based on fluorescent lamps.

Two types of additional insulation layers have been simulated: an external ~~insulation~~ consisting of a layer of rock wool, with various thickness values, with an outer protective layer, and an internal insulation consisting of expanded polyurethane only 0.05 m thick, with an internal layer of plasterboard, according to current construction practice. This because a greater thickness would reduce the interior space without significantly increasing energy savings.

To estimate the energy cost of obtaining thermal comfort in any season, it is assumed that a full air centralized HVAC system is installed.

Currently, the only solar control device is a diffusing curtain inside the windows. This device allows controlling glare phenomena but do not avoid unwanted solar gains and penalizes daylighting. Instead, the alternative solar control strategies examined here are based on various types of packable arrays of tiltable slats: one external to the glasses and two inserted between the glasses. One of the last two has diffusing surfaces, while the other has a specular upper surface (Fig. 2).

Figure 2:
The external slats (left) and those inserted between the glasses (right) hypothesized for the climate of Bologna. From ©Internorm catalogue.

The external slats are coupled with an internal diffusing blind, which is lowered when necessary to avoid glare, while the slats inside the glasses use their inclination for the same purpose. These devices are operated at first to minimize the thermal load but guaranteeing the required level of illuminance even in the most disadvantaged position. Then they can be further operated to eliminate glare phenomena if they are detected. The control logic of the specular slats differs from that of the diffusing ones because, before checking the thermal load and the glare, the slats are arranged in such a way as to redirect upwards the direct radiation as deep as possible in the room.

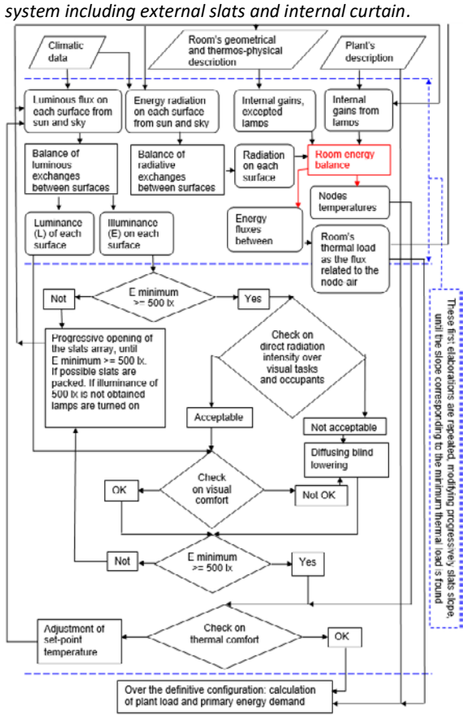
In all locations, the behaviours of hypothetical heavier and non-insulated masonries were also simulated: a brick wall 0.51 m thick (U-value = 1.27 $W \cdot m^{-2} \cdot K^{-1}$, C = 917 $kJ \cdot m^{-2} \cdot K^{-1}$) and a stone wall 0.51 m thick (U-value = 2.37 $W \cdot m^{-2} \cdot K^{-1}$, C = 1285 $kJ \cdot m^{-2} \cdot K^{-1}$). To evaluate the effect of a lower heat capacity of the envelope the behaviour of a more recent construction system was also simulated for the same building. It consists of a point structure: beams-pillars in reinforced concrete with latero-concrete floors and external walls in hollow bricks 0.12 m thick. Due to the presence of structural thermal bridges the average transmittance of this façade without insulation is higher than the current

one (U-value = 2.37 $W \cdot m^{-2} \cdot K^{-1}$, C = 199 $kJ \cdot m^{-2} \cdot K^{-1}$). With regard to this configuration, the optimal insulation was sought.

2. METHODS

Normally this type of analysis is carried out using different software to simulate the thermal and luminous behaviour of the building. This does not allow simulating within each calculation step the interactions between solar control actions, energy demand and comfort. The software used here *(Ener_Lux)* is an evolution of a software already presented in a previous PLEA Congress (Carbonari, 2012). It is mainly aimed at supporting the design of solar control devices and related control strategies.

Figure 3:
Flowchart of the software when simulating a solar control system including external slats and internal curtain.



The program takes into consideration the physical system composed by a room, its glazed surfaces, internal and external solar control devices as well as the surrounding urban environment. It simulates the dynamic thermal and luminous behaviour of the physical system at hourly time steps. Within each calculation step it checks the conditions of thermal and luminous comfort relatively to some significant occupants position within the room, by calculating the relative evaluation indexes (Fig. 3). Once the comfort checks have been carried out, any necessary feedback on the arrangement of the solar control devices and/or on the set-point temperatures is automatically simulated, by modifying the model. Then the program calculates the primary energy demand for HVAC and artificial lighting.

In energy field, the program uses an algorithm based on a heat balance of elementary zones (nodes): a thermal grid model. This algorithm provides the thermal flows between the nodes and their temperatures. The temperatures of the nodes corresponding to the internal surfaces are also used for the calculation of thermal comfort indices.

Starting from latitude and climatic data of the site, the program calculates solar energy impinging on each surface; its energy flow is associated with the affected nodes. The part of impinging radiation due to mutual diffuse reflections between surfaces is calculated solving an equation system.

A similar process is used in the luminous field to calculate the illuminance value on each surface and the luminance of it. The calculation of visual comfort indexes values are performed by means of an algorithm that simulates the human field of view, and uses the calculated luminance values.

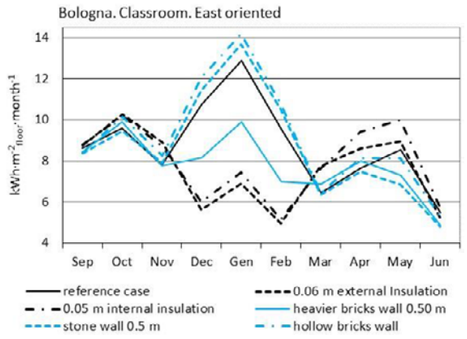
3. RESULTS

For reason of space, the results shown in the following graphs are mainly referred to the two most different climates: that of Bologna and that of Palermo. In the intermediate climate of Rome, the results are closer to those of Palermo.

3.1 Energy demand

In Bologna, for the classroom and the office, any type of additional insulation results to be useful only during the coldest period. In the half seasons, insulations only increase overheating, as they prevent the night's cooling of the masses (Fig. 4).

Figure 4:
Monthly specific primary energy demand (per square meter of floor area) for HVAC and lighting systems of the classroom on the 2nd floor, with various masonry and various types of insulation.

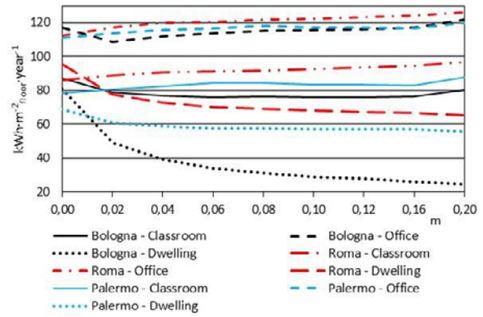


In the warmer period, they have no relevant effects due to the higher internal set point temperature (26 °C). For these reasons, in the climate of Bologna, the optimal insulation thickness is between 0.06 and 0.07 m (Fig. 5-6) in the case of the classroom.

In the case of the office, on the other hand, this minimum point is around 0.02 m. In facts the fewer occupants require a lower rate of ventilation, this significantly reduces the energy demand for heating, while it reduces less that for cooling, due to the smaller temperature differences between inside and outside in the hottest period.

Conversely, in the case of the dwelling, heating energy demand is preponderant; therefore, it is not possible to identify a point of minimum in total energy demand (Fig. 5).

Figure 5:
Total annual specific primary energy demand (per square meter of floor area) for HVAC and lighting systems of the room on the 2nd floor east oriented, as function of external insulation's thickness, for the different intended uses and in various climates.



In Bologna, internal insulation has fewer advantages than optimized external one, particularly in the case of offices where cooling energy demand is dominant. This insulation in fact prevents the exploitation of thermal inertia that reduces cooling energy demand in the half seasons. Therefore, in warmer climates the disadvantages would be even greater.

In the room of the upper floor, the total annual primary energy demand is slightly higher. This is due to the greater solar gains and the consequent greater cooling loads, 45% balanced by lower consumption for lighting.

In warmer climates, of Rome and Palermo, both in the case of the classroom and the office, the energy demand for cooling is much greater than that for heating, therefore any type of insulation only increases total energy demand. This does not happen for residential use.

Only in Bologna, a thicker brick masonry without insulation (0.5 m thick) has the advantages due to the lower U-value, even its greater thermal inertia provides advantages especially in the mid-seasons, for the classroom and the office, but these energy benefits are slightly less than those due to the optimised external insulation are. In the other warmer climates, the disadvantages related to the minor useful heat losses are dominant and these walls remain advantageous only for the housing.

Figure 6:
Total annual specific primary energy demand (per square meter of floor area) for HVAC and lighting systems of the room on the 2nd floor east oriented, as function of external insulation's thickness and different solar control strategies.

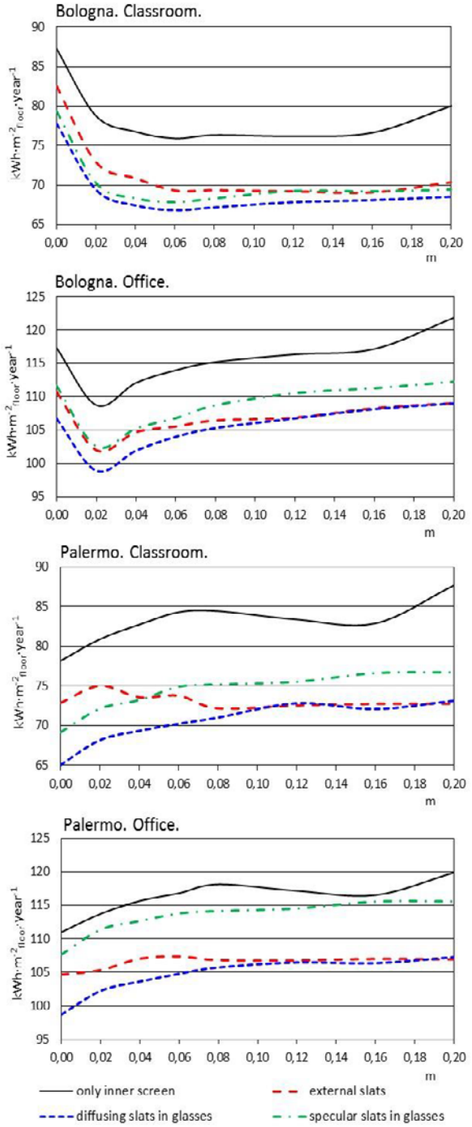
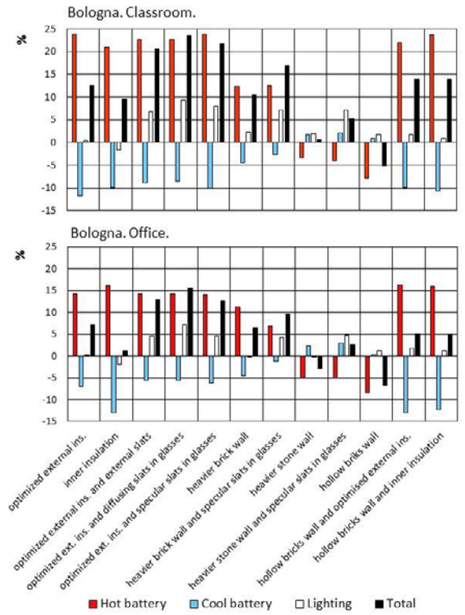
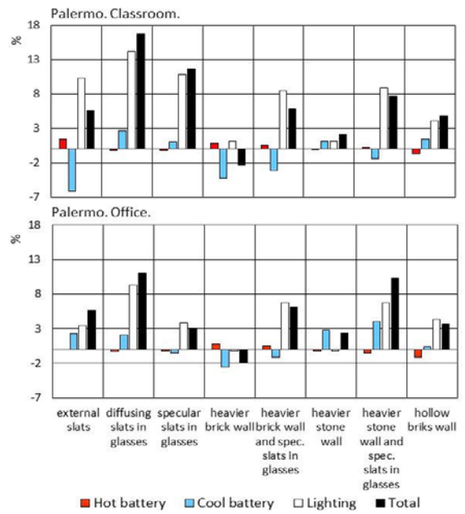


Figure 7:
Room on the 2nd floor east oriented. Percentage energy savings achievable compared to the current configuration. In case of heavier and lighter walls, only the best performant solar control device is represented.





The 0.5 m thick stone wall is characterized by increased U-value and a significantly higher heat capacity. Thermal inertia alone is advantageous especially in reducing cooling loads. Therefore, only in Palermo it would provide modest energy savings for the classroom and the office, while it would be disadvantageous for the housing in all locations.

In Bologna, a lighter facade in hollow bricks, without insulation, increases the total primary energy demand, due to the higher consumption from heating. The thicknesses of the optimal external insulation are not significantly different from those found for the reference masonry. In warmer climates, on the other hand, this technology involves energy savings, but these are essentially due to the lower consumption of the lamps, due to the lower thickness of the masonry.

Compared to the use of the internal curtain only, all the types of examined movable slats entail energy savings. This is because they reduce unwanted solar gains better than the internal curtain alone and avoid glare phenomena by reducing the incoming luminous flux less. Therefore, they reduce the use of lamps and the consequent thermal gains (Fig. 7).

Among the solar control strategies, the most energy efficient seems to be the use of diffusing slats inserted between the glasses, followed by the specular ones, always between the glasses.

In Bologna, the advantages of these slats are of the same order of magnitude as those due to optimal insulation. In warmer climates the percent savings due to solar control are higher (Fig. 7).

The introduction of these devices does not change the ideal insulation thicknesses previously identified.

A hypothetical facing south of the room's windowed external wall would result in a modest reduction in the total annual energy demand, mainly due to the lower use of lamps. With the south orientation, the savings due to all types of slats would increase, especially in case of the office with the specular slats.

3.2 Thermal comfort.

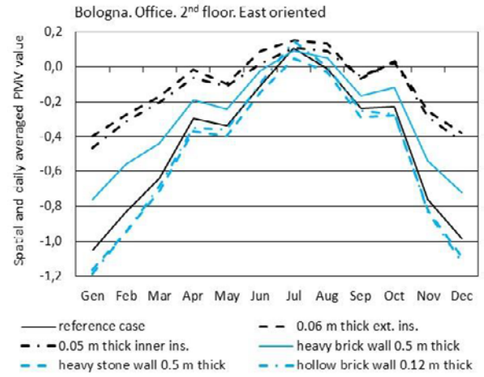
Thermal and luminous comfort indexes were calculated relatively to six significant occupant's positions within the room.

The results reported here refer to the office as they are also extended to the afternoon and to the summer (Fig. 8). The thermophysical characteristics of the building's envelope essentially affect the mean radiative temperature (MRT), which in turn affect the predicted mean vote (PMV) and the localized discomfort due to the asymmetry of the plane radiant temperature (t_{pr}).

To explore the influence of insulation, an external insulation 0.06 m thick and an internal insulation 0.05 m thick have been hypothesized in all the locations. In all the locations the insulations, in particular the external one, improve thermal comfort. The lower U-value of the heavier brick wall too improves the comfort, but in a less way than insulations.

Uninsulated walls in hollow brick and stone, having a greater U-value, slightly worsen comfort in the heating period. However, in the cooling period the stone wall, thanks to its inertia, contains the MRT and provides better performance even than the insulations in Bologna.

Figure 8:
Office on the 2nd floor east oriented. Spatially and daily averaged PMV values in typical monthly days, with different types of insulation and constructive technologies.



Solar control devices mainly influence the internal temperature of the windows. The diffusing slats between glasses keep this temperature a little higher in the cold period and reduce it slightly in the hottest period. The specular slats are less efficient in controlling this temperature, due to the lower inclination they assume. Instead, the external slats provide better thermal comfort during the warmer period, by limiting the temperature of the internal glass. In other periods, this effect is undesirable.

3.3 Visual comfort

Two types of glare were considered here: the disability glare from direct radiation on the visual task, and discomfort glare due to exceeding contrast of luminances inside the visual field. This last is assessed by means of the Daylighting Glare Index (DGI). Before the glare control actions, the most frequent discomfort is that of the first type, especially in the case of the curtain used alone.

Compared to the use of the single curtain all the types of slats improve the light comfort. Before the glare control actions, all the types of slats reduce the frequency of disability glare, in particular the specular ones. After the visual comfort control actions, all the type of slats guarantee a greater uniformity of the internal illuminances than just the curtain.

In Palermo, the number of hours of daylighting in comfort conditions is greater, given the greater availability of solar radiation.

4. CONCLUSION

Simulations results show that, for the examined type of building, the ideal retrofit strategy depends not only on the climate but also on the building's intended use, which determines the internal gains and the time profile of use. The optimal insulation thickness depends on the ratio between the amount of energy demand for heating and for cooling.

Windows orientation mainly influences the choice of solar control devices. Among the solar control strategies, the most energy efficient one is the use of diffusing slats inserted between the glasses, followed by the specular ones always between the glasses. The specular slats provide the best conditions of luminous comfort, while those outside the glasses provide the best thermal comfort in the hottest periods.

Therefore, in Bologna, from energy point of view, the best retrofit strategy consists in the optimized external insulation combined with diffusing slats internal to the glasses, while in the other warmer climates it consists in the introduction of the same solar control device and no insulation, except for the intended residential use. In the absence of insulation, a significant heat capacity of the walls provides modest energy savings only in the hottest climates and for uses other than the dwelling.

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Opportunities and challenges for LCA in India for innovative technologies

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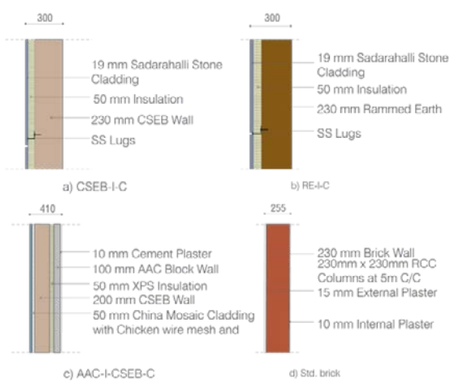
ABSTRACT: The building sector accounts for 10 $GtCO_2$ or 28% of global energy-related carbon emissions. These emissions are in the embodied impacts and the operation of buildings. An experimental building in Bangalore, India was made with different construction assemblies and materials to document performance and cost parameters. For this building, Life Cycle Assessment (LCA) is used to assess the environmental impacts of experimental walls. The paper describes the method and identifies the challenges for conducting such analyses in India, especially when unconventional materials have been used. The baseline wall system is the typical uninsulated brick wall with plaster on both sides. The three innovative wall systems use a combination of stabilized soil construction, light-weight concrete blocks, insulation and cladding with lower U-values. The scope of the study is cradle to handover + operational stage (50 years). The lack of data sources for conducting LCA is the major barrier to assessing the embodied environmental performance of buildings. For the embodied or cradle to handover stage, the highest carbon emissions resulted from the standard brick wall. The experimental wall systems showed a 52% to 78% reduction in embodied carbon content. In the operational stage too, the carbon emissions resulting from the standard brick wall were the highest, while the experimental walls show a reduction of 9% to 11%. Other impacts analyzed were, Ozone Depletion Potential Acidification Potential, Eutrophication Potential and Photochemical Ozone Creation Potential. KEYWORDS: Life cycle assessment, environmental impacts, cradle to handover, operational stage, embodied carbon, stabilized soil construction

1. INTRODUCTION

By 2030, India's energy demand is expected to grow by 33% from 2019 [1]. About 1/5th of the country's carbon emissions and 1/3rd of energy use is from the building sector [2]. However, there are no studies that quantify the impacts of the building sector in terms of different environmental indicators such as Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Creation Potential (POCP). Life Cycle Assessment (LCA) accounts for the environmental impacts of products considering their entire life cycle. Green building rating systems in India require LCAs of buildings to get credits or points. While LCA of building materials is sometimes undertaken for such ratings, a systematic use of the LCA for decision-making at a project or policy level was not found in the literature. It is difficult to find robust data sources for the environmental impacts of building materials in India. Hence, the International Finance Corporation (IFC) developed a database of materials with their environmental impacts that is used in EDGE [3]. The EDGE rating system and software enables users to estimate the embodied and operational carbon footprint of a building, but there is no provision to estimate other environmental impacts.

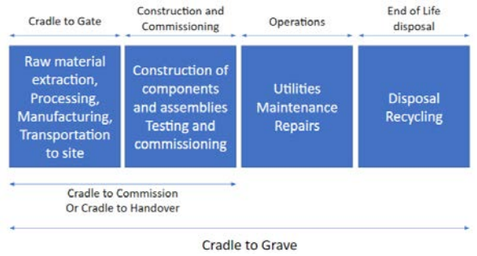
At an experimental building in Bangalore, India a few innovative technologies have been tested, and their performance and costs have been documented. The wall systems included the use of cement stabilized earth block (CSEB), autoclaved aerated concrete blocks (AAC), and extruded polystyrene (XPS) insulation. In this study, three wall systems: 1) CSEB masonry wall with insulation and cladding (CSEB-I-C), 2) Rammed earth wall with insulation and cladding (RE-I-C), 3) AAC and CSEB wall with insulation and china mosaic (AAC-I-CSEB-CM), are compared with a standard brick wall with plaster on two sides (Std. Brick), using LCA. The wall sections are shown in figure 1 below. The analyses of roofing and flooring systems are not included in this paper.

Figure 1: *a) CSEB-I-C b) RE-I-C c) AAC-I-CSEB-CM and d) Std. Brick wall sections of all wall systems*



The different stages in the life cycle of a building are raw material extraction, manufacturing, processing, transportation, construction, operational usage, maintenance, disposal, and if applicable, the recycling potential. Figure 2 shows these stages.

Figure 2: *Life cycle of a building*



The scope of this study includes cradle-to-handover + operations projected over 50 years. For the cradle to handover stage, all 6 environmental indices are calculated. For the operational stage, only the Global Warming Potential (GWP) and Embodied Energy (EE) are calculated due to the lack of data availability. The end-of-life scenario for the wall systems is assumed to be the same for all the wall systems compared and not included in the study.

2. LITERATURE REVIEW

LCA techniques have been adopted in industry and in the public sector to assist a variety of purposes, such as keeping the decision-makers informed about the environmental impacts of a product/process so that they can choose the right alternatives where they occur [4]. It is also used to determine which phase in the product/process life has the most environmental impacts.

2.1 LCA methods and standards

The international standards that provide the framework for LCA are ISO 14040:2006 [5] which defines the general principles, and ISO 14044:2006 [6] which further specifies the requirements.

As described by ISO 14040:2006 and ISO14044:2006, the methodology of LCA has four phases – 1) goal and scope, 2) inventory analysis, 3) impact assessment and 4) interpretation of results.

Three types of scopes are defined for accounting the GHG emissions of an organization [7]. Direct emissions within the boundaries of the organization are Scope 1 emissions. Scope 2 accounts for the offsite emissions from purchased electricity used within the boundary of the organization. Scope 3 accounts for all indirect emissions of the organization.

2.2 Data Sources

EPDs are third-party verified labels for the communication of quantitative product-specific environmental data based. They are regulated by ISO 14025:2011, and for construction products they are regulated by EN 15804:2012+A2:2019 and facilitate the decision-making processes of consumers [8]. There is evidence of LCAs conducted with EPDs as the data sources [9,10]. Some studies also showed that EPDs present an advantage when used as LCA data source compared to non-manufacturer-specific, or generic data [8, 11, 12, 13].

The International Finance Corporation has developed a database that provides generic data for construction materials and products as typically used in India, both manufactured locally and imported [14]. The environmental indicators for the materials are GWP, ODP, AP, EP, POCP, and EE. However, a thorough study was done for only GWP and EE [15]. Their data for the other four indicators are based on characterization factors obtained from CML–IA version 4.1, as used in EN 15804, which are generic values [14].

2.3 Phases of LCA

The production stage and the construction stage generate a lower environmental impact of about 8-20% in the life cycle of the building [16]. Adalberth, (1997) [17], Xianzheng, (2012) [18] and Chang et al., (2011) [19], found that 70-90% of the total impact is generated during the operational phase of the building with mechanical heating or cooling. Therefore, it is important to include the operational phase as a priority in the LCA [20].

3. METHODOLOGY

3.1 Cradle to handover

3.1.1 Inventory Analysis

The inventory data for the cradle to handover stage is collected for all the processes in the system boundary of the wall systems, as shown in table 1 below.

Data collection for these processes is categorized into three parts - materials, components, and system assembly.

Table 1: *System boundary of the wall systems*

Materials/ Processes	Carbon emissions			
	Scope 1	**Scope 2**	**Scope 3**	**Scope 3 {not included)**
Materials procured on-site	Diesel burning in soil excavation equipment	Electricity for pumping water	Nil	Emissions associated with vehicle and equipment making
Materials imported to site	Nil	Nil	Extraction, processing, manufacture, and transportation	Emissions associated with vehicle making, petrol pumps, roads and other infrastructure
Component making on-site	Nil	Manual labour only	Extraction, processing, manufacture, and transportation	Emissions associated with equipment making

Materials: The quantities of each material used in the wall systems, transport fuel, processing fuel for soil excavation and processing electricity for water pumping on-site are obtained from the construction records. Fuel for transport of materials includes the transport from manufacturer to retail supplier, and from retail supplier to the construction site. A heavy goods vehicle (HGV) lorry with a fuel efficiency of 6 km/l and vehicle payload of 40,000 kgs is assumed for transporting the materials from the manufacturer to the retail supplier. For the retail supplier to construction site calculations, we used construction records, which included the vehicle registration number, the retail supplier's name and address. This was used to determine the distance and the type of transport vehicle used. With this data, the transport fuel consumption per unit of raw material is calculated. The quantities of processing fuel for soil excavation and processing electricity for water pumping are obtained from the construction records.

Components: Processing fuel and electricity for making the components from raw materials are accounted for at the component level. However, the experimental building has some components such as the CSEB which were made with manual powered machines. Manual power is not included in this analysis.

System assembly: Processing fuel and electricity for constructing the wall out of either raw materials or components are accounted for at the system assembly level. For example, processing electricity to drill holes in the wall for fixing the insulation. Again, due to the building scale, these quantities are negligible.

The inventory consists of a summary of the material quantities, and the quantities of processing fuel and electricity for each of the materials, i.e., transport fuel, for all the wall systems.

3.1.2 Impact Assessment

The environmental impact database was selected based on the available data for important materials, data quality and the number of impacts. Table 2 summarizes the details of the databases studied for this paper.

Table 2: *Listing the potential data sources for this study*

Data Sources	Materials not available	Quality of the data	Number of Impacts
EPD	Fired clay brick, XPS, m-sand	Global (apart from cement and steel)	20
IFC	Paint	India	6
ICE	none	Global	1

The IFC database was selected because of its Indian context, and its large coverage of construction materials.

The inventory data corresponding to each wall system is multiplied by the environmental factors, i.e., GWP, ODP, AP, EP, POCP, and EE, for material, electricity, and diesel, to obtain the aggregate environmental impacts of each wall system. However, for electricity and diesel, only GWP and EE factors are available.

3.2 Operations

The operations emissions are estimated with simulations done using an Energy Plus calibrated model of the building. As-built drawings and materials specifications were used to build the 3-D geometry of the building. A detailed energy audit with measurements of the operational power of individual equipment and lighting circuits were used as an input for the model. HVAC system details and also the mixed mode operation of the building was used in the model.

Entry and exit logs of the building occupants were used for occupancy schedules. Weather data from a Davis weather station installed atop the building were used to update the temperature, humidity, wind speed, and radiation data fields in the TMY weather file of Bangalore. Hourly measured data for indoor air and surface temperatures were used to calibrate the model and achieve a Mean Bias Error of 9% and a Root Mean Squared Error of 17%.

The envelope assemblies with material layers were assembled in Design Builder. Their U-values and heat capacities are shown in Table 3.

Table 3: *Wall Systems and their thermal characteristics*

Wall Systems	U-value (W/m2K)	Specific Heat (KJ/m2ºK)
Std. Brick	1.90	159.90
RE-I-C	0.54	128.48
CSEB-I-C	0.52	157.25
AAC-I-CSEB-CM	0.34	230.27

4. RESULTS

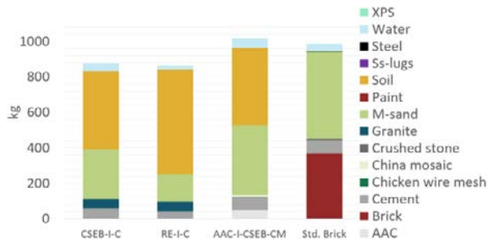
4.1 Mass input

Figure 3 shows a comparison of the mass of the materials per unit area for all four wall systems. Such a mass input analysis helps identify the materials used in larger quantities and give a context for the subsequent environmental impact results.

In the CSEB-I-C system, soil and M-sand make up over 82% of the mass input. In the RE-I-C system too, soil and M-sand make a similar proportion (86%). However, the mass of soil is more than the CSEB-I-C, and a lower quantity of M-Sand is used. In the AAC-I-CSEB-CM system too, soil and M-sand make up over 82% of the mass input, but in this case the mass of M-sand is higher and the mass of soil lower, than the RE-I-C system. In the Std. Brick system, 37% of the mass is from the fired clay bricks and about 50% of the mass is M-sand.

Among the four wall systems, the quantity of cement and water required per m^2 of the wall is the highest in the AAC-I-CSEB-CM system and the lowest in the RE-I-C system. Cement and water quantities used in the AAC-I-CSEB-CM system are comparable to the quantities used in the standard brick wall system. Overall, the share of cement in the total mass input is only about 5-7% and that of water is about 2-5%. All 4 walls have a similar mass input of water, with the RE-I-C have a little less water than the other 3. All 4 walls have a similar mass input of cement, with the RE-I-C have a little less cement than the other 3.

Figure 3: *Mass of input materials per m^2 of wall*



4.2 Cradle to handover stage: 6 environmental indices

4.2.1 GWP

Figure 4a shows the GWP of the wall systems and the contribution from the individual materials. The baseline Std. Brick wall system has the highest emissions, where bricks and cement are responsible for over 90% of the impact. This is despite the other wall systems having additional material layers such as XPS and stone cladding. RE-I-C system has the lowest GWP (reduction by 78% from the baseline), followed by CSEB-I-C (reduction by 70%) and AAC-I-CSEB-CM (reduction by 52%) systems.

Bricks, cement and cement products are the largest contributors to the impacts of the wall systems. However, as seen under the mass input results, the share of cement to the total wall's mass is only about 5-7%. This highlights the fact that even small quantities of cement in the wall systems are responsible for the overall GWP of the wall.

4.2.2 ODP, AP, EP, POCP, and EE

Figure 4b, c, d, e, f shows the ODP AP, EP, POCP, and EE of all wall systems. AAC-I-CSEB-CM has the highest ODP. We see that cement and cement products have the highest ODP, contributing to more than 75 % of the impacts. For AP, EP, and POCP impacts, the Std. Brick wall has the largest environmental impacts. For AP, EP, POCP, and EE, the impacts have the same pattern as those of GWP.

Overall, RE-I-C system has the lowest impacts.

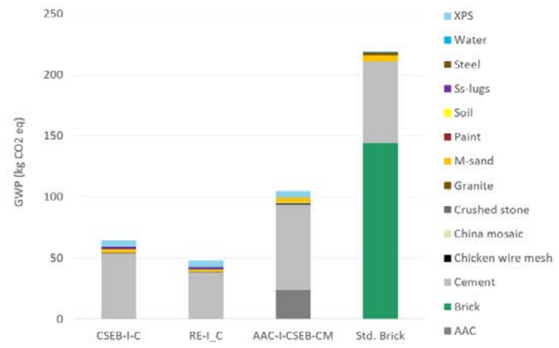
4.3 Operations: Carbon Emissions

Figure 5 shows the measured temperatures for the RE-I-C Wall. The indoor air temperature typically ranges between 25 °C and 30 °C. Having surface temperatures that are 2-3 °C below the air temperature (during occupied hours) results in operative temperatures that are lower than the indoor air temperatures to improve comfort in the cooling season and increases the period when the building can be operated without air-conditioning even with interior loads due to lights, people, and equipment. This is the value of the insulation combined with interior thermal mass even in the moderate climate of Bangalore.

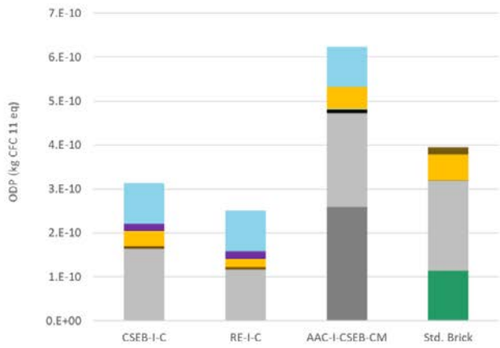
Any carbon emissions savings during the operations stage that results from changes in the wall will be due to the change in the thermal properties which affect cooling energy consumption.

Table 4 shows the impact of the wall assemblies on carbon emissions during the operations stage. As in the cradle to handover stage, in the operational stage too, the carbon emissions resulting from the standard brick wall are the highest at 1972 tCO_2e. Compared to the standard brick wall, the experimental walls show savings of 179 to 217 tCO_2e.

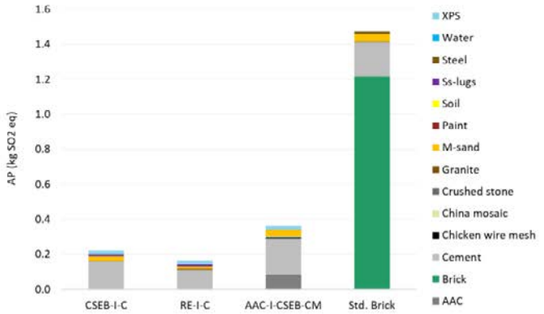
Figure 4: *Environmental impacts of all wall systems*



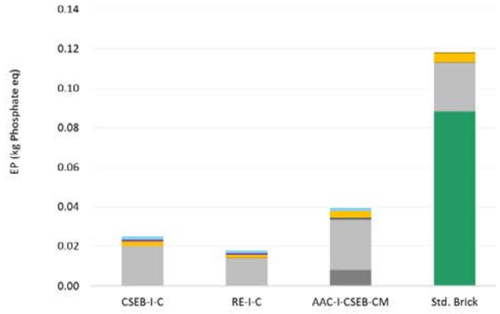
a) Global Warming Potential (GWP)



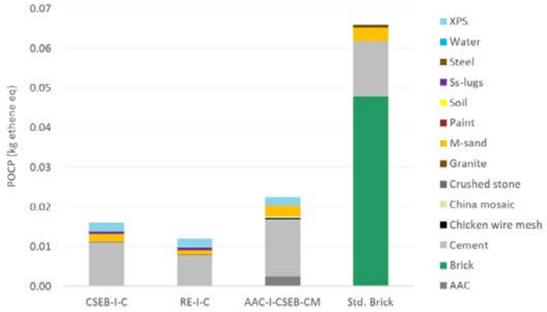
b) Ozone Depletion Potential (ODP)



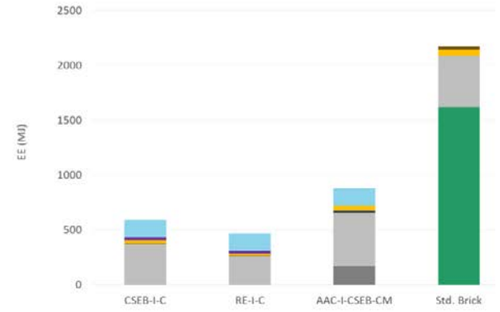
c) Acidification Potential (AP)



d) Eutrophication Potential (EP)

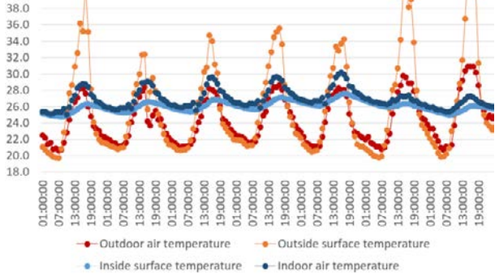


e) Photochemical Ozone Creation Potential (POCP)



f) Embodied Energy (EE)

Figure 5: *Temperatures for the RE-I-C Wall.*



4.4 Lifecycle Carbon Emissions

Adding the cradle-to-handover and the operational stages give us the lifecycle emissions (see table 4). The AAC-I-CSEB-CM wall shows the highest lifecycle savings of 257 tCO2e, with operations stage savings of 217 tCO2e, and cradle to handover savings of 40 tCO2e. The Insulated Rammed Earth wall and the insulated CSEB wall have total lifecycle savings of 239 tCO2e and 234 tCO2e respectively.

While the cradle-to-handover savings appear small in comparison to the total lifecycle emissions, they are about one-third of the total lifecycle savings.

Table 4: *Lifecycle emissions and savings per m² of wall area.*

Walls	Std. Brick	RE-I-C	CSEB-I-C	AAC-I-SCEB-CM
Operational 50-year Emissions (tCO_2e)	1972	1793	1792	1755
Operational Emissions Savings (tCO_2e)	NA	179	180	217
Cradle to Handover Emissions (tCO_2e)	77	17	23	37
Cradle to Handover Emissions Savings (tCO_2e)	NA	60	54	40
Total Lifecyle Emissions (tCO_2e)	2049	1810	1815	1792
Lifecycle Emissions Savings (tCO_2e)	NA	239	234	257

5. CONCLUSION

This LCA study for an experimental building in Bangalore identified data source issues and used the best available sources to compare 3 innovative wall systems with a standard brick wall. The analysis will be extended to the roofing and flooring systems in future. Furthermore, the experimental building has a load-bearing structure. To make the study relevant to framed structures, a separate analysis is needed.

The lack of data sources for conducting LCAs was found to be major barrier to assess the embodied environmental impacts. The study focused on 6 environmental indices for the embodied impacts, and only GWP was calculated for the operational stage. This is due to the lack of data for impacts of electricity generation in India.

Data in the form of EPDs were not available for important materials such as fired clay brick, m-sand, and XPS, and consequently, EPDs were not considered as appropriate data sources for this LCA. In general, there is a trade-off between the number of environmental indicators reported and the coverage of materials.

Furthermore, with the lack of EPDs in India, there are only two databases – the IFC database and the ICE database, that could potentially be used as the data source for an LCA study in India. The limitations of the ICE database are 1) only carbon related impacts, and 2) global scope which affects the regional accuracy of the analysis. More data sources that are India specific and contain multiple environmental indicators need to be developed.

This study found that all 3 experimental walls reduced both cradle to handover (embodied) and operational impacts. The operational emissions reduce by about 10% while the embodied emissions reduce by 50-75%. The operational stage were found to be an order of magnitude more than the embodied carbon emissions. However, for these wall systems the embodied emissions savings are about 1/3rd of the total life cycle savings. Moreover, embodied emissions (and savings) are not dependent on the building operations and the behavior of the users. This removes the issues related to persistence of savings over the life of a building system, which typically plague the operational energy reduction strategies.

Within the embodied emissions, this study found that the share of cement to the total wall's mass is only about 5-7% for RE-I-C, CSEB-IC and AAC-I-CSEB-CM. Even small quantities of cement in these wall systems are mainly responsible for the overall system's GWP, AP, EP, POCP and EE.

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Embodied energy in passive architecture strategies

A balcony and a glazed gallery for a dwelling in a Mediterranean climate

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ABSTRACT: This paper contributes to studies with a global view of buildings environmental impact, considering the main stages of the building life cycle. The objective is to determine the energy trade-off between the operational improvement gained with a passive strategy and the embodied energy associated to it.
The evaluation contemplates a hypothetical case study situated in Barcelona subjected to a Mediterranean climate. Three versions of the same south oriented dwelling are outlined according to local regulations. Two versions consider a passive architectural solution, a balcony as a solar shade and a glazed gallery performing as a greenhouse. Both elements control the energy demand for interior conditioning (cooling and heating). Calculations compare the energy reduction in the operational stage with the embodied energy and emissions data related to construction materials for a 50-year period.
Results show that sometimes, when energy and emissions from operational and embodied stage are accounted, the passive strategy can be counterproductive. So, attention must be paid on the election of passive solutions and their environmental impact, specially once they are declared as part of energy efficiency strategies. Only global calculations, considering the different stages in a building life cycle, can demonstrate the energy efficiency.
KEYWORDS: Passive Strategies, Embodied Energy, Building Materials, Building Life-cycle

1. INTRODUCTION

The building sector is among the sectors with the greatest impact on global energy consumption and generation of greenhouse gas (GHG) emissions [1]. Therefore, architecture can positively influence the mitigation of global warming by reducing buildings environmental impact.

This requires an evaluation on the whole building life cycle. Most policies, regulations and sustainable solutions are focused on controlling energy use during the operational stage, with very few regulations that have requirements on other moments of a building lifespan.

For this reason the development of operational efficiency has allowed extensive strategies for the use stage. Over the past decades low-energy, zero or nearly zero (nZEB) buildings are implemented over the conventional buildings. One of the many ways for reducing the operational stage energy use are the passive strategies. These strategies are significant solutions to cut down the building's energy demand, therefore they have a presence in different types of architecture and climates worldwide.

Passive strategies are designed to moderate the energy need for thermal conditioning by using environmental control strategies, for example there is the use of different kind of spaces and architectural components to function as greenhouses, shades, ventilation patios, thermal accumulators, etc. [2,3].

Usually, these strategies require an increase in the need of construction materials. Several studies verify the energy efficiency achieved with the incorporation of different passive strategies into buildings in diverse climates [4,5,6,7].

However few studies relate the operational improvement to the embodied impact of passive solutions, although literature reveals a high impact of two building's stages in the life cycle, the operating stage and the product stage [8,9,10,11].

Most references on environmental impact evaluation are complex and require a lot of information to understand each case study, so there is no simple way of relating the materials embodied impact to the energy efficiency solutions for the use stage.

This paper contributes to studies with a global view of buildings environmental impact, considering the main stages of the building life cycle. The objective is to determine the energy trade-off between the operational improvement gained with a passive strategy and the embodied energy and emissions associated to it.

2. METHODOLOGY

The methodology is based in comparing a hyphotetical dwelling with and without a passive strategy added to the building. In this comparaison, embodied energy and emissions of building materials for the strategy are considered in addition to the operational energy and emissions improvement gained with different passive strategies (Fig. 1).

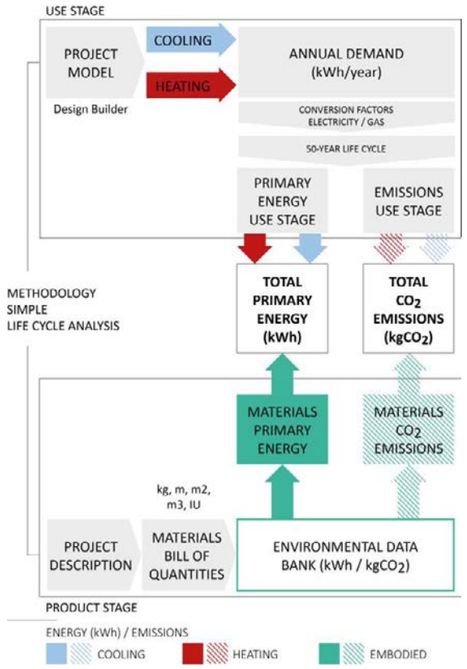

Figure 1. Methodology diagram

2.1 Case Study

For this purpose, a simple one space house was designed according to current regulations and a conventional building construction. The house is in an intermediate stage on a multistorey residential building (Figure 2).

The case study, representing a 68 square meters dwelling situated in Barcelona (Spain), is subjected to a Mediterranean climate. To test the performance of two passive strategies on a tempered costal area, three versions of the same dwelling are compared:

- Version A with no space or component added.
- Version B with a conventional balcony used as a solar shade.
- Version C with a glazed gallery performing as a greenhouse.

During summers, the floor from the upper floor in the balcony added to version B and in the gallery in version C function as overhang and solar protection from the south radiation.

In winters, the gallery added in version C serves as heat collector, due to the greenhouse effect of the glass, and interchanges warm air with the interior space. The gallery has no heating or cooling.

The considerations on orientation and obstructions are to visualize the best-case scenario results in a hypothetical case. The south orientation is chosen to accomplish the appropriate performance from passive strategies [5,6,7] and no surrounding obstructions are considered.

2.2 Calculations considerations

The evaluation considers calculations on the stages with the greatest representation in buildings life cycle [12]. First, in the use stage, the energy demand, primary energy and CO_2 emissions on a typical year for heating and cooling the conditioned interior; second, in the product stage, energy and CO_2 emissions related to construction materials (only initial embodied, not recurrent or demolition) are calculated; then, the results of the three version are compared on a 50-year period, summing the results of both embodied and operational calculations.

Taking the UNE-EN 15978 [13] as code guideline,

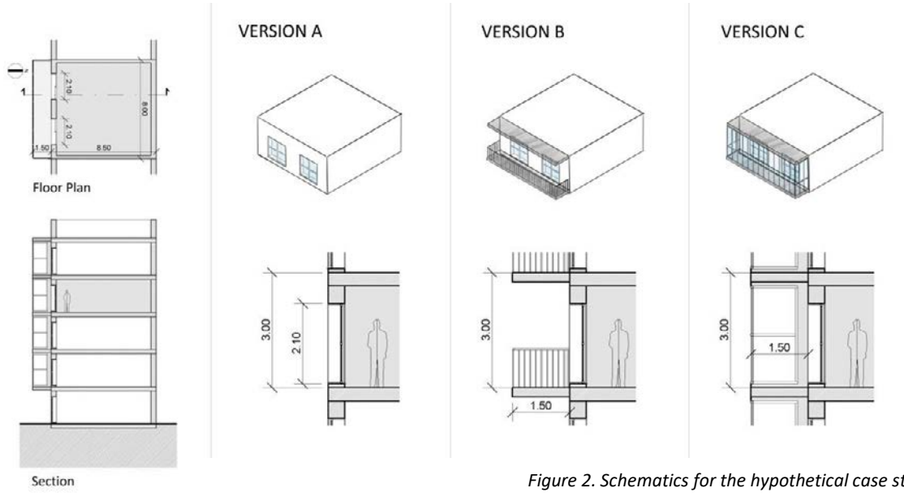

Figure 2. Schematics for the hypothetical case study

the evaluation contemplates the following stages of the building's life:

In the Use Stage, calculations consider only heating and cooling energy demand, extracted from the Operational energy use (B6 according with [13]), which have a direct relation with the passive strategy performance. These results are calculated with dynamic simulations using the DesignBuilder software [14]. Simulations obtain the monthly data on heating and cooling demand (kWh/month). Simulations are outlined to obtain the best performance from the passive strategy.

In the Product Stage, Raw material supply, Transport, and Manufacturing (A1, A2 and A3 in accordance with [13]) are considered. The data for this stage is extracted from the BEDEC Data Bank (2021 version) provided by the Technological Construction Institute of Catalonia [15]. This database is assimilable to the materials commercialized within the area of Barcelona, where the hypothetical case is located.

2.3 Simulations details

The operational calculation considers the heating and cooling necessary to maintain interior temperature in accordance with the local buildings' regulations "*Código Técnico de la Edificación CTE*", specially the "Energy Savings" chapter [16].

For heating the temperature setting is between 17ºC and 20ºC and for cooling is between 25ºC and 27ºC, depending on the schedule of the day. In addition, all versions consider a mobile solar protection in the original windows. The windows have an interior shade roll working with the night heating and the daily refrigeration.

For ventilation, the number of renovations per hour is 1 per infiltration all year round, and variable in summers from 1 to 10 renovations. The internal loads and illumination gains are simulated according to the use profiles established in the mentioned local regulations (CTE Energy Savings - Annex D table B).

The conditioning systems are configured as the local regulation indicates for the system of reference on residential use, using for heating a gas energy source with a Coefficient Of Performance COP of 0.92, and for cooling a electricity source with a COP of 2.6 (CTE Energy Savings 0 - Table 4.5).

For primary energy calculations natural gas and electricity are used as source energy. The trade factors from final energy to primary energy (2.368 for electricity and 1.195 for gas) and final energy to kg of CO_2 (0.331 for electricity and 0.252 for gas) are obtained from the Spanish government reports [17].

The enclosure composition complies with the thermal transmittance in the building's regulation for the winter climate zone (climate C for Barcelona region). The U-value for walls is 0.29 W/m^{2}K; for interior floors 0.47 W/m^{2}K, and for interior windows a U-value of 2.0 W/m^{2}K including the frame and glass. Except for the north and south walls all enclosure elements are adiabatic in the simulations.

3. RESULTS

3.1 Operational results

Results for yearly energy demand in the use stage (Figure 3) accounting cooling and heating, showed that compared to version A (976 kWh/year) both version B (859 kWh/year) and version C (608 kWh/year) reduce the yearly energy demand.

For cooling, version A demands 704 kWh per year, version B, 442 kWh/year and version C, 550 kWh/year. Version B and C reduce yearly cooling energy demand by 37% and 22% respectively in reference to version A. In summers, the solar shading resulting from the superior floor in the balcony and in the gallery produce a reduction in cooling demand compared to version A.

For heating, version C (58 kWh/year) has the best results: the demand for the conditioned interior is almost 80% less than version A (272 kWh/year), contrary to version B (417 kWh/year) that needs 53% more heating than version A.

This indicates that in winters, only version C demonstrates better results. In version B, the heating demand increases due to reduction on solar gains.

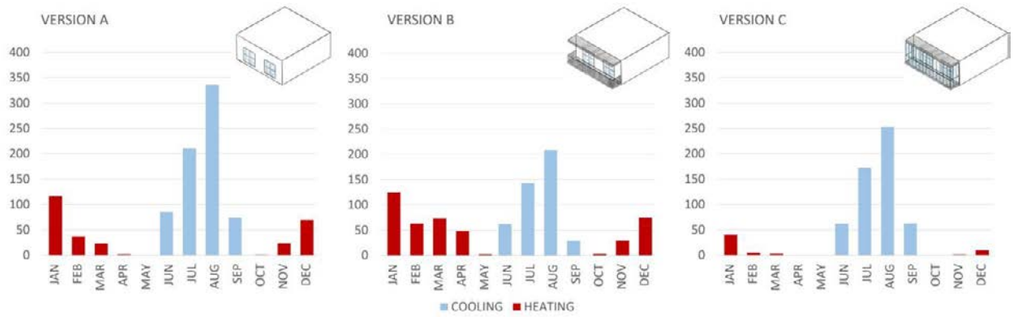

Figure 3. Results for monthly cooling and heating energy demand (kWh)

Results for yearly primary energy consumption and emissions are calculated with the yearly heating and cooling demand obtained from the simulations, the reference COP for the conditioning system and the national energy trade factors (Fig. 4).

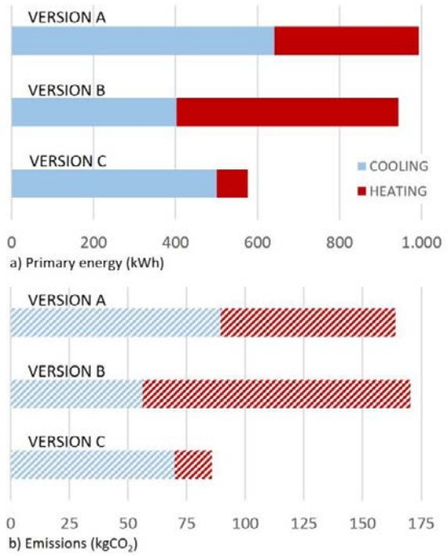

Figure 4. Yearly results for cooling and heating in primary energy (a) and kgCO_2 emissions (b).

The primary energy results (Fig. 4a) indicate that in reference to version A (994 kWh/year), version B (944 kWh/year) has a reduction of 5% and version C (576 kWh/year) has 42% reduction.

Results for yearly CO_2 emissions (Fig. 4b) indicate that compared to version A (164 kgCO_2), version B (170 kgCO_2) has 4% more CO_2 emissions and version C (86 kgCO_2) has 48% less CO_2 associated to operational energy use for cooling and heating. This indicates the importance of the energy source of the system used for providing the thermal comfort in buildings. It is observed that the reference COP from local regulations, gives a better COP for cooling than heating, so results are different for summer and winter results. The use of more efficient systems, with a better COP, would reduce the energy consumption and CO_2 emissions for the dwelling. Also, the consideration of other primary energy source, such as renewables would change the versions energy and emissions calculations.

3.2 Embodied results

From the inventory of building materials considering a conventional construction, the results for the initial embodied are calculated (Table 1).

Version A considers no additional materials for embodied energy and CO_2 emissions calculations.

BEDEC Code	Description	Energy kWh	Emissions kgCO_2
VERSION A			
NO ADDITIONAL MATERIALS		0.0	0.0
VERSION B			
B065710B	CONCRETE	638.3	413.6
E4BC3000	SLAB STEEL	526.5	109.7
E4B83000	BAND STEEL	38.0	7.8
E4B35000	BEAM STEEL	49.9	10.3
B0111000	WATER	0.5	0.1
B0310020	SAND	86.2	16.5
B0512401	CEMENT	387.4	307.5
B0532310	LIME	196.0	121.5
B0FG3JA3	CERAMIC TILE	158.0	43.2
B0FJ3QQ3	CERAMIC TILE EDGE	76.2	20.8
K71197G5	WATERPR. MEMBRANE	1,001.4	59.4
E898E240	HORIZONTAL PAINT	36.7	19.5
E898DFP0	VERTICAL PAINT	10.5	4.7
4B121AEE	STEEL RAILING	899.1	209.2
		4,104.5	**1,343.8**
VERSION C			
B065710B	CONCRETE	638.3	413.6
E4BC3000	SLAB STEEL	526.5	109.7
E4B83000	BAND STEEL	38.0	7.8
E4B35000	BEAM STEEL	49.9	10.3
B0111000	WATER	0.5	0.1
B0310020	SAND	86.2	16.5
B0512401	CEMENT	387.4	307.5
B0532310	LIME	196.0	121.5
B0FG3JA3	CERAMIC TILE	158.0	43.2
B0FJ3QQ3	CERAMIC TILE EDGE	76.2	20.8
K71197G5	WATERPR. MEMBRANE	1,001.4	59.4
E898E240	HORIZONTAL PAINT	36.7	19.5
E898DFP0	VERTICAL PAINT	10.5	4.7
B44ZF0C5	STEEL PILARS	1,725.2	595.9
B44ZF0C5	STEEL BEAM	1,219.2	421.1
B44ZF031	STEEL SUBSTRUCTURE	586.9	202.7
EC172R33	DOUBLE GLASS	3,281.7	719.6
K863U001	STEEL ENCLOSURE	652.6	187.9
E8985BN0	STEEL PAINT	38.5	20.5
EAF2813C	WINDOWS	2,712.1	1,436.0
		13,421.7	**4,718.3**

Table 1. Different versions descriptions with energy and CO_2 emissions results for construction materials

The results for the architectural element added in version B and version C indicates the construction materials for the gallery have higher energy cost (13,422 kWh) and CO_2 emissions (4,718 kgCO_2) than the balcony. More specifically 3.3 times more energy and 3.5 times more emissions than the results for the balcony (4,105 kWh and 1,344 kgCO_2).

In version B, the materials with higher embodied energy are steel elements (1,513 kWh), the waterproofing membrane (1,001 kWh) and concrete/mortars (1,308 kWh). As for the embodied CO_2 emissions the construction materials with higher results are concrete/mortars (859 kg CO_2) and steel elements (337 kgCO_2). These embodied energy and emissions results are mainly related to the structure of the balcony.

In version C, besides the steel elements (4,798 kWh), the glass/windows (5,994 kWh) have the highest embodied energy. The construction materials for the gallery enclosure (10,216 kWh) account for 76% of the total embodied energy. In the emissions results also the steel elements (1,536 kgCO_2) and the glass/windows (2,116 kgCO_2) have the highest embodied emissions.

Figure 5 is a graphic representation of the embodied energy for the construction materials for the balcony and gallery in each version. The scheme of colours represents materials embodied energy from lower to higher for each square meter of the passive element, with a total of 12 m^2 of constructed surface.

3.3 Operational and embodied results

The results for a 50-year evaluation are presented in Figure 6 considering both the embodied and the operational stage results in the three versions.

In version B (51,306 kWh), the primary energy improvement gained with the balcony during the operational stage is cancelled, it actually represents 3% more energy than version A in a 50-year period (Fig. 6a). In version C (42,213 kWh), adding a glazed gallery represents an improvement compared with version A (49,705 kWh), it is 15% less total primary energy once embodied energy is considered.

The CO_2 emissions results (Fig. 6b) show both version B (9,866 kgCO_2) and version C (9,010 kgCO_2) have more CO_2 emissions in a several life stage evaluation in comparison to version A (8,203 kgCO_2). The global evaluation demonstrate version B has 20% more total emissions and version C has 10% more CO_2 emissions than version A.

Resuming, when comparing the energy results only the gallery is favourable when the embodied energy is accounted in a 50-year period. Meanwhile the CO_2 emissions results are negative for both version B and C, finally the version A has less CO_2 emissions in a 50-year evaluation.

The use of a 50-year period for evaluating the buildings life cycle is the most common period of time [8,9]. If other time period is considered the efficiency of the passive strategy would be altered.

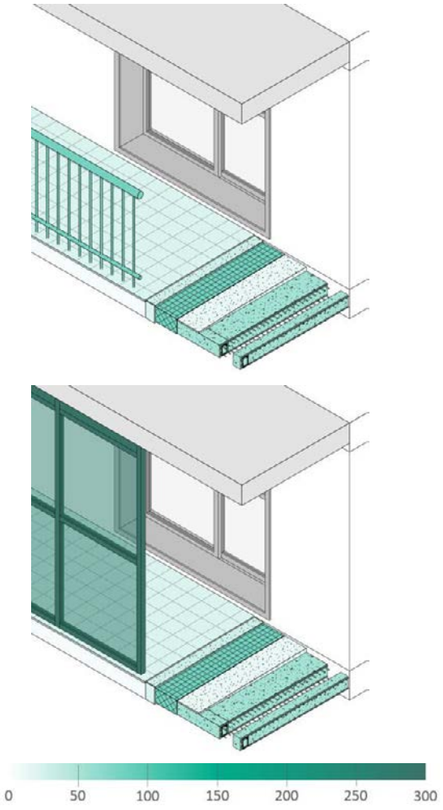

Figure 5. Graphic representation of version B and version C embodied energy (kWh per m^2).

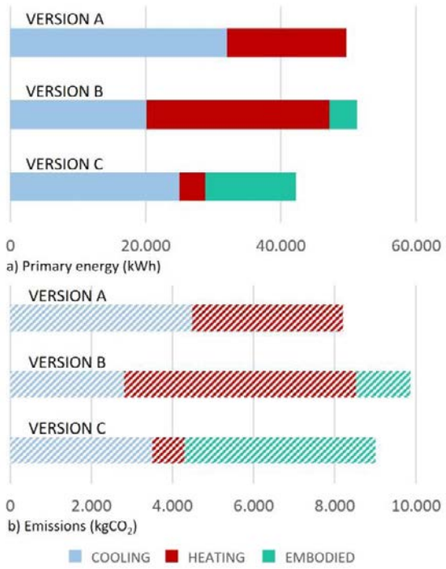

Figure 6. Primary energy (a) and CO_2 emissions (b) in a 50-year evaluation.

4. CONCLUSIONS

Attention must be paid on the election of passive solutions and their environmental impact, specially once they are declared as part of environmental impact reduction strategies. Only with global calculations, considering various stages in a building life cycle, the passive strategies can demonstrate its full performance.

The passive strategies chosen in this evaluation (balcony and gallery) prove to serve for the Mediterranean climate in reducing the energy demand for thermal conditioning. But in a 50-year period when both performance in the use stage and building construction materials in the fabrication stage are considered results are uneven. In primary energy results, the balcony has higher energy than the version with no passive strategy; and the gallery still represents an improvement. When accounting CO_2 emissions both strategies have higher emissions results in comparison to version with no passive strategy.

This investigation is centred in a south non obstructed optimal case to understand the passive strategies performance. Future studies will evaluate the effect of different orientations and urban context on real buildings cases.

Materials used in the conventional construction such as concrete, steel and glass have high environmental impact. A next step will be to study the use of less environmental impact and more sustainable construction materials, specially for the structure and enclosure to reduce the embodied energy and emissions.

Further research should calculate counterproductive design strategies and their related environmental impact for the different stages in the building life cycle. The trade-off between operational and embodied can be clear from early design stages and it contributes to the environmental impact benchmark for different passive strategies and the construction materials used in today's architecture.

ACKNOWLEDGEMENTS

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Net-zero building design

Demonstrating the use of agricultural waste and industrial by-products from rice cultivation belts

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ABSTRACT: Buildings contribute significantly to global carbon emissions, resulting in high greenhouse gas emissions that contribute to global warming. Stubble burning is a major issue in India, causing severe health and environmental problems every year. The primary reason is the disposal issues associated with rice cultivation by-products such as rice straws and rice husk. This paper aims to explore the means of using building materials made of rice cultivation waste and by-products in making a Net-Zero energy office building, also the possibility of using waste heat from the biomass boilers in running the air conditioning system. A case study of a rice processing plant situated in Karnal, Haryana, where a 3600 m^2 office building is planned was selected and iterative simulations were performed to analyse the step by step reduction in the annual EPI (Energy Performance Index) while incorporating energy saving strategies. Energy simulation software Design Builder v7.0 was used to assess the building performance. Life Cycle Assessment (LCA) was also performed to assess the reduction in initial carbon emissions while using low carbon building materials over conventional materials.
KEYWORDS: Energy simulation, Life Cycle Assessment, Low carbon, Rice husk, Rice straws

1. INTRODUCTION

Buildings have a significant impact on the environment. Construction of buildings and their operation accounts for 36% of global final energy use and 40% of energy-related carbon dioxide (CO_2) emissions. Also, the building sector has a strong potential to provide long-term energy and greenhouse gas emission savings without high financial costs [1].

To address the climate change challenge and meet the UN Sustainable Development Goals, there is an urgent need for sustainable development. Recycling waste reusing industrial by-products can help to reduce carbon emissions and energy consumption while also providing a healthy and comfortable environment for the occupants.

In the agricultural belt of India, stubble burning of crop residues contributes directly to environmental pollution in the surrounding areas and beyond. However instead of burning, this waste such as rice straws and husk can be used in construction materials and waste heat from milling plants can be used to supplement energy needs. These reuse strategies can lower the building energy use or EPI (Energy Performance Index) and also contribute to addressing the environmental hazard of stubble burning.

In this paper, we explore the energy performance of a case study building designed to reuse some of the agricultural waste and industrial by-products from the rice cultivation areas and nearby mills. This can function as a scalable solution to tackle both energy efficiency improvements and air quality problems of the region.

2. METHODOLOGY

This paper aims to examine the waste and by-products from rice cultivation and rice processing plants (such as rice straws, rice husk and ash) and their applicability in the production of construction materials, to configure a space conditioning system that uses waste steam from the rice processing plant, and to investigate the scalability and implications in a larger context. For the objective, literature reviews were conducted. Building energy simulations and Life Cycle Assessment (LCA) were performed on a proposed design of an upcoming office complex to test the impact of those materials and various energy-saving strategies on the thermal performance of the building envelope, building energy performance, and reduction in initial carbon emissions. For the simulation, DesignBuilder v7.0 software, a graphical user interface to EnergyPlus v9.4, is used.

3. BACKGROUND

Stubble burning is the deliberate incineration of crop residue by farmers following crop harvest. These are cut stalks left on the field after cereal grains or sugarcane stems have been harvested [2]. Stubble burning is one of the world's major sources of air pollution, emitting particulate and gaseous pollutants that have serious consequences for human health and the environment [3]. Stubble burning of crop residues in India generates about 150 million tons of CO_2, more than 9 million tons of carbon monoxide (CO), 0.25 million tons of sulphur oxides (SO_X), a million tons of particulate matter, and more than 0.5 million tons of black carbon [4]. According to the Energy and Resources Institute (TERI), in 2012 ambient and household air pollution caused approximately 2.75 million deaths in the Southeast Asia region [5].

This problem can be addressed by finding alternatives to stubble burning such as incorporating their use in building materials made from rice cultivation and processing by-products. In this paper, we will discuss the use of three major resources present in form of waste in a rice processing facility, rice straws, rice husk, and waste heat from the turbine extraction of the biomass plant used to run the rice mills.

3.1 Straw – Ash Blocks

Out of 82 Mt surplus residues from the cereal crops, 44 Mt generated from rice cultivation each year in India is set to fire According to the Indian Agricultural Research Institute (IARI) [6]. This stubble in form of rice straws can be combined with fuel ash to prepare straw ash blocks in a composition of 60% Paddy straw, 28% Fuel ash, and 12% Binder [7]. These blocks have better thermal and acoustic properties in comparison to conventional burnt clay bricks. These blocks are about 5 times the size of clay brick in India, therefore requiring less mortar for masonry, water for curing the wall after construction, and reducing construction time, thus reducing the overall cost of construction. Table 1 shows the properties of straw-ash and burnt clay bricks.

Table 1:
Wall construction materials properties

Materials	Conductivity (W/m-K)	Specific Heat (j-kg-K)	Density ($kg/m^{3)}$	Strength (MPa)
Straw-ash block	0.4	690	1400	7.5
Burnt clay brick	0.6	840	1800	7

3.2 Rice Husk Ash (RHA) Insulation

Rice husk is one of the most common agricultural wastes formed during rice processing. Because rice husk has a very low commercial value its disposal creates problems added by its transportation and handling problems due to low density [8]. About 200 kg of husk is produced for every 1000 kg of paddy milled, and when this husk is burned in biomass boilers, about 50 kg of RHA is produced [9]. In 2014 around 31 million tons of rice husk were produced in India resulting in the generation of 4.65 – 5.58 million tons of RHA. This RHA is currently being disposed of in low-lying areas and along roadsides, resulting in deterioration of ambient air quality due to low bulk density and posing health problems. The amount of RHA produced is significant, but it has not been put to productive use in any of the manufacturing processes [8]. However, RHA can be used for making building insulation in a composition of 88.28 wt % rice husk ash (RHA), 9.29 wt % of bentonite, and 2.41 wt % of exfoliated graphite. The thermal conductivity of this insulation is 0.0746 W/m-K [10]. It has the potential to be used as an insulation material to prevent heat loss or gain and also minimizes the negative environmental impact due to the open dumping of rice husk.

A building wall assembly can be made nearly the same thickness as a 230 mm conventional burnt clay brick wall assembly (Fig. 1) using Straw-Ash blocks and RHA insulation (Fig. 2) which can offer better thermal and acoustic performance. Additionally, the RHA insulation can be used to increase roof thermal performance (Fig. 3).

Figure 1:
Wall A (u value - 1.69 W/m^2-K)

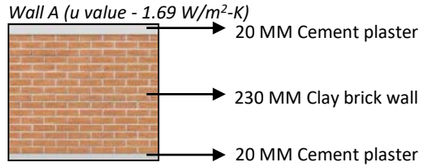


Figure 2:
Wall B (u value - 0.47 W/m^2-K)

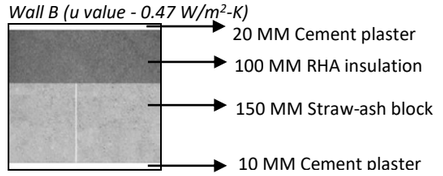
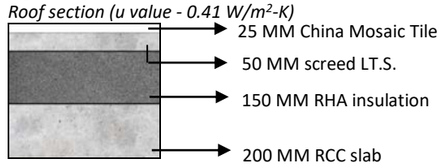


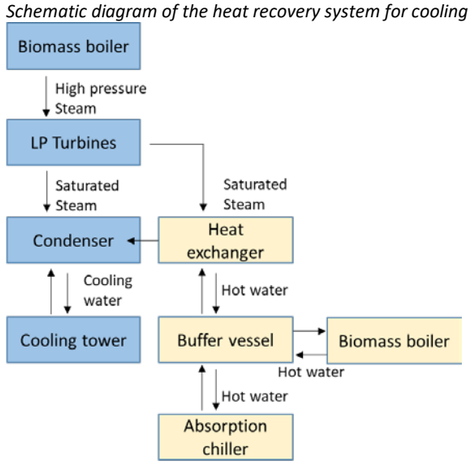
Figure 3:
Roof section (u value - 0.41 W/m^2-K)



3.3 HVAC System

Most rice processing plants use a direct combustion method for producing on-site electricity by burning rice husk in Biomass plants. Rice husk is used as a fuel in biomass plants to generate steam, which turns turbines and generates electricity. Waste heat in the form of steam extracted at low pressure (0.1 bar) from steam turbines can be used to heat water for running air conditioning systems as shown in fig. 4. Utilizing waste heat will also reduce the water loss in the condenser [11].

Figure 4:
Schematic diagram of the heat recovery system for cooling



For this purpose, a heat exchanger [12] can be introduced between the low-pressure steam turbine extract and the condenser through which water in the buffer vessel is heated up till 90-95°C temperature which is supplied to the generator of Low-Pressure Hot Water Absorption Chiller [13] for cooling water. The return water at a temperature difference of about 10°C is again pumped back to the buffer vessel. By storing heat, the buffer vessel improves system efficiency. The stored heat is used the next day to meet the generator's hot water demand while the biomass plant is starting up [14]. Additionally, a Biomass boiler that uses rice husk as fuel, can also be installed in a closed-loop circuit with the buffer vessel as a backup when the biomass plant is not working.

Utilizing waste heat as an alternative to electricity reduces equivalent carbon emissions happening during the production of electricity in thermal power plants.

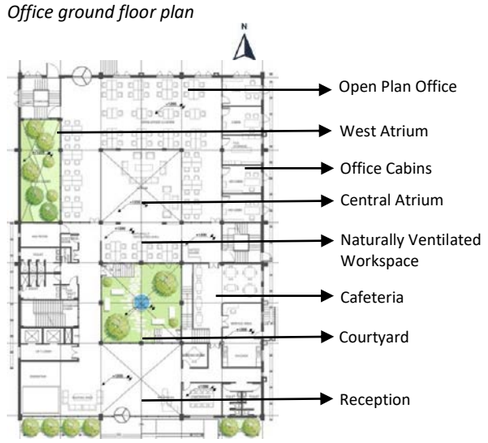
4. CASE STUDY

To explore the use of waste by-products (the materials and strategies mentioned above) and create a net-zero-energy building a 25-acre rice processing plant in the Karnal district of Haryana, India, was used as the case study. In this plant, a 3600 m² office building is planned. The site lies in the composite climate region in India (Max. Temperature of 45°C in summers and Min. temperature of 4°C in winters. The average annual rainfall is 582 mm). The planned office, in the proposed design, has an open plan and cellular workspaces, a cafeteria, a library, a gym, and guest rooms. The building is primarily mechanically ventilated and conditioned, however, some parts of the open plan workspace are naturally ventilated. A 3 MW on-site rice husk biomass plant serves the daily energy demands of the rice mill [15]. Subsequent subsections explain the proposed building design and its characteristics.

4.1 Architecture design

As the building lies in a rice processing facility, the air quality is poor which restricts the occupants from the opening windows to the outside. Therefore, for the naturally ventilated area, openings are provided in the internal courtyard which has a more controlled microclimate. Narrow floor plates, linked by the atrium and courtyard, create an open and interconnected environment with ample natural light. The atrium is provided with vents on top to let the hot air escape thus improving natural ventilation by creating a stack effect. To reduce heat gain in highly occupied open plan office areas due to the low angle sun, the atrium and the core is planned at West and less occupied office cabins at East, respectively as shown in fig. 5. To reduce the cooling load, spaces like the R&D Department and a part of cafeteria seating are planned on the lower ground floor.

Figure 5:
Office ground floor plan



4.2 Building fabric & shading

The building fabric is designed to use the previously discussed materials (RHA insulation and Straw-Ash blocks) and is highly insulated, shown in Figures 2 & 3. The building structure is made of Reinforced Cement Concrete (RCC). Table 2 shows the fabric details.

Table 2:
Building fabric Details

Walls	U-Value = 0.47 W/m²-K
Windows	U-Value = 1.6 W/m²-K SHGC = 0.4, VLT = 0.74
Roof	U-Value = 0.41 W/m²-K

Shading devices are a key requirement in building designs in warm climates to minimize solar gains. Through an iterative process of optimizing the right shading design, consisting of Overhang, Louvers, and Fins, different shading configurations were proposed for different orientations. For windows on East and West, where there is low angle morning and evening sun, a combination of 600 mm overhang, 400 mm side fins, and 400 mm louvers was used. For North and South windows, a 600 mm Overhang was proposed.

4.3 Lighting and equipment loads

The building is designed to have adequate daylight for the most part of the day. Lighting design and efficient LED fixtures were used to achieve an illuminance level of 300 lx at 800 mm above the floor. Total Lighting Power Density (LPD) achieved was 3.5 W/m². However, due to the integration of daylight sensors and Passive Infra-Red (PIR) occupancy sensors, total energy use for lighting was minimized.

Energy-efficient appliances were selected based on the Bureau of Energy Efficiency (BEE) energy rating scale in India. Taking realistic Plug and Process Loads (PPL) power capacities allows for more precise HVAC and electrical component sizing, which saves on operational costs. On average, the peak PPL energy use intensity for offices (without laboratories or data centres) is 0.5 W/ft^{2,} whereas ASHRAE (2009) specifies a 1 W/ft^2 peak PPL energy intensity [16].

Table 3:
Plug and Process load details

Office & Meeting rooms	5 W/m²
Kitchen	30 W/m²
Circulation area	1.85 W/m²
Guest rooms	3.15 W/m²
Toilets	1.85 W/m²

4.4 Building services

Most of the building is mechanically ventilated and conditioned. The cooling system is driven by an absorption chiller utilizing waste heat from the biomass plant as discussed in section 3.3. In comparison to the typically used VRF systems in similar buildings, this absorption chiller-based radiant cooling system is more suitable for this building type due to the free heat available from the biomass plant and the very regular nature of building occupancy. In practice, a backup smaller biomass boiler (just to meet the building's space cooling requirements) is planned to run the system in case of the primary system is not available.

The chiller is supplying chilled water at a temperature of 14°C to the radiant slabs (with embedded 20 mm PEX pipes at 50 mm from the slab bottom) and is connected to a cooling tower for the supply of cooling water to the condenser.

The chiller is also supplying chilled water to the water cooling coil in the Variable Air Volume Air Handling Units (VAV-AHU) equipped with a heat recovery system. In summers the zones are supplied with pre-cooled fresh air at 16°C temperature to meet the latent cooling loads, whereas, in the winter, it meets the fresh air requirements based on occupancy. Toilets have dedicated mechanical exhausts.

The office area planned between the atrium and the courtyard is cooled through Natural ventilation. Night cooling strategy is adopted to let the thermal mass cool overnight. The operative temperature for a naturally ventilated building in Delhi which also lies in composite climate is 30.68°C. The 90% acceptability range for adaptive models in India is ± 2.38°C [17]. Additionally, ceilings fans are provided to increase air velocity and the cooling thermal sensation [18]. The temperature increases of 2.5–3.5 C, for temperatures up to 31.0 C, can be compensated for with 0.7–1.0 m/s air velocities while maintaining the thermal comfort sensation [19, 20, 21].

4.5 Building occupancy and operations

The building is running six days a week and eight hours a day from 7:00 to 19:00 with diversified usage patterns. The total number of full-time occupants are 270. The occupancy, equipment, and lighting schedules follow the same typical profile. (Table 4) shows the thermal comfort parameter settings. The HVAC system is set to maintain the cooling setback temperature of 28°C from 6:00 to 9:00 to reduce the start-up cooling load. On Sundays and holidays HVAC, equipment, and lighting are turned off.

Table 4:
Thermal Comfort parameter settings

Office cooling Set point temperature	25°C
Circulation area cooling Set point temperature	26°C
Summer Operative Temperature Range	23-26°C
Minimum Fresh Air	10 l/s

5. SIMULATION RESULTS

Through the entire design process, iterative simulations were done while changing one parameter at a time for the reduction in the annual EPI of the building to achieve the net-zero target. The EnergyPlus weather file used is of Hisar, Haryana which is 172 km away from the site. Table 5 and Fig. 6 shows the various iterations performed for a subsequent reduction in EPI.

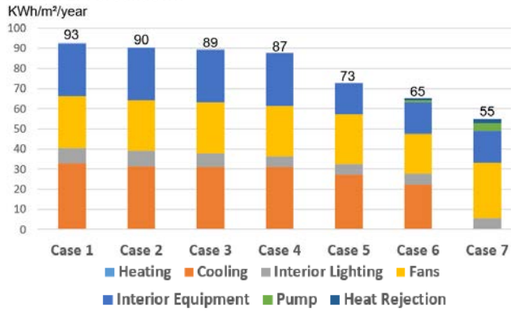
Table 5:
Iterations done to reduce the EPI

Cases	Wall U value	LPD	PPL	AC System	EPI
Case 1 Base case	1.69	5	11	VRF system + DOAS	93
Case 2 Wall Optimisation	0.47			VRF system + DOAS	90
Case 3 Window shading				VRF system + DOAS	89
Case 4 Efficient lighting		3.5		VRF system + DOAS	87
Case 5 PPL reduction			5	VRF system + DOAS	73
Case 6 Radiant cooling				Radiant cooling + DOAS	65
Case 7 Absorption Chiller using waste heat				Radiant cooling using Absorption Chiller + DOAS	55

Note: Wall U-Value (W/m^2-K), LPD (W/m^2), PPL (W/m^2), EPI (kWh/m^2/year)

The roof and glazing U-Values were kept constant throughout the iterations as described in table 2. First, the base case was simulated using conventional burnt clay brick wall envelope (shown in Fig. 1), VRF system with Dedicated Outdoor Air System (DOAS) for air conditioning, equipment, and lighting load to be 11 W/m^2 and 5 W/m^2, respectively. The annual EPI was determined to be 93 kWh/m^2. In case 2 the EPI was then reduced to 90 kWh/m^2/year after the burnt clay brick wall envelope was replaced with the wall assembly made of Straw-ash blocks and RHA insulation (shown in Fig. 2) with all other parameters remaining unchanged. In case 3, the east and west windows were shaded, resulting in an EPI reduction of only 1 kWh/ m^2 /year as the East façade has a WWR of 15% and no windows on the West except for the Lift lobby and staircase. However, shading windows reduces glare and, eventually cooling load in the cabins. In case 4, by the use of efficient lighting fixtures, the lighting load was reduced from 5 W/ m^2 to 3.5 W/ m^2, resulting in an EPI reduction of 2 kWh/m^2/year. Following that, in case 5, the ASHRAE-specified PPL energy intensity of 11W/m^2 was changed to 5 W/m^2, resulting in an EPI of 73 kWh/m^2/year. The reduction in PPL energy and Lighting load resulted in a significant reduction in cooling load. In case 6, for reducing cooling energy consumption, the VRF cooling system was replaced with a Radiant cooling system driven by a Water Cooled Screw Chiller, resulting in an 8 kWh/m^2/year EPI reduction. Followed by case 7, where an absorption chiller was used instead of the electric chiller to utilize waste heat from the biomass plant, resulting in a final EPI of 55 kWh/m^2/year.

Figure 6:
Annual EPI breakdown



In the naturally ventilated office area, the operative temperatures are at or below 31°C for 67% of the total occupied hours in summers (April to September), in case 7.

The Global Warming Potential factor (GWP) emission factors for Straw-Ash blocks and burnt clay bricks are -0.2 kgCO_2/kg and 0.57 kgCO_2/kg, respectively. Emissions factors are taken from manufacture provided data and the IFC Database of Indian construction materials [7, 22]. Emission factor for RHA insulation is assumed to be 0 kgCO_2/kg as it consists of 88.28 wt % rice husk ash (RHA) which is a carbon-negative material [23].

A Cradle to Gate Life Cycle Assessment (LCA) is performed as approximately 80% of initial EC can be reduced before construction commences [24]. The assessment revealed a significant drop in Embodied Carbon (EC) by approx. 48% while replacing wall envelope 'Wall A' with 'Wall B'.

6. DISCUSSION AND CONCLUSION

India has about 1,74,000 rice milling units [25]. These building technologies can be implemented at these rice mills for building net-zero energy buildings around them. Also, these building materials are found to be more efficient in terms of cost, durability, and thermal performance with a negative carbon rating.

In India, the annual production of bricks is around 250-300 billion bricks per annum and these numbers are expected to reach 750 - 1000 billion bricks/year in the next 20 years. Around 85% of these bricks are burnt clay bricks. In India, 0.75 billion m^2 of built-up area is expected to be added each year [26]. This emphasizes the importance of using non-fired bricks to replace burnt clay bricks to reduce GHG emissions and topsoil depletion. Annual production of Rice straws and RHA as discussed in sections 3.1 and 3.2, respectively, is capable of replacing a significant amount of burnt clay bricks from the construction industry if used to make construction materials.

The straw-Ash blocks provide better thermal and acoustic insulation than the burnt clay bricks but are weak in showing thermal mass effect because of their low specific heat capacity. Although RHA insulation being a carbon-negative material has promising properties to be used as insulation having a K value – 0.07 W/m-K, However, no information is available about the specific heat capacity or density, which can have an impact on envelope weight.

Additionally, the absorption chiller based radiant cooling system combined with DOAS is found to be more efficient than the VRF system with an EPI difference of 18 kWh/m^2/year between Case 5 and Case 7. A high reduction in cooling load is observed with an increase in fan and heat rejection energy consumption. The high water consumption in the cooling tower can be a concern at locations with low water table.

The final EPI of the building is calculated to be 55 kWh/m^2/year which falls under the GRIHA benchmark for commercial buildings in composite climate [27]. The installed 3 MW biomass plant, using the biomass from the rice mill meets the daily energy demands and enables the building to run in net-zero energy mode.

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Retrofit solutions for existing office buildings in European context

A Low-Tech approach

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ABSTRACT: In the European Union (EU) sector, buildings account for approximately 40% of energy consumption, followed by 36% of CO_2 emissions. The commercial building uses 27% of the energy and this increases every year. Therefore, it is important to retrofit existing commercial buildings to have substantial energy savings. Hence, the study aims to provide retrofit solutions for existing office buildings in the European context. The objective is to evaluate the feasibility check of the low-technology systems coupled with Ground source heat pumps (GSHP) and Concrete core activation (CCA) systems so that we can have a package of retrofit solutions. Building Performance Simulation (BPS) drove the method, by adapting the concept of low-tech, through various case studies. The study results show that providing Ground source heat pumps (GSHP) with Concrete core activation (CCA) systems can reduce 21% of energy consumption compared to a typical European office building, by providing optimum comfort to the users.
KEYWORDS: Retrofit, Energy consumption, Building Performance Simulation, Low-tech, GSHP

1. INTRODUCTION

Belgium has set its contribution to the European Union (EU) target of 32.5% regarding energy efficiency by 2030 [1]. The existing build stock in the EU accounts for approximately 40% of energy consumption, followed by 36% of CO_2 emissions and 50% accounts for heating and cooling of the EU energy consumption [2,3]. Currently, about 35% of the EU's buildings are over 50 years old and for a decade only 0.4-1.2% of the EU building stock was renovated yearly [4,5]. In 2017, the final energy consumption across the EU surpassed 3.3% where the annual target was supposed to reach the 2020 target of 20% for energy efficiency improvements [6]. Hence, to achieve the target by at least 32.5%, annual building renovation rates of 2–3% would need to be achieved [1,7]. Building and retrofitting in an energy and resource-efficient manner is one of the elements of the European Green Deal [8]. Therefore, retrofitting plays a vital role in achieving energy reductions, and greenhouse gas emissions and adapting to a low-tech approach can accelerate the drive towards such green goals.

This paper aims to provide retrofit solutions for existing office buildings in the European context. The objective is to evaluate the feasibility check of the low-technology systems coupled with Ground source heat pumps (GSHP) and Concrete core activation (CCA) systems so that we can have a package of retrofit solutions.

2. LITERATURE REVIEW

2.1 Low-tech approach

Low-tech buildings are simply designed buildings with the use of naturally found local resources [9]. The "low-tech" can be defined as 'The buildings which achieve a high user comfort and excellent energy performance by a minimum of technical installations'. A sustainable low-tech building means a building that uses a low level of technology from the planning until the dismantling phase which completes the life cycle. It covers 3-dimensional aspects of sustainability that are ecological, economic & social aspects. The ecological aspects include the use of the ecological resources (climate and location factors, during construction, design, etc.), the economical aspect focuses on the construction & development of building at low cost, and the social aspect focuses on four dimensions of comfort (thermal, hygienic & acoustic comfort), building health (harmless building materials, daylight, etc.), supply & disposal, and safeguarding aspects of potential hazards [10]. Hence, 2226 Office building in Austria was studied to adapt to the concepts of a low-tech building.

2.1.1 Case study: 2226 building

The 2226 building aimed to provide optimal comfort with minimal use of technology thereby eliminating the potential hazards from a conventional high-tech building. The name of the building represents temperature in the range of 22 to 26°C throughout the entire year while keeping the CO_2 level below 1000 ppm. The goal was to create a building with a good indoor environment without the use of mechanical heating, ventilation, or cooling technology. Thus, "Concept 2226" is based on two strategies: A new concept of building automation & High-performance building envelope [11].

2.2 Parameters of Intervention for a low-tech building

The parameters studied were: Building Envelope and Thermal Comfort (GSHP with CCA). An efficient External Thermal Insulation Composite System (ETICS) is a set of prefabricated components that consists of adhesive, insulation, render with mesh reinforcement, primer, and the finish coat. These systems are used in the European context to improve the energy efficiency of existing buildings, as it significantly reduces thermal transmission through outer walls and eventually help in reducing the costs of heating and cooling [12]. Ground Source Heat Pumps (GSHP) are coupled with Concrete Core Activation (CCA) systems to achieve optimum comfort. The system extracts heat or cold from the ground and rejects it in the building. These devices are most efficient at low temperatures. The concrete floor slabs store heating or cooling energy using hot or cold water circulating through the embedded water tubing inside the slab. The location of the water tubing inside the slab is of great importance to avoid thermal discomfort. In spaces where cooling is dominant (office buildings), the water tubing should be applied as low as possible inside the slab (chilled ceiling). Hence, these systems extract renewable energy from the ground and provide substantial savings on heating and cooling costs. [13]. Therefore, it is viable to use such technologies in the heating-dominated climate of Europe

3. CONTEXT

3.1 Climate & Site Data

Table 1:
Climate data of Belgium

Location	Brussels, Belgium
Latitude/Longitude	50.9ºNorth, 4.53ºEast
Elevation	58 m
Climate zone	ASHRAE 4A (Mixed-humid)
HDD65	5279
CDD50	173

Belgium has an oceanic warm-temperate climate. This means it has cool winters and mild summers. The building is located at latitude 50.9ºN and longitude 4.53ºE as shown in Table 1. The annual mean temperature is around 10ºC and most of the months lie below the comfort zone with low humidity. Hence, Belgium is a heating-dominated climate. The existing building is located in Kortrijk, Belgium at 45ºN. The orientation of the building is such that it has less solar radiations.

4. MODELLING SPECIFICATIONS

4.1 Modelling assumptions

4.1.1 Geomeric Model

The geometric realism of a building plays a crucial role in daylight and visual comfort modelling. We imported the architectural drawings into Design-builder software and the model having an aspect ratio of 1:1.

4.1.2 Zoning

We divided the typical office layout into three zones: Open Office, Circulation space, and Restroom. To create four thermal zones, it extended the existing internal partition of the space to the external walls and the overall building included 36 thermal zones between six floors.

4.1.3 Schedule

The heat gains for occupancy and the schedules were based on ASHRAE. It has been assumed that a person is equivalent to 80 Watts of heat gain, and the resulting number of people has been divided by the area of the respective spaces to obtain the number of people per unit area, and this value has been used in the model & fed into the Design-Builder as persons/m^2. The heat gains for lighting were assumed using space by space method and appliances heat gains were calculated as per ASHRAE 62.1.

5. MODELLING METHODS

5.1 Building Performance Simulation

The Building Performance Simulation (BPS) was performed using the EnergyPlus software for the model developed in Design-builder. We then evaluated the model using key indicators such as temperature and humidity trends, heating and cooling load among other outputs, got as simulation results.

5.2 Base Case Simulation

The base case model considers a medium-sized office building in Belgium. The input parameters of the base case model are shown in Table 2.

Table 2:
Input parameters for base case model

Sr. No.	Input Parameters	Base case
1	Construction details	Wall, U-value= 0.12 W/m² K Roof, U-value= 0.1 W/m² K Floor, U-value= 0.2 W/m² K Internal Wall, U-value= 0.24 W/m² K Windows, U-value= 0.7 W/m² K
2	Gains	Persons = 20m²/person Equipment = 6.5 W/m²
3	Lighting	Power = 10.5 W/m²
4	Model infiltration	Extremely air tight envelope ac/h = 0.1
5	Heating	Temperature set-point = 20°C Heating set back = 13°C Operation time 06:00- 18:00
6	Cooling	Temperature set-point = 26°C Heating set back = 32°C Operation time 06:00- 18:00
7	User/Profile	Workday/Weekend = 5/2

The aim of this retrofitting is to adapt the concept of low-tech, which prioritizes mainly on a High-performance building envelope, followed by a Building Automation Control system (BAC). The envelope is extremely air-tight to 0.1 ach. For external windows, triple glazed and argon-filled Low-E windows were adopted.

5.3 Design case parameters

5.3.1 Building Envelope

The building envelope is divided into two sections:

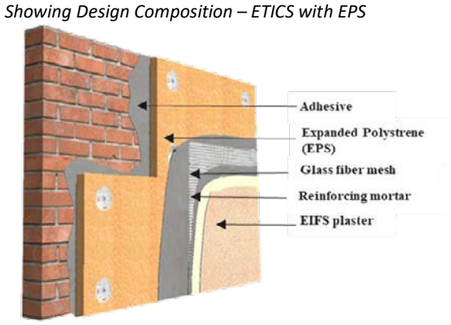
(1) Alternative wall composition- External Thermal Insulation Composite Systems (ETICS)

(2) Dynamic Thermal Characteristics (ISO 13786:2007) of different External Thermal Insulation Composite Systems (ETICS).

5.3.1.1 Alternative wall composition- External Thermal Insulation Composite Systems (ETICS)

To optimize the outside wall of the base case model, an efficient External Thermal Insulation Composite System (ETICS) was used. Firstly, ETICS with expanded polystyrene (EPS) was compared over mineral wool (MW) using the life cycle assessment (LCA) method [12], it was observed that the Mineral wool (MW) had more negative environmental impact than the equivalent systems with Expanded polystyrene (EPS). Therefore, ETICS with EPS was preferable over ETICS with MW. Tanle 1 shows the design of ETICS with EPS.

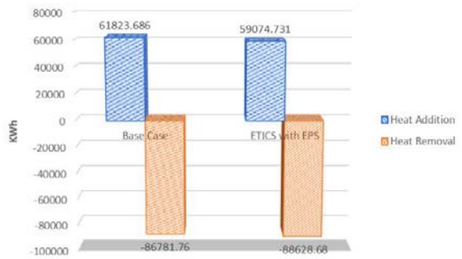
Figure 1:
Showing Design Composition – ETICS with EPS



Heat gain & Heat loss - Comparison of Base case model (Thermoplan-brick wall) with ETICS + EPS

From the below graph (Figure 2), it was observed that the heat gain was reduced by 4% & the heat loss was reduced by 2%. Therefore, ETICS with EPS is a slightly better solution to store more heat in comparison to the brickwork.

Figure 2:
Comparison of heat gains & losses of Existing case with ETICS with EPS



5.3.1.2 Dynamic Thermal Characteristics (ISO 13786:2007) of different External Thermal Insulation Composite Systems (ETICS)

ISO 13786:2007 provides guidelines related to the dynamic thermal behaviour of building components using specific calculation methods. Three of the most commonly used material systems – ETICS with Expanded Polystyrene (EPS), ETICS with Mineral wool (MW) & ETICS with Insulation cork boards (ICB) were selected and optimized to achieve a U-Value 0.13 of W/m²K. The thickness of the composition material was kept constant. Each material has its thermal properties dependent on three basic parameters: Density (kg/m³), Specific heat capacity (J/kg/K) & Thermal conductivity (W/m/K) of the material. All three materials were then compared, and the calculations were done using an HT flux calculator as shown in Table 3.

Table 3:
Comparison of results of ETICS with EPS, MW & ICB

U-value = 0.132W/m²K	ETICS with Expanded Polystrene (EPS)	ETICS with Mineral wool (MW)	ETICS with Insulation cork board (ICB)
Thermal conductivity (W/m/K)	0.038	0.038	0.04
Density (kg/m³)	15	73.5	110
Specific heat capacity (J/kg/K)	1400	920	1600
Decrement factor (f)	0.006	0.006	0.006
Time shift (h)	1.39	2.36	3.00

It was analysed that the position of the layers makes no difference to the U-values & decrement factor. Even, the internal areal heat capacity of all the compositions was nearly the same. The external areal heat capacity of ETICS with ICB was relatively higher by 22.39% over ETICS with EPS. The time shift of ETICS with ICB was higher by 115.8% in comparison to ETICS with EPS. This shows that the ETICS with ICB can store more heat & the negative sign expresses that the heat-flux lags the temperature swings on the other side of the wall. The External thermal admittance of ETICS with ICB was also higher by 22.41% in comparison to ETICS with EPS.

Hence, ETICS with ICB is a better solution, as it can store more heat & has a high thermal mass over ETICS with EPS & ETICS with MW.

5.3.2 Thermal Comfort

The evaluation approach to assess the thermal comfort situation of the retrofitted building was using the Adaptive Thermal Comfort Model

5.3.2.1 Adaptive Thermal Comfort Model (ASHRAE 55)

The adaptive thermal comfort temperature for free-running buildings was adopted. The relationship between the nominal operative temperature θ_c (for comfort) and the prevailing mean outdoor air temperature θ_{pma} is as described below:

$$\theta_c = 0.31 \cdot \theta_{pma} + 17.8°C \quad (1)$$

To find the adaptive thermal comfort of 80% & 90% of the acceptability limit inside the building, the following equation was used:

$$80\% \text{ acceptability band} = \theta_c \pm 3.5°C \quad (2)$$

$$90\% \text{ acceptability band} = \theta_c \pm 2.5\ °C \quad (3)$$

For the Belgium climate, the prevailing mean outdoor air temperature was calculated using the equation (4):

$$T_{rm} = \{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \ldots\} / \{1 + \alpha + \alpha^2 \ldots\} \quad (4)$$

where constant α is <1, T_{od-1}= the daily mean outdoor temperature for the previous day, T_{od-2}= the daily mean outdoor temperature for the day before that, and so on.

Table 4:
Calculation of comfort temperature and acceptability limits for all months as per ASHRAE 55

Months	Internal air temperature °C	Outside air temperature°C	Comfort temperature $T_c = 17.8 + 0.31T_o$	80% acceptibility higher limits T_c + 3.5°C	80% acceptibility lower limits T_c - 3.5°C
January	19.7	2.9	18.7	22.2	15.2
February	20.1	3.3	18.8	22.3	15.3
March	21.0	6.4	19.8	23.3	16.3
April	21.9	9	20.6	24.1	17.1
May	23.0	12.8	21.8	25.3	18.3
June	23.8	15.6	22.6	26.1	19.1
July	26.2	18.5	23.5	27.0	20.0
August	25.9	17.2	23.1	26.6	19.6
September	22.8	14.6	22.3	25.8	18.8
October	22.1	11.1	21.2	24.7	17.7
November	20.9	6.8	19.9	23.4	16.4
December	19.9	4.9	19.3	22.8	15.8

All other parameters that are Indoor operative temperature (Comfort temperature) & acceptability limits were calculated (Table 4)

As per EN15232 standard, the proposed building was considered to be of BAC efficiency class C that corresponds to the standard Building Automation Control system (BACS). The base case model was compared to the BAC efficiency class C (Table 5). The major difference in both the models was changing of the schedules and heating and cooling set-point temperatures.

Table 5:
Showing Input parameters for Base case in comparison with BAC efficiency class-C

Sr. No:	Input Parameters	Base case	BAC Efficiency class C
1	Construction details	Wall, U-value = 0.12 W/m²K Roof, U-value = 0.1 W/m²K Floor, U-value = 0.2 W/m²K Internal wall, U-value = 0.24 W/m²K	Same as per Base case
2	Gains		
	Persons	20 m²/person	13.3 m²/person
	Equipment	6.5 W/m²	10 W/m²
3	Lighting		
	Power	10.5 W/m²	13 W/m²
	Operation time		07:00 – 18:00
4	Ventilation		
	Air change (ac/h)	0.1	0.1
5	Heating		
	Temperature set point	20°C	22°C
	Heating set back	13°C	15°C
	Operation time	06:00 – 18:00	00:00 – 24:00
6	Cooling		
	Temperature set point	26°C	23°C
	Cooling set back	32°C	27°C
	Operation time	06:00 – 18:00	00:00 – 24:00
7	Solar		
	Shading factor	-	0.5m Manual
8	User profile		
	Workday/Weekend	5/2	5/2

Figure 3:
Showing Adaptive thermal comfort for Existing case

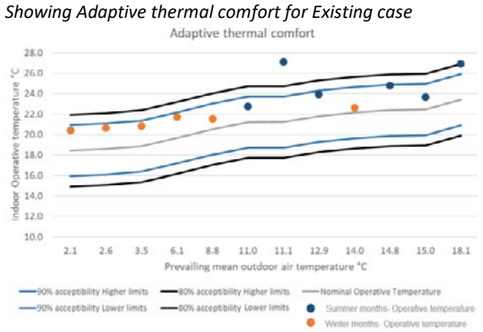
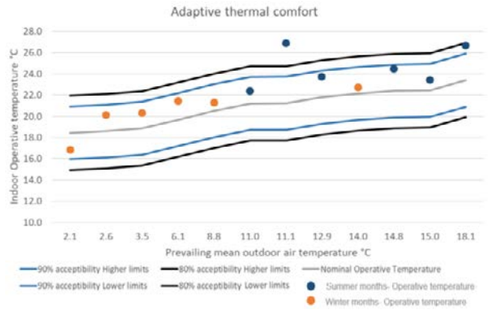


Figure 4:
Showing Adaptive thermal comfort for BAC efficiency class - C



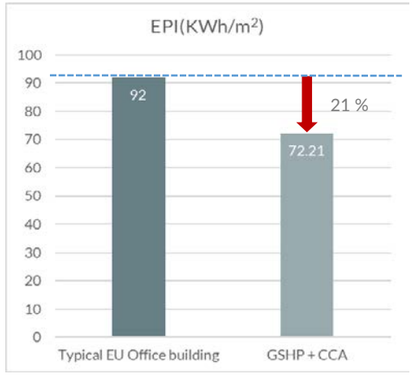
From Figure 3 & 4, it was observed that for the Base case most of the winter months & summer months lie under the 90% acceptability higher limits except the two months that is August which lies on the 80% higher acceptability limits & July month is out of the thermal comfort band, For Class-C only January month lies close to the 90% acceptability lower limits whereas all the months except July & August lie under the 90% acceptability higher limits.

5.3.3 Ground source heat pumps (GSHP) with Concrete Core Activation (CCA) system

Ground Source Heat Pumps (GSHP) coupled with Concrete Core Activation (CCA) systems provide optimum thermal comfort to the users by using the ground as a heat source. At a particular depth of 15m, the ground temperature remains constant Hence, heat can be easily extracted from the ground using GSHP, despite its relatively low temperatures. Therefore, to provide substantial savings on heating and cooling costs, Ground Source Heat Pumps (GSHP) works by tapping renewable solar energy from the ground. In the CCA system, the concrete floor slabs are embedded with water tubing, and the concrete has high thermal mass stores the heat. For heating, the water supply temperature needs to be around 5°C above the desired indoor air temperature. Later, heat is transferred into the room – 60% via radiation and 40% via convection.

The EPI of a typical EU office building was compared with the proposed Geothermal systems with the CCA system. It was observed that the proposed system was much energy efficient & can reduce up to 21% of energy in comparison with the typical European office building as shown in Figure 5.

Figure 5:
Showing comparison of a GSHP with CCA system with a typical EU Office building



6. CONCLUSION

This paper aims to provide retrofit solutions for an existing office building in the European context by using low-tech measures. The low-tech approach can be mainly achieved through a High-performance building envelope followed by Building Automation Control (BAC) system.

In the building envelope, using External Thermal Insulation Composite Systems (ETICS) would help in improving the thermal insulation of the building envelope. ETICS with Insulation corkboard (ICB) is a better solution, as it can store more heat & has a high thermal mass over ETICS with Expanded Polystyrene (EPS) and ETICS with Mineral Wool (MW). In addition, the conclusion of an overall analysis of thermal properties of different materials signifies that there's a correlation between thermal mass & its properties which directly influences the time shift of periodic thermal transmittance (time lag). Hence, this strategy would be more suitable for the heating-dominated climate of Belgium.

In the Thermal comfort parameter, using the Adaptive Thermal comfort model (ASHRAE 55), it was observed that for the base case and proposed model (BAC efficiency class C), most of the months lie under the 80% and 90% acceptability limits. Hence, it can be concluded that the effect of schedules & changing the heating & cooling set point temperatures does not have a significant impact on the Adaptive Thermal comfort model.

For a heating-dominated climate like Belgium, the Ground Source Heat Pumps (GSHP) coupled with Concrete Core Activation (CCA) systems represents an eco-innovative technology that has an energy-saving potential of 21% in comparison to an air-conditioning system.

Therefore, the overall energy performance was determined by adapting to the low-tech concepts that are, by optimizing the building envelope with a high thermal mass and using a Renewable source like Ground Source Heat Pumps (GSHP) coupled with Concrete Core Activation (CCA) systems which substantially decreases the energy use by providing optimum comfort to the users.

WAY FORWARD

Further, we shall carry studies with several other buildings in the European context showing comparative analysis against visual, thermal and acoustic comfort.

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Exploring “Golden Fiber” jute as tensile membrane architecture in Dhaka

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ABSTRACT: This paper explores the opportunity to use the jute fabric as an alternative material for tensile membrane structures. Jute has many environmental benefits. Jute is biodegradable, nontoxic and has high tensile strength. Application of Jute based product is green, sustainable and reduces carbon footprint. Jute cord, ropes, bags are being used for centuries, and Bangladesh is the natural home of the best quality Jute. Bangladesh is the largest Jute exporter in the world. Wide range of products are made from Jute. Technical textiles such as Jute geo textiles (JGT) made from Jute are being used in road construction, riverbank erosion control, filtration, etc. In this study a visitors shed is designed considering Jute as Tensile Membrane at Dhaka Zoo. Three varieties of Jute fabric were collected from local market and tested in BUET lab facilities. A simulation software ixcube Forten was used for form-finding and wind analysis. Data from simulation software and lab tests were checked and it is found that one side laminated 13x13 Jute fabric has sufficient tensile strength to withstand frequent nor wester storms in Dhaka.

KEYWORDS: Jute, Jute fabric, Tensile membrane structures, Lightweight structures, Environment friendly material

1. INTRODUCTION

Tensile Architecture is a lightweight structural system with a membrane, or fabric held in tension. The nature of it can be permanent, semi-permanent, or temporary form of structure. It has grown from the concept of Nomadic Tent, Arab Bedouins, Mongols, and other nomadic tribes had used in various ways for centuries. On the Indian subcontinent, the Mughals introduced “The Shamiana” tents for luxury and royal purposes [1]. Tensile Architecture is now used in various scales, from airport, stadium to temporary exhibition hall, disaster shelter or simple independent shade structure to building entrance portico. Currently, the market size of construction fabric is about 1.47 billion USD in 2018 and it is expected to grow 2.26 billion USD by 2023, as reported by Construction Fabric Market Global Forecast 2023 [2]. But unfortunately, there are very few alternatives to synthetic fabric. The global drive for bio-based and sustainable developments guided by Kyoto protocols on greenhouse gas reduction and CO2 neutral production provides a higher perspective on the natural fiber market [3].

Jute is an excellent example of eco-friendliness and sustainability. Jute nonwovens, jute reinforced composites, pulp & paper, particle boards, shopping bags, handicrafts, fashion accessories, apparels etc. are widely used in local markets in Bangladesh and are being exported worldwide. Bags made from jute are biodegradable and compostable. It has a very low carbon footprint and grows quick. Bangladesh is the natural home of the best quality Jute in the world. Jute is second after Cotton in terms of production, consumption, and availability worldwide [4]. One study shows that chemically treated jute fabric can last up to 20yrs [5]. Kenafine fabric has been developed by Japanese company Taiyo Kogyo group from natural Kenaf fabric and mixing it with polyester in a base fabric and then coated with a thermoplastic resin, this fabric can be recycled to be used as paper pulp after its life span [6].

Since Jute is an indigenous material, locally available, eco-friendly, cheaper, and has good tensile strength compared to other natural fibers (Table 01), so Jute fabric is used as an experimental tensile fabric material for the proposed shed structure in Dhaka Zoo for the benefit of the environment and economy. The combination of jute fabric and support structure will also add sculptural quality and aesthetic to the zoo.

2. OBJECTIVE

This paper investigates the potential of Jute fabric to be used as a tensile membrane for visitor shade at Dhaka Zoo. It will enhance the applicability of Jute fabric and lead the way to future in-depth study on Jute fabric as a membrane material paragraph.

3. METHODOLOGY

The study is based on problem identification through literature survey and field works. The field works involve finding the proper jute fabric for the shade structure based on its tensile strength capacity to withstand local windstorms. Through a literature survey it is identified that jute is a green sustainable eco-friendly material which has good tensile strength to be used as Tensile Fabric. It will open an area application for Jute. Readily available jute fabric types selected from the market to test their strength. Testing of the Jute fabrics has been done in the labs at the Bangladesh University of Engineering &Technology (BUET) and Bangladesh Jute Research Institute (BJRI).

3.1 Literature Review

Bangladesh is the natural home of the best quality Jute in the world. Jute is positioned second after Cotton in terms of production, consumption, and availability worldwide [4]. Jute is now being used in diversified fields such as technical textiles for civil engineering, automotive application, electrical and leather industries, medical, environmental protection, etc. Jute textiles are now used for making automotive parts, medical textiles for implants, Agro textiles for crop protection and protective clothing for heat and radiation protection for firefighters and metal welders.

Jute geo textiles are used for soil erosion protection. Specially treated Jute geo textile has higher durability [7]. Jute fabric and polymer-based Natural Fiber Composite (NFC) corrugated sheet termed as ‘Jutin’ has been invented by Bangladesh Atomic Energy Commission (BAEC) led by Dr. Mubarak Ahmad Khan in 2010. Jute based packaging bag “Sonali bag” has recently been developed by Dr. Mubarak Ahmad Khan and his team in 2018, which is comparable to the common polybag, but it is biodegradable and friendly to the environment. The Jute-cotton or other synthetic fiber blended yarn is well studied. Sulphonated Jute-Cotton blended yarn and fabric have almost equivalent properties of 100% Cotton fabric [8]. Jute-Polyester blend is studied by [9] and Jute-Acrylic blend is studied by [10].

Synthetic fabric or technical textiles are used in Tensile Architecture. The most used technical textiles in Tensile Architecture are such as PVC (Polyvinyl chloride) coated PES (Polyester) or PVDF (polyvinylidene bifluoride) coated PES material, etc. [11]. The reuse and recycle process of PVC coated fabric requires sophisticated procedures [12] and these materials are not biodegradable and pollute the environment [13]. So, there is a potential need for natural fabric in this field and jute fabric can fill that role.

3.2 Jute and its properties

There are two Jute types of trade: white (Chorchorus capsularis) and Tossa (Chorchorus olitorius). Tossa Jute is softer, silkier, and stronger than white Jute. It is also known as Paat in Bangladesh. Jute fiber is collected from the best or skin of the Jute plant. That’s why Jute fiber falls into the bast fiber category. Jute plant grows in hot humid rainy alluvial lands. Jute plant is photo reactive; it harvests within 120 days. It grows up to six to ten feet high. Matured Jute plants are cut, tied in a bundle, and put into slow flowing water for several weeks for fermentation. Jute fibers are pulled off from the bark, washed carefully and dried in the sun.

Figure 1:
Preparation of Jute fibre from jute bark

(Shahnewaz Karim, Auyon , 2011)

Jute is a cellulose-based material. It is stiff and yellowish because of hemicellulose and lignin. Each Jute fiber is composed of smaller units known as fibrils. They are arranged in right-handed spirals and make closely held molecular chains which known as micells.

The chemical composition of jute is as follows—

Alpha Cellulose	58-63%
Hemicellulose	21-24%
Lignin	12-14%
Pectin	0.2-0.5%
Fat & Wax	0.8-1.5%
Mineral Materials	0.6-1.1% [14]

3.3 Research Question:

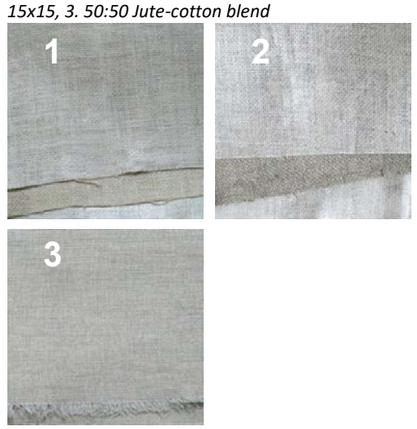
Based on the literature survey, the research question is that Does locally available Jute fabric have sufficient tensile strength to be used as Tensile Membrane Shade Structure in Dhaka Zoo?

To answer that question, we need to check the tensile strength of the fabric with simulated wind induced allowable strength for the fabric.

3.4 Selecting Jute fabric

Different Jute fabrics are manufactured in spinning and composite mills with conventional spinning and looms. Depending on drafts, twists, dollop weight, design such as plain, twill, basket, satin with closed, dense, and open structure, wide range of fabrics can be produced with different strength, thickness, porosity, and permeability. Composite types of fabrics such as Jute-cotton union fabric are also produced at different ratio. Following Jute fabrics are commonly used and available in market hessian, canvas, D.W twill, Jute-cotton blend. Hessian is the most porous; canvas is closely woven with flat type yarn and least porous. Double warp (D.W.) twill is also known as A-twill, which is a 2/1 twill weighing 750 g/m2 and is widely used for packaging [15].

Figure 4:
Jute fabric samples, 1. Laminated 13x13, 2. Laminated 15x15, 3. 50:50 Jute-cotton blend



3.5 Strength Test

For tensile strength testing purposes, one side Polypropylene (PP) laminated untreated hessian Jute 13x13, 15x15 and 50:50 Jute-cotton union fabric have been collected from Jute Diversification Promotion Center (JDPC) Dhaka. And the samples have been tested in Geotech Lab of Dept. of Civil Engineering, Bangladesh University of Engineering & Technology. Strip tensile strength was done according to ASTM D4595. One side laminated (13x13) Jute fabric has more tensile strength than (15x15) Jute fabric. Tensile strength of Jute-cotton fabric is the highest among three fabrics (Table 02), 15x15 Jute fabric has more elongation in MD than 13x13 Jute fabric but less elongation in XMD direction (Table 02). Jute-cotton fabric elongation in XMD is the highest and in MD is the lowest, because of the use of Jute in XMD direction and cotton in MD direction. Jute-cotton union fabric has the highest mass per unit area and thickness among the three-fabric tested.

Table 1:
Typical Properties of jute fibre in comparison with other fibres (reported in Doan Thi Thu Loan, 2006) [16]

Fibre	Density (g/cm3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation At break (%)	Specific Tensile Strength (MPa/g.cm-3)	Specific Young's Modulus (GPa/g.cm-3)
Jute	1.3-1.45	393-773	13-26.5	1.16-1.5	286-562	9-19
Flax	1.5	345-1100	27.6	2.7-3.2	230-773	18
Ramie	1.5	400-938	61.4-128	1.2-3.8	267-625	41-85
Sisal	1.45	468-640	9.4-22.0	3-7	323-441	6-15
Coir	1.15	131-175	4-6	15-40	114-152	3-5
E-glass	2.5	2000-3500	70	2.5	800-1400	28
S-glass	2.5	4570	86	2.8	1828	34

3.5 Conceptual Design Development

prototype shed is developed which can be repeated in various sites with minor changes. Several ideas are sketched. Simplicity, lightweight structure, attractive sculptural quality, and functionality are considered while designing visitors shed. A simple sculptural light form has been developed which gives good shadow. The fabric is supported mainly by two high masts, two low masts and cables. Masts are connected by safety cables. At the low points water will be collected and collection points will be designed.

3.6 Wind load

Dhaka Zoo is in Northwest part of Dhaka. Latitude and longitude of Dhaka is 23.7 and 90.38 respectively. Average annual wind flow is 2^5 (Beaufort scale). But Dhaka often experiences storms. Storms with 50-60 km/h are most frequent [18]. Basic wind speed 22.6 or Beaufort scale 9 is considered for the proposed membrane structure.

Basic wind speed V_b=22.6 m/s

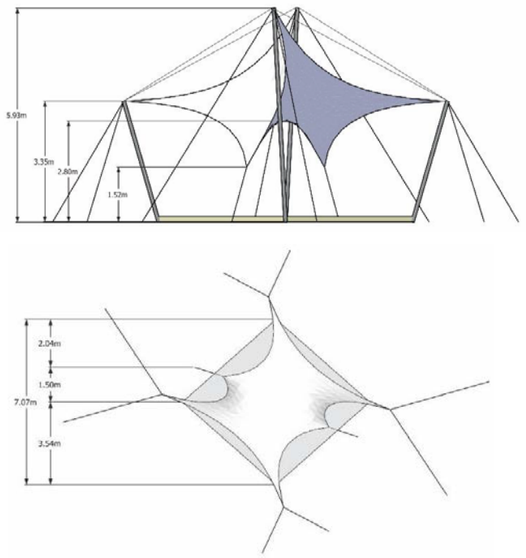
Resulting wind pressure $q_b=\frac{Vb^2}{1600}$ kN/m^2 = **0.32** KN/m^2

According to eq. 4.8 of Eurocode 1991-1-4: Wind loads, Peak velocity pressure $q_p(z) = c(z)*q_p$

Table 2:
Tensile strength test result

Fabric sample	Average mass per unit area gm/m2	Thickness, mm	Strip tensile strength MD/XMD kN/m	Strip tensile elongation MD/XMD %
(13x13) Jute fabric natural	376	.88	15.4/16.7	10/10
(15x15) Jute fabric natural	331	.756	14/12	12/8
Jute-Cotton 50:50 union	2213	1.025	18.1/15.2	4/22

Figure 2:
Conceptual design of a pavilion



For a height (z) of 6m and terrain category III or suburban settings the exposure factor c (z) is 1.3

Then the peak velocity pressure $q_p(z)$= **0.42** KN/m^2

According to eq. 5.1 of Eurocode 1991-1-4: Wind loads, Wind pressure on surfaces $w_e = q_p(z)* c_{pe}$

Where, c_{pe} is external pressure coefficient. Pressure coefficient c_{pe} has been determined according to European Design Guide for saddle structure [19].

3.7 Nonlinear Analysis review

The nonlinear membrane stress analysis was done using ixcube Forten which is a Tensile Membrane design software developed and maintained by Gerry D'Anza. Three load cases are analyzed ULS01 for self-weight, ULS02 for Self-weight and wind load combination, and ULS03 for factored self-weight and wind load combination. Maximum overall stress is found 4.45 KN/m in loadcase ULS03. Maximum stress 12.07 KN/m is in corner where double layer of membrane is required. Reduction factors for membrane material according to DIN 4134 material safety factor for membrane $\mathbf{Y_m=1.4}$

Then allowable strength

$\mathbf{f_d= f_{tk} /(Y_m x A_{res})}$

Where f_{tk}= Tensile strength of the membrane

Table 3:
Tensile strength after nonlinear analysis For wind load

Direction	Tensile strength KN/m	Safety factor γm	Reduction factor Ares Prestress	Allowable strength KN/m
Warp	16.7	1.4	2.94	4.1
Weft	15.4	1.4	2.94	3.7

Table 4:
Tensile strength after nonlinear analysis For Prestress

Direction	Tensile strength KN/m	Safety factor γm	Reduction factor Ares wind	Allowable strength KN/m
Warp	16.7	1.4	1.44	8.3
Weft	15.4	1.4	1.44	7.6

4. RESULT REVIEW

Allowable tensile strength of the laminated Jute membrane for permanent loading is sufficient as the allowable stress 4.1KN/m in warp and 3.7 in weft direction (Table 03) is more than overall stress 1.47KN/m after form-finding. And the allowable strength for wind load is 8.3KN/m in warp direction and 7.6kN/m in weft direction (Table 04), which is more than overall maximum stress found in loadcase ULS03 is 4.45KN/m. So, we can conclude that laminated 13x13 Jute fabric can withstand wind load and permanent self-weight through the nonlinear analysis as per European Design Guide for Tension Membrane Structures [19].

5. CONCLUSION

In conclusion, it is established that one side laminated 13x13 Jute fabric has the sufficient strength to be used as membrane cover for visitor

shed. But it needs environmental protection for durability in practical use as it may decay with ultraviolet ray and humidity. Further research should be done in this field to improve tensile strength, durability, and environmental protection of Jute fabric. Thus, jute fabric can be an eco-friendly, biodegradable, and recyclable material competing in conventional artificial fabrics in global markets.

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PLEA STGO 2022
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WILL CITIES SURVIVE?

Retrofitting pre-1919 Scotland's tenement flats

Investigating fabric retrofit potential for top, middle, and ground floor

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ABSTRACT: One-fifth of Scottish housing stock was built in the pre-1919s and more than a half of them are tenement flats. This presents a significant retrofit challenge due to their poor energy performance. This research explores the potential and limitations of achieving minimum energy-efficiency standards in Scotland's pre-1919 tenement flats through fabric measures, measured using Standard Assessment Procedure (SAP) and Passive House methodologies. This study highlights and quantifies the measures required to raise the EPC rating in the properties but identifies challenges in two areas; the assessment methodologies result in different outcomes and the position of the flat within the building significantly impacts its energy performance. The ground floor flat is evaluated as the least energy-efficiency using the SAP evaluation methodology, while the top floor is the worst performing according to the Passive House assessment. Overall, fabric retrofit measures are predicted to reduce up to 90% of the space heating demand with up to 35 SAP points increases but the fabric first approach alone will not manage to elevate the poorest energy performing of pre-1919 Scottish flats to the proposed minimum standard of EPC band C as proposed and further building measures are required.
KEYWORDS: Energy efficiency, fabric first retrofits, pre-1919 flats

1. INTRODUCTION

The UK Government's target to achieve completely net-zero emission by 2050 compared to the 1990 baseline (The Climate Change Act 2008 (2050 Target Amendment) Order 2019, 2019) is supported and implemented by many policies and legislations. In the dwelling sector, the UK government is planning to radically transform all homes to be highly energy efficient in both new and existing dwellings by 2025 through Future Homes Standards (UK Government, 2021). The task is more complex in Scotland than in the rest of the UK as Scotland has a huge number of the least energy-efficient of traditional-built tenement flats (40%), compared to 18% in England and 10% in Wales and Northern Ireland (Smith, 2021). In response to the UK's net-zero emission target in the dwelling sector, the Scottish Government is proposing the Heat in Building Strategy which aims to improve a large majority of buildings to a good level of energy efficiency, which is equivalent to EPC band C for homes by 2033 (Scottish Government, 2021).

This research focuses on pre-1919 dwellings as properties in this age often referred to as 'hard-to-treat' in terms of energy retrofit due to the difficulty of thermally insulating traditionally constructed solid stone external walls which are also comparatively expensive (Martin & Sheldrick, 2015). Properties in this age band have a mean Energy Efficiency SAP rating of 55.5, below the average of 65 for Scottish housing stock. 80% or 147,000 dwellings of the pre-1919 properties require to be improved to EPC band C by 2033 in the proposed energy efficiency standard, which is a challenging task for all retrofit stakeholders. Furthermore, Scotland's tenement suffers a high rate of disrepair (The Scottish Government, 2020). Tenements and flats are more complicated to retrofit due to multiple ownership and tenure overlap (Kerr & Winskel, 2018).

This research investigates fabric first approaches in reducing heat losses through the building elements. The aim is to explore the potential of achieving minimum energy-efficiency standards for the ground, middle, and top floor tenement flats by improving the thermal envelope. The research also explores two important factors underpinning the potential energy efficiency: firstly, the position of a flat within the overall building block and the impact this has on energy performance; and secondly a comparative analysis of the methodology for calculating predicted energy efficiency. This is crucial to understand if Scotland's efficiency standards policy is to be effective in reducing carbon emissions. The findings also identify the optimum fabric insulation measures to improve the energy efficiency of pre-1919 tenement flats and could provide a framework to support policy implementation.

2. METHODOLOGY: ENERGY SIMULATIONS OF CASE STUDIES

Modelling has been undertaken in three typical tenement flats to test three factors: efficiency outcomes of fabric measures by element; the impact of the position of the flat within a building block; and the outputs of two energy performance methodologies, SAP and PHPP. The selected case studies represent the worst-performing energy efficiency of the building type. They have main similarities; constructed before 1919 with solid stoned on the external walls, bay windows, single glazing sash windows, and a communal staircase that is called closed. The floor areas are within the average of pre-1919 dwellings in Scotland. Refer to Table 1 for the case studies' detail and U-value pre-retrofit.

Table 1:
Case studies base cases and details

Building materials pre-retrofit (applies to all): - External wall: (Front) sandstone ashlar, 600mm, U-value: 1.374 W/(m²K), (Rear) sandstone rubble: 600mm, U-value: 0.924 W/(m²K) - Wall to stairwell: 200mm, U-value: 1.525 W/(m²K) - Party wall: 410mm, U-value: 1.040 W/(m²K) - Roof (loft ceiling): 265mm, 1.356 W/(m²K) - Floor (suspended timber floor): 325mm, 1.747 W/(m²K) - Solid timber door: 3.00 W/(m²K) - Single glazed sash and case window: Glazing 5.4W/(m²K) Heating: gas central heating Air change rate/hr at 50pa: 15 m3/hr.m2@50Pa (SAP) and 17 ach^{-1} (PHPP), Insulation: non	
	Flat 1 (pre-1919) Orientation: Near the north Floor area (m²): 102 Wall areas (m²): 176; Stonewall: 43, party wall:62, wall to stairwell: 71
	Flat 2 (pre-1919) Orientation: North-west Floor area (m²): 76 Wall areas (m²): 123; Stonewall: 36, Party wall: 39, wall to stairwell: 48
	Flat 3 (pre-1919) Orientation: North-east Floor area (m²): 100 sqm Wall areas (m²): 136; Stone wall:40, Party wall:39, wall to stairwell: 57

2.1 Energy simulations using Design SAP (2012) and Passive House Planning Package (PHPP)

SAP is selected as a modelling tool as it is the methodology used for energy compliance with UK building regulations. SAP is an energy compliance tool designed for new buildings and is more suitable for this research compared to ReducedSAP, a tool designed for existing buildings. SAP can customise built up of all U-values and the generation of space heating demand, which are not available through RdSAP. SAP methodology works through predicting rating based on annual energy cost per square meter of floor area for space and water heating, ventilation, and lighting (Elmhurst Energy Systems Ltd, 2020), and gives estimates of the cost-effective performance. PHPP, an energy simulation assessment software designed by Passivhaus Institute is used to produce detailed energy simulation data to support the energy simulation analysis. The annual space heating demand [kWh/(m²a)] generated by the software is the main data used for this research.

2.2 Modelling pre and post-retrofit scenarios

Test 1 predicts the energy performance of the pre-1919 Scotland tenements. Base cases are modelled in Design SAP 2012 and PHPP using construction and materials data obtained through literature review and in-situ research projects in Scotland (Bros-Williamson & Currie, 2020; Gilbert & Flint, 1992; Historic Scotland, 2008, 2013; Historic Scotland & Baker, 2011). Airtightness values are derived from a tenement retrofit project (John Gilbert Architect, 2013). Test 2 models the flat units (in Test 1) as flats located on different block floors (top -T, middle M, and ground floor - G) and the impacts they may have on energy efficiency retrofit. Test 3 models various retrofit measures applied to the building elements as individual and combined measures to evaluate the potential of achieving minimum energy efficiency standards using fabric measures.

2.3 Insulation methods and materials

The insulation methods tested here are referenced from in-situ Historic Scotland's approaches that allow the buildings to function with maintaining ventilation and moisture permeability whilst retaining their historic characters. Measures should also minimise changes that affect their appearance (Historic Scotland, 2010)

Materials tested for fabric insulations are vapor permeable (hygroscopic) and non-vapor permeable. The hygroscopic materials are suitable for traditional building insulation as they can absorb and release moisture. This is important to buffer the peak of humidity created from domestic daily tasks (Historic Scotland, 2010). On the other hand, the non-vapor permeable materials are not suitable for traditional building insulation but are tested for comparison as they are widely used, claimed as easier to manage, water and pest resistant, and are more versatile (esub construction, 2020). The insulation thickness post-retrofit is referenced from Historic Scotland's projects and reports (Historic Scotland, 2010) and the maximum

improve u-values of building elements are guided by Scotland's building regulation (Technical Handbook: Domestic Building (Scotland) Regulations, 2013). Insulations of building elements (Table 2); loft, floors, walls, and door are tested with various insulation materials.

Table 2:
Fabric measures (M), insulation materials, insulation methods, and u-value, W/(m²K) post-retrofit

M1: Loft (cold attic)	
M1a: Natural insulations (Wood fibre/sheep wool/hemp) between joists, 450mm	0.095
M1b: Rigid insulation board (Phenolic foam/PIR/PUR board) between joists, 450mm	0.053
M2: Suspended timber floor	
M2a: Natural insulation (Wood fibre/sheep wool/hemp) at floor joists 300mm	0.188
M2b: Rigid insulation board (Phenolic foam/PIR/PUR board) at floor joists 300mm	0.146
M3: Solid stone wall *(F: front wall, R: Rear wall)*	
M3a: Held in a timber frame (Wood fibreboard/ hemp/ sheep wool, 120mm, plasterboard (lath and plaster removed)	F: 0.29, R: 0.289
M3b: Held in a timber frame (Rigid insulation – Phenolic foam/ PIR/PUR board, 100mm, plasterboard (lath, plaster removed)	F: 0.224, R: 0.217
M3c: Held in a timber frame *(*Aerogel board, 60mm, plaster coat (lath, plaster removed)	F: 0.288, R: 0.277
M3d: Blown behind lining (Cellulose/ Polystyrene beads, 50mm)	F: 0.527, R: 0.440
M3e: Direct on wall Lining (Aerogel blanket 10mm + mesh + plaster on existing wall lining	F: 0.663, R:0.563
M3f: Direct on wall lining (Calcium silicate board + permeable adhesive, 25mm + plaster	F: 0.827, R: 0.634
M4: Wall to the stairwell (*M4b* to *M4f* are identical to ***M3***)	
M5: Party wall (measures *M5b* to *M5f* are identical to ***M3***)	
M6: All walls (combination of all external walls measure with same techniques and materials except blown insulation type, *M6d* **combines with** *M4c* **and** *M5c.*	
M7: Door insulation (Aerogel board 10mm, fire-rated cloth, 2mm, plywood, 10mm	0.774
M8: Window improvement (Single glazing with secondary glazing system + insulated shutters)	1.00
M9a: Draught-proofing to 5m3/h.m2 @ 50Pa (SAP)	
M9b: Draught-proofing to 1 Ach @50Pa	
M10a: All fabric measures (all insulations + windows + draughtproofing) using natural insulations	
M10b: All fabric measures (all insulations + windows + draughtproofing) using rigid insulations	

3. RESULTS & DISCUSSION

3.1 Pre-retrofit energy performance of the dwellings in the case studies (Test 1 and Test 2)

Energy simulation results indicated that the pre-1919 tenement flats are poor in energy efficiency with scores of SAP 27 to SAP 45 (EPC band F to E) (Table 3 and Fig. 1). In all case studies, energy efficiency ratings are far below the mean energy efficiency rating of Scottish homes in 2019 (SAP 64.9) (The Scottish Government, 2020). The predicted space heating demand (SHD), ranges from 274 to 455 kWh/(m²a) (Fig. 1) equals 18 times more energy to heat the Passive House EnerPHit dwellings. The PHPP's space heating demand is higher than SAP 2012 due to the various assumptions underlying both energy modelling tools as also acknowledged in other research (Moutzouri, 2011; Oblecova & Musau, 2013). One of the important reasons that explain higher SHD in PHPP is due to different location and weather data used in both software. PHPP assessments are based on the location specific, Glasgow in this research. However, SAP methodology assumes all assessments are located in the central of the UK, the East Pennines (Elmhurst Energy Systems Ltd, 2020). Referring to various studies comparing the energy modelling systems with the government's standard (SAP), the Passive House methodology is considered more accurate due to its more detailed assessments that allow for more accurate input data (Morgan & Hill, 2011). Nevertheless, the results represent the uninsulated and the worst-case scenario of the pre-1919 tenement properties in Scotland. The predicted results which are close to other research (John Gilbert Architect, 2013; Morgan & Hill, 2011) are examples of unimproved hard-to-treat buildings that require urgent energy efficiency improvements to meet the proposed standards.

Table 3:
Pre-retrofit energy performance of case studies measured using PHPP and SAP 2012 (Test 1).

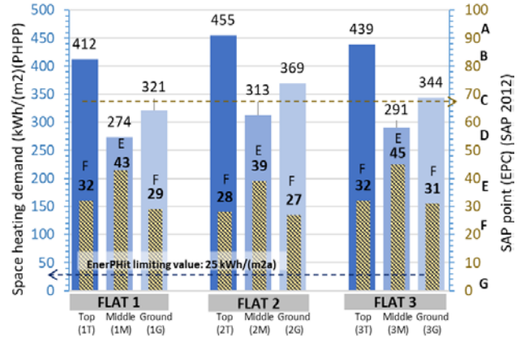
Flats	PHPP	SAP 2012	
	SHD (kWh/(m²a)	SAP (EPC)	SHD (kWh/(m²a)
Flat 1	412	32 (EPC F)	209
Flat 2	313	39 (EPC E)	167
Flat 3	344	31 (EPC F)	209

3.2 Impact of units' floor levels in a block of the tenement (top, middle, and ground floor) on energy efficiency (Test 2)

Test 2 gives a better understanding of how flats located on different floor levels in a block are different in their thermal performance and energy efficiency. The highest in energy efficiency is the middle floor flats with all rated EPC band E, compared to top and ground floors which are rated EPC band F (Fig. 1). Test 1 and Test 2 highlighted that energy efficiency ratings are lower for the ground floor flats, even though the poorest thermal efficiency predicted in PHPP is the top floor flats. This is due to different calculations of fabric heat losses between both software. PHPP uses a lower temperature factor applied to the ground floor which results to lower transmission heat losses of the building element compared to the roof for the top floor flat. On the other hand, SAP works differently. It does not apply any temperature difference to any building component. U-value, the thermal transmission of building materials, area, and kappa value, and the thermal capacity of building materials will be the only determinants of the amount of fabric heat loss. Thus, for the case studies using SAP assessment, ground floors have lower energy efficiency ratings compared to the top and middle floors due to the high u-value of uninsulated suspended timber on ground floors which contributes to higher heat losses.

What do these mean for tenements owners and landlords? It is likely that if they own uninsulated ground floor flats, their properties will get lower EPC scores than their neighbours' uninsulated properties on the topmost floor. However, they might pay lesser heating bills compared to the topmost floor flat owners or tenants as the predicted heating demands for the top floors are the highest among flats on other floors.

Figure 1:
Energy performance of Pre-1919 Scottish tenement flats; Flat 1, Flat 2, and Flat 3 simulated as top, middle, and bottom, measured through the space heating demand (SHD) and SAP ratings



3.3 Post-retrofit of case studies using fabric interventions: thermal improvements, energy efficiency ratings and retrofit limitations (Test 3)

Results of the pre-1919 fabric improvements are showing potential thermal improvement measures versus the predicted increase of energy efficiency rating for the top, middle, and ground floor flats (Fig. 2, 3, and 4). The results provide an understanding of measures and energy efficiency impacts of flats units located on different floors in a tenement block. This is beneficial to flats owners who would like to prioritise certain measures that can contribute to higher energy efficiency potential, especially for those taking step-by-step retrofits which can ease the financial burden related to high retrofit costs.

Both thermal improvement and energy efficiency rating can be maximized for the top-most floor by an insulating loft with as much as 450mm insulation thickness. Insulating loft space can improve thermal efficiency by up to 32% and this comes with a 9 SAP point increase (Fig. 2). Although there is less measured data for roof or ceiling intervention found in this type of dwelling thus far, results from a measured study of same building typology shows the same significant improvement to u-value post-retrofit (Stinson et al., 2015)

On the other hand, for the ground floor units, a significant thermal improvement can be achieved through draughtproofing (32%) but with just 4 points of SAP efficiency increased (Fig. 4). SAP rewards most when insulating the suspended timber ground floor with up to 11 SAP points increased. Contrary to the SAP result, only around 9% of thermal improvement was achieved through 300mm thick insulation at the suspended timber floor joist (Fig. 4). Limited solum space (usually less than 500mm) has restricted improvement potential for the ground floor flat and perhaps makes flats on this level the most difficult to retrofit. This also contributes to lower EPC rating and SHD post-retrofit of ground floor flats compared to the flat units above (Table 4).

The middle floor flats can be the easiest to improve, without the existence of heat loss floor and roof. Draughtproofing up to 1 air changes per hour (ach^{-1}) can contribute to the highest thermal improvement (38%), but with only 4 SAP points increased. Improving windows with secondary glazing is to be considered to achieve the highest energy efficiency rating with a 9 SAP points increase (Fig. 3).

This study also focuses on individual fabric measures to evaluate retrofit potential and limitations for the pre-1919 tenement flats. Insulating external solid stone walls only contributed up to 13% SHD reduction with a 3 to 4 SAP point increase to flats in all levels. The case studies have two types of external walls and insulating all the walls up to Scotland Domestic Building standard as shown here could reduce nearly a third (32%) of the SHD with an 8 SAP points increased. This shows that wall insulations are one of the important aspects of improving the energy efficiency of this type of dwelling. However, thick breathable natural insulation (M3a – 120mm) is required to achieve this which poses a high risk to interstitial condensation without the presence of good retrofit details. Internal insulation with this thickness will also reduce internal spaces especially if applied to a small room.

Furthermore, insulating the walls to stairwell can reduce higher SHD than the solid wall; 19% but with only

1 to 2 SAP points increased. This study shows better potential to reduce significant heat loss through insulating walls to the stairwell as the walls' area is higher than the solid stone walls (Table 1) and unfortunately the lowest in u-values pre-retrofit. Internal insulations are a better option due to space constraints at the corridor and unit's entrance. It is also important to highlight that limited thermal and energy efficiency improvement is noted when insulating the shared building elements (party walls) and door for flats on all levels. It could be a fair decision if flat owners want to keep the party wall uninsulated although studies (Palmer et al., 2018) inform present of heat losses through the element. These could provide solutions to building owners' concerns regarding difficulties to retrofit the shared elements.

Improving airtightness by draughtproofing the building envelope's gaps is important for significant thermal improvement to all flats, although not significant to EPC improvement. Windows improvement with secondary glazing and insulated shutters contribute 6 to 9 SAP increases with nearly one-fifth of thermal improvement. Window measures with higher impacts such as triple glazing are not tested in this study to reflect restrictions of the application in many historic buildings and conservation areas.

Combining all fabric measures is predicted to improve all case studies in all floor levels to only EPC band D, lower than the proposed Scotland energy efficiency target (Table 4). The predicted space heating demand for all improved flats (fabric) is up to 90%. However, the improvement did not meet the Passive House EnerPHit standard, even if the scenarios are modelled to be in the warmer area; London (Table 4). Based on PHPP energy balance results, the remaining fabric heat losses are from windows, external walls, ground floor, and ventilation. This is where the fabric retrofit limits appear for the traditional-built flats; 1) limited solum height below suspended ground floor has restricted optimum insulation thickness, 2) preserving original sash and case window with best possible windows measures is not optimum for preventing heat loss and benefitting heat gain, 3) internal insulation of external wall only feasible at certain thickness due to loss of internal areas and may not optimise efficiency.

Hygroscopic, natural insulation materials such as sheep wool, hemp fleece, and wood fibre are suitable for traditional building and construction but require slightly thicker insulation thickness to achieve the same u-value as the non-hygroscopic, rigid insulation materials. Aerogel, an open porous and high-performing thermal insulation can offer a much thinner application, half of the natural fibre materials tested in this research, but it comes with very high cost. In terms of insulation methods, the application of insulation materials in frames can maximise the thermal performance of the insulated walls. However, some solid stonewall insulation methods such as blown behind wall lining and applied on wall lining resulted in very minimum improvements.

Figure 2:
Topmost floor flat - % of space heating demand reduction and SAP point change with individual/combined fabric measures

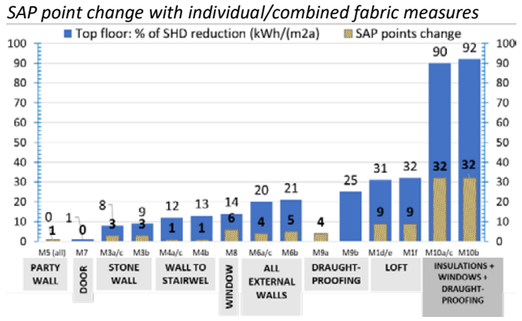


Figure 3:
Middle floor flat - % of space heating demand reduction and SAP point change with individual/combined fabric measures

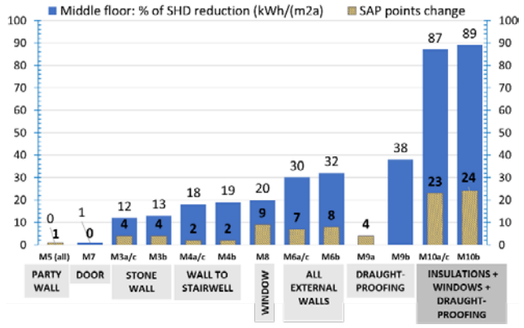


Figure 4:
Ground floor flat - % of space heating demand reduction and SAP point change with individual/combined fabric measures

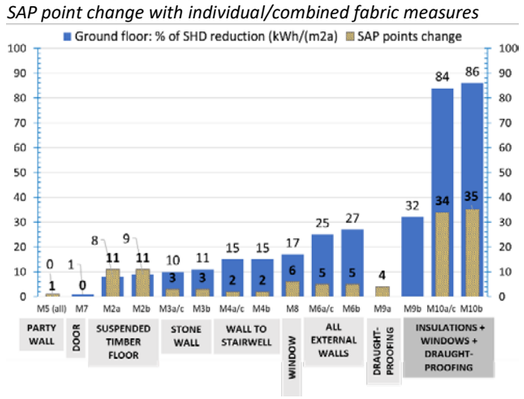


Table 4:
SAP (EPC) ratings of pre and post-retrofit (all fabric measures) and the percentage of space heating demand (SHD) reduction post-retrofit of case studies

Case studies	Pre-retrofit		Post-retrofit (All fabric measures)			Other location (London) SHD
	EPC rating (SAP 2012)	SHD (kWh/(m²a)	EPC rating (SAP 2012)	SHD (kWh/(m²a)	SHD reduction	
1T	32 (F)	412	64 (D)	42	90%	31
1M	43 (E)	274	66 (D)	35	87%	26
1G	29 (F)	321	63 (D)	52	84%	37
2T	28 (F)	455	60 (D)	58	87%	43
2M	39 (E)	313	62 (D)	52	83%	37
2G	27 (F)	369	57 (D)	71	81%	50
3T	32 (F)	439	61 (D)	54	88%	39
3M	45 (E)	291	68 (D)	42	86%	31
3G	31 (F)	344	65 (D)	60	83%	42

4. CONCLUSION

Fabric retrofit measures have contributed a significant thermal improvement (90% reductions) and increased energy efficiency ratings by up to 35 SAP points to achieve EPC band D, but still not reaching the proposed Scotland's standards of EPC band C by 2033. This suggests that the proposed minimum energy efficiency standard for the pre-1919 tenement flats may be achieved through the fabric first approach with a combination of other retrofit interventions such as heating systems and renewable or low energy applications. This theoretical research which modelled scenarios from actual in-situ data and retrofit projects are showing results in many aspects; (1) thermal and energy efficiency rating impact of fabric measures, (2) how flats on different floor levels are diverse in energy efficiency, (3) limitations when optimising the efficiency of retrofitting the pre-1919 tenement and (4) assessment methodologies predicted different outcomes. These findings can become retrofit guidance for homeowners and future policy frameworks. One of the significant findings is that the ground floor flats are the poorest according to the government's standard assessment procedure (SAP), which is expected to achieve minimum standards with more measures, hence costs. Interestingly, the units might not be the worst in reality as Passive House methodology indicated the most heat loss among the top floor flats. In achieving minimum energy efficiency standards for pre-1919 Scotland tenement flats, future policy should consider and address these potentials and limitations. The findings of this research are potentially beneficial to the same building typology elsewhere in the UK.

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Energy rehabilitation with External Thermal Insulation (ETICS) in Zaragoza, Spain

Application to Social Housing in Saltillo, Mexico

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ABSTRACT: The sustainability goals agreed by most countries have made them focus their attention on the high energy consumption of buildings and the weight within this consumption of the residential sector. This makes the energy rehabilitation of existing buildings a top priority. However, energy rehabilitation is not the same in all countries. In this study, we analyse two houses in Zaragoza, one rehabilitated with an external thermal insulation system (ETICS), while the other retained its original state. Their energy behaviour was monitored and the results of each case were analysed. The results obtained from this monitoring were used to propose rehabilitation strategies in single-family social housing in Saltillo, Mexico, where the residential sector is the third-largest energy consumer. This study demonstrates the interest in analysing and using successful real cases of energy rehabilitation interventions in similar climates as a useful knowledge transfer opportunity. In addition, the importance of this "technological know-how" is highlighted to carry out a more precise energy rehabilitation.
KEYWORDS: ETICS, Energy Rehabilitation, Sustainable Architecture, ETICS building rehabilitation, Building Thermal Comfort

1. INTRODUCTION

The buildings and their construction sectors are responsible for over one-third of global final energy consumption [1]. It makes the energy rehabilitation of this sector a priority given the UN sustainable development goals and the 2030 Agenda.

However, energy rehabilitation is not as widespread in all countries. Almost two-thirds of countries lacked energy building regulations in 2019 [1]. In Mexico, the use of insulation in buildings is low; currently, 95% of households do not have thermal insulation [2].

In Spain, the building sector represents 30% of total energy consumption, the weight of the residential buildings is 17%. Hence, there is a long-term strategy to update the stock of residential and non-residential buildings, making them energy-efficient and decarbonized by 2050 [3].

ETICS (External Thermal Insulation Composite System) is one of the most used thermal retrofitting solutions in the rehabilitation of façades of residential buildings [4]. In this study, two dwellings in Zaragoza (Spain) were analysed. One of them was energetically rehabilitated by cladding the exterior enclosure with ETICS, while the adjacent one is in its original state. Its energy behaviour was monitored for a year, and the results of each case were analysed.

The results obtained are used to propose rehabilitation strategies for single-family social housing in Saltillo (Mexico), where the residential sector is the third-largest final energy consumer [5]. Due to the similarities between both climates, the case of Zaragoza is useful to find the adequate rehabilitation solutions for Saltillo.

The goal of this study is to establish to what extent it is feasible to use ETICS as a strategy to improve the thermal conditions of social housing in Saltillo, Mexico.

2. ENERGY REHABILITATION IN ZARAGOZA (SPAIN)

The city of Zaragoza (41° NL) is situated on the banks of the river Ebro, in a continental area at about 300 km from the Mediterranean Sea. It has a cold semi-arid climate (BSk, Köppen climate classification), an annual mean temperature of 15,5°C, and a mean relative humidity of 61%. The city presents hot summers and cool winters, with monthly temperatures ranging between 6°C and 25°C. However, it can reach extreme temperatures of 44°C and -11°C, see Table 1.

Table 1: Zaragoza monthly data of average maximum temperature (AMT), mean temperature (MT), average minimum temperature (AmT), relative humidity (%) and daily global horizontal radiation (kWh/m²) [6]

Month	AMT °C	MT °C	AmT °C	RH %	kWh/m²
JAN	10,5	6,6	2,7	75	2,1
FEB	13,1	8,2	3,3	67	3,2
MAR	17,3	11,6	5,8	59	4,7
APR	19,6	13,8	7,9	57	5,8
MAY	24,1	18,0	11,8	54	6,8
JUN	29,3	22,6	15,8	49	7,6
JUL	32,4	25,3	18,3	47	7,8
AUG	31,7	25,0	18,3	51	6,6
SEP	27,1	21,2	15,2	57	5,3
OCT	21,4	16,2	11,0	67	3,5
NOV	14,8	10,6	6,3	73	2,4
DEC	10,8	7,0	3,2	76	1,8

Zaragoza characterizes by a compact urban form and the presence of mainly multi-family dwellings. The two monitored dwellings were built in 1969, before the Spanish thermal regulation (1979). The building does not have thermal insulation in any of their enclosures. The thermal transmittance value of the facades and roofs before the ETICS application is U= 1,67 W/m²K and 4mm clear glass for the windows [7].

The two dwellings have the same spatial and material characteristics; both are 90 m², and are located on a fourth-floor (ground floor + 4) under the building's roof and with three facades in contact with the outside, see Figure 1.

Figure 1. The analyzed building: the non-refurbished building in yellow and the refurbished building in green.

In the retrofitted case, the building envelope has been refurbished by cladding the exterior enclosure with ETICS, see Figure 2.

The material used in the façades is 80 mm rock wool panels with a density of 150 kg/m³ in the external layer and 95 kg/m³ in the interior layer. Regarding the roof of the building, a lightweight 120 mm rock wool blanket was used. For the windows openings, both on south and north façades, a second double glazed window was placed. The new values of the thermal transmittance of the external walls and roofs are U = 0,34 W/m²K and U = 0,22 W/m²K, respectively [7].

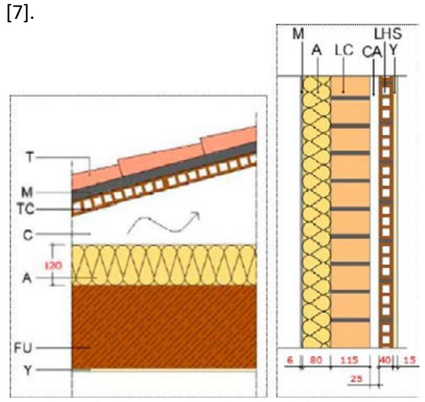

Figure 2: Construction details of the ETICS application on façade and roof in the refurbished building.

3. THE CASE OF SALTILLO (MEXICO)

Saltillo (25° NL) has a hot semi-arid climate (BSh, Köppen climate classification). It is in the Chihuahuan Desert but at an altitude of 1.600 m.a.s.l., which results in cooler temperatures than those corresponding to its latitude. This also generates certain similarities with the climate of Zaragoza, in both climates there is a need to use heating.

The city has a mean annual temperature of 18,3°C and a mean relative humidity of 60%, see Table 2. The city has slightly hot summers and cool winters, with monthly mean temperatures ranging between 12°C and 23°C. Yet, it can reach 40°C in summer and -14°C in winter.

Table 2: Saltillo monthly data of average maximum temperature (AMT), mean temperature (MT), average minimum temperature (AmT), relative humidity (%) and daily global horizontal radiation (kWh/m²) [8]

Month	AMT °C	MT °C	AmT °C	RH %	kWh/m²
JAN	19,7	12,1	4,5	59	4,4
FEB	21,4	13,6	5,7	55	5,3
MAR	24,7	16,7	8,7	52	6,4
APR	27,9	20,0	12,1	52	7,1
MAY	29,9	22,3	14,8	55	7,4
JUN	30,3	23,2	16,1	60	7,5
JUL	29,7	23,0	16,2	65	7,1
AUG	29,2	22,6	15,9	68	6,7
SEP	26,6	20,3	14,0	76	6,1
OCT	24,9	18,0	11,2	69	5,5
NOV	22,6	15,2	7,8	60	4,7
DEC	20,1	12,8	5,5	57	4,1

Unlike Zaragoza, Saltillo is characterized by following a dispersed urban growth pattern: low

densities and a predominance of one and two-story single-family houses.

The house simulated in this work is a one-story house as it is similar in terms of the amount of exposed skin surface to that of the dwellings in Zaragoza, see Figure 3. It has a living area of 51 m² and lacks thermal insulation. In this base case, the walls are of concrete blocks and simple 4 mm clear glass for the windows. The roof and the floor are a 0,15 m reinforced concrete slab.

Figure 3. Example of social housing in Saltillo, Mexico.

4. METHOD

The methodology followed in this study divides into two phases. The first one is the energy monitoring during a year of the two dwelling in Zaragoza (Spain): the non-insulated and the insulated one. The data obtained were then analysed to assess the effectiveness of the use of ETICS.

Secondly, a model of a single-family house, representative of a large number of similar constructions in Saltillo (Mx), is built. The objective is to simulate its energy performance under similar conditions to the monitored dwellings in Zaragoza (Spain) in order to evaluate the improvement that a similar refurbishment would represent.

We simulated a single-family house in Saltillo that has no insulation, and three different refurbishment levels of thermal insulation (Table 3):

- **Saltillo refurbished A**: adding ETICS on walls and roof, changing from a simple to a double glass window. The thermal transmittance value of the envelope is the same as in the retrofitted case in Zaragoza. However, due to the construction system of the Saltillo house, the thickness of the thermal insulation must be larger to achieve it.
- **Saltillo refurbished B**: adding the same thermal insulation thickness of the retrofitted case in Zaragoza to the envelope. The thermal transmittance value is higher than the refurbishment A.
- **Saltillo refurbished C**: The thickness of the thermal insulation added is less than in refurbishments A, B and Zaragoza. The value of thermal transmittance is greater than in the previous refurbishments.

This analysis consists of dynamic thermal simulations using DesignBuilder (with EnergyPlus as calculation engine) [9].

Figure 4 shows the model used for simulation. The parameter used to analyse the results is the indoor air temperature. The weather data used from the EPW file is from the Saltillo International Airport. To assess the performance of each case, we based our analysis on the number of hours of indoor thermal discomfort and accumulated degree-hours. That is, we quantified the number of hours with an indoor air temperature outside a temperature range (19°C - 27°C) considered neutral for people acclimatized to this climate [10] and the degrees accumulated for each hour outside this range.

Table 3: U-values and thickness of the elements of the envelope in the different cases.

	WALLS		ROOF		WINDOWS
	U (W/m²K)	Thickness (m)	U (W/m²K)	Thickness (m)	U (W/m²K)
Zaragoza non-ref.	1,67	0,00	1,67	0,00	5,80
Zaragoza refurb.	0,34	0,08	0,22	0,12	3,08
Saltillo non-ref.	2,75	0,00	3,77	0,00	5,80
Saltillo refurb. A	0,34	0,098	0,22	0,149	3,08
Saltillo refurb. B	0,41	0,08	0,27	0,12	3,08
Saltillo refurb. C	0,98	0,025	0,59	0,05	3,08

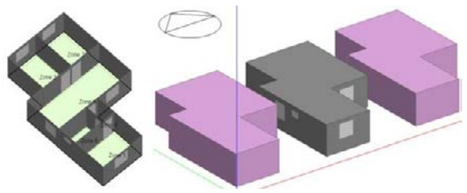

Figure 4. Simulation model. It has a north-south orientation, with no adjacency between houses.

We used the data obtained during a summer week, from June 10th to 19th, in the Zaragoza's retrofitted case to calibrate the model for the energy simulation process. Figure 5 shows the behaviour of the indoor air temperature, both in the rehabilitated case and in the simulation.

This chart shows a good agreement between both cases. The rehabilitated case has a mean indoor temperature of 25°C, and it stays in a range between 23,3°C – 28,3°C, and the simulated case has a mean indoor temperature of 24,7°C and stays between 23,2° and 27,9°C.

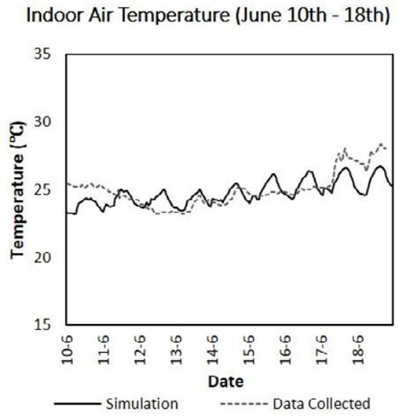

Figure 5. Indoor air temperature behavior of the refurbished case in Zaragoza and in the simulation during a summer week.

5. RESULTS AND DISCUSSION

The case of Saltillo

To ease the discussion of the simulation results, the four cases will be referred to as the non-refurbished case, case "A" (same U-value as in Zaragoza), case "B" (same thermal insulation thickness as in Zaragoza), and case "C" (the lower thickness of thermal insulation and U-value of the refurbished scenarios). All the cases present the same occupation rate (2 users, as the only internal gain), a ventilation rate of 4 ac/h, and an infiltration of 0,7 ac/h. The interior thermal behaviour during the year was analysed to make a balance between the behaviour in the warm season (May – October) and in the cold season (November – April).

Figure 6 shows how in cases with ETICS ("A", "B", and "C") the oscillation of indoor temperature is reduced when compared to the non-refurbished.

Nevertheless, differences and similarities arise caused by the different levels of thermal insulation: cases "A" and "B" have a similar behaviour throughout the year.

In the warm season, they have a mean temperature of 26,5°C and 26,4°C, while in the cold season are 19,3°C and 19,2°C. In case "C", with a lower insulation level, the mean temperatures are lower: 25,9°C and 18,9°C. The non-refurbished case is the only one that reaches mean temperatures above 30°C and below 10°C.

However, its mean temperature in the warm season is 25,3°C and 19,2°C in the cold season. These similarities in mean daily temperatures make it difficult to assess the efficacy of each intervention.

In figure 7 we can see that cases "A" and "B" have the highest number of hours (4.078 - 3.973 hours) outside the considered comfort range (19°C - 27°C). The house is out of comfort for 45% and 47% of the year, increasing it concerning the non-refurbished case (3.598 hours, 41%). Case "C" reduces the hours of discomfort compared to the non-refurbished case, going from 3.598 to 3.387 hours, which is equivalent to 39% of the year outside the comfort range.

Nonetheless, when analyzing the accumulated degree-hours, we observe little difference between the three interventions with ETICS. Case "C" reduces the number of accumulated degree-hours by 33% concerning the base case, while cases "A" and "B" do so by 31% and 32%, respectively.

Due to these results, we evaluated the same indicators during the cold season (Figure 8) and in the warm season (Figure 9). However, in the cold season, we considered only the hours and accumulated degree-hours below 19°C. In the case of the hot season, we only accounted for the hours and accumulated degree-hours above 27°C.

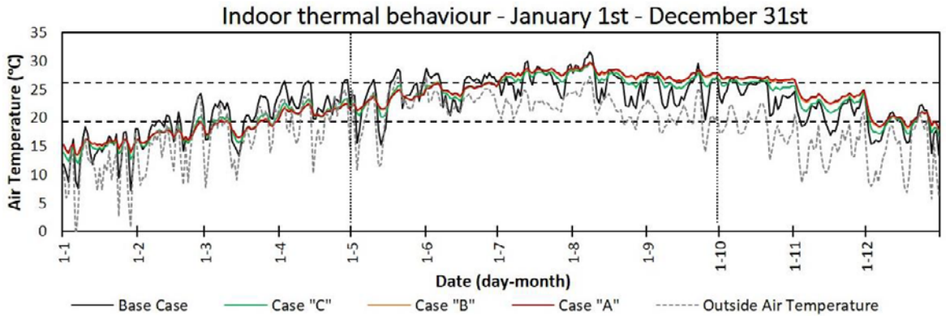

Figure 6. Chart with the outside air temperature, the neutral temperature range (19°C - 27°C), and the indoor temperature behaviour for all cases.

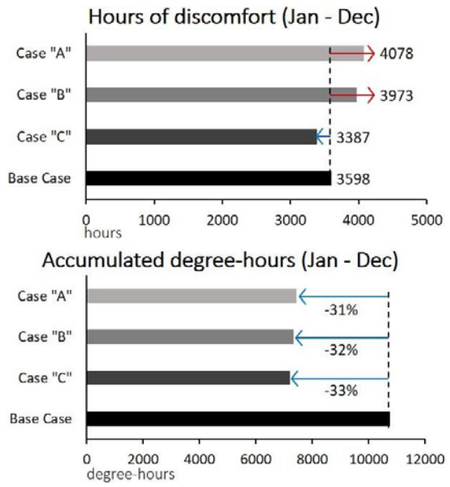

Figure 7. These charts show the results of the two comfort indicators for the entire year. The accumulated degree hours (ADH) are the number of degrees accumulated above 27°C and below 19°C, in which the use of cooling or heating is necessary.

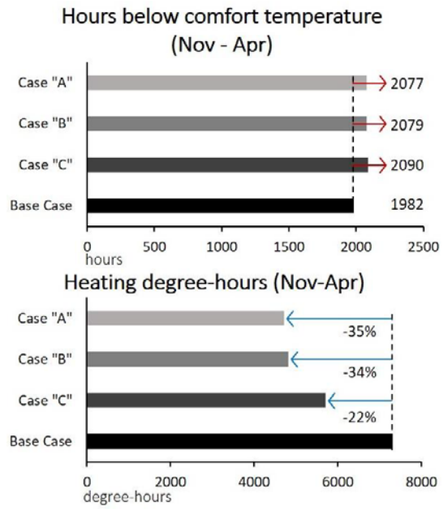

Figure 8. These charts show the results of the two comfort indicators for the cold season. The heating degree hours (HDH) are the number of degrees accumulated below 19°C, in which the use of heating is necessary.

During the cold season, in cases “A”, “B” and “C”, the number of hours below 19°C increases concerning the base case. They go from 1.982 hours (46%) to 2.077 – 2.090 hours (48%) of the season with thermal discomfort. Despite this, in the three cases, the number of HDH was reduced compared to the base case: Case “A” (-35%), Case “B” (-34%), and Case “C” (-22%). On account of the low temperatures of the cold season, these results could be a turning point in decision making. However, it is necessary to evaluate the effectiveness of different levels of thermal insulation during the warm season.

Figure 9 shows how the different cases behave during the warm season. Unlike the cold season, in summer, cases “A” and “B”, with the highest level of thermal insulation, considerably increase the number of hours above 27°C compared to the base case. In this situation, they go from 1.354 hours (31%) to 1.894 – 2.001 hours (43% - 45%) with thermal discomfort. Case “C” shows different behavior. It reduces the number of hours above 27°C, going from 1.354 hours of the non-refurbished case to 1.297 hours, 29% of the season out of thermal comfort.

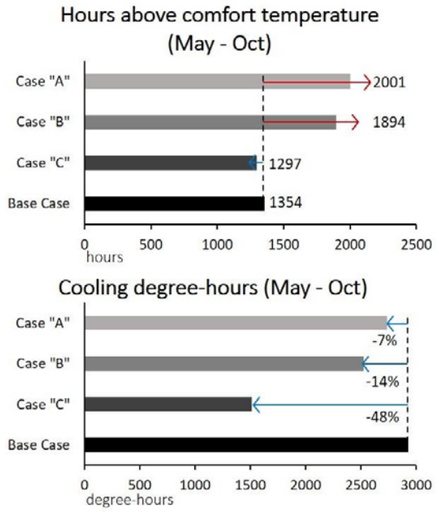

Figure 9. These charts show the results of the two comfort indicators for the hot season. The cooling degree hours (CDH) are the number of degrees accumulated above 27°C, in which the use of cooling is necessary.

The second chart in Figure 9 shows the number of cooling degree-hours for the different cases. Although the three interventions with ETICS manage to reduce the amount of CDH, case “C” stands out from cases “A” and “B”. It manages to reduce CDH by 48% in relation to the non-refurbished case. While cases “A” and “B” reduce them by 7% and 14% respectively.

Based on the results obtained, some doubts arise about the implementation of ETICS in temperate climates. On the one hand, when only the cold season is considered, a higher level of thermal insulation (cases “A” and “B”) is more effective than lower levels (cases “C” and non-refurbished). Thermal insulation reduces the number of HDH thanks to a smaller oscillation of the interior temperature. However, because the capacity to exchange heat with the outside is reduced, houses with external thermal insulation take longer to heat up compared to the base case, generating that they have a greater number of hours below 19°C.

On the other hand, during the warm season in a temperate climate, the exact opposite does not happen. Case “C” with a wall U-value of 0,98 W/m^{2}K and a roof U-value of 0,59 W/m^{2}K has the fewest number of hours above 27°C and achieves the greatest CDH reduction of the three interventions with ETICS. In cases “A” and “B”, with lower thermal transmittance values, the number of hours of discomfort increases due to the effects of a higher level of insulation.

6. CONCLUSION

This paper analyses the effectiveness of external insulation, ETICS, as a thermal improvement strategy in two types of housing in the cities of Saltillo and Zaragoza. Given that they are two climates with similarities (both need cooling and heating), the strategy of using ETICS works in both cases. However, there are some conditions to consider when implementing this strategy:

1) The use of external thermal insulation in building refurbishment reduces thermal oscillation. However, it also reduces the heat dissipation capacity of the house. Therefore, before applying ETICS, it is necessary to consider the thermal behaviour of the building throughout the year.

2) In the case of Saltillo, where the climate is milder compared to Zaragoza, in free-running conditions a lower level of thermal insulation is more effective. Although it has a lower performance in the cold season, it is compensated in the warm season.

3) Consequently, using a level of thermal insulation similar to that of a dwelling in Zaragoza, in free-running conditions, is not as effective in the warm season as in the cold season.

ACKNOWLEDGEMENTS

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Retrofitting high-density residential buildings

Application of passive cooling design strategies in hot and humid climate of Cyprus

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ABSTRACT: Experimental methods often failed to isolate the effect of retrofits from the numerous confounding factors, while modelling studies are prone to uncertainties and simplifications. The aim of this study is to provide a critical insight of previous studies that have applied experimental and simulation techniques to evaluate thermal retrofits, with a focus on data collection and simulation methods. The main question is how passive design strategies can contribute to the retrofitting of existing residential buildings and optimise the indoor comfort level of occupied spaces to combat exacerbated heatwaves in the summer. This paper discusses the findings of three different alternative passive design systems as a solution to reduce overheating, particularly in the summer season. In these passive design strategies, it shows the use of natural ventilation systems, appropriate shading devices, and fenestration designs to improve both energy performance of a prototype RTB and occupants' thermal comfort under the climate change impact. In this study, it can be seen that temperatures were significantly higher throughout the period with several periods in which the temperature was above 28 °C, and never below 22°C. In this prototype RTB, temperatures were significantly higher throughout the period with several periods in which the temperature was above 30°C, and never below 22°C.
KEYWORDS: Calibration; Optimisation; Overheating risk; Parametric analysis; Uncertainty quantification

1. INTRODUCTION

Many European post-war buildings were designed and built-in accordance to criteria, which usually did not take into account reducing energy requirements [1,2]. Most of these residential buildings have not yet undergone systemic retrofit interventions and constitute a residential building stock characterised by poor energy performance and thermal comfort issues. As per the European Council conclusions in the 2021 Energy Efficiency Plan, the residential sector is estimated to be responsible for 41% of the total energy consumption in the European Union (EU) [3]. Hence, it is important to upgrade the existing energy performance of these buildings. In Cyprus, there are no standards, codes of practices or building regulations related to building energy performance, which does not help resolve issues of overheating of thermally inefficient building envelopes, particularly in post-war residential building stock [4]. There are also no measures or benchmarks for building energy performance, nor an official roadmap for regulating retrofit strategies to address energy efficiency [5,6].

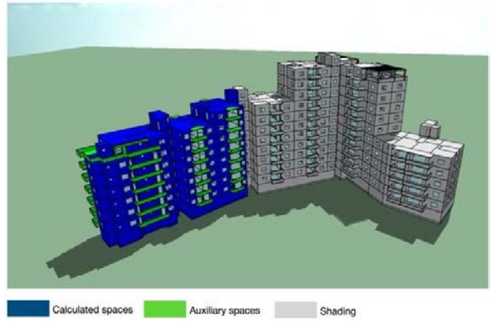
The absence of energy conservation measures derives mainly from the fact that the lack of implementation of EU directives presents a variety of guidance. The Town Planning Department in 2015, allowed architects to design buildings according to their clients' requirements, taking into consideration only a limited number of guidelines related to solar aspects of thermal properties of residential buildings [7,8]. The previous scholars' work indicates that construction-led growth occurs due to a change in the physical characteristics of the larger states in Cyprus, particularly in the coastal town of Famagusta [9-11]. As a consequence of that, the need for the protection of a fragile ecosystem and energy conservation measures becomes evident as income per-capita rises. The reason is that, in most states, some of the construction activities concerning the energy savings of residential buildings to the adoption of European Union implementation in both the planning and construction phases failed to understand the environmental effects of their projects.

Many scholarly articles have commended the architectural style and traditional construction methods for naturally ventilated buildings of the Mediterranean Island of Cyprus [12,13]. However, little research has been conducted concerning the thermal performance of traditional buildings in order to learn from and apply to contemporary buildings. Several studies have investigated internal thermal quality of vernacular houses, comparing it with inefficient building envelopes of most contemporary residential buildings [14]. Additionally, two studies were published by Serghides where the first study investigated the energy performance of a detached post-war contemporary residential building in Cyprus [15,16]. The study concluded that the owners of a typical multi-family dwelling would have spent from 29% to 51% of their income for cooling their indoor environment in the summer. The study also argued that insulating the building envelope led to a significant decrease in cooling energy consumption simultaneously. Nowadays, problems on mass housing estates are currently a topic for research on energy and policy interventions in the Republic of Cyprus (RoC). Modernist low-rise, medium rise and high-rise residential tower block developments often have insufficient green areas and lack consideration of the climatic features of the building site where the neighbourhoods are designed without concern for urban planning laws and regulations. These purpose-built residential building stock models represent 56% of the existing building stock in the RoC. At the same time, there is developing interest in improving energy performance of existing residential building stock within considering occupants' thermal comfort, particularly in residential tower block (RTB) type developments where possible operational energy savings may be offset by new construction materials or implementing passive design strategies (i.e. ventilation, shading).

Retrofitting existing residential buildings has been increasingly gaining momentum in the past decade, particularly thereafter by introducing cutting zero carbon emission targets until 2050 by the EU-27 countries [15]. In a more recent and relevant study, Gaetani et al. investigated the occupants' motivation to protect their residential building stock from climate-related overheating [16]. This research revealed that an unintended consequence of assumed retrofit measures is that summertime indoor overheating occurs, and indoor air temperature is increased due to energy efficiency building systems implemented during the retrofitting process.

The present study aims to investigate and consolidate the current energy consumption patterns (heating and cooling demand) of a sample of representative flat units in the RTB prototypes and the tangible outcomes of implementing retrofitting scenarios in testing applicability of passive design systems accordingly. The study objectives are threefold. The first objective is to evaluate the current thermal comfort and energy performance of prototype base case study building in the coastal city of Famagusta (Cyprus – South-eastern Mediterranean) where the weather is hot and humid in summer. To accomplish this evaluation, a high rise retrofit type block (RTB - prototype) was identified as a base case scenario development, since such structures represent the most commonly built housing typology and building-construction materials considered in this study, as shown in Figure 1. The second objective is to evaluate CO_2 levels of each occupied space in order to provide a basis for the subsequent research phase. The third objective is to develop and test the applicability of various passive design strategies as potential retrofit measures to the high residential buildings to achieve improved thermal comfort and reduced cooling energy loads.

Figure 1:
The analytical energy model of a base case residential tower block development.



2. MATERIALS AND METHODS

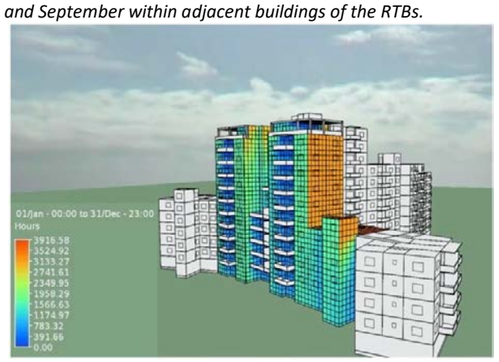
Experimental methods often fail to isolate the effect of retrofits from the numerous confounding factors while modelling studies are prone to uncertainties and simplifications. The aim of this study is to provide a critical insight of previous studies that have applied experimental and simulation techniques to evaluate thermal retrofits, with a focus on data collection and simulation methods. This paper discusses the findings of three different alternative passive design systems as solutions to reduce overheating, particularly in summer seasons. In these passive design strategies, it shows the use of natural ventilation systems, appropriate shading

devices, and fenestration designs to improve both energy performance of a home and occupants' thermal comfort under the climate change impact.

A quantitative research design was employed, involving the development of a questionnaire-based survey for the existing RTB prototype, incorporating high-level building parameters and the energy use of the occupants; analysis of the existing energy performance of the existing representative RTB prototype; embedding building energy performance modelling and simulation methods; the investigation of the prototype case study RTB to model the energy performance of a retrofitted RTB' energy demand for cooling and occupants' thermal comfort during the overheating period.

As an initial step, the performance of a case study building was modelled and simulated by employing the software suite; Integrated Environmental Solutions' Virtual Environment (IES-VE), and by taking into account the life cycle impact of retrofitting a prototype RTB as a climate-responsive building to improve energy efficiency using the questionnaire survey findings and simulation data, as shown in Figure 2.

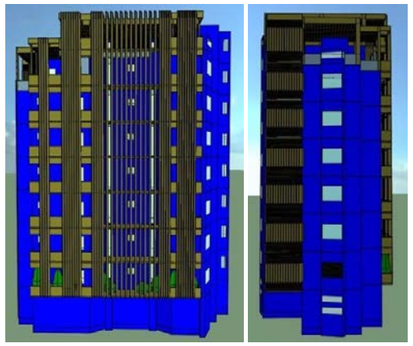
Figure 2:
The solar calculation of the building envelope between May and September within adjacent buildings of the RTBs.



Additionally, an ASHRAE 7-point scale was used to assess the correlation between pairs of variables. Correlations between multiple variables were collected from the questionnaire surveys to investigate the relationship between occupants' thermal comfort and thermal sensation levels. The significant level of the analysis was set at 0.05. This means that the results were statistically significant when *p*-value <0.05.

The dynamic thermal performance simulation studies of each building were carried out in an analytical energy simulation environment between May and September, the peak demand period for cooling energy use. The periods were spread throughout the summer with the aim of measuring the risk of overheating the RTB prototype. In each of the occupied zones (i.e. living rooms and master bedroom spaces), calibration studies were taken of the characteristics needed for energy use per area (naturally or mechanically) in order to take into account occupancy, the electrical energy use of equipment, internal temperature, the energy use of artificial lighting and of mechanical A/C units.

Figure 3:
Implementation of passive shading systems onto the existing building envelope.



The aim of the selection was to capture a variety of space energy use cases using relatively simple assessment benchmarks to import the data to the IES-VE simulation software for testing the validity of simulation results by embedding Computational Fluid Dynamics (CFD) modules into the IES-VE software package.

2.1 Location and Climate

Cyprus is the third largest island in the Mediterranean after Sicily and Sardinia, as shown in Figure 4. It is located in the eastern part of the Mediterranean area and sits at latitude 35° North and longitude 33°East. According to the Köppen Geiger climate classification, Cyprus has climate characteristics that are typically Mediterranean. The Köppen Geiger climate data shows that the overall climate of Cyprus is a subtropical (*Csa*) type climate and a partly semi-arid (*Bsh*) type climate in the north-eastern part of the island [17].

Figure 4:
Location and Köppen Geiger climate classification type of Cyprus.

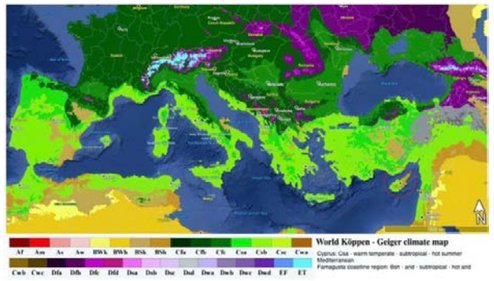


Table 1:
Climate conditions of the Mediterranean Island of Cyprus.

Month	Zone 1	Zone 2	Zone 3
Climate type	Mediterranean climate (*Csa*)	Mediterranean mild climate (*Csb*)	Humid subtropical climate (*Cfa*)
Location	Coastal	Semi-mountainous	Inland
City	Famagusta	Larnaca	Nicosia
Average high	36.8°C August	37.2°C August	42.3°C August
Average low	3.8°C January	4.3°C January	1.2°C January

That is to say, the climate characteristics of Cyprus are hot and humid during summertime. Table 1 illustrates the average minimum and maximum outdoor temperatures in summer and winter, as well as the humidity levels in summer.

The 2018 Cyprus Meteorological Service statistics show that significant differences exist between mid-summer and mid-winter temperatures. Winter temperatures vary from 18°C inland to about 14°C on the coast. There are also wide differences between day and night-time temperatures, especially inland in the summer [18]. The coastal city of Famagusta has a mild Mediterranean climate with an average annual temperature of 16.7°C.

The 2018 Annual Report of the Ministry of the Environmental and Natural Resources Department of Meteorology demonstrates that the winter is not so severe, with an average of 21 days with temperatures below 0°C. January is the coldest month, with an average temperature of 12.3°C. The hottest month, August, has an average temperature of 34.7°C [18].

2.2 Thermal Comfort Approaches and Implications

Some current and previous research has been conducted on assuring indoor comfort conditions and predicting the comfort level of a room in line with the reference of the European CEN BS EN 15251. A considerable amount of literature review has been published on the evaluation of an assessment method regarding the summer performances of unconditioned residential buildings.

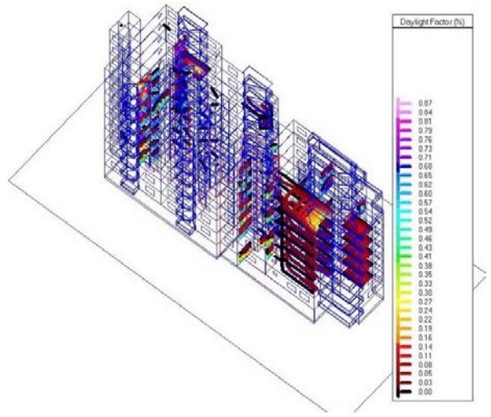
The adaptive approach is currently implemented in the main international standards (EN 15251 2007; ASHRAE 2004) concerning thermal comfort. Therefore, it is usually considered as an assessment method regarding the summer performances of unconditioned residential buildings. In fact, it is worth noting that following the work of Humphreys (1978) in the 1970's de Dear and Brager (2001) and many others, there has been increasing realisation that the Predicted Mean Vote (PMV) model is not appropriate, especially in naturally ventilated buildings that are in free running mode, including heated or cooled seasons. This has led to new formulations of various standards throughout Europe CEN standard BS EN 15251, which include 'adaptive' temperature limits for naturally ventilated or free running residential buildings. It is desirable that the ISO standard concerned with indoor environments is BS EN ISO 7730, also an applicable benchmark to measure the night-time ventilation in residential buildings.

2.3 Case Study – RTB Prototype

The prototype design research is employed with the general aim of providing a series of guides, tools and findings which may inform energy consumption reduction and optimisation of occupants' thermal comfort into retrofitting processes of the existing residential building stock, as well as neighbourhood urban blocks in Famagusta, Cyprus.

This residential block location, the home ownership-based purchase agreement, the average citizen resident type and the quality of the building. The prototype RTB are 4 to 12 storey buildings located in the border of the 'fenced-off Varosha territory' of the urban agglomeration of Famagusta, which is surrounded by several large-scale mass housing estate developments. The prototype buildings are located on the river delta, around 5 km from the Famagusta Bay coastline of the Mediterranean Sea. The estate was built in the early 1970's, and there are 88 apartment units with 10 different floor plan layouts and similar construction characteristics as shown in Figure 5.

Figure 5:
The analytical energy model of a base case residential tower block development.



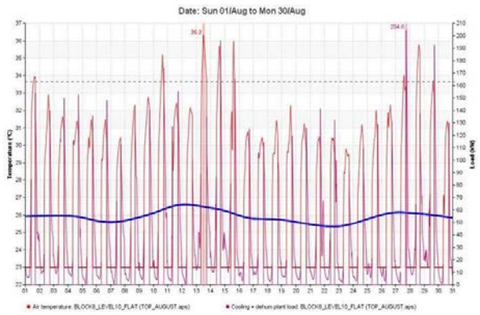
Since 2000's, some of the flats have been internally and externally retrofitted, but without any homogenous criteria. The conditioned gross floor area of the case study multi-family apartment unit is 115 m^2. The original U-values were 4.05 W/m^2K for external walls, 2.94 W/m^2K for the internal walls, 5.26 W /m^2K for the roof and 1.39 W/m^2K for the windows and doors.

3. RESULTS AND DISCUSSIONS

The preliminary calibration studies find that energy use varies significantly by occupants' energy use patterns and their comfort levels in different seasons. The worst-case RTBs risk overheating, particularly in the summer. Correlations between energy use and occupants' adaptive thermal comfort and context were explored to help establish guidelines for the next stage of developing retrofit scenarios.

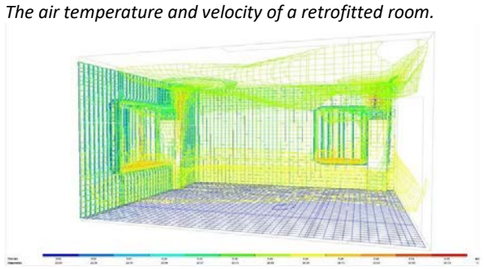
The results of the initial prototype analysis demonstrate that the difference between retrofitted buildings and the pre-existing state of a building in energy use could be correlated with the degree of energy management by implementing passive cooling strategies, bringing a 52% reduction in energy consumption in peak summer cooling demand. Figure 6 demonstrates that the base-case representative top floor flat unit showed an annual energy demand for cooling calculated at 204.6 W/m^2K before retrofitting. The indoor temperature is, in the worst-case, higher than 33°C, reaching, at times, a maximum temperature close to 37°C, as shown in Figure 6.

Figure 6:
The total electricity energy usage of a south-west facing flat from a sample of the 1st floor apartment unit.



According to the results of the dynamic thermal simulation, energy savings of around 46% are expected, with the main goal of the study a reduction of 50%. As could be expected in a residential building located in a hot and humid climate zone, in the non-retrofitted case, cooling and heating (57%) together comprise the largest proportion of total energy consumption. It is remarkable to note that the weighted annual average use of energy consumption in the current state was 204.6 kWh/m^2. However, after implementation of the energy-efficiency systems, the economical optimum of annual energy consumption reduction measures for a base case prototype RTB is around 120 kWh/m^2, which corresponds to the requirements for low-energy residential buildings.

Figure 7:
The air temperature and velocity of a retrofitted room.



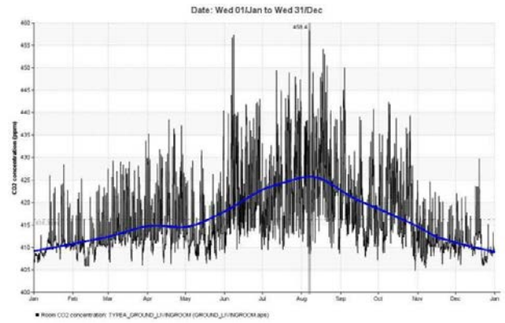
In Figure 7, the Computational Fluid Dynamics (CFD) summarises the results of the proposed changes done in the model. By implementing passive shading devices (exterior venetian blinds and internally operable ventilation openings), cooling consumption decreases 52%.

Therefore, a 30% reduction in cooling load for the prototype case building is also achievable by improving the building envelope (new U-value 0.15 W/m^2K) by fitting external cladding with good thermal mass characteristics. Occupied spaces within the flat would then enjoy acceptable thermal comfort conditions a large percentage of the time throughout the year. Respectively, comfortable indoor air temperatures (18% of the hours below the 26°C indicator) and acceptable thermal comfort (15% of the hours below the BS EN 15251 Category II upper limit) are also reported in the retrofitted base-case.

The results demonstrated that in relation to the static 'comfort' range for non-air-conditioned living room and kitchen, the indoor air temperatures in living room were mainly within the 'comfort' range (25°C +3K), although there were some instances of temperature above 28°C, and below 22°C. In this prototype RTB, temperatures were significantly higher throughout the period with several periods in which the temperature was above 30°C, and never below 22°C. The average mean temperature across the five monitored rooms was 25.5°C.

To provide an overall information about the indoor air quality, Figure 8 demonstrates annual CO_2 concentration within the living room starting from January; it is at 410ppm and fluctuates in a similar trend up to June to 440ppm. From June to November, it peaked up to 460ppm and fluctuated around this level the rest of the year. Between November and January, it dipped down again to 410ppm. The living room benchmark level of CO_2 concentration is given at 415ppm.

Figure 8:
The annual CO_2 concentration within the living room in the representative ground floor flat.



In this study, there is an interesting finding from these simulation measurements that the CO_2 concentration of this room remains always above the generated benchmark. According to the CIBSE Guide A, the benchmark level should be at 1000ppm for the residential buildings. On the contrary, in the peak time heat wave monitoring, it showed the CO_2 concentration of this room is at 400ppm.

4. CONCLUSION

The study aimed to evaluate the risk of overheating and potential ways to overcome this through the implementation of passive cooling design strategies (i.e. shading and natural ventilation) of a tower block in Famagusta, Cyprus. This is a crucial finding that must be investigated in further research to assess and optimise the risk of overheating and to understand occupants' thermal comfort when enhancing night cooling effects in RTB in the Mediterranean climate.

The results illustrate the necessity of considering passive measures in a state-of-the-art retrofit of existing residential tower block developments. Moreover, this paper concludes that a thorough economic appraisal is required to select the best environmentally and economically viable forms of retrofitting.

ACKNOWLEDGEMENTS

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Data Access Statement: The datasets generated during and/or analysed during the current study are publicly available at - https://doi.org/10.15123/uel.8q713

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The (un) sustainable futures of glass architecture

A life cycle assessment of curtain wall retrofit scenarios in Brussels

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ABSTRACT: Fully glazed office buildings embody the paradoxes of our built environment, both as a symbol of modernity and as energy-intensive architecture. The use of glass regardless of the orientation increases cooling loads, while older facades offer low light transmission and poor thermal and acoustic insulation. Consequently, this type of architecture has become an important focus of European thermal retrofit policies, while a wide range of glass products has been developed to achieve better energy efficiency, from special coatings on triple glazing. The implementation of these products is based on the assumption that the resulting reduction in cooling and heating loads during the use phase would offset the environmental effects caused by their production and transport, as well as by the disposal of the old façade. However, this assumption remains little discussed today. This paper therefore considers a case study of façade replacement scenarios for a generic office building in Brussels. Different retrofit strategies are analysed through a life cycle assessment that focuses on the uncertainties related to the potential evolution of energy systems and practices in a climate changing world.
KEYWORDS: Glass, Curtain Wall, LCA, Uncertainty, Sensitivity

1. INTRODUCTION

The spread worldwide of the glass curtain wall is inextricably linked to fossil fuels, which are burned to heat and cool otherwise uninhabitable office spaces. The large panes of glass favour the entry of solar energy and trap the heat accumulated inside the building, leading to dramatic overheating during the hot season. In contrast, glazing, mullions and transoms are weakly insulating elements and their exclusive use, to the detriment of much more insulating opaque walls, considerably increases heat loss in winter. But, glass curtain walls have become a fashionable landmark in the business districts of global metropolises, regardless of the climate, site and orientation. In that sense, they are part of the elements that has driven the Great Acceleration since the 1950s and leads to the socio-ecological threats our societies are facing [1].

The question now is how to transform these fully glazed buildings to cope with the urgency of building a post-carbon society. This paper conducts a life cycle assessment (LCA) of curtain wall retrofitting scenarios based on a case study in Brussels, Belgium. The objective is to assess the environmental impact of different technological solutions in the light of uncertainties relating to users' behaviour, climate change and the evolution of the electricity mix. This sensitivity analysis provides a better understanding of the socio-technical paths that are most likely to meet the urgency of the ecological challenges.

2. METHOD

Drawing on the conceptual and methodological framework of LCA [2], this research is structured in four stages.

First, a case study is defined based on the analysis of a series of fully glazed office buildings identified in Brussels. Taking into account their technical and morphological parameters, a generic architectural design is developed with a typical open-plan, a curtain wall and a concrete structure.

Secondly, building energy simulations are conducted with the EnergyPlus simulation program [3]. The results are compared to the data gathered on the energy use of office buildings in Brussels, thus providing a calibration of the model.

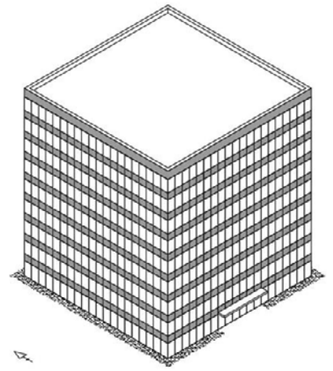
Thirdly, the building energy modelling is extended to a series of curtain wall retrofitting scenarios. They include sixteen types of façades with different insulating glass units, ranging from solar control double glazing to electrochromic glass. Drawing on studies in the sociology of energy and building, a series of behavioural parameters are also defined: three areas of indoor temperatures are considered [4-5].

Finally, an environmental analysis of each of these scenarios is performed using Brightway2, an open source LCA framework based on the python programming language [6-7]. Given the length of this paper, the results of the life cycle impact assessment (LCIA) are normalised and weighted to give a single score per scenario. This normalising and weighting stage is based on factors defined according to the European product environmental footprint (PEF) methodology [8].

2.1 Definition of the case study

The LCA concerns the renovation of an office building, and in particular the glazed elements of its façade (Fig. 1). Focusing on renovation leads not only to study the production and transport of new products, but also the disposal and management of waste—in this case, used façade elements—which therefore become part of the LCA and highlight the specific issues related to the end of life. Here, the new construction elements replace those of a curtain wall assumed to have been built in the 1970s with metal frames and bronze-coloured glass, tinted in the mass as was common at the time. This generation of façades has gone through an intensive renovation campaign in recent years, where, among other elements, the glazing units are replaced with more efficient ones.

Figure 1:
General axonometry of the case study. The offices are organised around a concrete core which houses the vertical circulation.



Based on these examples, the case study consists of a 9-storey building, entirely dedicated to offices distributed on a square plan with each of the four façades facing one of the cardinal directions. The existing bronze-tinted double glazing is supported by a network of mullions and transoms made of steel. The LCA therefore focuses on the impact of replacing these elements with a new curtain wall, whose multiple configurations provide the basis for a comparative analysis of glass units according to the performance they seek to achieve (Table 1). The functional unit is thus the replacement of 1 m² of double glazed units implemented in a curtain wall to bring daylight into an office building and to ensure the safety, tightness, acoustic and thermal insulation of the indoor space for 40 y. The LCA includes the following stages: extraction and transport of raw materials, production of glazing and frames, disposal and treatment of the existing ones, impact on the building heating and cooling, and finally the end-of-life treatment after 40 years of service life.

Table 1:
List of glazing units considered in the façade replacement scenarios.

Type of glazing	*Ug*	*SHGC*	*VT*
	W/m².K	-	-
Single glazing (sg)			
clear	5.6	0.8	0.9
clear and coated	3.1	0.4	0.7
Double glazing, low efficiency			
bronze tinted w/ air (dg_init)	2.7	0.5	0.4
clear with air (dg0)	2.7	0.7	0.8
Double glazing, high efficiency (dg)			
coated with 90% argon	1.1	0.6	0.8
-	1	0.4	0.6
-	1.1	0.4	0.7
coated twice with 90% argon	1	0.2	0.4
coated with 90% argon	1	0.3	0.6
-	1	0.4	0.7
Triple glazing, high efficiency (tg)			
coated twice w/ 90% argon	0.6	0.5	0.8
-	0.7	0.4	0.5
-	0.7	0.4	0.6
-	0.6	0.2	0.3
coated w/ 90% argon	0.6	0.2	0.5
-	0.6	0.3	0.6

Note: Single glazing and "low-efficiency" double glazing use aluminium frame with *Uf* = 5.5 W/m².K. All others have aluminium frame with *Uf* = 1.5 W/m².K. *Ug* and *Uf* stand for the thermal transmittance coefficient of glazing and frames respectively. SHGC means solar heat gain coefficient and VT stands for visible transmittance.

2.2 Scope of the sensitivity analysis

This research relies on a sensitivity analysis to determine how technological improvements (energy efficiency of glazing) and environmental practices (temperature setpoint) contribute to reducing the environmental effects of office buildings. Moreover, as the lifetime of a curtain wall can easily exceed a quarter of a century [9], significant changes can be expected in the future in the climate and electricity mix of the region. The LCA therefore takes into account the current Belgian electricity mix as well as a range of other European mixes, from the least carbon intensive (e.g., Switzerland and France) to the most carbon intensive (e.g., Poland). Similarly, two sets of weather data are integrated to the building energy modelling to assess the impact of climate change on the performance of the curtain wall retrofitting

scenarios (current climate conditions and future RCP 8.5 trajectory for the Brussels region).

The use phase of the different glazing units is analysed through a series of building energy simulations. Starting from an initial situation defined by an old curtain wall, we take a consequential perspective to assess the impact of replacing the glazing and frames. As the objective of this renovation is to reduce the environmental impact of the building, we assess the consequence of this intervention by comparing the energy use before and after the transformation, the difference corresponding to the part allocated to the new curtain wall, the latter being the only element modified between the two simulations. Accordingly, a positive value reflects the inefficiency of the new façade design compared to the old one. On the contrary, a negative result represents energy savings and might also corresponds to a certain amount of avoided ecological damages.

Each of the façade systems defines a specific scenario for the replacement of the existing curtain wall. These scenarios are first analysed according to a standard building configuration based on average data on the design and use of office buildings. A sensitivity analysis is then conducted on a series of parameters, which relate to the HVAC system, the heating and cooling setpoint temperatures, the occupancy density and the internal heat gains. Each configuration comes with a building energy simulation, providing an estimate of the amount of natural gas and electricity used for the HVAC system, appliances and lighting. These data are then integrated into the life cycle inventory.

2.3 Methodological framework of the LCA

The life cycle inventory records the material flows and energy use of each activity occurring from cradle to grave. At each stage of the life cycle, information is collected using two complementary approaches: the first seeks to understand the industrial processes specific to the consumption of glazing and the construction of curtain walls in Belgium; the second uses the Ecoinvent database to collect detailed inventories of the activities concerned. Regarding the life cycle model, We follow the “cut-off” system defined by Ecoinvent. We then use 16 midpoint indicators relating to climate change, ecosystem quality, human health and resources. In line with the efforts made to harmonise LCA in the EU, we use the Environmental Footprint (EF) midpoint method [10-12], called in the Ecoinvent database “ILCD 2.0 2018 midpoint.”

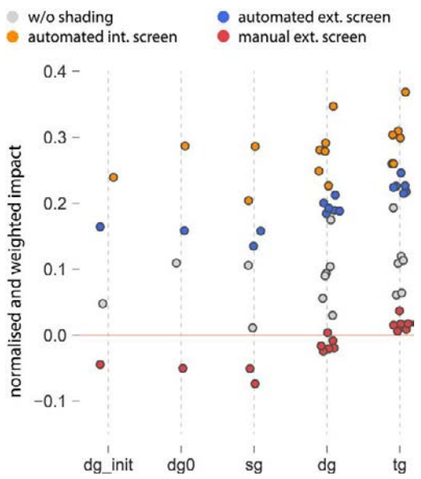
3. OUTCOMES AND DISCUSSION

This section relies on building energy modelling to compare different scenarios of curtain wall replacement according to the performance that the new construction system seeks to achieve. The energy simulations feed an LCIA that estimates the environmental impact of each scenario over 40 years of service life. The relevance of the results is questioned through the sensitivity analysis.

3.1 The role of shading devices

When solar screens are installed outside, they contribute to reducing the use of natural gas and electricity. This result is reflected across a range of impact indicators, such as the potential for climate change and ionising radiation, and the exploitation of fossil resources and land. But this observation is strongly undermined by the results on other indicators. Indeed, the use of an automation system leads to a particularly significant increase in some environmental impact indicators, such as the use of mineral resources and metals, and the freshwater ecotoxicity and eutrophication. This indicates that the reduction in natural gas and electricity consumption during the use phase of the building does not contribute enough to the reduction of these categories of environmental impacts, and thus fails to offset the footprint left by the production phase. When the environmental impact is calculated for all scenarios, those without shading devices and those with one inside are disadvantageous. They all turn out to be much worse for the environment than the do-nothing option, where the building is left as it is, and represented on the graphs by the horizontal zero line (Fig. 2). In contrast, scenarios with manual external shading devices are quite efficient, with the exception of the one integrating triple glazing.

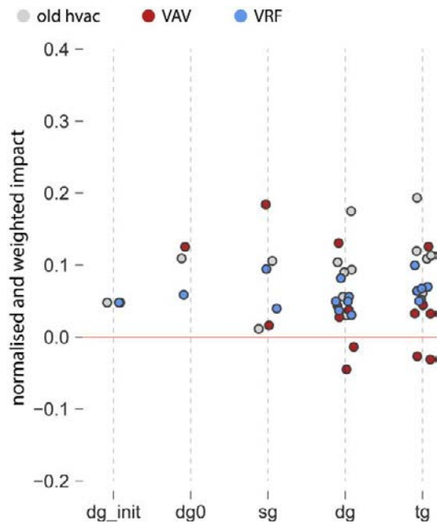
Figure 2:
Normalised and weighted impact for different façade replacement scenarios, with and without solar screens.



3.2 How HVAC system matter

The results discussed in the previous section are given for a certain configuration of the case study, which is defined according to a series of hypotheses concerning its energy technologies. The potential influence of these hypotheses on the LCIA has to be estimated, especially since the HVAC system is a key element in the operation and energy performance of buildings. The system used so far is a fan coil unit with a natural gas boiler, but this type is only one of many models found in office buildings. In this sense, an important question is to what extent the LCIA results are sensitive to this hypothesis and whether this may alter the conclusions that can be drawn? In other words, does the efficiency of the curtain walls and their glazing depend on how the boiler and chiller have been modelled? To answer this question, the same simulations are performed, but with two different HVAC systems (Fig. 3). The first is a variable air volume (VAV) chiller with gas boiler reheat. It is a common solution in office buildings today and is known for its high energy efficiency. The second uses the variable refrigerant flow (VRF) technology and relies exclusively on electricity.

Figure 3:
Normalised and weighted impact for different façade replacement scenarios, with various HVAC systems.



The reduction of natural gas and electricity consumption during the use phase has a considerable influence with regard to certain indicators, such as the exploitation of fossil resources and the potential for climate change and ozone depletion. But this reduction has little effect on other indicators. For example, the ecotoxicity and acidification of freshwater, the use of mineral, metal and water resources, and the potential effects of particulate matter breathing remain quite high since their value is mainly determined by the industrial processes taking place during the production phase. In the case of the VRF model, this observation is especially true since the use phase is based on low energy use and no longer depends directly on fossil resources, apart from those supplying the Belgian electricity infrastructure. Furthermore, the calculation of the overall impact further underlines the low potential of glazing for reducing environmental effects when a VRF system is used. In the case of a VAV system, this calculation confirms the efficiency of half of the double and triple glazing units, those with a low solar factor.

Finally, the sensitivity analysis conducted on the HVAC system reveals the high variability of the LCIA results and the difficulty of drawing conclusions on the potential of glazing to reduce environmental impact. When all the results are aggregated, the uncertainty about glazing performance is considerable and underlines the risk of conducting an LCA whose conclusions would in fact be very specific to the context set through the modelling. Depending on the hypotheses and indicators chosen, the study undertaken here shows that the same assessment can lead to either the promotion or the exclusion of high-efficiency glazing.

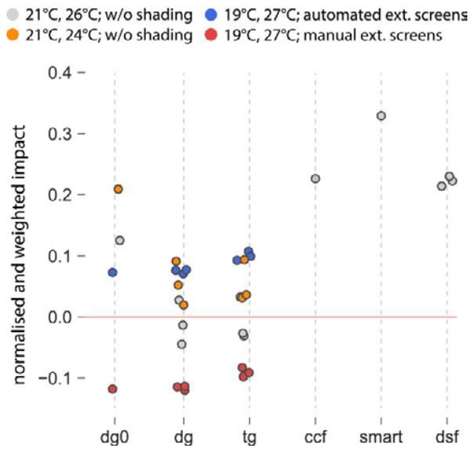
3.3 How energy practices matter

Two batches of simulations are defined to study the influence of the setpoint temperature that control the HVAC system, which in this case is a VAV unit. The first batch keeps the heating temperature at 21°C, but lowers the cooling temperature by 2°C, bringing it from 26°C to 24°C in summer during occupancy. The second batch models the building with a setpoint temperature of 19°C and 27°C for heating and cooling respectively. These temperatures, together with those defined in the previous simulations (21°C and 26°C), describe three patterns of indoor comfort that meet both the recommendations given in the standards and the observations made in workplaces (Fig. 3).

Changing the setpoint temperature has a considerable influence on the building energy use and environmental effects. Lowering the temperature by one degree in summer increases the cooling loads by 20-30%, which represents a 5-10% rise in the overall energy use in comparison to the scenarios with setpoint temperatures of 21°C and 26°C respectively. These results have a clear influence on the LCIA. When the weighted impact is calculated, the result is very conclusive. Widening the comfort zone, which here translates into a broader indoor temperature range, is by far the

most efficient strategy to reduce the environmental effects of the building. In this context, the scenarios of façade replacement using manual external shading devices and clear air-filled double glazing, or more efficient argon-filled double glazing with solar control coating, are more sustainable. They have a normalised and weighted impact lower than other scenarios with the same glazing type, with closed cavity façade (CCF), double skin façade (DSF), or smart glazing, but with a setpoint temperature 1°C lower for heating and 2°C higher for cooling. On the contrary, façade replacement scenarios that also see a shift in cooling temperature from 26°C to 24°C thwart the potential of more efficient façade design. Indeed, the replacement of the old bronze-tinted double glazing unit with solar control coated, high light transmission double or triple glazing does not offset the deleterious effects of a more energy-intensive indoor comfort.

Figure 4:
Normalised and weighted impact for different façade replacement scenarios according to indoor temperatures.

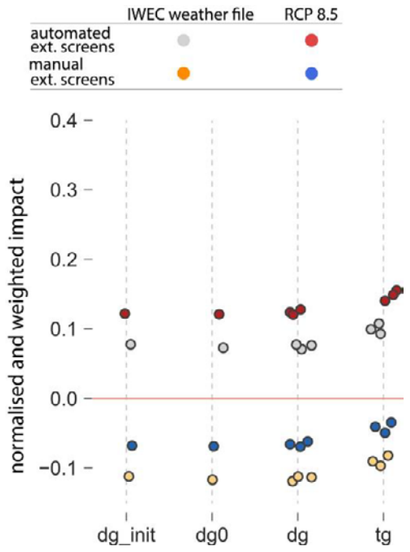


3.3 Electricity mix and climate change

The energy modelling of the case study has so far been based on Brussels weather data from the 1980s and 1990s. These are "typical" weather files derived from 18 years (1982–1999) of hourly weather records archived at the US National Climatic Data Center. But today's climate is already very different from that of the late 20th century. Given this fact, how should the results of building energy simulations be interpreted? And in view of the increasing intensity of climate change, how should the uncertainties that characterise the meteorological context of buildings in the coming decades be taken into account?

Delphine Ramon has recently conducted research on the issues of building modelling and design in the perspective of the transformation of the energy and environmental context in Belgium, including a study of future weather data [13]. Her work has led to the publication of a data file for the period 2069–2098 under the IPCC RCP 8.5 scenario [14]. The sensitivity analysis related to climate change therefore consists of re-running the LCIA with the weather data corresponding to the RCP 8.5. The LCIA results show an increase in environmental effects across the 16 impact categories. Accordingly, comparing the overall impacts reveals how even the offset potential of the most efficient scenarios is greatly reduced (Fig. 5).

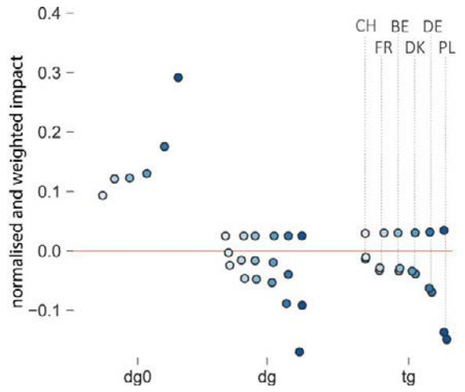
Figure 5:
Weighted environmental impact score for different façade replacement scenarios according to weather data.



The sensitivity analysis now focuses on the potential influence of the transformation of the electricity mix that powers the building. While many processes and activities throughout the life cycle of facades use electricity, we focus here on the use phase of the case study. The aim is to understand how a change in the grid could modify the efficiency of the façade replacement scenarios and their potential to offset the environmental impact caused by the production, transport and end-of-life phases.

The LCIA results show an interesting pattern: the more carbon intensive the electricity mix, the more important the thermal performance of the facades is in reducing the environmental effects of the case study (Fig. 6). Following a movement that starts with the low-carbon case of Switzerland and ends with coal-intensive Poland, the performance gap measured in terms of weighted environmental impact steadily widens. The difference between the least and most efficient double or triple glazing units varies greatly depending on electricity mix.

Figure 6:
Normalised and weighted impact for different façade replacement scenarios according to electricity mix.



Therefore, this sensitivity analysis highlights once again the strong context dependence of the efficiency of facades, and of glazing in particular. As just seen, the same double glazing can have its weighted environmental impact divided by three depending on the electricity mix, while the performance of the most efficient triple-glazed façade sees its normalised and weighted impact score dropping as the grid goes from the most carbon intensive to the least.

4. CONCLUSION

This paper highlights the major role that modelling hypotheses play in the results of the LCIA. It also highlights how the definition of energy efficiency is intimately linked to these hypotheses since they shape the context of the case study. In this sense, the environmental offset potential of building products, and in particular glazing, can only be determined if the building use, energy system and practices, the indoor climate conditions and the territorial electricity mix are clearly expressed. Therefore, strategies to reduce the environmental effects of this architectural type should not be based on the performance of the building components alone, but on a series of measures that take into account both the plurality of factors that make up the socio-energetic system of a building and the uncertainties about their future evolution. The paper also shows that certain conditions can, however, make the case study more resilient to the uncertainties that are likely to arise during its service life. For example, widening the comfort zone is by far the most efficient strategy to reduce the environmental effects of the building, especially when combined with the use of exterior screens.

ACKNOWLEDGEMENTS

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Indoor daylight level assessment of a micro-algae integrated double glazed façade system

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ABSTRACT: Lighting conditions have a significant impact on all aspects of human life and health. They affect our physiological and psychological health, and their dynamic changes have positive effects on several aspects of human well-being. Apart from the effects on human health and well-being, the lighting environment affects task performance. Previous research indicated that there is a positive correlation between daylighted classrooms and student learning rates. Therefore, along with energy efficiency practices, there is a need for a comprehensive understanding of the occupants' needs and preferences as well as the factors influencing their performance in indoor environments, two topics that are not necessarily overlapping. Recently, investigating micro-algae integrated building facade systems has increased due to its environmentally friendly nature. This study measures the effect of density and green colour of a micro-algae glazing system on visible light transmittance (VLT) along with the quality of light inside a building. A series of VLT was measured using 12 test scenarios by combining different algae densities with three glazing panels. The test results were then used in a simulation procedure to evaluate the daylighting performance of the micro-algae glazing system. The results showed that different densities of the algae glazing system with varying growth conditions are expected to contribute to improving the indoor daylight environment by being able to use the optimal density of micro-algae glazing depending on time of the day and seasonal changes.

KEYWORDS: Daylighting, Visual Comfort, Microalgae, Building Façade, Visual Light Transmittance

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1. INTRODUCTION

Daylight level and quality are significant factors in indoor environmental quality. Occupants' acceptable light levels should be provided to guarantee comfortable and productive spaces [1]. Daylight not only improves health, awareness, productivity, and sense of comfort but also results in energy consumption reduction [2]. Also, direct sunlight is a good source of green energy production by harnessing transferred heat by solar radiation [14]. Therefore, it is necessary to understand which factors affect daylight quality and quantity. Daylighting is a challenging field in applying building performance metrics to evaluate [5]. Many researchers attempt to predict the daylight quantity under varying experimental situations. So far, there are several metrics available, and little is known about their application. Daylight indices which have been developed to assess different aspects of visual comfort (i.e., amount of light, light uniformity, light quality, and glare), differ from each other for several features, e.g., their accuracy, simplicity, space, and time discretization [6]. Daylight metrics are implemented in technical standards and rating systems, suggesting simplified methods and values for assessing daylight and glare performance in buildings (e.g., LEED, BREEAM, IES, DNGB, EN 17037, BIS 8206) [7]. Among these daylight metrics, this study focuses on visual light transmittance (VLT) of a proposed glazing system that combines façade engineering with a bio-organism such as micro-algae to assess the effect of its colourful cells and density on daylight passing through to building interior space.

1.1 Micro-algae facade

Algae are a diverse group of aquatic organisms that range from single microscopic cells to macroscopic and multicellular organisms. Different species of algae can thrive in freshwater or saltwater and depending on the species, are able to endure a range of temperature, solar intensity, O2 and CO2 concentration, acidity and turbidity [3,4]. Among the above-mentioned categories, micro-algae have drawn the attention of researchers and entrepreneurs with an inclination of improving them as a future resource providing different kinds of renewable bio products. Recently, investigating micro-algae related to building technology especially in the building facades system has increased considerably due to its benefits as an environmentally friendly organism that can be applied for indoor air purification, visual comfort enhancement, daylight management, cooling load reduction, and so on.

1.2 Problem description

To accomplish an indoor visual task a "sufficient" amount of light is necessary; this means that either too high or too low amount of light may cause visual discomfort, impacting performance on tasks. Accordingly, Useful Daylight Illuminance (UDI) was introduced by Nabil and Mardaljevic [16]. According to many psychological studies, natural light inside buildings will affect not only human healthiness, but also productivity and tiredness, especially in workspaces. The focus of this scrutiny is to investigate the daylight performance of a micro-algae facade that offers dynamic VLTs through controlling multiple algae densities. This research is conducted through experimental measurements by preparing a façade prototype designed to contain and control the algae cell density. Spirulina, a blue-green algae typically used for food supplement, is one of optimal strains to be considered for applying in the building facade due to its fast growth rate and easy cultivation. Among other types of algae, we measured previously, Spirulina showed the highest growth rate given appropriate conditions, which directly results in quicker harvesting cycles, thus offering good daylighting control and fast carbon reduction. It also ensures a constant growth rate for different harvesting methods and its motile attribute minimises biofouling that affects aesthetics, maintenance issues, and the purpose of daylight control.

1.3 Research objectives

To the knowledge of the authors, currently there is an absence of studies on how the various algae densities if used in a building façade, can affect the indoor daylight factor and quality. Therefore, this research attempts to shed light on this less known organism by evaluating what indoor daylight levels are created by different densities of Spirulina in the designed prototype façade systems and how the different combinations of algae cell density and facade systems impact indoor daylight conditions.

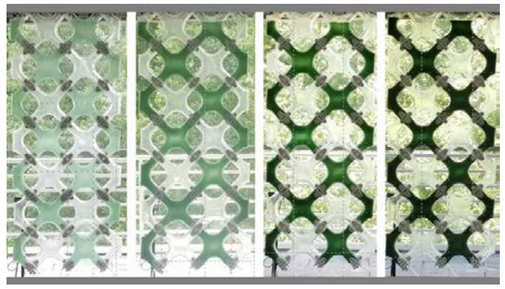


Figure 1: Different micro-algae density of the prototyped façade (from left to right: 25%, 50%, 75%, 100%)

2. METHODOLOGY

2.1 Physical preparation

In order to assess the research questions, the experiment conditions were prepared in lab environments. Firstly, Spirulina was cultivated in a controlled growth condition with appropriate daylight and temperatures. When it reached the stationary stage after the exponential growth, the cell density becomes a dark green from light green. The grown micro-algae then can be prepared with four different densities for the test conditions of 100% density (full growth) and 75%, 50%, and 25% densities diluted with growing medium. Secondly, three double glazed panels to incorporate different microalgae cell densities were built out of acrylic panels. The required thickness of each acrylic panel layer was calculated to match the stiffness of the glass to reflect the real situation. Three one-foot by one-foot panels were prepared; each of which with one Inch, half Inch, and quarter Inch air gap space between two-sides that were sealed all around except for one part to be filled with Spirulina. Thirdly, an Illuminance Spectrometer device was used for the spectral data measurements to get more accurate and detailed data to be used for the daylighting simulations. The device used is KONICA MINOLTA CL-500A which can measure most of the visual metrics such as illuminance, colour temperature, spectral distribution, colour rendering index etc.

2.1 Experiment process

The experimental procedure was conducted on a sunny day to be able to measure the illuminance of the glazing panels in direct and indirect(reflected) daylighting conditions. Three glazing panels and four Spirulina densities were prepared resulting in 12 testing scenarios to assess daylight quantity and quality filtered by spirulina filled glazing panels. Firstly, the dark green Spirulina which is considered here as 100% algae were diluted with medium grown algae precisely in four measuring pots to achieve the cell density of 75%, 50% and 25%. Then, each filled panel with one of the four micro-algae dilutions was tested by the spectrometer device, once exposing to the direct sun and measuring the VLT on the interior surface of the panel, then the same panel was measured exposing to the indirect sun. Figure 2 shows the panel with half Inch cavity containing four different micro-algae densities exposed to the direct sun. The spectrometer used is able to register all the visual properties of each spectral data point to be used for the further computational analysis, hence after each measurement the data were also inserted in an excel file to assure the accuracy of data collection and prevent confusion due to similarity of the data points. These data which are presented in Table 1, were used for the daylighting simulation of a case study building using the micro-algae façade system.

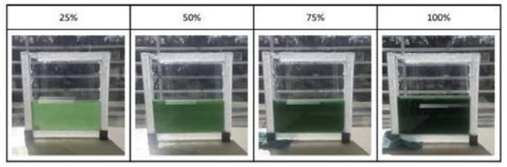


Figure 2: Tested glazing panel with different micro-algae densities (from left to right: 25%, 50%, 75%, 100%)

The following visible light transmittance (VLT) equation was used to compare the VLT (%) values of 12 different microalgae double-glazing panel conditions.

$$VLT\ (\%) = 100 * I / I_0$$

where I - transmitted light (lux);
I_0 - Incident light (lux);

Table 1: Illuminance values (Lux) from testing conditions used for VLT analysis of each scenario

Lux	Algae cavity		
Algae cell density	1 inch	½ inch	¼ inch
100% cell density	167	6739	11110
75% cell density	865	12100	20130
50% cell density	2914	18520	27590
25% cell density	12930	35700	44660

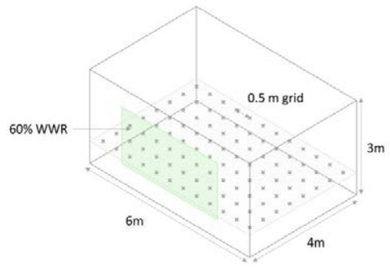
2.2 Simulation process

Daylight simulation was carried out to understand how different algae densities in the facade influence indoor daylight environments. The VLT data applied in the daylight simulation was obtained from the illuminance measurements. The VLT levels converted from illuminance data are shown in Table 2. With different micro-algae densities and panel thicknesses which were prepared for this research, the microalgae system can dynamically regulate daylight transmissions and achieve desired luminous environments based on the manually prepared algae densities.

Table 2. VLT values of different tested scenarios scaled from 0 representing 0% and 1 representing 100%

VLT	Algae cavity		
Algae cell density	1 inch	½ inch	¼ inch
100% cell density	0.002	0.064	0.105
75% cell density	0.008	0.115	0.191
50% cell density	0.028	0.176	0.262
25% cell density	0.123	0.339	0.424

From the measurements, it can be observed that the visible light transmittance values of the algae glazing using different densities can be controlled from 0.002 to 0.424. However, in the case of a one Inch cavity panel, due to its thickness, the VLT value of 25% density is 0.123, which is like the value of 100% algae density of the quarter inch or 75% density of the half inch cavity panel. Also, the case of the half inch panel showed that the range of VLT is narrow compared to



the results of the quarter inch panel. Even though the difference between min/max VLT of the 1" panel is higher than 1/4" panel, contemplating on the VLT results resulted in some insights toward the simulation step. Firstly, in order to achieve practical results from this research for architectural design implementation, it is wise to consider the VLT range of today's market windows. Although, it is possible to manufacture a window with a VLT range from 0 to 1, the general VLT range for the windows that are using in building construction has a range from 0.3 to 0.8. By looking at the measurement results, it can be observed that the VLT measurements data for 1/4" panel is ranged from 0.1 to 0.42 which is more appropriate than other tested panels. In the case of the 1" panel, the results of 50%, 75%, and 100% is pretty similar to an opaque wall, so it cannot have an impact by running simulations nor to understand the algae panel as a window system even if the min/max ratio of 1" panel is higher than 1/4".

Secondly, the daylighting simulation engine in Radiance and Daysim is not capable to recognize the VLT values of less than 0.1 and since the VLT results of 100%, 75%, and 50% of the 1" panel had values less than 0.1, consequently they cannot be used as the simulation input data. On the other hand, the VLT values of 1/4" showed different results for each case of algae density with VLT values greater than 0.1 and closer to regular market windows. Based on the insights reasoned, the research simulations were conducted using the 1/4" panel VLT data as the target panel.

For the simulation setting, a shoebox model with 6 m(width) x 4 m(depth) x 3 m(height) was modelled which consists of 60% window to wall ratio (WWR) on the south faced facade of the model (Figure 3). The geometry was generated by using grasshopper, parametric scripting plug-in for the Rhino, 3d modelling software and the daylight simulation was performed by using Honeybee and Ladybug environmental simulation plug-in for grasshopper environment. These simulation plug-ins are validated energy simulation tools and have been used in many scientific studies in the architecture field.

The simulation surface was aligned 0.7m above the floor level to better simulate the real daylighting conditions. This analysis plane considered the height of a person's sitting position and an analysis grid with 0.5m interval between measuring points was used for fast simulation times and good data resolutions. For the weather data, EPW format of TMY3 for Charlotte, North Carolina, US were used.

Figure 3. Shoebox model set up for daylighting simulations

3. RESULTS AND DISCUSSION

The illuminance simulation results at point in time of three different days, June 21st, Dec 21st, and March 21st as indicators of the seasonal climate conditions are presented in tables 3, 4 and 5. In order to evaluate the indoor daylight environment, this study used the criteria of the useful daylight illuminance (UDI) where the illuminance values are classified with three ranges [6]:

- Illuminance ranges lower than the adequate amount of daylight which shows that daylight cannot be the sole source of illumination and additional artificial lighting is needed for accomplishing the task without visual discomfort. Illuminance below 100 lux is considered as low range daylight.
- Illuminance range is considered as the adequate (useful) range of light, which is between 100~2000 lux.
- Illuminance ranges higher than the adequate amount of daylight in which the over-supply of daylight is likely to cause visual discomfort (Glare), which is over 2000 lux.

As a result, this research assumes that the algae façade density with the highest useful daylight (%) is performing satisfactorily. In the case of June 21st and December 21st, when the density of the algae façade increases, the percentage of useful daylight, which means good illuminance decreases. For June 21st, the useful daylight (%) was decreased from 45.9% to 14.6% about 31.3% and the useful daylight (%) of winter was decreased from 71.9% to 20.8% about 51.1%.

In both cases, when considering only the lighting environment, the results showed that a 25% density condition provides the best indoor daylight environment. In particular, on Dec 21st, the algae glazing with 25% density provides UDI of 71.9 % which is the highest percentage among other simulated cases. Therefore, from the results, it can be inferred that the algae density requires to be maintained around 25% or less to provide a satisfactory indoor daylighting environment in both summer and winter season.

However, when heating and cooling loads is considered, the best (or optimum) algae density is changed. In winter, low algae density in the façade also helps to save the heating load by maximising winter solar gains. Unlike winter, in summer a low algae density is less effective in blocking solar radiation. Hence, in the case of summer, the optimum algae density should be determined by considering both useful daylight and solar radiation mitigation.

Table 3. UDI simulation on June 21st.

Algae density -VLT	Average lux (Min-max)	Area (%) by UDI range (A:0~100 B:100~2000 C: over 2000)	Simulation Image
25% -0.424	274.11 Min:70.1 Max:822.6	A: 54.17 B: 45.83 C:0.0	
50% -0.262	155.6 Min:39.5 Max:459.5	A: 72.92 B: 27.08 C:0.0	
75% -0.191	107.29 Min:27.3 Max:316.7	A: 85.42 B: 14.58 C:0.0	
100% -0.105	53.6 Min:12.4 Max:154.2	A: 100.0 B:0.0 C:0.0	

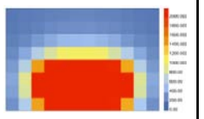
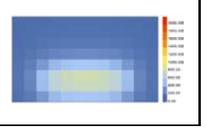
Table 4. UDI simulation on December 21st.

Algae density -VLT	Average lux (Min-max)	Area (%) by UDI range (A:0~100 B:100~2000 C: over 2000)	Simulation Image
25% -0.424	315.7 Min:40.4 Max:577.9	A: 28.13 B: 71.88 C:0	
50% -0.262	186.4 Min:23.0 Max:340.9	A: 56.25 B: 43.75 C:0	
75% -0.191	132.1 Min:15.9 Max:240.9	A: 79.17 B: 20.83 C:0.0	

100% /0.105	68.9 Min:7.8 Max:125.1	A:100 B:0.0 C:0.0	

Unlike the simulation results for June and December where the UDI (%) was decreased by increasing the algae density, in March, even though the algae density increased, the UDI (%) was not decreased, as it was maintained between 44~47% up to the 75% density and then slightly dropped to around 32% at 100% density.
These results showed that the increased algae density is effective in blocking the illuminance over 2000 lux which causes glare while maintaining the useful daylight illuminance constantly. Therefore, in March, the appropriate algae density of the façade for a proper lighting environment is in the range of 25 to 75%, which is more flexible than in summer and winter.

Table 5. UDI simulation on March 21st.

Algae density -VLT	Average lux (Min-max)	Area (%) by UDI range (A:0~100 B:100~2000 C: over 2000)	Simulation Image
25% -0.424	Ave:1078.7 Min:73.6 Max:3885.4	A: 29.21 B: 44.79 C: 26.0	
50% -0.262	Ave:611.0 Min:43.5 Max:2166.1	A: 45.83 B: 45.83 C: 8.3	
75% -0.191	Ave:420.5 Min:28.7 Max:1489.6	A:52.08 B:47.92 C:0.0	
100% -0.105	Ave:207.7 Min:16.2 Max:734.7	A:66.67 B:33.33 C:0.0	

The graph in figure 4 shows the UDI (%) according to the different densities in winter, summer, and spring. In the case of March, the UDI (%) increased even though the algae façade inclined to darker colour.

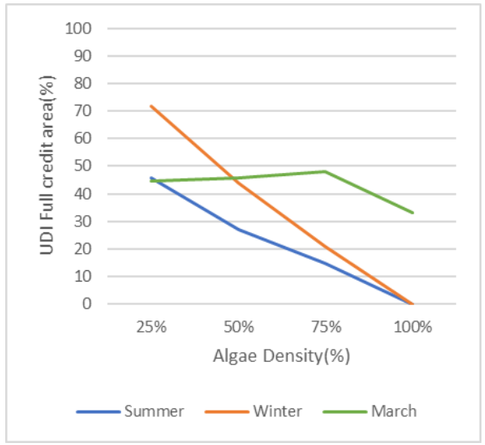


Figure 4. UDI (%) in different seasons

In order to understand the useful daylight result in March, it is necessary to look at the range of lux values on the room surface of the shoebox model (Figure 5). In the case of March, compared to June and December, the range of lux reaching to the simulation points on the surface is very wide from 73.6 to 3885.4 lux. The illuminance over 2000 lux causing a glare issue is moderated by the increased density of the algae façade. It shows that the density changes of the algae façade using the natural process of algae growth depending on the daylight levels can minimise artificial lighting loads and improve indoor luminous environments.

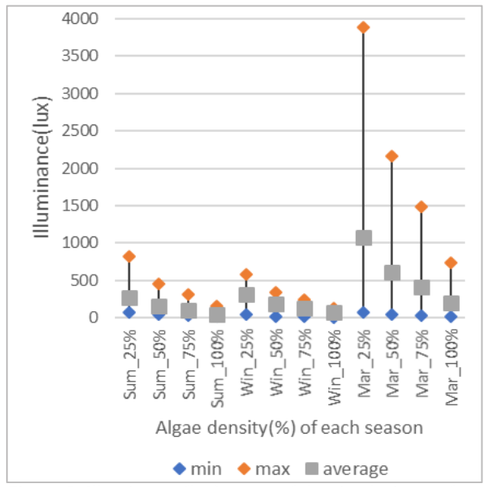


Figure 5. Illuminance(lux) range of the simulation surface by different algae densities

4. CONCLUSION

Researchers found that not all the existing research methods can accurately evaluate visual comfort, which resulted in low consistency between laboratory-driven measures and occupants' experience in buildings (Jakubiec and Reinhart, 2016). Therefore, many researchers are trying to improve some issues through the study of human-level cognition. Moreover, satisfying levels on lighting conditions differ significantly between individuals (Chraibi et al., 2016) due to the known inherent variability between occupants concerning visual comfort perception, preference, and acceptance (Van Den Wymelenberg, 2014). Therefore, there is no consensus yet as to what performance metric can accurately predict visual comfort, and it is necessary to understand the relationship between metric assessments relative to human evaluations through field studies (Nezamdoost and Van Den Wymelenberg, 2017b).

After careful measurements and simulations, the authors have found the following outcomes for this study. Firstly, the best cell density of the algae facade for better daylight performance can be changed depending on the season. Particularly, in the case of spring, the algae density to provide an appropriate lighting environment requires a wider range of VLTs than in other seasons. These targeted algae densities can be met by automatically controlling the dilution cycle during the operational stage. Secondly, this study found that the algae density directly affects indoor daylighting environment. Although the algae density of 25% showed the best daylight condition in June and December, the best density of the algae facade also can be changed when considering the heating and cooling energy reduction.

To further this research, we plan to investigate the holistic energy performance of the algae façade with different densities and to establish a methodology for optimising the façade density considering both daylighting quality and energy savings. It is also worth mentioning that automatically controlling algae density at large scale is a challenging matter which needs further developments.

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An initial approach to the impact of roller screen curtains on colour rendition of transmitted daylight

Experimental measures in real space

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ABSTRACT: Several studies on roller screen shades performance have been conducted focusing on glare, outdoor vision, daylight availability and energy performance. However, other properties—such as chromaticity and colour rendition—of daylight transmitted through this type of shading system have hardly been addressed. Against this background, the present study focuses on the impact of woven shade fabrics on daylight conditions in indoor spaces, targeting variations in colour rendition properties. The hypothesis of this work is that the fibre colour and the openness factor of woven shade fabrics, as well as, the solar incidence position affect the colour rendition properties of the transmitted daylight. Seven screen fabrics were evaluated in a test room, where the CRI and the spectral power distribution (SPD) were measured, at two distinct times of the day. Based on the SPD the Fidelity Index, the Gamut Index and the red Local Chroma Shift were calculated. Results show that the daylight passing through the fabrics has good or excellent colour rendition capacity for the tested samples and the testing conditions. And that the solar position impacts on the studied colour rendition metrics, whereas the openness factor and the colour of the fabric do not.
KEYWORDS: Daylight, Colour Rendition, Woven Shade Fabrics

1. INTRODUCTION

Roller shades are dynamic shading systems widely used globally, as they combine solar and visual protection with an aesthetically appealing presence at a relatively low price. Their properties can improve visual comfort by reducing glare and energy consumption. They consist of different fabric materials produced with varying degrees of openness and transmission characteristics (type of weave, colour, etc.). Several studies have analysed the performance of roller blinds, focusing on the following aspects: glare, outdoor vision, daylight availability and energy performance.

While these are the parameters on which most studies have focused, other measures of lighting quality, such as the spectral transmittance of woven shades and its impact on chromaticity and colour rendering, have not been studied as extensively. The spectral transmittance of glazing and solar shading devices may have an impact on correlated colour temperature (CCT) and colour rendition properties (colour rendering index (CRI), colour fidelity (R_f), gamut index (R_g)). For many years CCT and CRI were the two major components used to understand the spectral power distribution (SPD) of transmitted light. Other parameters used to analyse the colour rendition of light are currently emerging. Some of them are overall average properties (R_f, R_g) and some are hue-specific properties (chroma shift, hue shift) of a light source [1].

Within this framework, this study seeks to analyse the impact of roller screen woven shades on daylight conditions in indoor spaces, targeting variations in colour rendering properties. Colour rendition refers to the effect of the light source SPD on the colour appearance of objects [2]. Moreover, it is relevant to highlight that the impact of woven shades fabric on this parameter has scarcely been explored so far. The hypothesis of this work is that the fibre colour and the openness factor of woven shade fabrics, as well as, the solar incidence position (altitude and azimuth) have an effect on the colour rendition properties of the transmitted daylight.

2. METHOD

2.1 Study case

Seven woven shade fabrics were tested. The fabric selection criterion is based on the colour and openness factor of the fabrics. Woven fabrics with white and grey fibres and their combinations were selected. Furthermore, fabrics with an openness factor of 3 and 5 were chosen. Considering the previously mentioned criteria, the most frequently sold screen fabrics in the local market were selected. Table 1 shows the properties of the selected fabrics. The woven shades tested in this study are only for indoor use.

Table 1:
Properties of selected screen fabrics: fibre colour and openness factor (OF).

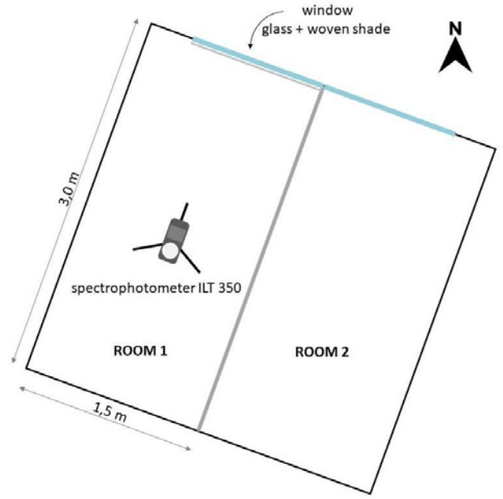
Code	Image	Fibre colour	OF
4301		white/white	3
9801		white/white	5
4001		white/white	5
4308		grey/white	3
4008		grey/white	5
2007		grey/white	5
9808		grey/grey	5

2.2 Experimental measures

Fabrics were analysed under daylight conditions in a test room (Figure 1). The left room (Figure 2) of the lighting research laboratory was used for this study. The room has an opening of 1.00 m x 1.00 m, where the samples were placed. The tests mentioned below were first performed on a setting with no sun protection on its opening, used as the base case. The base case features in the window a 6 mm clear glass. CRI and the spectral power distribution were measured with an ILT 350 Chroma Meter Spectrophotometer (spectral wavelength range: 380 - 780 nm; wavelength accuracy: ± 3 nm; spectral bandwidth: approx. 2.5 nm (half bandwidth); and total uncertainty: ± 7.5%), placed in a horizontal position (1 m in height) on a tripod in the centre of the room. Readings were taken at 11:00 (average altitude: 31.90°, SD 3.87; average azimuth: 26.37°, SD 4.47) and 16:00 (average altitude: 33.35°, SD 4.72; average azimuth: 84.04°, SD 3.17), between April and May. All assessments were conducted under clear sky conditions. A more detailed description of the measurement methodology is presented in Villalba et al.[3].

Figure 1:
Outside view of the lighting research laboratory.

Figure 2:
Top view of the measurement setting. Left: room 1; right: room 2.



Although the effect of woven shade fabrics on colour rendition metrics could be determined from the spectral transmittance data measured in a bench-top spectrophotometer [4], in this study, they were measured in a test room at two different times of the day. This approach allows analysis of the impact of the solar incidence angle on the colour rendition parameters.

2.3 Analysed parameters

The colour rendering index (CRI) is a measure of the degree to which the psychophysical colour of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation [5]. CRI values go from 0 to 100 [6] where values between 80 and 90 are acceptable (neutral) for most applications. Due to the shortcomings of the CRI related to colour space, sample set and reference illuminant [2,7], this index is now being replaced by the Colour Fidelity Index (R_f), which is a more accurate measure of average colour fidelity.

Currently, several experts [7,8] suggest that the colour rendition properties of a light source should be defined by more than one metric. According to this approach, the method proposed by the ANSI/IES TM-30-20 [1] entails the determination of both overall average properties (colour fidelity, gamut area) and hue-specific properties (chroma shift, hue shift) of a light source.

As the ANSI/IES TM-30-20 focuses only on describing the objective aspects of colour rendition [2] characterization techniques, and it does not relate values to a subjective evaluation, in this study, the colour preference specification criteria determined by Royer et al. [9] will be used. Royer developed these criteria according to results obtained in several psychophysical experiments [9–11]. These criteria are based on the R_f, the Colour Gamut Area Index (R_g) and the red Local Chroma Shift ($R_{cs,h1}$). Royer et al. [9] set three tiers with different levels of stringency:

-Best: Tier A: $R_f \geq 78$, $R_g \geq 95$, $-1\% \leq R_{ch,h1} \leq 15\%$;

-Good: Tier B: $R_f \geq 74$, $R_g \geq 92$, $-7\% \leq R_{ch,h1} \leq 19\%$;

-Acceptable: Tier C: $R_f \geq 70$, $R_g \geq 89$, $-12\% \leq R_{ch,h1} \leq 23\%$.

The R_f represents how similar the colour appearances of 99 test-colour samples are rendered on average by a test light compared to those under a reference illuminant [12]. R_f ranges from 0 to 100, with higher numbers indicating more similarity to the reference [1].

The R_g is the ratio of the area spanned by the average coordinates (a',b') of the colour evaluation samples in each hue-angle bin illuminated by the test source and by the reference illuminant [1,2]. In this manner, it measures an increase or decrease in saturation. Values close to 100 mean that the test source on average does not modify the chroma compared to the reference illuminant. Values above 100 indicate an overall average increase in saturation, while values below 100 show an overall average decrease in saturation.

The $R_{cs,h1}$ represents the relative average chroma shift for hue-angle bin 1 (red). A negative value indicates a decrease in chroma, whereas a positive value indicates an increase in chroma for the averaged samples within the red hue-angle bin [1]. The values of $R_{cs,hj}$ are given in per cent. The reason for the selection of $R_{cs,h1}$ is that red plays a more substantial role in human preferences than other hues [9–11].

The R_f, the R_g and the $R_{cs,h1}$ were calculated based on the SPD measured in the test room, according to ANSI/IES TM-30-20.

3. RESULTS

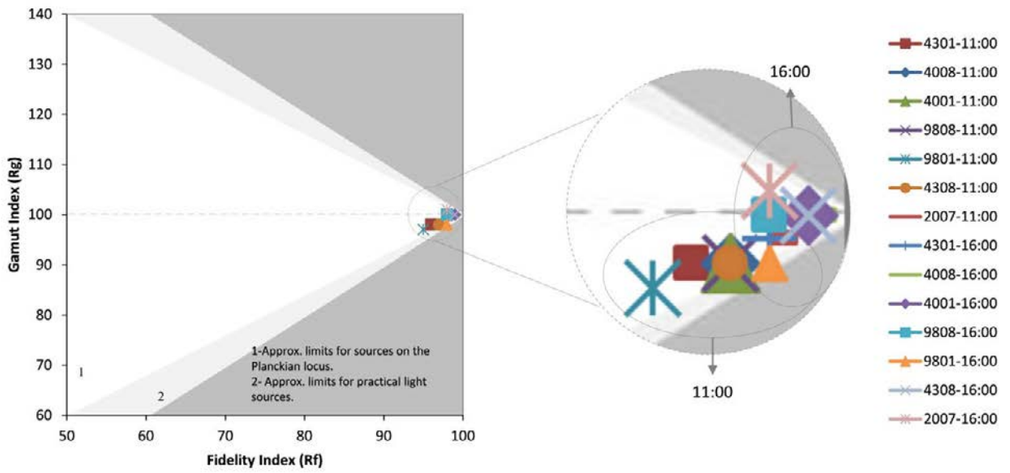
Concerning the CRI, it is observed that (Table 2), all the scenarios with roller fabrics at both hours analysed show values ≥95. These values are lower than those of the clear glass base scenario (99). This suggests very good conditions in terms of colour perception according to EN 12464-1:2011 [13]. R_f scores also approach 100, and in all cases, are ≥95. This suggests a high similarity to the reference source. Both indexes show a slightly higher value in the afternoon, when the incidence of direct sunlight on the window is weaker and the angle of azimuth exceeds the cut-off angle of this type of woven shade fabric (65° and 75°) [14]. A correlation analysis (Pearson coefficient) was conducted between these indexes and the solar incidence angle according to the time of day (11:00 or 16:00) in order to check for collinearity. The azimuth and altitude at which each measurement was taken were selected as variables to represent the solar position. No correlation was detected between either of these two metrics and solar altitude. Significant positive collinearity of both CRI and R_f with azimuth angle was detected (CRI/azimuth 0.5530, p-value 0.0402; R_f/azimuth 0.6829, p-value 0.0071). However, the average difference of CRI and R_f between the two analysis settings is less than two (CRI 1.14/ R_f 1.57).

Table 2:
CRI, R_f, R_g and $R_{ch,h1}$ values for the scenario with clear glass and the scenarios with roller screen shades at 11:00 and at 16:00.

	11:00				16:00			
Code	CRI	R_f	R_g	$R_{ch,h1}$	CRI	R_f	R_g	$R_{ch,h1}$
clear glass	99	99	99	-1%	99	99	100	0 %
4001	98	97	98	-1%	99	99	100	0%
4301	97	96	98	-1%	98	98	99	-1%
9801	95	95	97	-2%	97	98	98	-2%
2007	97	99	99	-1%	99	98	101	-1%
4008	98	97	98	-1%	99	99	100	-1%
4308	98	97	98	-1%	99	99	100	0%
9808	97	97	98	-2%	98	98	99	-2%

Figure 3

Left: R_g versus R_f plot. Right: Detail showing how the different woven shades are distributed in the plot at 11:00 and 16:00.



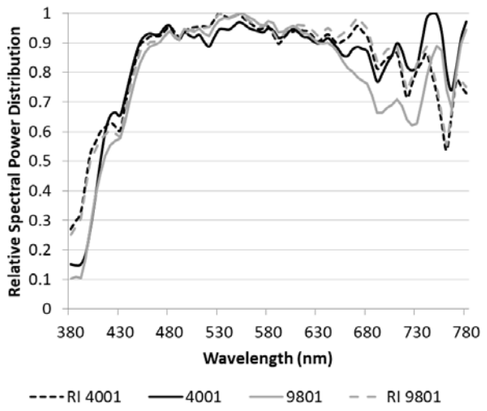
Regarding the R_g values, it was observed that at 11:00 the values were slightly under 100 in all settings, which indicates a slight average reduction in chroma (Table 2). In the afternoon hours, this situation is less uniform. Fabrics 4001, 4008, and 4308 have an R_g value of 100 which means that the transmitted light does not increase or decrease chroma compared to the reference illuminant. Woven shade fabric 2007 slightly increases the saturation (R_g 101) while fabrics 4301, 9801, and 9808 slightly reduce the R_g value, indicating an overall average decrease in chroma compared to the test illuminant. Significant positive collinearity between R_g and the azimuth angle was also found (R_g/azimuth 0.7301, p-value 0.0030). Similar to the R_f values, the average difference in R_g for the two schedules is low (1.57 points). This can be clearly seen in Figure 3, R_g versus R_f plot, where textiles have lower R_f and R_g values in the morning than at 16:00. At 16:00, both parameters are closer to 100. Collinearity between solar altitude and R_g was not observed.

The absence of a significant correlation between altitude and the studied colour rendition metrics was probably due to the fact that the analysed range of this variable was between 26.89° and 38.24°. Considering that the cut-off angle (angle from which the direct transmission is reduced to zero) of this type of fabric is between 65° and 75° [14], the altitude did not reach these values at any time, while the azimuth (20.74° to 87.31°) exceeded 65° in some periods. This possibly explains why the influence of altitude on CRI, R_f, and R_g was not statistically significant.

The analysis of $R_{ch,h1}$ shows that during the hours when direct sunlight is most intense (11:00), the transmitted light decreases by 1 to 2% in saturation for this hue angle bin (red) in all analysed settings. While at 16:00 settings 4001 and 4308 do not modify the saturation of the transmitted light with respect to the reference illuminant and the other textiles maintain the same behaviour as at 11:00. The textiles 9801 and 9808 are those with lower values of $R_{ch,h1}$ (-2). Figure 4 shows the SPD curves of fabrics 9801 and 4001 at 16:00 and those of their respective reference illuminants.

The differences in the SPD functions explain the variation in the colour rendering performance of the transmitted light in each of these settings. This difference in spectral transmittance at wavelengths 640 nm-750 nm of these two fabrics with similar properties (OF 5 and colour "white-white") could be due to the materials used: 9801 PVC-coated fiberglass and 4001 PVC-coated polyester. This was previously identified by the authors in spectrophotometer laboratory measurements [4].

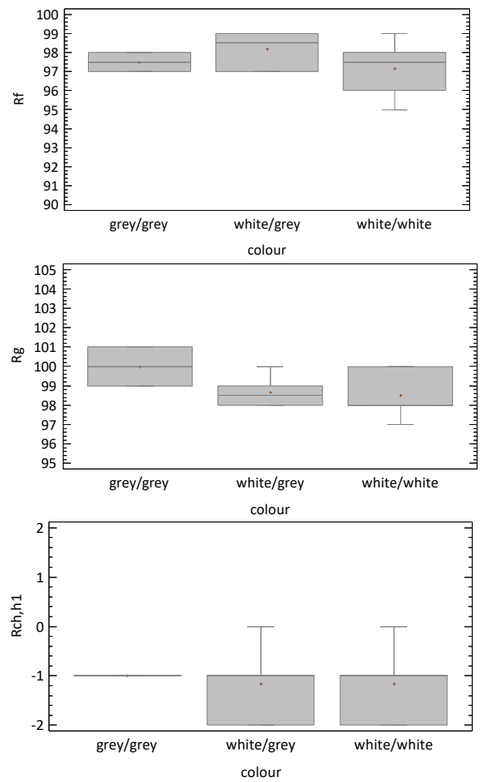
Figure 4:
Relative spectral power distribution for woven shades 4001 and 9801 settings at 16:00 o´clock and their reference illuminants.



According to the criteria proposed by Royer et al. [9], most of the roller shade scenarios would qualify as "Best: Tier A" (Table 2). Fabrics 9808 and 9801 present $R_{ch,h1}$ values outside the acceptable range for this class in the two schedules analysed and therefore correspond to "Good: Tier B". Therefore, in most settings, the light that passes through the fabrics has excellent colour rendition.

Finally, for the tested sample, no specific effect of colour or openness factor on the colour rendering capacity of the light passing through the screen fabrics was observed. Collinearity between OF and rendition properties (CRI, R_f and R_g) was checked by means of a correlation analysis (Pearson coefficient). All the Pearson's correlations calculated were low, and in all cases, they were not statistically significant. As fibre colour is a categorical variable, an analysis using box plots was performed to check its association with the analysed colour rendition metrics (Figure 5). From the observation of the graphs, it is assumed that R_f, R_g and $R_{ch,h1}$ are not associated with fibre colour as the distributions of these variables do not show an appreciable variation across fibre colour categories.

Figure 5:
Boxplot of fibre colour and R_f (top). Boxplot of fibre colour and R_g (middle). Boxplot of fibre colour and $R_{ch,h1}$ (bottom).



4. CONCLUSION

Firstly, it is important to stress that this study also shows the need to use more than one colour rendition metric to analyse the colour performance of light. If only the CRI is considered, it is observed that all the fabrics in both analysis settings show excellent colour rendering capability. However, if a set of metrics, such as colour fidelity (R_f) and colour gamut area measures (R_g and $R_{ch,h1}$), are considered, a more comprehensive and accurate classification of the colour preference of light is achieved. Including updated colour rendition metrics in shading system assessments, in addition to those traditionally used (glare, view clarity, visibility), becomes crucial if we want to achieve daylit spaces that truly consider the needs and preferences of the users.

Secondly, analysing the colour rendition properties of daylight transmitted through woven shade fabrics in real contexts -test room- enables analysing the impact of environmental variables (for example, solar position) on sunlight, in addition to the impact of opto-physical properties of the material, which can be analysed through bench-top spectrophotometer measurements.

Finally, it is necessary to emphasize that this is an initial study, and therefore the results obtained are preliminary. In order to further advance on definitive results regarding the influence of these properties on the colour rendition of transmitted daylight, it is necessary to extend the sample. It is also important to extend the analysis to different times of the day, seasons of the year, and different facade orientations. As the SPD of daylight strongly depends not only on the latitude but also on the façade orientation [15].

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PLEA STGO 2022

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ARCHITECTURE FOR HEALTH AND WELL-BEING

DAY 01
12:00 — 13:30

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PAPERS
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14TH PARALEL SESSION / ONLINE

WILL CITIES SURVIVE?

Promoting healthy city through ICT technologies
An experience of particulate matter low-cost monitoring

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ABSTRACT: The Pandemic emergency related to COVID-19 has renewed the interest in the Healthy City promotion and design. Ensuring a genuine life quality for all in healthier urban environments is a central issue in the contemporary architectural debate, as well as fundamental to achieve Sustainable Development Goals 11 and 3. In the urban context, both natural and anthropogenic factors drastically affect health and economy. Monitoring, simulating, assessing, and controlling such environmental factors is a prerequisite in promoting the Healthy City. In this perspective, ICT technologies and data processing offer new opportunities and tools to understand and manage complex and heterogeneous urban phenomena. The aim of this paper is to demonstrate the effectiveness of low-cost ICT technologies in widespread air quality monitoring. To this, the Particulate Matter (PM) 2.5 and 10 sensors developed by the research group is tested in a real world case-study. Results obtained from field monitoring campaigns in most relevant seasons, compared to data by the official meteorological municipal station, highlight benefits and barriers for developing a widespread urban monitoring infrastructure in a Healthy City site-specific design perspective.
KEYWORDS: Healthy City, ICT, Particulate Matter, ENVI-met, SDG11

1. INTRODUCTION

The urban environment drastically affects human health. Atmospheric Particulate Matter (PM), as well as nitrogen dioxide and tropospheric ozone, is considered among the risk factors for cardiovascular, respiratory, and carcinogenic diseases [1]. Data produced by the scientific community reports a worrisome picture. In the World, each year about 4.2 million premature deaths due to stroke, heart disease, lung cancer, and chronic respiratory illnesses are attributable to excessive exposure to PM [1]. For the same causes, in Europe, where 15% of premature deaths are due to environmental factors, life expectancy has been reduced by about 8 months [2]. In this context, the pandemic emergency related to COVID-19 has further highlighted how the strong correlation between environmental factors (on virus spread and exacerbation of symptoms and effects) and human health is to be considered in the promotion of healthier urban environments [3]. The complexity of phenomena determining air quality – at a local, continental, and hemispheric scale – is related to anthropogenic activities (e.g., domestic heating, mobility, industries, etc.) and microclimatic conditions turning primary emissions into secondary ones, thus facilitating their dispersion [4]. In this scenario, low-cost ICT technologies enable a digitally integrated urban environment. On the one hand, they may represent a fundamental tool for widespread monitoring and, on the other hand, a highly effective mean to actively engage people by raising awareness on health issues and fostering the ecological transition [5][6]. Several ongoing researches are moving towards the use of a widespread network of air quality sensors embedded in light poles, cars, bicycles, building components, flowerpots, or wearable devices [7][8][9][10]. Specifically, the development of IoT (Internet of Things) technologies and their widespread application in cities foster monitoring several variables that may affect air quality, thus human health. Furthermore, the spread of integrated technologies supports a growing number of open urban platforms [11] that monitor input and output flows of energy and matter in real-time urban metabolism models [12].

Starting from these premises, this paper presents the first results of an air quality monitoring campaign carried out at the neighbourhood scale in Turin, northern Italy, one of the most critical areas in Europe due to the orography and population density. The aim of this research is twofold: first, to demonstrate the effectiveness of low-cost ICT technologies for widespread air quality monitoring; second, to investigate the effect of the urban fabric on the distribution of pollutants. The methodologic approach and the main results obtained are presented by the description of a test carried out within an ongoing national research project. Finally, in the Conclusion section, perspectives and barriers in the ICT development for urban monitoring infrastructure are discussed, in the perspective of a site-specific Healthy City design.

2. METHODOLOGY

The article describes the experience of a monitoring campaign on air quality (PM2.5 - PM10) and environmental parameters (i.e., air temperature, humidity, and pressure) carried out at a neighbourhood scale at high temporal resolution. The campaign at micro-urban scale allowed us to investigate a possible more direct relationship between some built environment features (e.g., morphology, presence of green areas, exposure to the street, height of buildings, orientation, etc.) and the distribution of pollutants, to potentially inform climate change planning policy and design [13]. Before the monitoring campaign, the plot was modelled in ENVI-met™, a Computational Fluid Dynamics software (CFD). Microclimatic simulation was necessary for interpreting the propagation of pollutants. Through 3 monitoring campaigns, lasting about two weeks each for over a period of 1 year (March 2021-February 2022), the research compares data acquired from different 4 monitoring stations distributed in the area. Acquisitions by low-cost sensor stations developed by the research group at Polytechnic of Turin – DAUIN (Department of Control and Computer Engineering) are compared with data provided by the official urban measurement network of ARPA (Regional Environmental Protection Agency), the municipal authority in charge of urban air quality control. Data coming from the nearest official station (namely Torino Grassi – Reiss Romoli), approximately 4 km as the crow flies from the analysed area, was used for the comparison. Furthermore, data analysis over different seasons and different exposures to primary emission sources is performed to investigate the incidence of seasonal anthropogenic phenomena.

3. CASE STUDY

3.1 The neighbourhood

The case study is in the north-eastern suburbs of Turin (Italy), a city characterised by Cfa climate conditions (Humid subtropical climate; coldest month averaging above 0 °C, at least one month's average temperature above 22 °C, and at least four months averaging above 10 °C) according to Köppen–Geiger classification. The neighbourhood, namely Milan Barrier (45°05'N 7°42'E), is located near the Po River and some main green infrastructures. The plot is approximately 22.000 m^2, and it is characterized by a large presence of public housing facilities (Fig. 1). More precisely, the area consists in two 3-4 storeys building block courtyards, built in the 1920s and 1940s. The residential complex is owned by ATC (Housing Territorial Agency in Piedmont Region). Both courtyards were renovated from a technological and functional point of view in 2012, upgrading façades, adding external lifts and new balconies, and renewing of water systems. About 200 people currently live in the two courtyards, with about 30% of the population over 60 years old. The choice of the plot is due to the heterogeneous presence of natural and artificial elements allowing to evaluate how the distribution of pollutants propagates in the urban fabric. In particular, the closed-courtyard morphological type, recurrent in the Turin historical fabric, was chosen to assess possible differences between the façades facing the street (therefore more exposed to car emissions) and those facing the internal green area. The whole area borders an old railway path in the North, which is about to be part of the new metro line infrastructure and with a great environmental potential (see section 3.2). All the monitoring stations were placed on balconies at a similar height above the ground (about 6 m), in order to not to have different possible pollution patterns due to height.

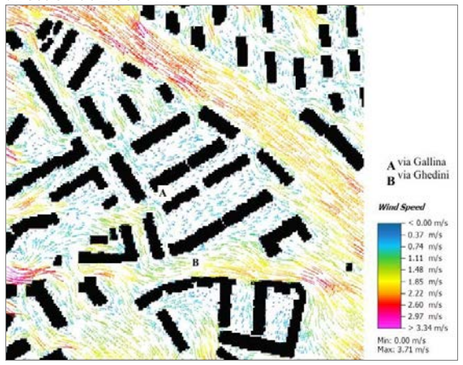
Figure 1:
Aerial view of the case study.

3.2 CFD simulation

Prior to the installation of the sensors, an outdoor CFD analysis was carried out on the area (Fig. 2). Considering that the propagation of pollutants is strictly linked to ventilation, it was necessary to understand how this could affect the results. The analysis of the area was made using ENVI-met, one of the most used tools in academic and professional fields. It is a prognostic non-hydrostatic CFD model used to assess complex interactions between built and natural environment

[14]. Once modelled the plot and set built environment features (e.g. material albedo, greenery typology, soil humidity, etc.), it is necessary to set meteorological boundary conditions on weather (e.g., temperature, humidity, wind, solar radiation, etc.). The simulation provides results on many outdoor parameters (e.g., PAT – Potential Air Temperature, SF – Surface Temperature, WS – Wind Speed, etc.) and thermo-hygrometric comfort indices (such as PET – Physiological Equivalent Temperature). The case study analysis identified how the linear area to the north-east of the plot (the former railway yard) drastically favours ventilation. The simulation was carried out injecting initial wind speed and direction provided by ARPA in 2020 hottest summer day (1.70km/h, NW). Although simulation results are representative for a specific microclimatic condition, these wind speed and direction are quite typical values in Turin. Two main exposures in the positioning of the sensors facing the street were defined to investigate how PM propagation is affected by wind: one towards a more open road (via Ghedini) and one towards a more closed one (via Gallina). The other 2 sensors were positioned facing towards the court, where less wind was expected according to the simulation output.

Figure 2:
CFD analysis in the plot by ENVI-met. Wind speed and direction at 2:00 PM.



3.3 Monitoring board station

Specifically, the monitoring results report the values acquired by PM 10 and 2.5 sensors (Fig. 3), temperature, humidity, and pressure. More precisely, the following hardware components for the board station are used.

Monitoring board: The Raspberry Pi 0 Wireless was chosen as the single-board computer. The operating system chosen for this project is Arch Linux for ARM, which ensures that just the essential OS components are running and that no resources are wasted. All sensors are questioned using Python scripts that are run as System Units.

PM sensor: Honeywell HPMA115S0-XXX. Detecting PM2.5 and PM10 particle concentrations in the air. Its output values range from 0 to 1000 µg/m³, with a 15% accuracy, which corresponds to a price of around $25 to $30 USD. The Light Scattering technique is used in this gadget. In simple terms, a rotating fan flows air into a chamber, which is subsequently hit by a laser beam, and a proprietary algorithm inside the device estimates particle concentration using a photodiode. The sensor communicates with the board through UART (Universal Asynchronous Receiver Transmitter) communication, with the sensor writing a new datum every second.

Temperature and Humidity: the DHT22 is a low-cost digital temperature and relative humidity sensor that is both cheap and accurate. Its humidity readings range from 0% to 100% with a 2 percent to 5% accuracy; temperature readings range from 40 to 80 degrees Celsius with a 0.5-degree Celsius precision, and the sample rate is roughly 0.5 Hz. Dedicated APIs are used to interact with the sensor.
Pressure: Bosch's BME280 is a precise barometer pressure and temperature sensor. Barometric pressure sensing range: 300-1100 hPa; resolution: 0.03 hPa/0.25 m; operational range: 40-85°C, with 2°C temperature precision; values are conveniently retrieved via I 2 C interface utilizing specific APIs.

Time: a clock for Unix time is used to temporal data synchronisation.

Although the experimental data collected by the board stations do not have normative value because measured with instruments that have not been officially calibrated, they do allow qualitative considerations to be made regarding the system's potential.

Figure 3:
Monitoring board station designed by DAUIN, Polytechnic of Turin.

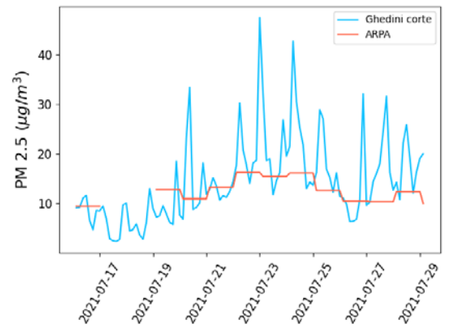
4. RESULTS

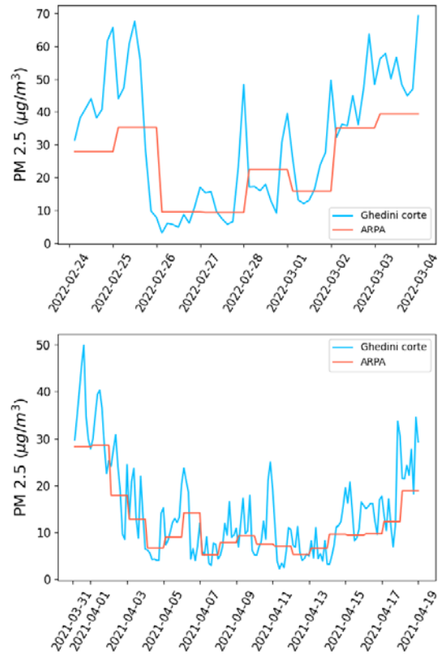
The results obtained from the experimentation have a twofold purpose. First, to evaluate the benefits offered by widespread low-cost monitoring compared with the current official monitoring system provided by ARPA; second, to investigate the effect of the urban fabric and traffic on their propagation. The time frequency of monitoring made it possible to build up a significant dataset for analysis. Over the three monitoring campaigns, approximately 30,000 data were collected on PM levels and approximately 14,000 on temperature and humidity. The collected data were reprocessed, outliers removed, and the data grouped according to different time frames.

A first significant insight can be drawn from the granularity of the data. While ARPA only reports a daily average, the low-cost stations can map the hourly and daily trends highlighting any critical periods. The graphs below (Fig. 4) show PM2.5 values from the same sensor in the three different monitoring campaigns compared with the official data provided by ARPA. Although the trends and daily average values of the low-cost stations are similar to the official one, it is evident that the daily PM trend can show significant differences. Especially in the winter period, where the PM presence is higher, deviations of 25-30 µg/m³ can occur on the same day.

In the first two campaigns, carried out in spring and summer seasons, there is a more significant difference between the monitored data and the official data. This, confirmed by other ongoing research, seems to indicate that the accuracy of the low-cost sensors used is directly proportional to the PM values. The higher the PM value, the greater the margin of accuracy of the data.

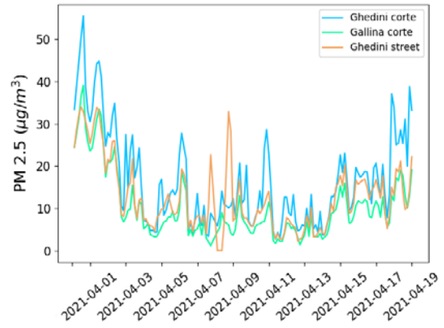
Figure 4:
PM2.5 trends in the three monitoring campaigns (a. April; b. July; c. February). In red, the official data provided by ARPA





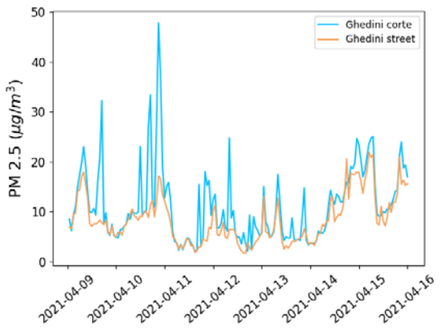
To answer the second research question, two main analyses were carried out. The first one compares the four points monitored during the same period. The second one compares a sensor facing the road and one facing the street (therefore more subject to the presence of traffic and wind). Fig. 5 shows the PM2.5 trend during the first monitoring campaign, considered by authors the most significant for the comparison. The average variation between different points is around 6 µg/m³, a relatively low value considering the total. For all three campaigns monitored, no significant differences between four station sensors emerged.

Figure 5:
PM2.5 trends in the same campaign monitoring by different stations.



A more in-depth analysis on the differences between the sensors placed in the inner courtyard (namely "corte" in the figures) and on the balcony facing the road were presented (Fig. 6). By analysing a shorter period, it is possible to highlight the daily trend of PM2.5 values without any significant variation. The action of wind and the presence of cars for the specific context considered cannot be assessed. Nevertheless, the simulated wind speed (Fig. 2) showed homogeneous values in the streets as well in the courtyards of the experimental field, thus confirming possible similar PM values.

Figure 6:
PM2.5 values comparison between sensor facing courtyard (blue) and street (red)



5. DISCUSSION

The values obtained depict a worrying picture of air quality in the city of Turin. The average values of the campaigns carried out, in line with official data, show values above the limits set at European level. The technologies proposed and the results obtained, although still at an experimental stage, may open new scenarios for monitoring environmental parameters that affect the healthiness of neighbourhoods. The acquisitions confirm that the winter season is more subject to the pressure of pollutants in the context analysed.

It must be stated that the values obtained from the monitoring campaigns are to be considered in a qualitative way as they are monitored with sensors that are not officially calibrated and are specific to particular times of the year. However, the calibration of the data carried out by the research group allows us to report greater reliability of the data collected in the winter period, where PM levels are higher. Among the limitations of the research carried out, the case study analysed did not prove particularly efficient in validating the comparison between urban fabric and the proximity to streets. The low traffic volume in the area does not allow for further analysis. The same approach used in denser and busier city areas could bring quite different results. Finally, the question of scale is a central issue. Although air quality is a complex issue influenced by global and regional factors, local monitoring can be crucial in understanding the impact of anthropogenic actions and influencing the citizen behaviour.

6. CONCLUSIONS

The ongoing pandemic and climate emergency require to drastically renew the urban environment by promoting the Healthy City, thus fostering the role of cities as major implementer of the Sustainable Development Goals and challenging the way cities are currently built [15]. Among the few positive effects of the pandemic, the reduction of car traffic resulted in the increase of the air quality and perceived road safety, thus improving the quality of life [16]. Besides, many positive externalities could be generated by the air quality improvement and pro-environmental citizen behaviours, although challenging to assess (such as economic benefits by reducing the costs of the national health service expenditure). Greater knowledge about the interlinkages between phenomena of a different nature occurring in cities is evolving fast thanks to technologies [17]. In this context, ICT and IoT become enablers of the ecological transition. Data-driven approaches are entering increasingly the management and planning of the territories, by providing deeper understanding on parameters determining health and supporting evidence-based planning. As planners, we are now called upon to rethink an urban environment that, as history has been teaching, necessarily evolves after each pandemic. In the Healthy City perspective, a widespread IoT network for real-time measurements, supported by advanced environmental simulations, become essential tools for promoting data-driven design.

In this perspective, urban neighbourhood scale represents the ideal dimension at which to intervene, as the patterns of land-use, building type, technologies and behaviour affecting environmental quality may vary significantly throughout the city. As such, the implementation of an auxiliary monitoring network to the official one may offers greater awareness on site-specific issues closely related to health. Nowadays, the technological maturity of low-cost sensors systems makes it possible to think of a real widespread application in the urban context. Advances in the field of sensors, ICT, and algorithms for data processing open up an extremely interesting scenarios. At the same time, some critical issues are still present. If, on the one hand, the overabundant production of data can represent a problem both in the management of the information flow and from an environmental point of view, on the other hand, management aspects with respect to data ownership and privacy issues still need to be regulated. Given data's primary role, future research will still have to focus on creating new public-private relationships in which the production of such data is regulated and valuable.

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Healing architecture
A review of the impact of biophilic design on users

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ABSTRACT: This paper presents a systematic review conducted to identify, compare and synthesize published qualitative and quantitative data related to biophilic design parameters and their impact on human health and well-being within therapeutic environments, from the user's perspective. This work is part of a broader research study whose ultimate goal is the redefinition of a holistic and scientifically underpinned biophilic design framework for therapeutic environments. This study aims to specifically collect, identify, analyse and hierarchise those biophilic design parameters critical for clinical environments, in a way that can more efficiently guide designers. This paper focuses on explaining our research methodology and presenting the resulting key biophilic parameters for each type of user and space.
KEYWORDS: Therapeutic Environment, Biophilic Design, Systematic Review

1. INTRODUCTION

The biophilic design discipline refers to the innate human connection to nature and natural processes to promote health and well-being in the spaces we inhabit (E. Wilson, 1984; E. O. Wilson, 1979). The principles that define biophilic design can be examined from three different perspectives: as established in building regulations and standards, as used in design practice and as investigated in research practice. When examining each of these areas, we can find several issues and disconnections. In practice and regulatory frameworks, we can observe the use of an unbounded design framework that is not underpinned by scientific facts and do not prioritise principles or parameters. In scientific academic environments, there is abundant research on many of the different aspects of biophilic design, but all of this in-depth research providing scientific facts about the importance of nature on humans has happened separately or for a specific design parameter, and not in a holistic way. Thus, the ultimate goal of this research project is the redefinition of a holistic and scientifically underpinned biophilic design framework, with a focus on therapeutic environments. This research also aims to hierarchise the biophilic design parameters included in the new framework in a way that can more efficiently guide designers. Our thesis believes that an efficient biophilic design framework should be specific to building function and context, where only specific parameters from the established general frameworks are relevant.

There are three established general frameworks of biophilic design parameters (Browning et al., 2014; Kellert et al., 2011; Kellert & Calabrese, 2015).These parameters relate not only to the physical environment (e.g., Fresh Air, Daylight, Thermal Comfort, Multisensory Environment, Spaciousness, View, Natural Colour, Greenery-Plants, Natural Material Seasonal Changes, Water) but also to emotional and psychological wellbeing (e.g., Refuge-Privacy, Prospect, Sense of Belonging, Curiosity, Welcoming and Relaxing Feelings, Mastery and Control).

The provision of healthcare has evolved to what has been termed 'Factory Hospitals', where the design focuses on the efficient delivery of medical mass treatment, regardless of the mental and sensory well-being of human-beings (Jencks, 2017). Patients receiving a chronic disease diagnosis and undergoing treatment might be subjected to high levels of psychological distress, with many reporting symptoms of fatigue, anxiety or depression (Zabora et al., 1997). As there is evidence of growing research interest in nature's role in physically and psychologically supporting patients, this research aimed to provide an account of generated knowledge from users' experiences, to better inform human-centred policy and design. This paper specifically discusses a systematic review conducted to identify, compare and synthesize the published scholarly literature on biophilic design parameters and their impact on human health and well-being within clinical therapeutic environments, from the user's perspective.

	Inclusion Criteria	Exclusion Criteria
Population	Those who use therapeutic places regularly	Those who are not related to therapeutic environments
Nature of the Intervention	Therapeutic environment, Clinical settings Healing environment, Hospitals or healthcare	Retail or shopping, Residential buildings, Neighbourhoods or urban districts, Universities or schools, Workspace or Office setting
Comparators	Biophilic design parameters, Biophilic variables of the biophilic design patterns	Non-biophilic elements
Outcomes	Studies that give strong insights or scientific facts to compare or rank a cluster of biophilic patterns	Studies that examine only one or an inadequate number of patterns.
Cultural / Linguistic	English	Non-English
Period	1973 to current	Pre-1973
Study Design	Empirical research, Qualitative or Quantitative Any primary comparative study	News, reports and reviews
Types of Documents	Academic Journals	Editorials commentaries, News reports, Magazines, Books, Reports, Proceedings (published or unpublished) Thesis or Dissertation

Table 1:
Inclusion and exclusion criteria

2. METHODOLOGY

The systematic review methodology follows a review question, a systematic search strategy, screening and selection of literature, data extraction and quality assessment. The general review question decided for this research is:

a) Which biophilic criteria are most critical in a clinical therapeutic environment
b) and in which way they inform design?

This paper presents the first part (a) of the review question.

The search strategy consisted of searching keywords, searching syntaxes based on the databases used, and a set of inclusion and exclusion criteria (Table 1). The search was conducted on six selected databases. The language was limited only to English, and the searching period goes from 1973, when Fromm coined the term biophilia, up to September 2020. The type of document was restricted to peer-reviewed academic journal articles, in order to compile less biased data. A total of 1,095 publications were exported to Rayyan QCRI, a software that supports systematic review processes by expediting the initial screening of abstracts and titles using a semi-automated system (Ouzzani et al., 2016). After removing 193 duplicates, the initial screening was done by reading abstracts and checking full texts in some particular cases. The initial screening was repeated five times and peer-reviewed, to ensure that all requirements had been met rigorously. Eventually, 16 studies were employed for the full-text reading stage, while 879 papers were excluded. Meanwhile, five more publications were also included externally for full-text reading in this stage.

The selected 21 full-text papers were read and reviewed by two researchers separately to reduce the risk of bias. Lastly, seven studies (Abdelaal & Soebarto, 2019; Blaschke et al., 2017, 2018; Nejati et al., 2016; Peditto et al., 2020; Tanja-Dijkstra & Andrade, 2018; Tinner et al., 2018) were included in the synthesis. An updating search was conducted on 26.09.2021. A total of 106 new publications were exported to Rayyan QCRI. In the end, two more studies were included in the synthesis (Putrino et al., 2020; Wiltshire et al., 2020), reaching nine studies in total (Fig. 1). All nine studies were published between 2016 and 2020. Four studies were from the USA, three studies were from Australia, one study was from the UK, and one study was jointly carried out between the UK and the Netherlands.

The analysis of the decided final papers and the data extraction for this systematic review followed individual methods for each study, as all studies used divergent methodological approaches. Another reason for this was that the extracted data (biophilic design parameters) were referred to in a wide range of definitions since there is no standard framework.

Figure 1:
Identification of the included articles in the systematic review

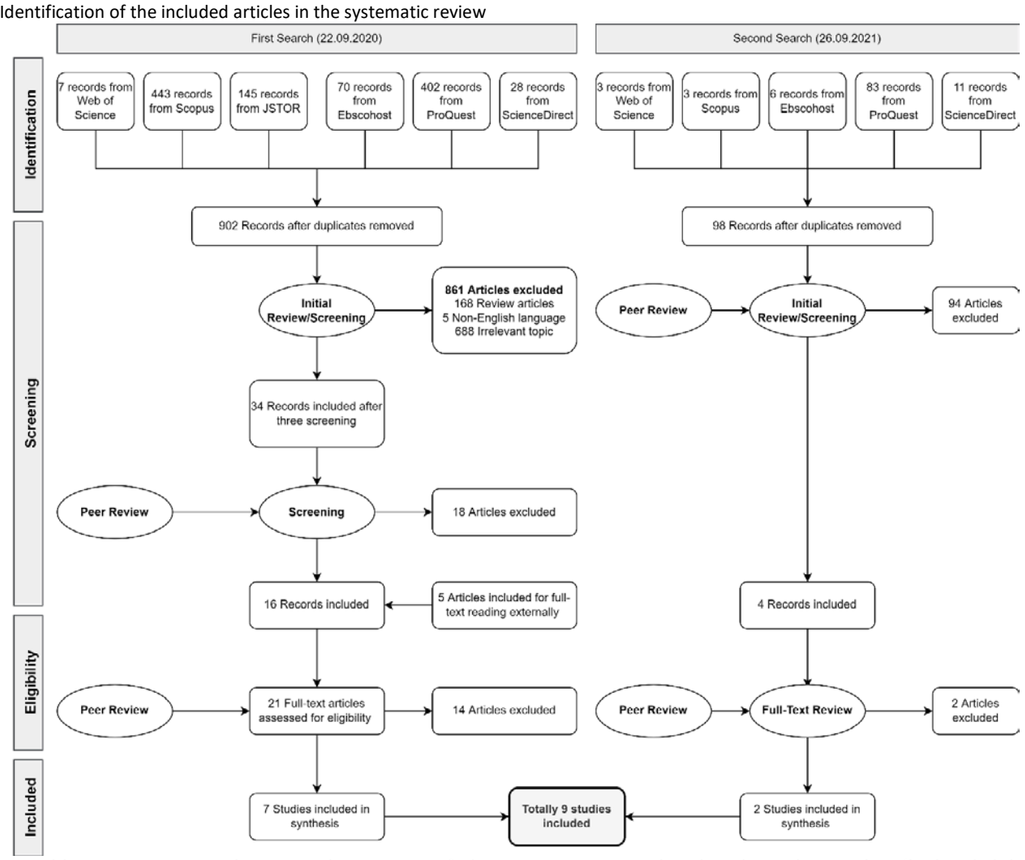

Table 2 summarises the general overview of the selected studies. Study 1 and Study 2 were qualitative researches, the data extraction followed a second analysis of the statements and facts reported in these studies by using NVivo 12 software, a tool to support qualitative analysis by organising and visualising unstructured or semi-structured data through a system of codes (NVIVO, 2012).

Study 3, Study 4, Study 5 and Study 6 represented quantitative data from different groups of the population. Finally Study 7, Study 8, and Study 9 employed mixed-method research. All studies contributed to the goal of the systematic review from both patients' and staff's perspectives.

The quality assessment tool in this systematic review was adopted from the study developed by Holloway Cripps (Holloway Cripps, 2016) and modified in accordance with the systematic review guideline from Boland et al. (2017) in which the reliability of the studies is assessed through 13 questions forming a checklist. According to this checklist, Study 3, Study 5, and Study 7 were considered High-Quality studies (high reliability). Study 1, Study 2, Study 4, and Study 6 could not satisfactorily respond to one, three, one, and two questions respectively. Accordingly, these four studies were classified as Good Quality. Lastly, Study 8 and 9 were rated as Poor Quality, but they were nonetheless kept as a control group for assessing the results obtained from the other seven studies.

3. RESULTS

The analysis of the selected studies proved that clinical settings cannot be examined as one whole environment in terms of the users' requirements and the importance of biophilic design parameters. The clinical spaces assessed in the studies were places where patients received treatment as well as working environments for the staff. Therefore, this systematic review study examined biophilic design parameters in clinical environments from two different perspectives: patient-based perspective and staff-based perspective. Within this classification, further differentiation was determined to be needed, as the analysis revealed some differences in environmental perception between the inpatient users and outpatient users. Thus, the synthesis was also carried out separately considering inpatients' and outpatients' needs for a biophilic environment.

Table 2:
General overview of the selected studies

Study	Reference	Method	Participant number	Population /Context	Contribution to the Systematic Review
1	(Blaschke et al., 2018)	Qualitative	20	Patient/Oncology	Inpatient / Clinical
2	(Wiltshire et al., 2020)	Qualitative	18	Cancer Patients	Outpatient/ Clinical
3	(Blaschke et al., 2017)	Quantitative	38	Experts/Oncology	Inpatient/ Clinical
4	(Peditto et al., 2020)	Quantitative	104	Young Cancer Patient Facilities	Inpatient/ Clinical
5	(Tinner et al., 2018)	Quantitative	72 Staff, 62 Patient	Staff and Patient/ Cancer Centre	Staff, Outpatient/ Clinical
6	(Putrino et al., 2020)	Quantitative	496	Frontline Healthcare Workers/ COVID-19	Staff/ Clinical
7	(Nejati et al., 2016)	Mixed	10 Interviews, 993 Surveys	Professional Nurses and Healthcare Workers	Staff / Clinical
8	(Abdelaal & Soebarto, 2019)	Mixed method review	NA	Patients	Inpatient and Outpatient/ Clinical
9	(K. Tanja-Dijkstra & Andrade, 2018)	Review-Mixed	Case 1: 62 Survey	Cancer Patients	Outpatient and Inpatient / Clinical

3.1. The prominent biophilic design parameters in clinics for patient-based perspective

In terms of the patient-based perspective, the studies focused on the most commonly used spaces by cancer patients in clinical environments: chemotherapy units, waiting rooms, wards/rooms, outdoor areas accompanying hospitals or clinics, break areas, and doctor/diagnosis rooms. The studies that recruited outpatient participants (Abdelaal & Soebarto, 2019; Tanja-Dijkstra & Andrade, 2018; Tinner et al., 2018; Wiltshire et al., 2020) mainly focused on chemotherapy units and waiting rooms as well as doctor rooms. In the inpatient-based studies, the main focus was ward or hospital room environments and, in some cases, outdoor areas for patients who can go out for refreshment (Abdelaal & Soebarto, 2019; Blaschke et al., 2017, 2018; Peditto et al., 2020; Tanja-Dijkstra & Andrade, 2018).

The data in relation to the outpatients' perspective was collected from four studies. While Study 8 and Study 9 employed both inpatient and outpatient participants, Study 2 reported data for only outpatients and Study 5 had both outpatient and staff perspectives. The results showed variations depending on the studies because of the directed questions, different approaches and existing environment of the population, and scope of the studies. Although these differences in the results made the progress more complicated in terms of extracting general conclusions and obtaining a clear ranking of biophilic design parameters, they contributed to making the study more extensive and less biased.

The synthesised groups of the biophilic design parameters for a clinical environment for outpatient users are summarised in Table 3. All these parameters were explicitly commented by outpatient participants as required biophilic design parameters, but some of them were emphasised and reported as more critical. Therefore, three different groups were created in order to hierarchise these biophilic design parameters. The parameters within the groups were listed alphabetically regardless of any ranking since there was no exact comparison of parameters in the examined studies. These specified biophilic design parameters should be taken into account to create stress-reducing, relaxing and comfortable environments for outpatients in cancer clinics.

Table 3:
Biophilic design parameters for outpatients in clinical settings based on synthesis results in order of importance

Importance Level	Biophilic Design Parameters
1st Group	Fresh Air Light-Daylight Thermal Comfort Welcoming and Relaxing
2nd Group	Multisensory Environment and Quietness Refuge-Privacy Spaciousness View-Prospect
3rd Group	Bringing Outside to Inside Colour Greenery-Plants

	Natural Material
	Seasonal Changes
	Water

Five of the examined studies reported data about the environmental needs of inpatients, particularly in oncology settings. Study 1, Study 3 and Study 4 focused only on inpatients' environments. While Study 1 and Study 4 collected data directly from cancer patients, Study 3 used professional experts' views. Furthermore, Study 8 and Study 9 employed data about both inpatient and outpatient groups.

Even though the important parameters for inpatient-based environments were not much different from outpatient-based environments, the detected priority differences may impact the environmental quality since the function of the spaces and patients' physical conditions are different. The synthesised groups of the most prominent biophilic design parameters for a clinical environment for inpatient users are summarised in Table 4.

For patients who are usually spending their time in wards or hospital rooms on their beds, the most important parameters were View, Prospect, and Daylight through windows. Therefore, the beds' position and connection with windows were important to apply these biophilic features efficiently.

Another outstanding parameter in the first group was Refuge, Security and Protection showing the patients need to feel safer because of their health conditions, fear of death, and desperate neediness on unfamiliar people (healthcare workers).

However, it should be considered that these parameters were usually mentioned in the studies with their visual impact, not for physical contact as these patients' movement is quite restricted, but the studies also sought access to outdoor settings where it is compatible with the patients' health condition.

Table 4:
Biophilic design parameters for inpatients in clinical settings based on synthesis results in order of importance

Importance Level	Biophilic Design Parameters
1st Group	Feeling Relaxed and Comfortable
	Prospect
	Refuge, Security and Protection
	Light-Daylight
	View
2nd Group	Fresh Air
	Greenery
	Mastery and Control
	Multisensory Environment
	Thermal Comfort
3rd Group	Bringing Outside to Inside
	Colour
	Natural Material
	Seasonal Changes
	Water

3.2. The prominent biophilic design parameters in clinics for staff-based perspective

The studies in relation to staff (Nejati et al., 2016; Putrino et al., 2020; Tinner et al., 2018) mainly examined the restoring characteristics of spaces. Study 6 and Study 7 collected data about staff break areas, while Study 5 assessed the clinical environment from both patient and staff points of view.

The synthesised groups of the biophilic design parameters for a clinical environment for staff are summarised in Table 5.

Like in previous users, all these parameters were stipulated as required biophilic design parameters by staff participants, some of them were emphasised and reported as more critical by the participants. In this case, four different groups were created in order to hierarchise the most relevant biophilic design parameters, listed following the same procedure as before.

The most outstanding demand was for Privacy and Refuge, with the need for Quietness also frequently emphasised. The studies indicated the importance of physical access to the outdoor environment. Interestingly, Greenery – Plants was ranked very low, two main reasons for this, the chore of having to water them and the presence of pathogenic fungi that pose a threat of infection to patients. However, the visual impact of Greenery, particularly in the outdoor break areas, was praised in the same studies.

Table 5:
Biophilic design parameters for staff in clinical settings based on synthesis results in order of importance

Importance Level	Biophilic Design Parameters
1st Group	Privacy-Refuge
	Quietness
2nd Group	Fresh Air
	Natural Light
	Prospect
	Thermal Comfort
	View
3rd Group	Multisensory Environment
4th Group	Greenery - Plants
	Water

4. CONCLUSION

The systematically selected data helped to qualitatively reveal the biophilic design parameters that are the most critical for promoting and supporting human health and wellbeing in clinical therapeutic environments, from the user's perspective. This strand of research provides crucial knowledge on how the impact of nature-based design features on human wellbeing best informs our design decisions for this specific building typology. The available case studies are limited and highly localised in developed countries, thus based on specific building typologies. The perception and relationship humans establish with nature is climate and culture dependant, therefore, these are aspects that need to be factored in. As more studies develop in different regions, in different climates and in diverse cultures more data will help to shape reliable design frameworks. A more detailed analysis of the biophilic parameters and recommendations for implementation in practice will follow in a subsequent publication. Research focused on non-clinical therapeutic environments in the UK, developed by the authors (Tekin et al., 2021, 2022), revealed the importance of other biophilic parameters for the patient experience, such as Curiosity or Sense of Belonging, expected in this study but not even mentioned. Likewise, a holistic design framework also needs to be supplemented by the analysis of objective scientific facts on the impact of nature on humans, which is currently undergoing work.

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Optimizing building form to improve thermal comfort and indoor air quality

A context in crises

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ABSTRACT: Indoor Air Quality (IAQ) refers to the conditions within buildings that can impact a person's health. IAQ monitoring became a priority during the COVID-19 pandemic when people stayed indoors longer due to lockdowns. However, indoor pollutant levels increased due to the lack of appropriate ventilation. In addition, high energy demand is caused by extended hot summer days in some regions leading to less Thermal Comfort (TC). So, more evidence is required to determine the relationship between energy-efficient building forms and the air quality that improves ventilation. This research aims to present an optimization approach towards an improved design for building forms that will enhance IAQ while also lowering indoor air temperatures due to exposure to solar radiation on the east-west side of the structure. We propose energy-efficient buildings that minimize incident solar radiation (insolation) and enhance indoor air quality while considering a crisis zone as a context due to the need of wide-scale reconstruction. The optimization uses the computationally efficient Penalty Successive Linear Programming (PSLP) technique. The evaluation is based on two performance metrics: Insolation and Air Changes per Hour. The results show that the optimization tool provides building forms with less insolation and better IAQ.
KEYWORDS: Indoor air quality, energy, ventilation, thermal comfort, COVID-19

1. INTRODUCTION

The World Health Organization (WHO) declared the coronavirus disease 2019 (COVID-19) as a global pandemic in March 2020. Given such or similar events in the future, the architectural built form will have to adapt to other expected epidemics. Recent studies show how adequate ventilation in buildings plays a vital role in containing diseases [1-2]. Some studies conclude that the indoor airborne transmission of viruses becomes more serious when these indoor environments are crowded and poorly ventilated. In particular, one of the critical environmental factors in the COVID-19 pandemic is the Indoor Air Quality (IAQ) [3]. In addition, high energy demand is caused by increased cooling and ventilation on extended hot summer days in some regions. The high energy demand needed to maintain Thermal Comfort (TC) is caused mainly by the Heating, Ventilation, and Air Conditioning (HVAC) system, which can deteriorate IAQ as well, and it can lead to sick building syndrome (SBS) [4].

Therefore, this paper addresses the relationship between energy-efficient building forms and the air quality resulting from improved ventilation, thus confining the spread of diseases like Covid-19. The methodology aims to design energy-efficient buildings that minimize incident solar radiation (insolation) and enhance indoor air quality. Furthermore, this paper identifies a crisis zone as a context because such areas allow for wide-scale rebuilding activity [5].

Researchers have been exploring the topic of ventilation and its necessity in post-pandemic architecture within a particular framework such as window sizes and locations, materials used, etc. Some approaches consider climate-adapted buildings to optimize energy [6, 7]. Several studies found that the ventilation and airflow characteristics are primarily influenced by the dimensions of the façade and the size of window openings [8]. In [9], the authors compare natural ventilation and heating systems with forced air flow inside the geothermal tube. In addition, some recent approaches are exploiting the advances in the fields of artificial intelligence and machine learning to design energy-efficient buildings [10]. Other researchers aim at studying specific types of structures such as historic buildings to find the interrelationships between heritage conservation and the need for ventilation [11]. Numerous research works also discuss the use of specific materials to provide cooling savings, such as Phase Change Materials (PCM) along with controlled natural ventilation [12].

However, to the best of our knowledge, no work in the literature looks into the problem holistically to optimize the building form and improve the airflow characteristics. This paper intends to show that when designing a building in a post-pandemic world and especially in a context of a crisis in an urban environment, it is crucial to optimize the building form at an early building design stage. The aim is to reduce insolation while considering better air quality and comfort by minimizing the energy demands to cool spaces.

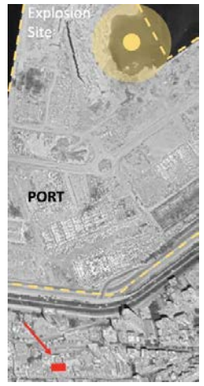
2. METHODOLOGY

A critical component in buildings is the design that incorporates lessons learned from crises such as the COVID-19 pandemic and the Beirut port explosion in Lebanon. The objective is to help the architectural design team find the most appropriate building form in an urban environment at the early stages of the design process. The proposed methods take as input the multiple design variables and output a proposed form that holistically reduces the insolation and improves the IAQ in an urban context.

2.1 Crisis context

A site, defined by a particular location, is impacted by surrounding buildings and needs to account for the applicable building regulations (allowable built-up area, setbacks, heights, etc.). The first case study focuses on the area surrounding the Beirut port where several buildings had to be demolished as a result of the explosion that took place in August 4, 2020. An example of the target site is shown in Fig. 1. The other case studies compare the performance of the proposed approach in different latitudes including war zones such as Ukraine which should be rebuilt after the war.

Figure 1:
The site within the context affected by the Beirut explosion. Geographical location: 33.5°N, 35.3°E.

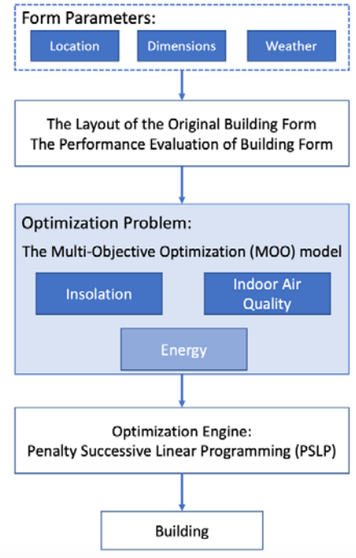


2.2 Framework

The framework is illustrated in Fig. 2. It takes as input the geographical location of the building in addition to the different dimensions of the target site and the weather metrics that help in calculating the amount of insolation and the potential for natural ventilation such as the wind, the solar azimuth, and the solar altitude. Then, the layout of the building form is studied such that it is composed of triangular meshes, which provide maximum flexibility and allow the building to take free forms [13]. The envelope of the building is composed of triangles, and each triangle is defined by three vertices. The 3D coordinates (x, y, and z) represent the optimization variables. The initial building layout is a conventional rectangular mesh building.

Given the building layout and the different geographical and environmental inputs, the problem is formulated as a constrained multi-objective optimization (MOO) problem where the objective function minimizes the total insolation and improves the indoor air quality; thus, improving the energy efficiency of the building. Then, the optimization problem is solved using an optimization engine based on Penalty Successive Linear Programming (PSLP) with guaranteed convergence properties and efficiency in computation [14]. To ensure that any architectural design team can easily use our proposed framework, we developed a graphical user interface (GUI).

Figure 2:
The framework to optimize the building form to reduce insolation and improve indoor air quality.



2.3 Insolation efficient building form

To optimize the building form in terms of insolation, the location of the building, the habitable area, the building law of the region, and the

surrounding buildings that might shade the target building area during specific times of the day should be determined. To optimize the building for TC and IAQ, the need for air conditioning during warm days must be decreased because closed spaces with air conditioning will facilitate the spread of a virus.

The total insolation of the building is defined as follows:

$$I_{total} = \sum_{t} \sum_{r} i_{tr} \qquad (1)$$

where I_{total} – total insolation absorbed by the building;

i_{tr} – amount of insolation per triangle t and sun ray r;

t – triangle in the building mesh;

r – solar radiation during a particular timeframe.

2.4 Ventilation enhanced building form

In addition to optimizing the building form to get less insolation, the proposed approach puts further constraints on the depth of the building so that the volume can integrate a natural cross ventilation strategy. Moreover, the Window-to-Wall Ratio (WWR) has a direct effect on the ventilation of the building. Therefore, managing the size and location of each window would affect the performance and the efficiency of such a natural ventilation strategy. In addition, the Clean Air Delivery Rate (CADR) is a term used to describe the amount of clean air delivered to space [15, 16].

The best technique to measure ventilation is to estimate how often the air in a space will be completely replaced, referred to as Air Changes per Hour (ACH). The CADR metric is used to estimate the ACH of air being delivered to the room. The following mathematical equation allows calculating the air change rates:

$$\boldsymbol{ACH = \frac{3600 \times q}{V}} \qquad (2)$$

where $\boldsymbol{q}$ is the CADR metric or airflow rate in m^3/s and $\boldsymbol{V}$ is the space volume in m^3. The airflow is a function of the velocity, direction of the air, and the area of the opening/window.

2.5 Optimization problem

The optimization objective of our proposed approach is to decrease the amount of energy consumed in the optimized building. Decreasing the insolation will lead to lower energy demand to cool indoors. In addition, increasing the ACH by relying on the opportunities provided by the local climate will also lead to cooling demand reduction in addition to better IAQ. Hence, the optimization problem can be formulated as follows:

$$\min_{x,y,z}(I_{total} - ACH) \qquad (3)$$

where the aim is to find the triangles forming the meshes in the building represented by the 3D coordinates. This optimization problem is constrained because several architectural and construction constraints exist, such as fixing the ceiling height to avoid unhabitable floors.

We formulate the problem as Penalty Successive Linear Programming (PSLP), which has been proven to converge [17]. The proposed PSLP approach formulates the linear programming (LP) sub-problems that can be solved in a computationally efficient manner. The original non-linear optimization problem shown in Equation (3) is approximated using these LPs that are formulated using the first-order Taylor series approximation. The PSLP is an iterative approach involving multiple iterations using successive linearization. The decision variables change in each iteration by a maximum value defined as bounds on the step-change over successive LP iterations. The PSLP iterations continue until the value of the objective function changes within a predefined tolerance range [17].

3. SIMULATIONS

We implemented a simulation-based design workflow to optimize the form of the building.

3.1 Parameters

3.1.1 Insolation and sunpath

Given a geographic location defined by the longitude and latitude and the specific date and time, the sun's position can be calculated based on equations proposed by Duffie and Beckman [18]. The sun's azimuth and altitude angle are calculated in the backend of the graphical user interface. Hence, the architectural team using our proposed approach does not have to perform any calculations. The user inputs different basic requested information about the location of the target building.

3.1.2 ACH

Air is continuously exchanged between a building's interior spaces and the external environment. The rate at which this air is exchanged in a room (ACH) is a critical property that helps assess the natural ventilation in a building. The higher the *ACH*, the more frequent air changes in the room, reducing the risk of inhaling viral particles such as COVID-19. In order to optimize the natural ventilation of the building, a constraint on the depth of the building is added, and the WWR is addressed so that it supports the increase of the airflow rate $\boldsymbol{q}$.

3.2 Setup

A complete validation process is used to evaluate the insolation and the air changes per hour using MATLAB, CPLEX, and AutoCAD. The performed simulations used MATLAB as an interface program running on a PC with Intel Core i7-6850K CPU and 32 GB of RAM. CPLEX was used to solve the PSLP optimization problem. In addition, we used ROOM [19], an interactive courseware for learning environmental building design, to assess the natural ventilation in the original versus the optimized building form. The original initial building form is the conventional rectangular building.

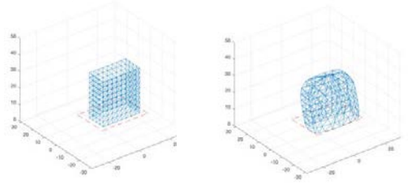
4. RESULTS AND DISCUSSION

To assess the performance of the proposed approach, several experiments are done to evaluate the multiple objective functions.

4.1 Amount of insolation

Figure 3 shows how the form of the building changes after optimization, considering only the insolation as an objective function at a latitude of 32° North. The table below Fig. 3 shows the reduction in the amount of insolation. The figure shows that the optimized shape is tilted towards the south to shade itself. This is due to the sun path which reaches its highest point in the sky at an angle of 58° above the southern horizon. Both buildings have the same built-up area of 2592 m^2 (12 meters × 24 meters × 9 floors in the conventional building form). These are the dimensions of the building destroyed by the explosion, as represented by the red rectangle in Fig. 1. The amount of insolation (in KW) dropped by 28%; therefore, the need to use energy to cool down this building during extended hot summer days will also decrease significantly. It is also worth noting that both forms are restricted by the same terrain area represented by the dotted red line in Fig. 3

Figure 3: *Form change and improvement in insolation*



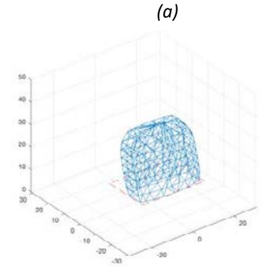
	Original Building	Optimized Building
Insolation	582.7 KW	419.4 KW
Improvement	28%	

4.2 Air changes per hour

Figure 4 shows the result of adding the constraint to the optimized building. Hence, this figure shows how the form of the building optimizes, considering both the insolation and the ACH as objective functions, as shown in Equation (3). As the ACH values depend on the room volume, the original non-optimized building form presents the lowest air rates and hence the lowest ventilation. On the other hand, the optimized building presents better ACH, and the optimized structure with a constraint added gives the best performance in terms of IAQ. Figure 5 shows a plan view of the optimized rooms generated using ROOM software [19]. Fig. 5 (a) shows the optimized room when only insolation is considered, whereas Fig. 5 (b) shows the optimized room when taking both insolation and ACH in the MOO. The figure shows how considering ACH in the objective function gives a room with less depth. Hence, this room will have better natural ventilation.

Figure 4: *Form change after adding a constraint to enhance the air quality further. (a) The optimized shape considering only insolation. (b) The optimized shape considered insolation and ACH in the objective function.*

(a)



(b)

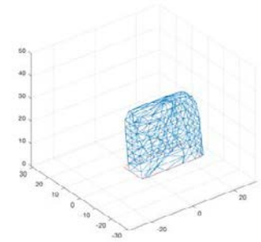
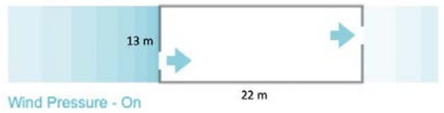
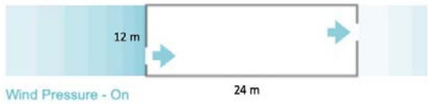


Figure 5: *A plan view of the output shapes of the optimized rooms considering natural cross ventilation through two windows. (a) represents the optimized room when only insolation is considered whereas (b) shows the optimized room when taking both insolation and ACH as objective functions.*

(a)



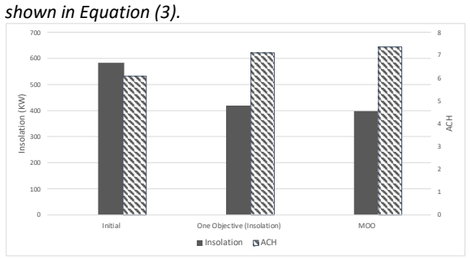
(b)



4.3 Insolation and ACH measurements

Different scenarios have been analyzed and compared: the initial rectangular conventional building without any optimization, the insolation-optimized building where only insolation is considered in the objective function, and the optimized design scenario where the target building is optimized considering both insolation and ACH. Figure 6 shows the insolation and ACH values in the different scenarios considered. The results show that our proposed approach provides less insolation and higher ACH values, resulting in less energy to cool and ventilate the interior spaces. Hence, the proposed approach provides better IAQ.

Figure 6: *The insolation and the ACH of the optimized form considering one objective only which is the insolation versus considering the two objectives in an MOO format as shown in Equation (3).*

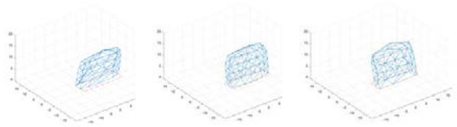


4.3 Varying the latitude

Different scenarios are considered in this case study where the same initial building form is optimized at different latitudes. This case study helps in understanding the variation of the improvement through minimizing insolation and improving the IAQ in different countries at several latitudes ranging from 0° to 48° North. The countries at these latitudes suffer from hot summers; hence, applying our proposed optimization will result in the reduction of cooling loads. In addition, some of these latitudes contain countries with war crisis such as Ukraine on latitude 48° where several buildings will be rebuilt post war [20]. In this case study, we considered the building with five floors to account for the average number of floors in buildings worldwide.

Figure 7 shows the variation of the improvement at the aforementioned latitudes considering insolation and ACH in the objective function. The earth receives different amounts of solar radiation at the different latitudes. In addition, at 24° latitude, the sun's radiation is perpendicular to the earth's surface at the Tropic of Cancer (23.5° north latitude) because this is the degree of tilt of the earth during summer [21]. As shown in Fig. 7, the percentage of reduction in insolation is dependent on the latitude. Hence, each latitude receives different amounts of solar radiation. The percentage improvement in insolation is highest at 0° latitude and drops until it reaches its minimum at 24° where the sun is overhead and the days are shorter. At 48° North (Ukraine), the percentage improvement in insolation rises again. In addition, the ACH improves by an average of 33.3% depending on the average wind speed at each latitude.

Figure 7: *The percentage of improvement in insolation and ACH at different latitudes at different latitudes of 0° (Uganda), 24° (Egypt) and 48° (Ukraine).*



Latitude	0	24	48
Original Insolation	157.3 KW	136.6 KW	184.5 KW
Optimized Insolation	99.1 KW	100.7 KW	124.9 KW
Improvement	37 %	26.2 %	32.2 %

4.4 Discussion

The proposed approach gives an optimized building form with natural ventilation. This framework is considered one of the essential future directions to establish an environmentally friendly urban environment, especially in areas with high temperatures. In addition, the proposed approach is a computationally efficient method that can be easily implemented by a design team consisting of architects and engineers through using our simple user interface. Based on the outcome of this study, the proposed optimization strategies show energy-saving potential in the range of 28–37%. In addition, the ACH improves as well in the range of 16–33%, which is considered a noticeable improvement considering the recommended ACH values, especially during pandemics such as COVID-19 [22]. Finally, our model is based on fundamental principles that are already validated and therefore we believe that it captures the performance of the actual building with good accuracy.

5. CONCLUSION

The increase in urbanization along with the COVID-19 pandemic have resulted in social conditions where most of the daily human activities take place within an indoor environment, which is often characterized by unsatisfactory air quality. This paper presents a novel approach to reduce insolation and improve IAQ. This paper identifies a wide-scale crisis zone as a context such that addressing these issues at the early stages of the design process will help rebuild such areas providing efficient and healthy spaces. The findings in this paper can help design and operate buildings that maintain occupant comfort while preserving amounts of energy.

Future works will evaluate the solar access and insolation in urban environments, especially public streets, to optimize the insolation and provide urban solutions to buildings in crises contexts.

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Indoor environment quality analysis of a new-build UK primary school in the context of COVID-19

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ABSTRACT: This work involved a field study to assess indoor air quality and overheating in a recently constructed low-carbon primary school in the UK during heating and non-heating seasons. The findings indicate that most of the classrooms monitored experienced overheating for over 40% of school hours, with CO_2 levels above the maximum threshold (1,000 ppm) for over 60% of school hours during both the heating and non-heating seasons. $PM_{2.5}$ exceeded 20 µg/m³ during the heating season and 10 µg/m³ during the non-heating season. Computational fluid dynamics simulations assessed indoor ventilation further, with the results showing that classrooms with single-side ventilation provided poor ventilation and could increase the COVID-19 risk, among other respiratory concerns. This paper provides guidance on improving ventilation in classrooms to help mitigate future pandemics.

1. INTRODUCTION

School buildings are complex spaces to design, construct, and operate because they need to perform within the required standards set for indoor environmental quality (IEQ), including thermal comfort conditions, indoor air quality (IAQ), noise comfort, and light comfort. Achieving adequate IEQ while accommodating specific periods characterised by substantial occupant densities can be particularly challenging due to the high internal gains, high carbon dioxide (CO_2) levels, indoor pollutants and dust (i.e. $PM_{2.5}$ and PM_{10}), and overheating. Designing learning cluster zones (i.e. classrooms) in schools can be particularly challenging because these should accommodate flexible educational methods that might change over time. Furthermore, strategies implemented to meet the carbon and energy emissions targets have a considerable impact on the internal environment, including stricter regulations being introduced for the school building fabric and ventilation. Although meeting these standards involves managing conflicting interests, it is important that healthy and comfortable spaces are provided for the occupants, who are mostly pupils. Therefore, the present study uses field measurements to investigate classrooms in newly constructed schools, comparing the findings to the Building Bulletin 101 (BB101) and Chartered Institution of Building Services Engineering (CIBSE) school building standards. The problems with providing a holistic system combining technological and design solutions will be identified. Given that ventilation can provide fresh air and save on energy consumption, this approach has attracted increasing attention in recent years, especially during the COVID-19 pandemic (Day, 2020; Zhang & Bluyssen, 2019), when fresh air has been critical to public health. Accordingly, this paper's results are also compared with school guidelines to determine how effectively the new schools performed in the COVID-19 context.

2. ENVIRONMENTAL PERFORMANCE OF NEW-BUILD SCHOOLS

Several studies have investigated the operational and environmental effects of new-build low-energy schools (Ian Pegg, Andrew Cripps, & Kolokotroni, 2007; Jenkins, Peacock, & Banfill, 2009; Pegg, Cripps, & Kolokotroni, 2007). This research has shown that new schools fail to meet even the basic indoor air quality (Mumovic et al., 2009) and energy consumption (Pegg et al., 2007) requirements.

For Jain et al. (Jain et al., 2019), if building design's primary focus continues to be energy use, unintended IEQ underperformance impacts can result from conflicting energy and IEQ objectives. Poor IEQ can impact student and teacher health and productivity and the school building environment, particularly the classroom, affects pupil attention and, thus, the education process. Many factors contribute to thermal comfort, including low ventilation rates and limited air movement, uncomfortably high temperatures, unsuitable daylight levels, low humidity and high electromagnetic radiation from appliances (Benjamin M. Jones & Kirby, 2012; Camacho-Montano, Cook, & Wagner, 2020; Jain et al., 2020; Korsavi & Montazami, 2020; Luther, Horan, & Tokede, 2018). Building-related problems, including 'building-related illness' (McMullan, 2002), have been characterised by the World Health Organisation (WHO) as 'sick building syndrome' and can lead to serious illness (Anderson, Thundiyil, & Stolbach, 2012; Bakó-Biró, Clements-Croome, Kochhar, Awbi, & Williams, 2012; De Giuli, Da Pos, & De Carli, 2012; Lan, Wargocki, Wyon, & Lian, 2011). Roaf and Hancock (Roaf S, 1992) suggest some such diseases cannot be clinically diagnosed or treated.

2.1 COVID-19 risk in schools

Evidence has appeared that SARS-CoV2, the virus that causes COVID-19, spreads via tiny particles (known as aerosols) emitted by an infected person when they cough, sneeze, speak, or breathe. These aerosols can remain airborne for several hours. Emerging evidence of increased infection rates in poorly ventilated rooms indicates that we should regard this as a transmission route and take measures to avoid the threat. Recommended measures include improving air supply and exhaust ventilation by delivering as much fresh air as possible (Gameiro da Silva, 2020). Although this is likely to promote energy penalties, these are considered necessary to minimise infectious virus particles. According to one report (REHVA, 2020), ventilation measures are the most important engineering control for preventing infections. While physical distance is also necessary, good ventilation and efficient air circulation methods can minimise the risk of aerosol concentration. Notably, COVID-19 has refocused attention on good IEQ, prompting increased use of CO_2 monitors in classrooms to indicate ventilation levels (Italian Society of Environmental Medicine (SIMA), 2020).

2.2 Indoor air quality

Regarding the effect of CO_2 concentration on classrooms, an analysis by (Heudorf, Neitzert, & Spark, 2009) demonstrated that CO_2 concentrations above 1,000 ppm increase absenteeism by about 10–20%. (Shendell et al., 2004) have suggested that decreasing CO2 concentrations to below 800 ppm is likely to decrease headaches, fatigue, and eye/throat discomfort (Seppänen, Fisk, & Mendell, 1999). Elsewhere, Myhrvold et al. (1996) revealed that CO_2 concentrations above 1,500 ppm could contribute to headaches, dizziness, tiredness, difficulties in concentrating, and unpleasant classroom odours.

The presence of $PM_{2.5}$ has significant negative health implications, having been associated with oxidative DNA damage, lung cancer and cardiovascular diseases (Hu et al., 2014; Siskos, Bouba, & Stroubou, 2001; Sørensen et al., 2003), and poor cognitive performance. Children are more vulnerable to airborne pollutants than adults because their developing lungs take in more air in relation to their body size, they demonstrate higher breathing rates during physical activity (Bateson & Schwartz, 2007; Brunekreef et al., 2005), and they are less able to communicate concerns in response to pollutant levels. Increased incidence of respiratory illness has prompted increased research on IAQ in schools (Fig 1).

Although SARS-CoV2 is undeniably transmitted primarily via particles emitted by infected persons, it is also critical to consider particulate matter (PM), for which different relationships between the category or the classification and size exist (see Table 1).

Figure 1:
Smaller particles have a higher hazard index, can cause alveolar obstruction and impede respiratory function.

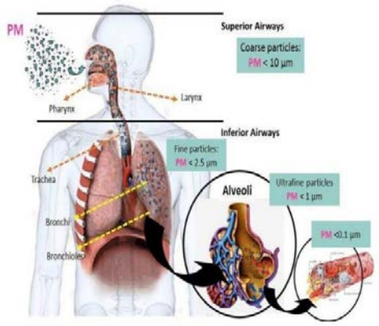


Table 1:
Airborne particle matter classifications.

Diameter (µm)	Penetration Level	Classification
> 7	Oral and Nasal Cavities	Inhalable
4.7 – 7	Larynx	
3.3 – 4.7	Trachea and Bronchi	Thoracic
2.1 – 3.3	Secondary Bronchioles	
1.1 – 2.1	Bronchioles	Breathable
0.65 – 1.1	Alveoli	

Inhalable particles are absorbed by the hair in the nose or the mucus in the oral and nasal cavities and the larynx. Thoracic particles can enter the trachea and the bronchi, where they are preserved by the mucus. Meanwhile, breathable particles reach the bronchial tubes and the alveoli.

SARS-CoV2 particles are spherical and between 0.06 µm and 0.14 µm in diameter, averaging roughly 0.125 µm (Zhu et al., 2020). Thus, SARS-CoV2 particles are smaller than $PM_{2.5}$ but larger than dust and gas particles. Researchers suggest indoor human occupancy zones be highly ventilated with fresh air to reduce the risk of suspended particles and, decrease the possibility of infection [1].

To highlight the importance of ventilation, (Setti et al., 2020) observed the potency of airborne transmission in enclosed environments with limited ventilation. It should be noted that given the atmospheric stability in the Po Valley in northern Italy, it can be said to clearly represent an enclosed atmosphere where long-distance viral transmission is supported by high PM concentrations.

The CIBCE (2020)Ventilation Guidelines for COVID-19 [49] address SARS-CoV-2 aerosol transmission, recommending improved ventilation in conjunction with other measures, including

working from home, social distancing, face masks, appropriate hygiene practices, workplace residue cleaning, and routine testing. However, during the cooler months, providing both heating and ventilation is likely to be energy-intensive and require some degree of recirculation. This means the risks associated with recirculating air must be considered against the risks of reducing outdoor airflow, which might be needed to ensure air supply to a space at a comfortable temperature. Windows and openings are often the mechanisms for delivering outdoor air for natural ventilation, with the natural forces driving air in the colder months being wind and temperature differences indoors and outdoors. Opening only high-level vents, rather than low- and high-level vents, enables a greater combination of outside air with indoor air before it reaches the occupied zone. If natural ventilation openings are the only mechanism for transmitting outside air to a room, it is vital to avoid closing them completely when the space is occupied. School and government authorities, therefore, owe a particular duty of care to pupils to ensure that appropriate indoor environment conditions are maintained (Chatzidiakou, Mumovic, Summerfield, Hong, & Altamirano-Medina, 2014). The CIBSE (CIBCE, 2020) is now collaborating closely with other organisations to provide consistent solutions and guidelines for ventilating more complex indoor spaces. The present work aims to improve the existing knowledge on basic flow characteristics of cross-ventilation, interpret internal classroom environments according to internal airflow patterns, and to link those interpretations with the design of openings and their placement on classroom walls, especially in the COVID-19 context.

2. METHODOLOGY

The present study involved three main steps: (1) field monitoring of school, (2) evaluation of classroom IAQ and overheating in comparison with standards; and (3) computational fluid dynamics simulations to investigate indoor and thermal distribution in single-side-ventilated classrooms.

3.1 Field study monitoring a new-build school

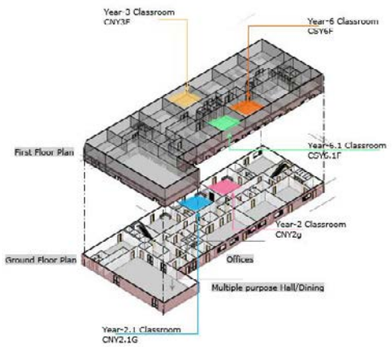
The extensive field study of existing indoor thermal classroom conditions in new-build primary school buildings included measurements taken during both the heating and non-heating seasons with the objective of observing the IAQ during each season. The field measurement results were compared with the latest environmental standards for school guidelines (i.e. CIBCE TM52 and BB101).

An in-situ method was adopted, generally following the monitoring strategies described in ENISO 16000_1 (2006). This meant each school was monitored for 15 consecutive working days during both the heating and non-heating seasons.

The equipment was selected for accuracy, volume, robustness, and acoustic activity and calibrated against the manufacturer's appendix. The data were downloaded and equipment tested after each field recording day. The measurement devices were positioned 1.1 m from the floor and away from sun patches (e.g. windows) and heat sources (e.g. computers), in accordance with ISO 7726 recommendations. Such positioning both minimised disturbances and maintained proximity to student desks. Devices were initiated before the children arrived each morning. The case study school (Mansfield) is a double-storey building featuring north-facing ground-floor classrooms (see Fig. 2). It was built in 2014 as a low-carbon school building. Students in years one and two have direct access to the playground, with a long corridor providing classroom access.

3.2 The case study school building

Figure 2:
3D section of the case study school.



The school chosen for the case study uses a hybrid ventilation approach, following the UK norm of using windows as the main source of ventilation, especially during the summer. This impacts how occupants practice adaptive performance, given it has been demonstrated that manual window operation significantly improves IAQ (Stabile, Dell'Isola, Frattolillo, Massimo, & Russi, 2016) and occupant relaxation. Accordingly, it is also important to analyse the types of windows in the classrooms.

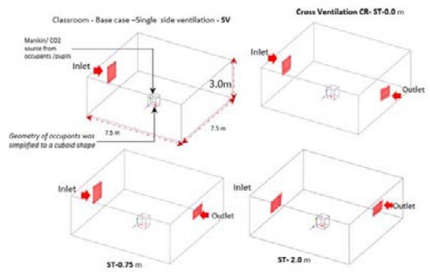
Fig. 3 shows a classroom with single-sided double openings (with the degree of opening manually controlled along the classroom's length) and a classroom with two 1.8-m windows.

Figure 3:*Window design in one case study classroom*.

3.3 Computational fluid dynamics simulations setting and parameters

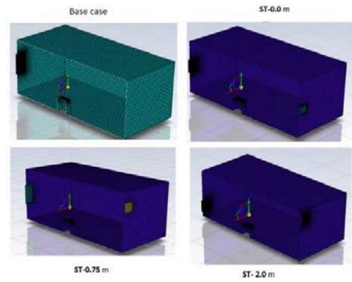
The computational geometry corresponds to this reference classroom, featuring the real dimensions of a standard classroom (7.5x7.5x3; WxLxH) and allowing multiple ventilation configurations to indicate different stack height (ST) effects between inlets and outlets. This study uses four different cross-ventilation approaches to measure differing ST effects for comparison with the existing situation and based on classrooms with single-side ventilationsee Fig. 4. The computational domain for these simulations followed best-practice guidelines developed by (Tominaga et al., 2008).

Figure 4:
Case setups for different ventilation modes to signal classrooms with different stack heights



Generating high-quality meshes critically contributes to the accuracy of the results obtained from modelling and the model's convergence. A non-uniform poly-hexcore mesh was applied to a computational model to initially understand the airflow characteristics for the classroom reference case and other classroom ST scenarios, including how these might be affected by ventilation. A sensitivity analysis was conducted to verify the modelling and ensure that results were independent of the size of the mesh. This required comparing the results using the same model with different mesh sizes. Due to the limited scope of this paper, the mesh analysis is not included. Nonetheless, a domain with a maximum grid size of 1,252,846 cells was created, an increase of 643,893 cells from the initial mesh used for this study's results (Fig. 5).

Figure 5:
Meshes of the case study classroom base.



The 3D steady Reynold-Average Naiver-Stocks (RANS) approach is the most commonly used computational flow dynamics approach in natural ventilation studies (Blocken, 2014, 2018; Chen, 2009), with this study performing 3D-steady isothermal RANS simulations with turbulence models RNG k-ε, following (Yakhot, Orszag, Thangam, Gatski, & Speziale, 1992). The steady RANS equations are solved in combination with a shear stress transport (SST) K-$^{\varepsilon}$ model. The SIMPLE algorithm was used for pressure velocity coupling, with pressure interpolation and second-order discretisation schemes used for convection terms and the viscous term of the governing equations. Streetwise velocity was monitored at three points to assess the convergence of the solution. To obtain a reliable, steady value for the solution variables, the results were monitored over 10,000 iterations after the simulation reached a statistically stationary solution.

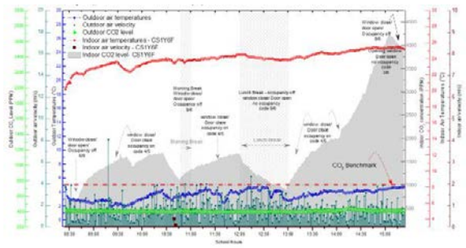
4 RESULTS AND DISCUSSION

4.1 Indoor Air Quality Field Study Results

During the heating season, the highest recorded indoor CO_2 levels were for classrooms CS1Y6F and CS1Y6.1F, with concentrations reaching above 4,000 ppm, vastly exceeding the recommended daily average of 1,000 ppm for more than 20 minutes.

Fig. 6 demonstrates the gradual increase after the lunch-time break. Despite the mechanical exhaust controlled by a CO_2 sensor implemented in classrooms CS1Y6F and CS1Y6.1F, neither classroom maintained an average daily concentration below 1,500 ppm, meaning that an operable approach alone was insufficient to provide adequate ventilation.

Figure 6:*The continuous monitoring of all field study parameters*.



As expected, higher indoor CO_2 levels were associated with higher indoor temperatures, with both seeming to increase with occupancy, including in terms of sensible and latent heat gain. However, the association between CO_2 levels and indoor temperature remained significant after controlling for occupant density and number, indicating that reducing ventilation rates promotes overheating.

Hourly $PM_{2.5}$ levels were higher during occupied periods, with the first of three sharp increases recorded at the beginning of the day. A second sharp peak was obvious just before the lunch break, when intense student activity re-suspended previously deposited particles. The third peak followed the lunch break, a combination of intense activity and limited ventilation. At the end of the school day, $PM_{2.5}$ levels decreased to below 20 $\mu g/m^3$. Temperature also impacted indoor $PM_{2.5}$ levels, with a positive correlation between high indoor $PM_{2.5}$ levels and higher indoor temperatures (Fig. 7). The typical $PM_{2.5}$ levels during the heating season were above 20$\mu g/m^3$ and sometimes reached above 45$\mu g/m^3$. During most school hours, levels were above 10µg/m3. These numbers indicate daily concentration levels above WHO recommendations for the second half of the day and annual concentration levels above WHO guidelines throughout the year (Fig. 8). This supports several findings linking COVID-19 virus transmission and $PM_{2.5}$ and IEQ (Ali et al., 2021; Zoran, Savastru, Savastru, & Tautan, 2020).

4.2 Classroom ventilation in the COVID-19 context

Despite several insights surrounding COVID-19, several limitations should be noted. First, the study was performed for a single isolated and simplified classroom geometry and did not investigate the impact of indoor thermal performance. Second, mean airspeed was used as the parameter of primary importance, with no evaluation of outdoor and indoor turbulence intensities and turbulence diffusivities, which are particularly important for the dispersion of indoor contaminants

Figure 7:
Concentration of $PM_{2.5}$ and indoor air temperatures during school hours in classroom CN1Y2G.

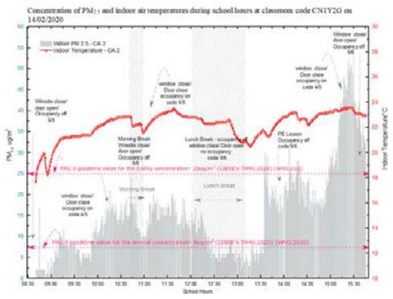
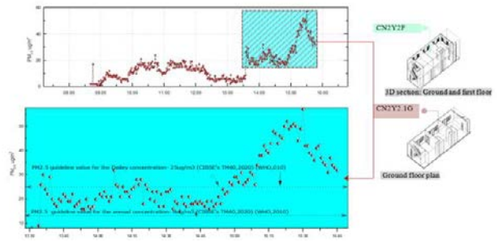


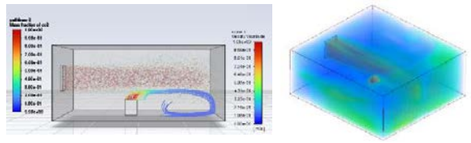
Figure 8:
Comparing $PM_{2.5}$ concentrations and indoor temperatures during school hours for classroom CNY2.1G with the WHO and CIBSE's TM40 benchmark.



By examining the case study configuration to evaluate the classroom's thermal and ventilation performance, it is possible to understand the thermal flow field and age of air in the breathing zone to develop potential solutions in the form of design proposals which, for every current design context, incorporate the best approach to air movement and distribution, enabling improvements to IAQ in the classroom breathing zone in the COVID-19 context. For single-side-ventilation layouts, the airflow in the middle of the classroom is relatively low and not fully developed, indicating that inlet arrangement cannot improve ventilation efficiency. Fig. 9 shows the horizontal section velocity contours at a height of 1m.

Fig. 9 also shows that the airflow cannot cover a larger area horizontally; thus, air coverage at the inlet is relatively satisfying. Given there are no outlets at the leeward wall, the geometry is not conducive to airflow, with airflow velocity in the classroom decreasing significantly to 0.4m/s. This means that the reference case is unsuited to dilution ventilation during COVID-19. The airspeed values obtained for the examined classroom air distribution configurations are not suitable for the occupant's internal environment in the reference classroom case. The poor performance of the single-sided ventilation room has been previously reported (Fan et al., 2021); here, our evaluation with full-field data and simulation further demonstrate how unsatisfactorily current single-sided ventilation classrooms perform, with particles suspended in the room and no outlet to remove these particles.

Figure 9:
Baseline particle and CO_2 suspension in the air.



The supply air jet that enters the classroom initially forms a layer of fresh air along the classroom domine. The results of the simulation of the air flow pattern of the baseline case, ST-00, ST-0.75, and ST-2.0, are presented in the measurement plane. For ST-2.0 cases, it is observed that the plume of the fresh air enters the classroom domine at the lower inlet window, leading to the breathing zone at 0.6 m and into the buoyant plume of particles that forms above occupants, demonstrating how the fresh air pushes the particles to the outlets more prominently than in the case of the baseline case study (Fig. 10).

Figure 10:
CO2/particles mole fraction and airflow streams with different stack height effects of the windows.

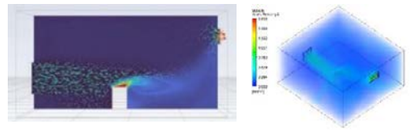
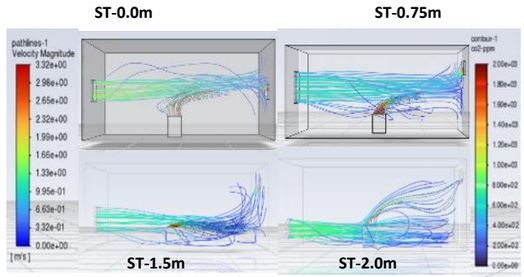


Fig. 11 shows that the bigger ST and the opening located at the bottom part of the windward wall seem to allow more air to penetrate and more particles to escape from the classroom.

Figure 11:
The plotted velocity and CO2 distribution for the case study classroom.



5. CONCLUSION

This paper has evaluated the IAQ and overheating in a new-build primary school using data collected during the heating and non-heating seasons, considering different ventilation approaches, comparing the results with benchmarks and modelling how the school might mitigate the risk of COVID-19. Given its high occupancy rates, school buildings must be safe and secure, requiring architectural and technological retrofits to avoid the threat of COVID-19 and other airborne illnesses. The results show that the PM2.5 levels recorded in all classrooms were higher than 20 µg/m3 and 10 µg/m3 respectively, indicating that the individuals' annual exposure to PM within the classroom may be higher than WHO 2010 and CIBSE TM40 guidelines. PM2.5 concentrations were above the daily guideline values for most classrooms.

The study's findings indicate that achieving adequate ventilation was a challenge for most classrooms monitored, with cross-ventilation prevented by the school's original design. This low ventilation rate, combined with the increased airtightness of the building envelope and the single learning cluster design, led to CO2 concentrations and PM2.5 levels beyond the recommended guidelines. These measurements are considered a useful proxy for IAQ in the school context.

Given ventilation can both provide fresh air and save energy, it has received more attention in recent years, especially during the COVID-19 pandemic [2, 3], with fresh air becoming vital to public health. Accordingly, this paper's findings guide determination of the effectiveness of new schools in the COVID-19 context. Based on the computational fluid dynamics simulation results, a low ventilation rate may not effectively remove indoor pollutant sources due to the ventilation system employed and the building's orientation. Airborne infection risk can be reduced by increasing the supply of outdoor air (i.e. increasing ventilation). In the reference classrooms studied, achieving adequate ventilation rates has been problematic because the school's original design prevented cross-ventilation and the school had further reduced ventilation with its single learning cluster plan and windows occupied with louvers elevating temperatures and increasing particle concentrations beyond the recommendations for schools, especially in the COVID-19 context.

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Quantifying harm from exposure to fine particles ($PM_{2.5}$) emitted by cooking

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ABSTRACT: Emissions from cooking have been estimated to contribute to two-thirds of total fine particulate matter (particles with diameter ≤ 2.5μm, $PM_{2.5}$) pollution in homes, so assessing $PM_{2.5}$ emissions from cooking complete meals is a growing need of research. Furthermore, indoor exposure to $PM_{2.5}$ has been associated with an increased risk of adverse health effects. Quantifying health effects can be performed using metrics based on health. Here, we use averted-Disability Adjusted Life Years, a performance-based health-centred metric, to investigate and quantify the tangible change in the burden of disease for mitigating exposure to $PM_{2.5}$ pollution using ventilation strategies proposed by England's statutory Approved Document F. The median [mean] annual DALYs for the worst ventilation scenario was found to be 6063 [7368] (95%CI: 1108 - 21788), which reduces to 1822 [2437] (95%C.I. 364-8165) when using an exhaust system through a 30L/s cooker hood during cooking time plus 10 minutes (best ventilation scenario). Both estimations assumed exposure to $PM_{2.5}$ from cooking occurs every day and all exposure represent the intake, and as such represent extreme cases. A change from worst to best scenario results in 3187 [5016] (95%C.I. 499-20310) annual averted DALYs per 100,000 of exposed population. The focus should be made towards these health metrics, as wide information and data sources exist for computing them. Expected interested parties in these results include policymakers, scientists, and the public.
KEYWORDS: DALYs, Cooking, Health, $PM_{2.5}$

1. INTRODUCTION

Air pollution is a primary cause of morbidity and premature mortality worldwide. Current standards attempt to minimize exposure by specifying threshold average-concentrations. However, this does not necessarily indicate the impact on human health. To do this, methods can use reference values, risk or damage factors, and health centred metrics, such as DALYs or QALYs [1]. The DALY (disability-adjusted life-years lost) metric was developed in the 1990s, and corresponds to the years of life lost, and the time lived with a disability, attributable to some cause [2]. The DALYs for a disease is defined as the sum of the Years of Life Lost (YLL) due to premature mortality in the population and the Years Lost due to Disability (YLD) [2-4]. DALYs can be computed for any disease or cause of mortality over a lifetime, allowing for a comparison of causes and the prioritization tasks. The harm caused by chronic exposure to airborne contaminants can be quantified using DALYs [5].

Exposure to airborne contaminants primarily occurs indoors. Indoor air pollutants (IAPs) lead to a variety of diseases. Thus, a standard metric of harm is needed to prioritize mitigation methods and to compare IAPs. Logue et al. [6] proposed a method to quantify and compare health impacts (harm) from the inhalation of a subset of IAPs. They used available information on disease incidence and impacts for specific pollutant–disease combinations and data on the uncertainty in IAP concentrations measured in US dwellings. They showed that indoor exposure to fine particles (with diameter ≤2.5μm, $PM_{2.5}$) causes more harm than any other contaminant, by an order of magnitude. For 2016, estimates of the joint effects of household (HAP) and ambient air pollution (AAP) indicated that, globally, 7 million deaths were attributable to exposure to $PM_{2.5}$, 4.2 million to AAP and 3.8 million to HAP [7]. Furthermore, in 2017, long-term exposure to $PM_{2.5}$ contributed to a burden of 83×10^6 disability-adjusted life years (DALYs) globally; specifically, household air pollution contributed to 59×10^6 DALYs (2.4% of total DALYs) from ischemic heart disease, stroke, COPD, lower-respiratory infections, and type 2 diabetes [8].

Cooking is a significant source of $PM_{2.5}$ in dwellings [9] and can be removed from a space using ventilation [10]. England's statutory Approved Document F (ADF) [11] prescribes three ventilation strategies to control the quality of air in a kitchen: (1) an intermittent ventilation rate of 30 l/s through a cooker/range hood; or (2) 60 l/s elsewhere; or (3) a continuous ventilation rate of 13 l/s. The provision of one of these strategies is obligatory in new dwellings, whereas it is only necessary to maintain an existing ventilation system when refurbishing any other dwelling. These ventilation rates were chosen to remove moisture, with the further expectation that they will dilute NO_2 and CO emitted by gas cooking. $PM_{2.5}$ and other contaminants generated during cooking, were not considered.

A cooker hood captures a proportion of all emitted contaminants and extracts them directly outside [10]. This has been shown to be the most effective kitchen ventilation strategy for minimising mean $PM_{2.5}$ concentrations, especially when the fan is also run for 10 minutes after cooking finishes [10]. However, ADF does not require a performance verification mechanism for cooker hoods. Cooker hood *capture efficiency* (CE) is defined as the fraction of an emitted contaminant that is extracted before it mixes with room air [12]. The CE of a hood is a function of its airflow rate, installation height, hood capture volume, and the fraction of the stovetop covered by the hood [13,14]. An ASTM standard prescribes a steady-state test of CE [15,16]. CEs have not been measured in UK dwellings, but they have been found to vary between 12% [12] and 98% [13] elsewhere. ADF implicitly assumes a CE of 50%.

To test the efficacy of ADF, it is important to investigate whether using a cooker hood makes a tangible difference to the health of the occupants of existing dwellings at a population scale. Therefore, to investigate the reduction in harm to the English population attributable to the installation of a cooker hood in a proportion of all domestic kitchens, this paper uses *averted Disability Adjusted Life Years*, a performance-based health-centred metric, to quantify the change in the burden of disease in a population.

2. THEORY

The US EPA's National Ambient Air Quality Standard (NAAQS) defines six *criteria pollutants*[1] as common contaminants that have an adverse effect on health and wellbeing, and they include particulate matter (PM). In response, an Intake-Incidence DALY method (IND) was defined to estimate chronic health impact for criteria pollutants [6]. The IND-method (eq. 1) uses epidemiology-based Concentration-Response functions to quantify disease incidence rates that, combined with a damage factors (DF), yield the expected DALY losses.

$$DALY\ losses = \frac{\partial DALYs}{\partial(incidence)case} \times \partial(incidence)case \quad (1)$$

A damage factor represents adversely affected life years per disease case, in DALYs.(case)$^{-1}$. The DF for a contaminant h and a specific disease k is represented by

$$\frac{\partial DALYs}{\partial(incidence)case} = DF_{k,h} = Damage\ factor. \quad (2)$$

[1]https://www.epa.gov/criteria-air-pollutants.

The disease incidence refers to a relationship between a contaminant concentration (IAP in eq. 3), a disease (β), and a baseline incidence rate (γ_0). This relationship is modelled with a log-linear Concentration-Response function determined by eq. (3). It is expected that mortality will have a greater effect on the global burden of disease than morbidity and so, for most air pollution-related diseases [5], mortality data is recommended over morbidity data to represent the incidence of a disease.

$$\partial(incidence)case = \gamma_{0_{k,h}} \times (1 - e^{-(\beta_{k,h} \times IAP_h)}) \times population \quad (3)$$

where, $\gamma_{0_{k,h}}$ is the baseline incidence rate of disease k for the contaminant h, and IAP_h is a statistic that describes the concentration of contaminant h. $\beta_{k,h}$ is an empirical parameter that denotes the change in a risk estimate for a given change in contaminant concentration, ΔC, for the disease k and contaminant h. It is represented by

$$\beta_{k,h} = \frac{Ln(Risk\ Estimate)}{\Delta C} \quad (4)$$

3. METHOD

We followed the evaluation of ventilation scenarios presented by [10] for a statistically representative sample of English domestic kitchens. They considered a significant, but not extreme, emission profile where three meals were cooked per day: (1) breakfast that involves the toasting of bread; (2) lunch that involves the cooking one of four typical northern European meals using a gas hob/stove/burner; and (3) dinner that involves the cooking of another of the four typical meals. The duration of each cooking event and the emission rates were all uncertain, and so this was accounted for using a Monte Carlo (MC) approach. The varying geometry of kitchens was also accounted for by sampling volumes from the UK Government's English Housing Survey [17], a statistically representative survey of the English Housing stock.

To investigate the efficacy of ADF, we estimate the harm (DALYs) and benefits (averted DALYs) that occur when the six ventilation strategies, given in Table 1, are applied in all English kitchens.

Table 1:
Ventilation strategies

Strategy	Fan flow rate (L/s)	Details
A	0	Infiltration only
B	13	Constant general extract ventilation at the high rate from ADF
C	60	Intermittent general extract ventilation just during cooking
D	60	Same as C but for an additional 10 minutes after cooking
E	30	Intermittent extract through a cooker hood, CE=50%, just during cooking
F	30	Same as E but for an additional 10 minutes after cooking

The concentrations for each of the six ventilation strategies (parameter IAP_h in eq. 3) are predicted and reported as 24-hour mean average concentrations (μg/m^3) for the existing stock of dwellings in English kitchens [10]. These values are also given probabilistically, so it is possible to sample from their distributions. Methods and outputs that describe the concentration analysis are given in [10].

For the other parameters described in Section 2, there will often be more than one available value or data set; see table 2. Combining or pooling independent data points is the recommended strategy for data synthesization [18] Values for the beta (β), baseline incidence (γ_0), and damage factor (DF) parameters were obtained by combining global systematic reviews with complementary references. To be consistent with the recent literature, we use the WHO's pooled estimate data that describes relative risks associating *All-Cause mortality* (ICD-10 A00-R99) with $PM_{2.5}$ [19]. The baseline incidence rate of diseases was mined from epidemiological studies presented by [19]. The damage factor values are derived from pooled values determined from a systematic review of the environmental burden of disease studies (conducted by the authors) for *All-Cause mortality* and attributed to $PM_{2.5}$.

The number of DALYs associated with the intake of estimated exposure concentrations of $PM_{2.5}$ for the six ventilation strategies were calculated using Equations 1-4. To compare between different ventilation scenarios, *averted DALYs* are calculated as the difference between the best and worst-case scenarios (difference between strategy A and strategy F).

To account for the uncertainty of the parameters, a Monte Carlo (MC) approach was applied as follows. Firstly, a bootstrapping technique is applied to populate a synthetic database for each parameter, which are then described using probability distribution functions (PDFs). Then, the PDFs are combined with the bootstrapped results to generate random samples of inputs that, in turn, are used to calculate the DALYs and averted DALYs. The process is repeated until the results are normally distributed (*convergence criterion*). This technique results in a vector of DALY losses, and so it can be reported using a defined PDF, with its median and 95% confidence interval.

A preliminary analysis of the input data showed that they can be well described by LogNormal distributions around their median. This type of distribution is widely used and accepted to fit right-skewed data adequately [20].

To visually represent the distributions of parameters, we use (violin)plots. The Monte Carlo analyses were carried out using MATLAB. All pooled estimates (meta-analysis) were performed using the "*metan*" commands from statistical software STATA 16.0, which applies the DerSimonian and Laird (random effects) estimator for pooling estimates [22]. Graphs are plotted using MATLAB and *R*.

4. RESULTS

O'Leary [10] predicted median (mean) $PM_{2.5}$ concentrations to be 186 (250) μg/m^3 (96%CI: 39-867) for the worst scenario (Strategy A: infiltration only) and 31 μg/m^3 (96%CI:14-81) for best (Strategy D: using extract through a cooker hood). These values represent exceedances of current WHO-recommended thresholds for (indoor)-$PM_{2.5}$-24h of 15 μg/m^3 [19]. This general exceedance of a recommended threshold was already highlighted by [10] however, the magnitude of the change in health impacts remains. Here, we have extended the analysis to quantify tangible health impacts (harm) associated with their kitchen exposures, assuming that the whole population is exposed.

Table 2 provides descriptive statistics and recommended values for input parameters (See section 2). Table 3 summarises the estimated annual disease incidences and DALYs per 100,000 population for the six strategies on ADF. Estimated mortality due to exposure to $PM_{2.5}$ in the kitchen area is 3.5 times higher for strategy A than for strategy F, therefore, about a threefold reduction in expected mortality cases could be associated with that recommendation on ADF. Here, the chronic exposure-relevant $PM_{2.5}$ concentrations from cooking scenarios was set 100% of the indoor concentration (total intake), assuming exposure occurs every day (all time exposure), therefore, our values must be interpreted as extreme, but possible cases.

Table 2:
Summary descriptives of the model inputs for ALL-Cause.Mortality, $PM_{2.5}$.

	Central estimate (95% C.I.)	Main reference	Datasets
Risk estimate	1.08 (95%C.I. 1.06-1.09)	WHO (2021)	25
Beta[A]	0.008 (95%C.I.0.000-0.002)		
$\gamma 0$[B]	0.007 (95%C.I.0.004-0.015)	Crouse et al. (2015)	1
DF[C]	15.303 (95%C.I.11.798-19.850)	Own data/ syst. review	40

Note: all PDF assumed LogNormal (LogN)
[A] Current global recommended approach [19]; [B] Consistent with [21,23,24]; [C] Consistent with [25].

Table 3: *Summary Annual estimated disease incidences and DALYs, per 100,000 population, and averted DALYs between the best and worst-case scenarios.*

	Disease Incidence Median [mean] (95%C.I.)	DALYs Median [mean] (95%C.I.)
Strategy A	406 [482] (95%C.I. 76-1351)	6063 [7368] (95%C.I. 1108-21788)
Strategy B	214 [264] (95%C.I. 57-778)	3194 [4035] (95%C.I. 814-12456)
Strategy C	209 [270] (95%C.I. 39-866)	3133 [4148] (95%C.I. 563-13774)
Strategy D	107 [140] (95%C.I. 23-458)	1605 [2140] (95%C.I. 331-7160)
Strategy E	178 [236] (95%C.I. 31-784)	2666 [3599] (95%C.I. 444-12302)
Strategy F	121 [159] (95%C.I. 25-511)	1822 [2437] (95%C.I. 364-8165)
Averted $DALYs_{A-F}$	-----	3187 [5016] (95%C.I. 499-20310)

Figure 1 shows the estimates and distributions for annual disease incidences (and corresponding distribution) computed for each ventilation strategy, represented in log-scale on the y-axis. A visual decrease tendency can be noted from scenario A to scenario F, as expected. Figure 2 shows the quantified harm (and corresponding distribution) by different ventilation scenarios. The predicted median for annual DALYs per 100,000 of the exposed population of scenario A (infiltration only) is 6.1×10^3 (95%C.I. $1.1\text{-}21.8\times10^3$). Although the lowest estimates for DALYs are associated with strategy D (60 L/s general extract), strategy F, which represents half that ventilation rate using cooker hoods, yields equivalent DALYs, around 1.8×10^3 (95% C.I. $0.4\text{-}8.2\times10^3$). Regarding the PDFs of the disease incidences and DALYs (see Fig. 1 and 2, bottom), they show similar right-skewed distributions for the different scenarios. Data indicate that the disease incidence and DALYs can be described using log-normal distributions; this detail gains importance when using incidence as an input for the Monte Carlo (MC) approach. Furthermore, it promotes using a median over a mean as the best estimate for a central tendency, for reporting, and discussing these health impact metrics.

We quantified changes in health (as *averted DALYs*) due to interventions designed to lower the exposure to household air $PM_{2.5}$ pollution, defined by the ventilation strategies on ADF (see Tables 1, 3 and blue line in Fig. 2). The results suggest that half of the households (Med) could have approx. median 53% (mean 68%) of reduced harm by implementing a 30 L/s cooker hood with 50% CA, and fan use for the cooking period plus 10 minutes (strategy F), compared to using infiltration only (strategy A) (averted median DALYs as 3.2×10^3, 95% CI:0.5-20.3×10^3 annual DALYs per 100,000 of exposed population).

Similar work by Rosenthal et al. [26] on the health benefits of implementing clean cooking technology for households in a study of 40 low and middle-income countries, following the methodology for averted DALYs proposed by Pillarisetti et al. [27], found that a change from 285 μg/m^3 to 35, 74, and 182 μg/m^3 of the mean exposures in the cooking area resulted from three strategies: changing to LPG, using an advanced fan, and implementing locally made cookstoves. These changes were estimated as 9, 7, and 1.5×10^3 averted DALYs, respectively.

Although both studies quantify the health benefits of applying cooking-related intervention strategies, two main differences are highlighted to fully interpret the comparability of results: (1) Rosenthal et al. [26] focus on $PM_{2.5}$ from combustion sources used for cooking, whilst the present work dwells on $PM_{2.5}$ associated with the meals, and (2) the underlying differences in the methodologies used for the quantification of DALYs. Nevertheless, these harm costs and benefits show the importance of setting intervention strategies and standards that aim to reduce exposure to $PM_{2.5}$, including cooking activities, for high, middle and low-income countries.

Figure 1:
Annual Disease Incidence (in number of cases), per 100,000 population. (Top) Central estimate and 95% C.I. in black; (Bottom) Violin plots for distribution and density of predicted data. The interquartile ranges and mean are shown at the core, while the exterior of the plot shows the data distribution.

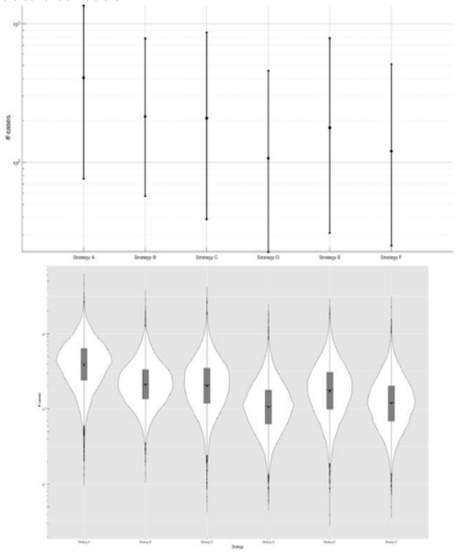
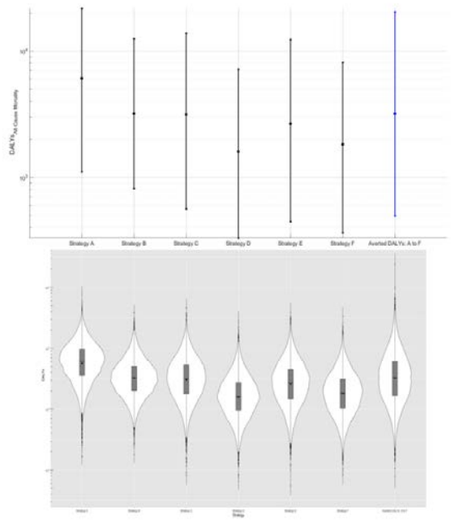


Figure 2:
DALYs by ventilation strategy. (Top) Central estimate and 95% C.I. of DALYs by ventilation strategies in black; Central estimate and 95% C.I. of averted DALYs between strategy A and F in blue. (Bottom) Violin plots for distribution and density of data. Interquartile ranges and means are shown at the core of the plots, while the exterior shows the data distribution.



5. CONCLUSIONS

Averted Disability Adjusted Life Years, related to disease incidence data, were used to compare ventilation strategies on England's statutory Approved Document F for mitigating exposure to $PM_{2.5}$ air pollution from cooking meals, on existing dwellings at a population scale. Our approach yielded a median annual DALYs per 100,000 of an exposed population of Strategy A (infiltration only) of 6.1×10^3 (95%C.I. $1.1\text{-}21.8\times10^3$), whereas instituting a 30 L/s extract through a cooker hood with 50% capture efficiency for the cooking period plus 10 minutes (Strategy F) lowered the harm to 1.8×10^3 (95% C.I. $0.4\text{-}8.2\times10^3$), representing a median decrease by 53% (mean 64%). Health benefits are quantified as 3.2×10^3, 95% CI:0.5-20.3×10^3 averted Disability Adjusted Life Years per 100,000 of exposed population per year by implementing Strategy F over A. Therefore, using a cooker (has the potential to)-make a tangible difference to the health of the occupants. These numbers describe the burden from all-time exposure/intake of $PM_{2.5}$ pollution from the cooking scenarios.

A focus should be made towards health-based metrics, as wide information and data sources exist for computing them. Relying solely on threshold-based approaches might lead to un-accounting the benefits on health burden associated with implementing a pollution reduction strategy, since this change would not be tangible in high (ambient- or indoor)- air pollution scenarios exceeding the chosen threshold. Expected interested parties in these results include policymakers, scientists, and the general public.

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November 22 - 25, 2022

ANALYSIS AND METHODS

DAY 01
12:00 — 13:30

CHAIR
FRANCOIS SIMON

PAPERS
1147 / 1376 / 1459 / 1334 / 1191 /
1687 / 1178

15TH PARALEL SESSION / ONLINE

WILL CITIES SURVIVE?

A structured approach to the evaluation of evidence for the purported role of occupants in energy performance gap

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ABSTRACT: The term energy performance gap appears frequently in literature to describe the gap between energy predictions and actual energy consumption of newly constructed and retrofitted buildings. It has been suggested that occupants' behaviour is responsible for a large share of this gap. In order to obtain a better understanding of the scope and causes of the energy performance gap, a closer look at the occupants' role is needed. In this paper, the purported role of occupants in energy performance gap is assessed via examination of the quality of evidence provided in the respective studies. Toward this end, a quantitative assessment approach is undertaken, whereby numerical rating is assigned to a number of studies in this area. The rating is based on a set of criteria that are believed to be indicative of the strength of the provided evidence. The results of the assessment show that 98% of the studies point to the occupant behaviour as the main cause of the energy performance gap. However, only 6% of the studies provided evidence, whose strength can be characterized as "high". The claimed central role of occupants in buildings' energy performance gap is thus insufficiently supported by the available empirical evidence.
KEYWORDS: Energy performance gap, Occupant behaviour, Numerical assessment, Data, Modelling methods

1. INTRODUCTION

The energy performance gap (EPG) denotes, in this paper, the frequently observed difference between buildings' actual energy use and the corresponding prior predictions. Recently, there has been an increased interest in investigating and understanding the causes of energy performance gap. Multiple instances of recent publications in this area point to occupant behaviour as the dominant contributor. However, related claims have not been conclusively verified. The uncertainty of available occupant data and modelling methods affect the credibility of evidence for the contribution of occupants to the energy performance gap [1,2]. Specifically, the relative contribution of occupants' role as compared to other possible contributors (such as the physical characteristics of the building envelope [3]) remains an open question.

Propelled by a recent international review effort [4], the present contribution explores the potential of a structured approach to the evaluation of evidence for the purported role of occupants in building-related energy performance gap. The elements of this approach and its application are illustrated based on the information reported in recent literature in this area.

2. APPROACH

A recent review effort [4] identified some 144 studies that included content related, among other things, to the occupant-related causes of the energy performance gap. This review involved an explicit definition of the energy performance gap and minimum requirements to include pertinent research papers. For instance, it was expected that the studies include actual measured data on both energy and occupants. Hence, the number of ultimately selected papers for review were reduced down to 51 studies. In the present contribution, we revisit this review toward examining the potential of a structured – numerically framed – rating scheme for assessing the energy performance gap causes in general and the related role of occupants in particular.

2.1 Assessment criteria

Three main assessment criteria were identified, namely the quality of data, the extent (coverage) of normalisation, and the variable match (method used to infer the cause of gap).

The quality of data criterion pertains to the assessment for both energy and occupants. It considers data resolution, duration of monitoring, sources of data, single versus multiple methods for data collection, and the number of measured occupant-related variables.

Normalisation is meant to account for the deviation, in actual building operation, of model parameters other than those related to occupants. The normalisation coverage considers thus the number of variables adjusted for energy use. When more variables (e.g., weather condition, envelope properties) are included in the calculation method used for the energy use prediction, the effect of the suspected cause – in that case – occupant behaviour is better isolated. This helps validate the comparison between predicted energy and actual consumption.

The variable match describes whether the identified cause was directly or indirectly measured. It is sometimes the case when the identified cause is only indirectly determined via the measured variable (e.g., use of artificial lighting as indicator of occupants' presence patterns). However, it is possible that the occupant is present but is not using the artificial lighting. Therefore, the exact match of the suspected cause and the measured variable is included as one of the criteria for the assessment of the evidence for the suggested cause of the buildings' energy performance gap.

2.2 Point system

In order to quantify the assessment of the evidence, three rating categories were assigned, each with a numerical value (see Table 1). Specifically, a weighting scheme was considered involving a simple 2:2:1 ratio for quality of data, normalisation coverage, and variable match.

The variable match criterion is important especially if the suspected cause is indirectly measured. Nonetheless, assigning a lower rating to this criterion was motivated by the (qualitatively ascertained) expectation of its effect on the overall evidence assessment. A larger fraction of studies involved the direct observation of the suspected cause. This implies a smaller effect of this variable on the differentiation among studies in view of the entailed evidence for the purported cause of the energy performance gap.

Table 1: Assessment criteria.

Strength of evidence assessment								**Overall assessment**	
Quality of data				**Normalisation coverage (Number of factors)**		**Variable match (suspected cause directly observed?)**			
Energy		**Occupants**							
Low	0	Low	0	None	0			Low	0 - 2
Medium	½	Medium	½	1	1	No	0	Medium	2½ - 4
High	1	High	1	>=2	2	Yes	1	High	4½ - 5

Energy and occupants' data quality was rated as "low" (point value: zero), "medium" (point value: 0.5), or "high" (point value: 1). Normalisation coverage category was rated according to the number of variables considered for energy use adjustment. Thereby no factors, one factor, and two or more factors resulted in values 0, 1, and 2, respectively.

The variable match criterion received a value of 1 in case the suspected cause was directly measured, otherwise the value was zero.

Given this numeric assessment scheme, a range of values were identified for each category and aggregated toward an overall evidence assessment. Thereby, cumulated points in the range of zero to two points, 2.5 to 4, and 4.5 to 5 resulted in evidence strength labels low, medium, and high, respectively.

Each study was given a code for the purpose of facilitating the search across studies (see Table 2). Thereby, C denotes the suggested (candidate) cause of gap in the study (1: occupant; 2: weather; 3: building systems; 4: construction), T refers to the building's type investigated (1: residential; 2: commercial; 3: office; 4: other), and E expresses the estimated strength of the study's evidence (1: low; 2: medium; 3: high).

3. RESULTS AND DISCUSSION

The outcome of the review is presented in compact form in Table 3. This outcome suggests that 98% of the studies pointed to occupant behaviour as the major cause of the energy performance gap. As it can be seen from Table 3, the code of the majority of reviewed papers starts with C1, which is the code for the suggested cause, namely occupant behaviour. In this context, the frequently mentioned kinds of occupant behaviour included manipulation of temperature set-points (58%), the use of equipment (52%), the presence patterns (44%), and the operation of windows (33%) (Figure 1).

However, according to the numeric assessment results, only 6% of the studies obtained the predicate "high" in view of the strength of their underlying evidence (Figure 2). With this regard, the majority of studies were classified as "medium". As such, most of these studies earned a numerical value of 2.5 points, which is the lowest value in "medium" category (Figure 3).

Table 2: Coding system of individual studies.

Code	**C**	**T**	**E**
1	Occupant behaviour	Residential	Low
2	Weather	Commercial	Medium
3	Building systems	Office	High
4	Construction	Other	

C: Candidate cause; T: Typology; E: Strength of evidence

Table 3: Assessment of studies.

Code	Quality of data		Normalisation coverage (Nr. of factors)	Variable match (cause vs measurement)	Assessment (Numerical value)
	Energy	Occupants			
C1T1E2	Low	Medium	>=2	Yes	3.5
C1T1E1	Low	Medium	0	Yes	1.5
C1T2E3	High	Medium	>=2	Yes	4.5
C4T1E1	Low	Medium	0	Yes	1.5
C1T1E2	Low	Medium	1	Yes	2.5
C1T1E2	Medium	High	1	Yes	3.5
C1T1E2	Medium	Medium	>=2	Yes	4
C1T1E2	Medium	Medium	>=2	Yes	4
C1T1E2	High	High	0	Yes	3
C1T1E3	High	Medium	>=2	Yes	4.5
C1T1E2	Medium	High	>=2	No	3.5
C1T1E2	High	Medium	>=2	No	3.5
C1T1E1	Medium	Low	0	Yes	1.5
C1T1E1	Medium	Medium	0	Yes	2
C1T4E2	Medium	Medium	1	Yes	3
C1T1E2	High	Medium	0	Yes	2.5
C1T1E2	Low	Medium	1	Yes	2.5
C1T1E2	Medium	High	0	Yes	2.5
C1T3E2	Low	Medium	1	Yes	2.5
C1T1E3	High	Medium	>=2	Yes	4.5
C1T1E1	Low	Low	0	Yes	1
C1T1E1	Low	Medium	0	Yes	1.5
C1T1E1	Low	Low	0	Yes	1
C1T3E2	Low	Medium	1	Yes	2.5
C1T2E2	High	High	1	Yes	4
C1T2E1	Medium	Medium	0	No	1
C1T2E2	Medium	High	0	Yes	2.5
C1T1E2	Medium	Medium	>=2	Yes	4
C1T2E2	High	High	0	Yes	3
C1T3E1	Low	Low	0	Yes	1
C1T1E2	Low	Medium	>=2	No	2.5
C1T4E2	Medium	High	0	Yes	2.5
C1T2E1	High	Medium	0	No	1.5
C1T2E1	Medium	Low	1	No	1.5
C1T1E1	Low	Low	0	No	0
C1T1E2	High	Medium	0	Yes	2.5
C1T2E1	Low	Low	0	No	0
C1T1E1	Low	Low	0	Yes	1
C1T1E2	High	High	1	No	3
C1T2E1	Low	High	0	Yes	2
C1T2E2	High	High	0	Yes	3
C1T1E1	Medium	Low	0	Yes	1.5
C1T1E1	Medium	Medium	0	No	1
C1T2E2	Medium	High	0	Yes	2.5
C1T1E1	Low	Low	0	Yes	1
C1T1E2	Medium	High	1	Yes	3.5
C1T2E1	High	Medium	0	No	1.5
C1T3E2	Medium	Low	1	Yes	2.5
C1T1E1	Low	Medium	0	Yes	1.5
C1T2E1	Low	High	0	Yes	2
C1T1E1	Medium	Medium	0	No	1

C: Candidate cause; T: Typology; E: Strength of evidence

Note that energy predictions are typically made based on standard assumptions and not empirical data. In the majority of studies, the temperature set-point is underestimated, particularly in high performance buildings. This is often attributed to occupants' tendency to be less concerned about energy conservation in case of buildings with high thermal quality that are hence considered as energy efficient.

In most cases, equipment use is difficult to predict given the possibility of changes in occupancy situation over time (e.g., increase the number of family members, occupants' age, and occupation). This explains in a number of cases the difference between the expected and actual energy use. This is consistent with a tendency to underestimate, in certain cases, the number of occupants present at different times.

As indicated earlier, indirect monitoring of occupancy lessens the certainty of statements concerning its role in the energy performance gap. A few studies pointed to one of the more straight-forward ways occupants' behaviour can contribute to the energy performance gap, namely the winter-time operation of windows (for ventilation purposes) while simultaneously operating radiators (for heating purposes).

There is high variance in the reviewed studies concerning data quality. The distribution of studies with regard to data quality is shown in Figure 4. Figure 5 shows the data quality separately for energy-related and occupant-related data. The prevalence of low and medium quality assessments in case of energy-related data is mainly the consequence of the data's temporal resolution, as most commonly available energy data are given in monthly or annual formats.

Energy data is mainly collected from bills and energy meters, however other methods (e.g., site visits, occupants' interviews) were used as well. In some cases, additional energy auditing equipment (e.g., separate meters) were used to obtain separate energy data for different energy types (e.g., electricity, natural gas, district heating). In these cases, a clearer view of the distribution of energy consumption and hence a better quality of data could be achieved. In some cases, two or more distinct collection methods were used to obtain more credible energy use data. Most studies process energy data on annual basis.

Concerning the spatial dimension, different scales were considered. Some studies measured energy use per appliance, floor, and several buildings. The majority of studies obtained annual data on the building scale as annual values, which explains the attribution of "low" label to the respective data quality assessment.

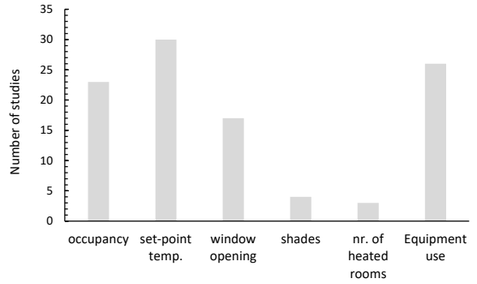

Figure 1: Distribution of the identified causes of EPG.

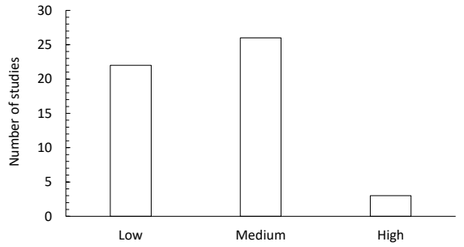

Figure 2: Distribution of the evidence assessment.

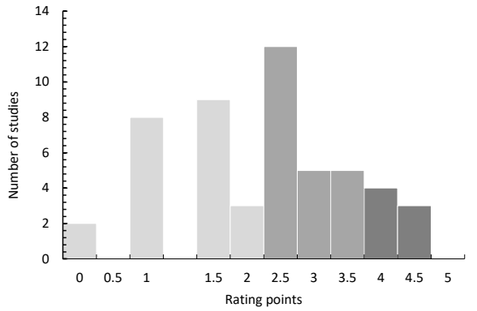

Figure 3: Distribution of studies according to the assessment quality value.

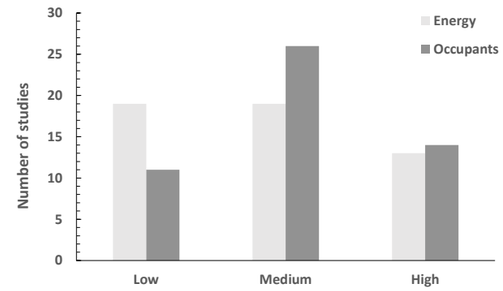

Figure 4: Classification of studies with regard to quality of data.

The distribution of the quality of the occupant-related data is shown in Figure 5. The high frequency of "medium" data quality category is due to data collection method aspects, involving sensors (38%) and questionnaires (37%). A few studies used interviews, observation, and occupancy schedules.

In the majority of studies, the identified causes correspond to the variables measured. Hence, the distribution of the identified causes in Figure 1 corresponds to the distribution of the monitored occupants' behaviour across different studies. It includes set-point temperature, occupancy, window operation, number of heated rooms, and the use of shades. In most studies more than one factor related to occupant behaviour was monitored, which contributes to more "high" than "low" assessments (Figure 5).

Figure 6 shows the distribution of the studies in view of normalisation coverage (i.e., number of factors considered in normalisation). This result sheds light on the distribution of the overall evidence strength as illustrated in Figure 2. Most studies did not include normalisation, resulting in a higher "low" attribution rate.

As to the method to infer the gap cause (direct versus indirect measurement), the distribution of the studies in Figure 7 displayed a pattern similar to that of the normalisation.

Furthermore, the assessment of evidence involved a description rationale for the numerical rating given to each study. This description highlights some issues that need to be considered in future assessments. An example of such an issue can be referred to as the "interdependency of measured variables". What is meant thereby is that the quality of data assessment can be influenced in case of measuring several interdependent variables. When the change in one variable is not explained in the context of other interdependent variables, the data quality and consistency regarding all monitored variables appears questionable.

Consider, for instance, the case where the following variables are concurrently monitored: opening windows, use of thermostat, and indoor temperature. In this case, a plausible scenario would be as follows: When a window is opened, the indoor temperature must change (given a prevailing indoor-outdoor temperature difference), unless the thermostat was also altered or another variable interfered (e.g., increased occupant presence) [5]. Therefore, it is necessary to include a holistic scrutiny of the measured variables, when considering the quality of the respective data.

In the aforementioned large-scale review [4], the gap magnitude (expressed in terms of the relative deviation of the actual energy use from the predicted value) was found to be about 55% (±90%). According to the results of the present contribution, the median value of EPG was highest in the "low" evidence strength category, followed by the "medium" evidence strength category (see Figure 8). Interestingly, studies in the highest evidence strength category displayed both the lowest EPG median and the smallest variance (note that two "outliers" are not included in Figure 8).

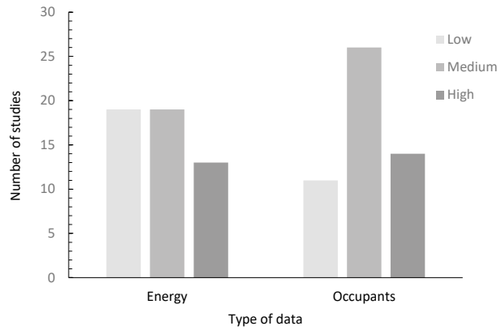

Figure 5: Classification of studies with regard to data quality concerning energy and occupants.

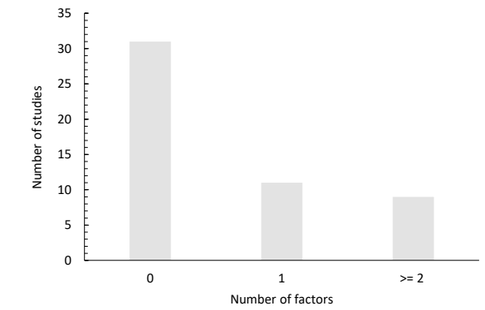

Figure 6: Distribution of the normalisation coverage.

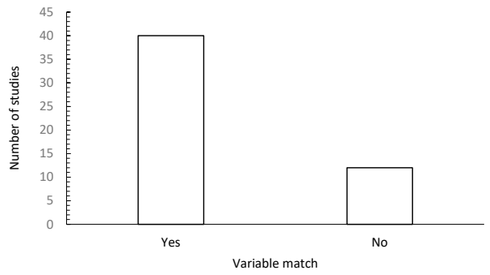

Figure 7: Distribution of the variable match (cause vs measurement).

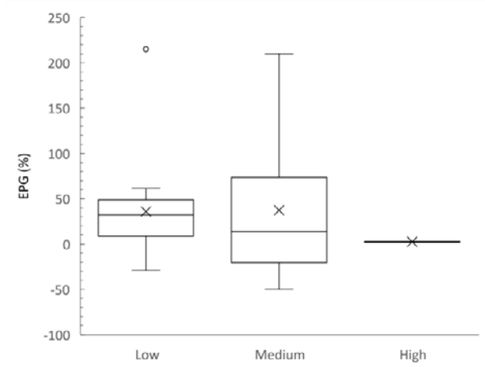

Figure 8: Distribution of EPG with regard to the assessment categories.

4. CONCLUSION

The magnitude of energy performance gap is related to the methods to calculate buildings' energy use. The methods used to estimate energy demand vary across the reviewed studies. Some studies depend on very simple calculations, while others use simulation tools. It has been suggested that the deployment of more complex simulation tools involving detailed occupant models provide more reliable estimations of energy use. However, the review results suggest that more complex models do not necessarily yield better predictions, nor do they necessarily a better job in reducing the energy performance gap.

The majority of the studies do not mention the source of occupant-related model assumptions, which is a data problem. It would be more likely to reduce the occupant-centric performance gap, if, instead of standard occupant-related model input values (e.g., presence patterns, set-point temperatures, equipment use frequency and intensity), observation-based and locally adjusted data could be used. However, this option can be more realistically considered in building retrofit scenarios. A few studies, which investigated retrofit cases of existing structures and utilized actual energy and occupant data in terms of model input assumptions, could display a smaller gap magnitude.

Most studies either did not undergo normalisation or did not disclose the variables for which energy use was normalised. In such cases, a proper comparison between predictions and actual energy use is rather unlikely.

Due to these shortcomings, the purported role of occupants in energy performance gap remains inconclusive. The results of the assessment suggest that only 6% of studies provide a "high" standard of evidence. Most studies were categorized as medium, obtaining mostly the lowest numeric value in this category (2.5 points). As such, it must be concluded that the majority of studies provide rather insufficient evidence with regard to the occupant-related causes of the energy performance gap. In other words, the purported responsibility of occupants for buildings' energy performance gap cannot be suggested to have been generally and conclusively documented in the past research in this area.

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The role for personal comfort systems and room interior layout to improve thermal comfort in the context of insufficient ceiling fan induced air distribution in residential living rooms

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ABSTRACT: Ceiling fans are widely used in Indian residences along with natural ventilation to induce higher air movement for achieving thermal comfort. However, the location of ceiling fans is mostly predetermined in the centre of room and creates a non-uniform airflow distribution. Previous studies have established the effect of these non-uniform airflow on thermal comfort in a living room. The current study explores the seating preferences and factors influencing the decision of interior layouts along with the possibilities for inducing higher air movement for better thermal comfort. Questionnaires are asked to the occupants of the residence, where the air velocity measurements were conducted, to explore the preferences towards various seating locations. The availability of airflow when ceiling fan is operated at maximum speed and the resultant thermal sensation for the four layouts is also assessed. A conscious application of comfort perspective is required in terms of localizing the fan size and number considering the proposed activities and furniture in the interior spaces. Further inadequacy of ceiling fan induced airflow can be substituted by adopting task specific PCS to improve thermal sensations. Such an approach can also reduce the dependency on energy intensive solutions like air conditioning systems for attaining thermal comfort
KEYWORDS: Spatial adaptation, Personal Comfort Systems, Ceiling fans, Seating Preferences, Residences

1. INTRODUCTION

A recent study in Indian households points out that approximately 8% of the households only have room air conditioners, which implies that 92% of the residences depend on natural ventilation (India Cooling Action Plan, 2019). Along with the natural ventilation, fans are widely used to induce higher air movement for achieving thermal comfort. However, the location of ceiling fans is based on generic norms rather than catering to the performance requirements. Even though the presence of ceiling fans increases the air movement in a space, it results in a non-uniform distribution of air, since the higher air flow is limited to the zone directly below the fan (Babich et al., 2017; Jain et al., 2004; Parkinson et al., 2020; Present et al., 2019; Raftery et al., 2019) The air flow inside a space is also affected by the presence of furniture (Gao et al., 2017; Luo et al., 2021), window operation, presence of insect-proof screen (Ravikumar & Prakash, 2011; TK et al., 2021), speed of fan (Bassiouny & Korah, 2011; Chen et al., 2018; Present et al., 2019) and even the room size. The current pandemic situation where people are forced people to work from home (Islam, 2021; Parthasarathy, 2020; Xu & Gao, 2022) has increased the relevance of thermal comfort in residential spaces. Availability of required air movement for thermal comfort can reduce the energy consumption. Ceiling fans play an important role in this aspect. But the location of ceiling fans is predetermined most of the times without considering the proposed activities in a space. This results in unavailability of sufficient air movement as required for multiple activities in the space. A recent study by the authors (Tadepalli et al., 2021) had assessed the distribution of airflow with ceiling fans in residential living rooms with variation in furniture layout. Locations marked away from the ceiling fans experiences a lesser airflow for thermal comfort and experiences a higher thermal sensation. However, there are many other factors which influences the arrangement of furniture. Wagner (Wagner et al., 2018) has identified several factors namely, Physical Environmental Triggers, Physical Environmental Factors, Psychological Factors, Social Factors, Physiological Factors and Non-Adaptive Triggers, which influences the occupant behaviour. Another study by the authors has identified Physical Environmental Factors as major factor influencing the arrangement of furniture in residential living rooms. The current study explores the seating preferences and factors influencing the decision of interior layouts along with the possibilities for inducing higher air movement within the existing context with Personal Comfort Systems (PCS) for enhancing the thermal comfort of the occupants.

2. METHODOLOGY

Previous research by the authors have identified the possible layouts in a living room and the availability of airflow for thermal comfort. However, it was also identified that many other factors also influence the furniture layout. The current study intends to explore the influence of these factors on the seating layout preferences and the role of PCS in enhancing the thermal comfort in a residential living room (Figure 1) in warm humid climate. Outdoor environmental conditions were monitored with a HOBO U30 USB outdoor weather station. HOBO U12-013 Data Logger was installed to monitor Indoor Air temperature, Globe temperature and Relative humidity in the living room. The data obtained from July 2019 to June 2020 is considered for thermal comfort assessment in this study.

Figure 1:
Photograph of the room given in Layout 1

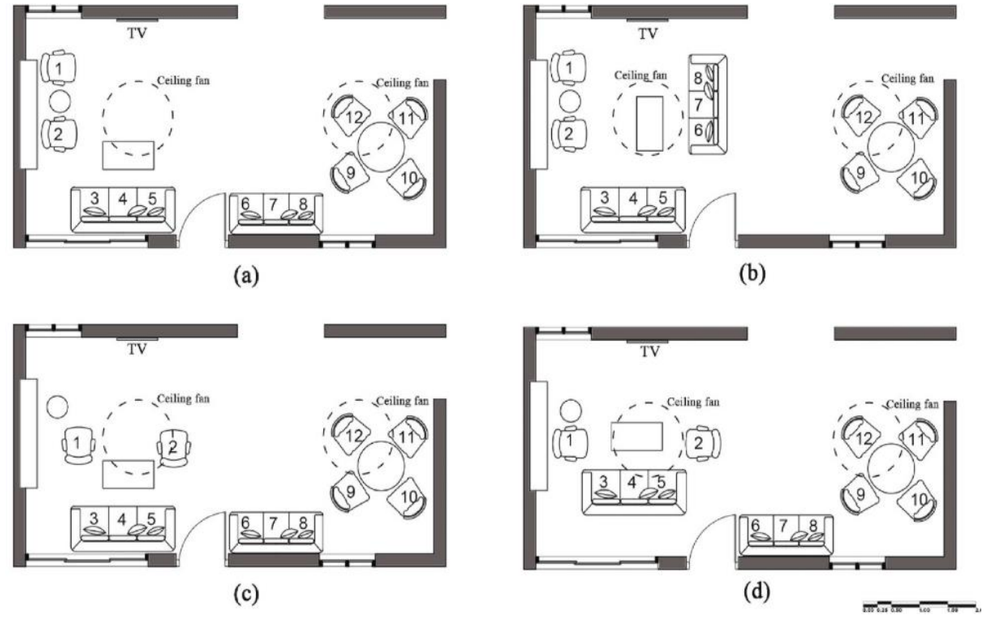

Figure 2:
Layouts of the living and dining room (Tadepalli et al., 2021)

The four layouts identified in a previous study (Tadepalli et al., 2021) are considered in the current study to obtain an overview of the factors influencing the arrangement of furniture layouts in the chosen residence. Accordingly, interviews and informal discussions are conducted with occupants with respect to the furniture layouts as given in Figure 2. A structured questionnaire is also asked to the occupants of the residence, where the air velocity measurements were conducted. The questionnaire explored the preferences towards various seating locations identified and the reasons behind preferences. The respondents were the occupants of the residence which includes 4 adults and a kid.

3. RESULTS AND DISCUSSIONS

3.1 Assessment of the selected layouts and preferences of the occupants

Watching TV was identified as a major activity and the seats were arranged to ensure unobstructed view to TV. Other activities carried out mainly includes family interactions and welcoming occasional guests. Seats 9, 10, 11 and 12 corresponds to the dining space and are placed around the dining table under the ceiling fan. These seats are not changed in any of the layouts owing to the spatial and activity needs in the residence. The inferences for layouts are given as follows:

- Layout 1: The layout was decided to ensure the spaciousness of the room by keeping most of the furniture along the wall. Seats 6, 7 and 8 receive very less air movement from fans and

are relatively uncomfortable and not preferred to be occupied when there is an option.

- Layout 2: The layout ensures higher availability of airflow for comfort. Seats 1, 2, 3, 4 and 5 received lesser air movement while seats 6,7 & 8 received higher air movement. Room was congested with furniture.
- Layout 3: The layout was ensured to have seats 1 & 2 receive higher air movement. Moveable furniture is placed below fan whereas heavy sofa is placed along the wall for spaciousness.
- Layout 4: Seats 1, 2, 3, 4 & 5 were placed below the fan and received higher air movement. Spaciousness of the room is compromised.

With respect to the preferences of the occupants, the occupants preferred seats getting higher airflow from fan while there is an unobstructed view towards the TV. The major drawback identified was the unavailability of higher airflow to all the seats in space. This influences the preference of seats considerably. Previous study (Tadepalli et al., 2021) has identified that certain locations does not receive sufficient air movement irrespective of the fan speed and natural ventilation. Irrespective of complying to the ceiling fan number specified in ceiling fan design guide (Paul Raftery & Douglass-Jaimes, 2020), the required airflow is not attained. Also, as identified from literature, several other factors than comfort needs, influences arrangement of layouts.

The discussions with occupants of the residence revealed that general preferences for seating in living rooms are determined based on relative location of seats with respect to the fan centre, convenience for performing various activities intended to be performed (watching TV, welcoming guests, family interactions etc.), spatial aspects of the building (size of the room, location of windows, door, plug points, light and fans) and expectations and preferences regarding the general aesthetics and functions of the living room.

The factors influencing the furniture layout in the living room under consideration is categorised according to the classification introduced by Wagner (2018) as potential influencing factors driving occupants' behaviour in a building are as follows:

- Physical Environmental Triggers: This includes Indoor air & mean radiant temperature, Indoor air humidity, Indoor air velocity, Contaminants, concentration of air, Outdoor air temperature & humidity, Solar radiation, Wind speed, Rainfall, Illuminance, Luminance, Colour temperature, Daylight factor and Sound level. However, it is identified from the discussions with occupants that only air temperature and velocity were taken into consideration while arranging the layouts. All the furniture were placed under the fan in Layout 2 and majority of the furniture were placed below the fans in Layouts 1,3 and 4.
- Physiological Triggers: The factors under this category are Body temperature, Skin temperature and Skin wetness. None of these factors were considered while deciding the furniture layout. It was justified that these triggers are temporary and if required, occupants move the furniture as required. For example, the occupant would occupy the seat below the fan after a vigorous exercise.
- Physical Environmental Factors: This includes Season, Duration of presence in the room, Frequency, Building quality, Building use, availability & accessibility of controls, operable devices, State of other devices, Clothing insulation level, Interior design and furniture, Ease & convenience of using building system interfaces (light switches), Economics of energy, Presence of feedback systems for energy and View to outside. These factors significantly influence the decision of furniture arrangement in the room. Beginning from the size of the room to the relative importance of the activities being performed in the space are given due importance. A major activity in living room is watching TV. The furniture arrangement is decided based on the availability of plug points, unobstructed view towards TV, spaciousness of the room etc. Layout 2 ensured the unobstructed view towards TV and availability of air from fan while compromising on the spaciousness aspect of the room.
- Psychological Factors: Psychological factors consist of Knowledge, expectations, Preference, acceptability, Perception, Needs about comfort, health, safety, Awareness, Mood, Habit, lifestyle, View/interaction with outdoors and Previous activities which are very subjective in nature. Needs about comfort, habits and general perceptions of the occupants are reflected in the four layouts considered.
- Social Factors: This includes Group interaction, Presence of multiple occupants (e.g., Privacy), Group composition, Social constraints (e.g., dress code), Social status, Education, Country of origin, Safety, Ownership of the building. Living room is the area where guests are welcomed and entertained in a residence. This general perception is indicated in the layouts and area for social interaction is created in the layouts. Layout 2 provides a better case for face-to-face interaction between a larger number of occupants, if required.
- Physiological Factors: This includes Age, sex, weight, Body dimensions, Health state and Ethnic group. The residence consists of occupants with different age, sex and physical features. There has been no major variation in the layouts.
- Non-Adaptive Triggers: Non-adaptive triggers consist of Time of the day and Scheduled activity. The major activities in the living room as identified as watching TV, interaction among family members and welcoming guests. Most of these activities tend happen on evenings or weekends. There has been no major influence of these activities in the arrangement of layouts.

3.2 Requirement of higher air movement for thermal comfort

From the thermal comfort perspective, the requirement of higher air movement for better thermal sensation is a major factor behind the preferences for furniture layout in residences of warm-humid climate. However, the number and location of ceiling fans are pre-decided, and the users have minimum flexibility in altering these aspects. The location of fans were fixed in the centre of the room which can be divided into two 'fan cells' as recommended in Ceiling Fan Design Guide (Paul Raftery & Douglass-Jaimes, 2020). The diameter and spacing of the fans satisfy the recommended criteria. However, the measurement of air velocity in the layouts with different furniture layouts and calculated thermal sensations (Tadepalli et al., 2021) suggest an inadequacy of air movement for thermal comfort.

The monitored data of environmental parameters indicate that the month of May is critical in terms of thermal environmental parameters. The details of the monitored data for May are given in Table 1. The assessment of thermal sensations is conducted with this weather data along with the measured air velocity values when the ceiling fan is operated at maximum speed.

As observed in Figure 2, the higher air velocity in all the layouts is limited to the area directly below the fan even when the fan is operated at maximum speed. Seats farther from the fan location (For e.g., locations 1 & 2 from Layout 1 and Layout 2 and locations 6, 7 & 8 in Layout 1, Layout 3 and Layout 4) experience very lesser air velocity which in turn influences the thermal sensation of the occupants. The thermal sensation of the occupants calculated based on the measured air velocity values (Tadepalli et al., 2021) when the fan is operated on maximum speed are presented in Table 2 in terms of Tropical Summer Index (TSI) and Predicted mean Vote (PMV). Occupants at locations farther from the fan feel 'Slightly Warm' to 'Too Hot' thermal sensation (Tropical Summer Index) even when the fan is operated at high speed, whereas the PMV assessment indicates 'Warm' to "Hot' thermal sensation. Only the locations under the fan where a higher air movement is received experience a better thermal sensation.

Table 1:
Monitored weather data in the month of May

Weather Parameter	Value
Maximum Outdoor Air Temperature (^{0}C)	41.2
Relative Humidity when the outdoor air temperature is maximum (%)	34.8
Maximum Indoor Air Temperature (^{0}C)	37.1
Relative Humidity when the indoor air temperature is maximum (%)	42.9
Average Indoor Air Temperature (^{0}C)	34.4
Average Indoor Globe Temperature (^{0}C)	34.0
Average Indoor Relative Humidity (%)	56.0

Furniture influences the ceiling fan airflow patterns, and the available research is limited to some standard office furniture. Residential furniture is of a very different nature and its impact on the ceiling fan induced airflow pattern is explored minimally (Omrani et al., 2021) except few studies (Jayasree et al., 2021; Tadepalli et al., 2021). The placement of ceiling fans in relation to occupants and furniture appear as a potential design challenge due to the spatial inhomogeneity created by the resulting non uniform air movement (Gao et al., 2017; Liu et al., 2018; Luo et al., 2021). This raises a concern for a critical thinking in terms of the relevance or effectiveness of the guidelines in ensuring required air movement by employing ceiling fans or other Personal Comfort Systems (PCS) in residential activity spaces with furniture.

The study establishes the relevance of:

(a) A more conscious approach towards the selection, number, and size of ceiling fans to be installed in different spaces,
(b) Task specific Personal Comfort Systems (PCS) required for different activities being conducted in a space. This is more applicable to larger rooms where the fan jet zone does not cover the activity areas in the room.

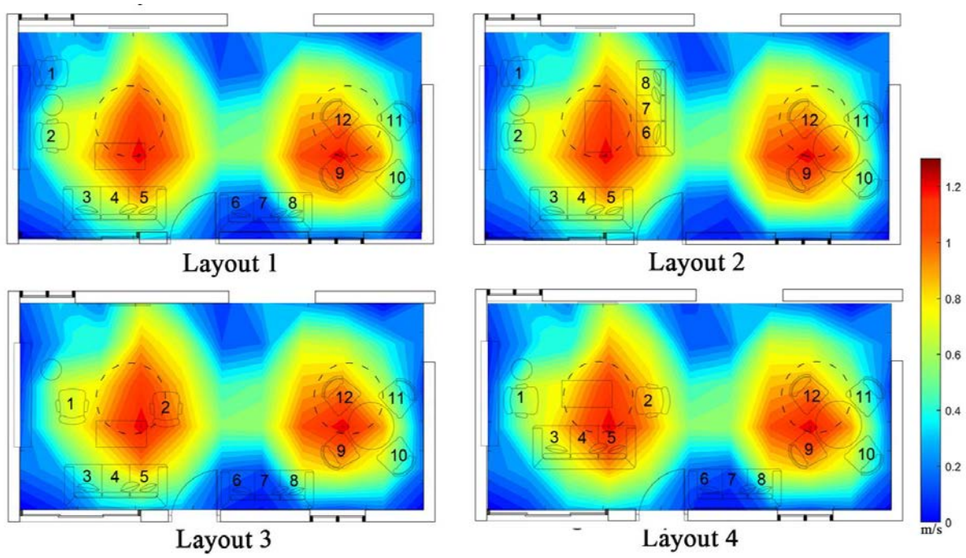

Figure 2:
Air velocity at the four layouts when the fan is at maximum speed.

Table 2:
Calculated thermal sensations (TSI and PMV) based on the measured air velocity values

Location	Layout 1		Layout 2		Layout 3		Layout 4	
	TSI	PMV	TSI	PMV	TSI	PMV	TSI	PMV
1	33.8	2.5	33.8	2.5	33.4	2.1	33.3	2.0
2	33.6	2.3	33.7	2.3	32.7	1.7	32.8	1.8
3	33.6	2.3	33.7	2.3	33.7	2.3	33.2	2.0
4	33.3	2.1	33.3	2.0	33.4	2.1	32.8	1.8
5	33.1	1.9	33.1	1.9	33.1	1.9	32.7	1.7
6	34.1	2.9	33.0	1.9	34.1	2.9	34.1	2.9
7	34.1	2.9	33.2	2.0	34.1	2.9	34.1	2.9
8	33.7	2.3	33.2	2.0	33.7	2.3	33.7	2.3
9	32.7	1.7	32.7	1.7	32.7	1.7	32.7	1.7
10	33.6	2.3	33.7	2.3	33.6	2.3	33.6	2.3
11	33.6	2.3	33.7	2.3	33.7	2.3	33.6	2.3
12	32.7	1.7	32.8	1.8	32.7	1.8	32.8	1.8

3.3 Relooking at the furniture layouts for better thermal comfort and reduced energy consumption

The operation of ceiling fans creates a higher airflow for better thermal comfort. The non-uniformity of air distribution can be reduced to a larger extent by conscious decision of number, size, and location of ceiling fans. Along with this, improvements in layouts to ensure sufficient air movement in each proposed seat can enhance the thermal acceptance of all the occupants. This has a direct implication on the energy consumption in residential sector especially in warm & humid climate. A comfortable thermal environment can be attained with required air movement in humid climates and as a result, the rely on air conditioning systems would be reduced. This approach can bring in a dimension of stability to interior layout and reduce the need for moving furniture for higher air movement.

4. CONCLUSION

This study explores the furniture layouts in a living room and establishes the relevance of adding a 'comfort dimension' to the designing of interior layouts. The availability of airflow when ceiling fan is operated at maximum speed and the resultant thermal sensation for the four layouts is also assessed. A conscious application of comfort perspective in designing interiors is required in terms of localising the fan size and number considering the proposed activities and furniture in the interior spaces. Further inadequacy of ceiling fan induced airflow can be substituted by adopting task specific PCS to improve thermal sensations. Such an approach can also reduce the dependency on energy intensive solutions like air conditioning systems for attaining thermal comfort.

ACKNOWLEDGEMENTS

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Analysing the life cycle carbon performance of a Passivhaus-standard retrofitted suburban dwelling in Hunan, China

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ABSTRACT: Against the background of climate change and resource exhaustion, sustainable retrofitting of existing residential buildings has been widely accepted as a vital way to lower global energy consumption and greenhouse gas emissions in the building sector. The Passivhaus EnerPHit retrofit is considered to have the potential to achieve a large percentage of energy saving compared to most existing buildings. However, research that focused on the environmental impact of the Passivhaus is still considered a small amount. This study aimed to carry out a deep life cycle carbon assessment based on a case building under the hot summer and cold winter climate region in China. The embodied carbon and transport carbon of each retrofitting measure was gathered using the carbon source from the One Click LCA database. The operational carbon of both the pre-retrofit case and retrofitted case for 30 years lifespan was simulated by DesignBuilder with current and future weather files. For the result, the life cycle carbon footprint of pre-retrofit and retrofitted cases showed a significant difference in the changing trend over the lifespan, and at the end, a carbon reduction of 83.4% was achieved in the retrofitted case which equalled to 4 tonnes of carbon saving per square meter of the floor area.
KEYWORDS: Life cycle carbon footprint, Embodied cardon, climate change, Passivhaus

1. INTRODUCTION

Energy retrofitting of existing housing has been recognised as a method with great potential for sustainable intervention in the building sector, in order to respond to climate change and resource depletion. China is expected to take a reasonable responsibility for this intervention because there is a great housing stock in China and the majority of its stock has a poor energy performance. How to efficiently reduce the energy consumption while keeping a good indoor thermal comfort in the existing housing is an important topic. Passive houses can lead to 80-90% energy saving compared with traditional buildings, so are considered to be one of the most effective ways to reduce building energy consumption [1].

Among the existing residential buildings in China, those in the hot summer cold winter zone have the dual demand of space heating and cooling, and so are undoubtedly significant energy consumers. Thus, this paper discusses the efficiency in terms of both energy saving and carbon emission of retrofitting existing dwellings achieving the Passivhaus EnerPHit standard, through a life cycle study of case building located in suburban area of Hunan province, which belong to the hot summer cold winter climate area.

2. LITERATURE REVIEW

The performance of Passivhaus has been widely proven, especially in Europe and cold climate regions [2]. In Europe, over 100 Passivhaus buildings were investigated as part of the CEPHEUS project, and they achieved a space heating demand which was 15-20% of that for standard new buildings [3]. In China, however, the Passivhaus standard is a relatively new concept. The first certified Passivhaus was the Hamburg House at the 2010 World Expo in Shanghai. Since then, over 100 Chinese Passivhaus projects have been completed or are under construction, mainly in the cooler northern regions of the country [4]. According to Yang's study about four Passivhaus projects built in northern China, the simulated results show that the Passivhaus only requires 46% of the total heating and cooling energy if the buildings were built in accordance with the local energy saving standard- which already required a 65% energy saving compared with the conventional building [5]. The first residential Passivhaus built in southern China achieved a 95% energy saving standard compared to conventional dwellings [6].

However, for achieving the strict energy criteria of Passivhaus standard, extra material inputs to the entire envelope fabric, airtightness and mechanical systems of the building are involved [7]. The manufacture of those extra materials can consume a large amount carbon emissions, which are expected to be factored into the construction process of Passivhaus buildings [8]. Moreover, the deep retrofitted building is supposed to operate for many more years, so the time period is actually a significant factor for the performance evaluation. As such, a considerable uncertainty could appear to the initial evaluated results, as many important factors, such as energy consumption and carbon emissions, could accumulate over the lifetime of the building [9].

Life cycle analysis (LCA) is an advanced technique which assesses the entire investments and paybacks over a considered time period [10]. The benefit of life cycle analysis is that it allows many factors to be involved in its evaluation boundary, and it assesses the retrofitted results according to the relative effectiveness and robustness of the retrofitting measures over different time scales rather than a stabilised performance [11]. Overall, life cycle assessment involves all activities, such as the manufacturing process of building materials and products, transportation, distribution, use, maintenance, disposal and recycling that occur in a building's entire lifetime [12].

Although the projects in China suggest that substantial operational energy use in buildings could be reduced by achieving the Passivhaus standard, examples of benefits analysed through life cycle studies are very limited. Therefore, this study is trying to fill this gap through a case study which was previously retrofitted to the Passivhaus EnerPHit standard.

3. SCOPE AND METHODOLOGY

3.1 Case study

The case building (Figure 1) in this paper was a semi-detached 4-storey occupied residential building with a reinforced-concrete structure and no insulation. This building is in the southwest of Hunan province in China and is situated in the hot summer – cold winter climate region. A previous analysis of the case building [13] suggested the annual heating and cooling demand could be decreased from 150.6 kWh/m2a and 42 kWh/m2a under the pre-retrofit status, to 14.9 kWh/m2a and 11.5 kWh/m2a for heating and cooling respectively after a Passivhaus standard retrofitting process. This study aimed to evaluate the performance of the Passivhaus standard retrofitting through a 30 years life cycle assessment, the energy saving and carbon payback time will be analysed.

Figure 1:
The case building of the study.

Figure 2:
The location of the case building on the China's climate map.

3.2 Life cycle analysis

Table 1 demonstrates the building's whole life cycle stages based on sustainability of construction works framework in standard BS EN 15978 and the stages were included in this study.

The embodied carbon data of all the materials and products involved in the retrofit, and the transportation carbon were collected and calculated through software One Click LCA. For the in-use stage, software DesignBuilder was used for simulated the operational energy consumption during the 30 years lifespan with future weather condition considered. The current weather and future weather files for the case region for year 2030, 2040 and 2050 used in DesignBuilder simulation were generated by Meteonorm weather generator using the IPCC AVR4 A1B scenario. For the operational carbon emission during the assumed 30 years lifetime, a carbon conversion factor of 0.87

kgCO2e/kWh for electricity, which represents the current carbon emission for the electricity generated in China based on the One Click LCA database, was used to convert the yearly energy consumption of the pre and post retrofit cases to yearly operational carbon emissions. For the whole life cycle carbon emission, Eq. (1) demonstrates how it was calculated.

Table 1:
The whole life cycle carbon stages and the scope of this analysis

Stages	Include?	Scopes
A1-A3: Product stage	√	Embodied carbon of retrofitting related materials and products
A4: Transport	√	Transport carbon for delivering materials to building cite
A5: Construction	×	Out of scope due to no reliable data source
B: In use	√	Heating and cooling carbon emission over the assumed lifespan, retrofitting products replacement
C: End of life	×	Out of scope due to no reliable data source
D: benefits to future life cycle	×	Out of scope due to no reliable data source

$$LCCF = \sum_{i=0}^{i}(EC^i m^i + TC^i m^i d^i + RC^i) + \sum_{y=0}^{y} OC^y \quad (1)$$

where LCCF - life cycle carbon footprint ($kgCO_2e/m^2$);
EC - embodied carbon value of material i ($kgCO_2e/m^2$);
i - item of material;
m - mass of material I, (kg or m^2);
TC - transport carbon value of material i ($kgCO_2e/m^2$);
d - distance of transport for material i, (km);
y – year;
OC - operational carbon in year y ($kgCO_2e/m^2$);
RC - replacement carbon of material i, ($kgCO_2e$).

4. Results

4.1 Embodied carbon

Table 2 illustrates the embodied carbon data of the materials and products required for retrofitting and building operation, and as mentioned earlier, those data were sourced from the China database of the software One Click LCA. However, there are several products for which the software has no data for Chinese manufacture, thus generic data were used. In addition, produces replacement due to technical life ends during the 30 years lifespan was also considered, - the MVHR system and Air conditioning system required in the retrofitted case and pre-retrofit case respectively both have a technical life of 15 years and one replacement of them is needed during the considered lifespan. Table 2 listed the embodied carbon of those two systems, however, their carbon emission was included in the operational carbon emission rather than the embodied carbon emission in this study.

Table 2:
Embodied carbon data of the retrofitting related materials sourced from software One Click LCA.

Materials list	Embodied carbon
Insulation Rockwool	1.31 $kgCO_2e/kg$
MVHR system	1420 $kgCO_2e$/unit
Air conditioning system	814 $kgCO_2e$/unit
Electricity	0.87 $kgCO_2e$/kWh
Window-triple glazed	80.4 $kgCO_2e/m^2$
Window blinds	23.64 $kgCO_2e/m^2$

Table 3 demonstrates the breakdown of embodied carbon value for each building component and their total embodied carbon. The total carbon emission of the retrofitting was converted to a function unit of $kgCO_2e/m^2$, which was divided by floor area ($297m^2$) of the retrofitted space. Rockwool insulation for exterior wall took the biggest share in the retrofitting, and if the insulation for roof and floors are also taken in account, the insulation material accounts for 73% of the total embodied carbon of the retrofitting, which was 99.33 $kgCO_2e/m^2$.

It is therefore meaningful to highlight that selecting an insulation material with a low embodied carbon value would be a potential way of decreasing the environmental impact. One efficient way is to use organic insulation materials, such as cellulose insulation which is made mainly from recycled paper fibres. It has an embodied carbon value around 0.22 $kgCO_2e/kg$, and it is nearly six times lower than that of Rockwool. In this study, however, Rockwool was originally selected in the retrofitting analysis because it is one of the most used insulation materials in Chinese market. The environmental impact of Rockwool is relatively low compared with other traditional insulation materials; thus, it was decided not to replace Rockwool with an organic insulation material in this case study, in order to reflect carbon influence in the general situation.

Table 3:
Breakdown of retrofitting embodied carbon (EC) of each building component.

	Mass	EC
Ex wall insulation	7563 kg	9907 $kgCO_2e$
Roof insulation	2238 kg	2931 $kgCO_2e$
Floor insulation	2238 kg	2931 $kgCO_2e$
Int floor insulation	4475 kg	5862 $kgCO_2e$
Windows	62 m^2	4985 $kgCO_2e$
Blinds	62 m^2	1456 $kgCO_2e$
MVHR system	-	1420 $kgCO_2e$
Sum		99.33 $kgCO_2e/m^2$

4.2 Transport carbon

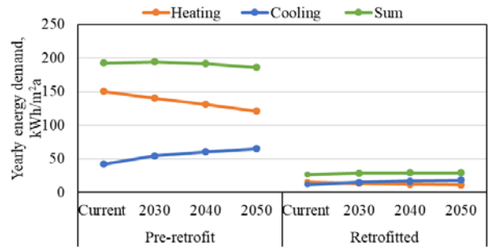
The amount of carbon emissions from transporting the retrofitting related materials from the factories gate to construction site in this life cycle analysis was calculated based on the One Click LCA database, which has a regional typical value for the transport distance and transport method for each product type. The actual distances of the materials that were applied in this case study were unfortunately not managed to record during the site investigation. However, the regional typical values could be more representative of the general situation of the transport released carbon emission in the case region.

For insulation materials, One Click LCA considered they were transported by trailers that has 40 tons of capacity and the distance was fixed to 60 km. For windows and the related items, they were considered with the same transport type with insulation materials, but the distance was 380 km. For the MVHR system, it was delivered by trucks with 9 tons of capacity and the delivery distance was 320 km. As a result, a total transport carbon for the retrofitting plan was 90.9 $kgCO_2e$, and after converted to a function unit in this study, the value was 0.31 $kgCO_2e.m^2$, which could almost be ignorable when compared with the embodied carbon.

4.3 operational carbon

According to the discussed analysis scope, the heating and cooling energy consumption values were required for calculation of the operational carbon emission during the 30 years lifespan. Figure 3 demonstrates the DesignBuilder simulated yearly energy consumptions of both the pre-retrofit case and the retrofitted case under current, 2030, 2040 and 2050 weather condition. The simulated results indicated a big energy consumption difference between the pre and after retrofit condition, which the energy consumption of the retrofitted case was much lower no matter the different weather condition. Moreover, the heating and cooling energy demand had an opposite trend over the time, which were rise and fall respectively for both the pre and after retrofit cases.

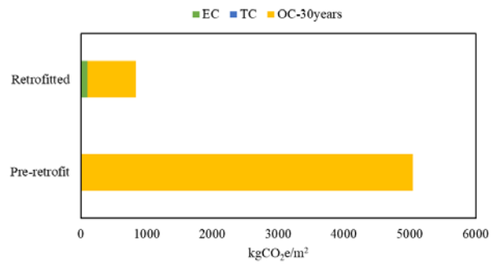
Figure 3:
Energy demand of the case building under pre-retrofit and retrofitted cases and different weather conditions.



4.4 life cycle carbon footprint

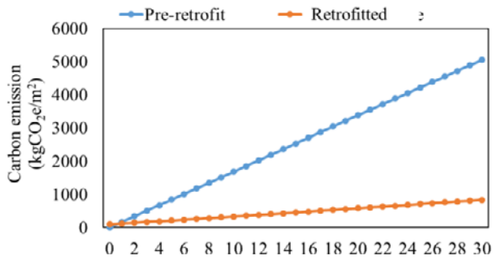
Once the carbon emission in each of the life cycle stages had been calculated, a comparison between the total embodied, transportation and 30 years operational carbon under the pre and post retrofit cases was made. As the result is shown in Figure 4, for the retrofitted case, the percentage of the embodied carbon took about 11.9% in the total emission, and the rest of carbon emission was basically from the operational stage, as the transport carbon could essentially be ignored. For the pre-retrofit case, its operational carbon was about six times more than that in retrofitted case, which was expected, as its energy consumption was higher than the retrofitted cases by large proportions, especially under the current weather condition.

Figure 4:
Comparison between Embodied (EC), transport (TC) and operational (OC) carbon in the retrofitted and pre-retrofit case.



Then, the life cycle carbon footprints of both pre and post retrofit cases were determined and are presented in Figure 5. From this figure, a much obvious upward trend in the footprint of the pre-retrofitted case than the Passivhaus standard retrofitted case could be view. Due to the yearly operational carbon of the pre-retrofit case (165.8 $kgCO_2e/m2$ in current weather condition) was much higher than the retrofit caused carbon emissions (99.3 $kgCO_2e/m2$), the carbon payback time of the retrofitting plans was only one year, and a carbon saving of 85.3% could be achieved in the retrofitted case at the end of 30 years lifetime.

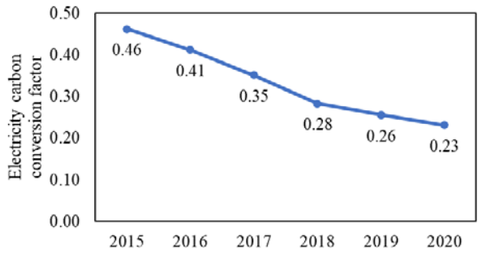
Figure 5:
Life cycle carbon footprint of the pre and post retrofitted cases over 30 years lifespan.



4.5 The uncertainty of carbon emission for energy generation

Furthermore, an issue that should be highlighted is the carbon emission of the secondary energy generation, which could heavily affect the LCCF analysis result, and therefore it is significant uncertainty for life cycle analysis. Operational carbon usually accounts for the largest share of the life cycle carbon, whilst the carbon emissions of the energy production source could change markedly over a building's lifetime. For example, Figure 6 illustrates the carbon conversion factor for the electricity which has been produced in the UK in recent years, where the value was dropped from 0.46 $kgCO_2e/kWh$ in 2015 to 0.23 $kgCO_2e/kWh$ in 2020 because of a decrease in coal use and increase in gas and renewable sources involved in electricity generation [14].

Figure 6:
Carbon conversion factors for electricity produced in the UK in recent years.



Including this factor into the LCCF calculation in this study, the final life cycle carbon result when was greatly changed. When the UK 2020 carbon emission factor for electricity generation was adopted, the life cycle carbon results for the pre-retrofit case and the retrofitted case was doped from 5048 $kgCO_2e/m^2$ and 837 $kgCO_2e/m^2$ to 1354 $kgCO_2e/m^2$ and 299 $kgCO_2e/m^2$ respectively, which were around 3.7 times lower than the results calculated with China's electricity carbon conversion factor. Therefore, it is important to take the change of environmental impact from energy generation in the future into consideration, and the uncertainty from this issue could be lower if the carbon payback could be achieved in the early years after retrofitting is completed.

5. conclusion

The significant benefit in energy-saving of the Passivhaus buildings was widely proven with cases all over the world, while their environmental impact of carbon emission was overlooked by the Passivhaus standard. This study focused on the life cycle carbon analysis in order to assist a comprehensive analysis of the performance of EnerPHit retrofitting measures from perspectives other than energy efficiency, using a case building in China that experienced a hot summer - cold winter climate. The life cycle analysis was carried out for a lifespan of 30 years, and the energy consumption needed for life cycle analysis was simulated with future weather files.

Analysis of the carbon payback time suggested that the retrofitting plans had a very short payback time of just one year, because the retrofitting embodied carbon was less than the operational carbon emission of the pre-retrofit case in just one year. Throughout the life cycle, a carbon reduction of 83.4% relative to the carbon emission of the pre-retrofit case was expected from implementation of the retrofitting plan, equal to a reduction of around 4 tonnes of carbon emissions. However, it was found that the carbon result is highly dependent on the carbon factor of the energy source to operating the building. The above-mentioned results were calculated with the electricity source currently being produced in China. If UK electricity production sources had been used instead, then the carbon payback time would increase to 2 years, and the potential carbon savings in the lifespan would decrease to around 1 tonne. The carbon emissions from producing electricity are expected to be reducing in the future, therefore, the short payback of one year was positive news since the embodied carbon savings could be paid back quickly, and carbon savings in following operational time could be committed even if the carbon efficiency of producing electricity could be largely improved in the future.

In conclusion, the results from this study showed that a significant carbon reduction could be achieved by the Passivhaus EnerPHit retrofitting under China's hot summer and cold winter climate. However, the findings provided by this research were limited within the research scope, which only considered the main life cycle stages of a building. Moreover, economic analysis should be another essential factor to consider for Passivhaus standard retrofitting because it is a major element for the building industry to select this method of retrofitting. Therefore, further analysis should cover a detailed life cycle cost assessment in the next step of this study.

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Impact of Plan-Form on climate loading of an office building

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ABSTRACT: Buildings consume more than one-third of the world's total primary energy. The weather has a unique and vital role since it directly impacts thermal loads. The early design stage requires an informed design decision regarding building system strategies, such as the shape and size of the plan form. Thus, the relationship between the climate variables and plan-form needs to be analyzed. This study uses different plan forms, orientations, depths, and a fixed window-to-wall ratio to evaluate small to medium size office buildings. The paper's first part establishes the environmental load's threshold impact on different plan forms. The second part demonstrates the relative impact of each climate variable at the minimum and the threshold of each plan---form. The study forms the basis for building engineers and architects to select the best plan form for the desired location.
KEYWORDS: Energy, Comfort, thermal load, weather file, climate variables.

1. INTRODUCTION

In the advent of rising energy demand and climate change, energy efficiency is crucial for maintaining thermal comfort levels. As per the Bureau of Energy Efficiency (BEE), buildings account for 35% of India's total energy consumption, with an annual growth rate of 8% [1]. Their analysis under the UNDP-GEF-BEE Project covering 1160 commercial buildings shows a higher energy performance index (EPIs) for small-sized buildings with extended operating hours [1]. Thus, this paper aims to develop a methodology to identify and establish the relationship between different plan forms of various sizes with climate thermal loading.

The building plan form is the only variable that does not change during a building's lifetime and may impact its long-term performance. As per studies by Y.Hong et al., the plan ratio is the most sensitive passive strategy for building energy performances in high-rise office buildings [2]. Another paper by Rajapaksha states that it is essential to comprehend the importance of plan-depth as a design element in dispersing indoor air temperature due to heat stress through building façades in the tropics [3]. Similarly, N.Thakur et al.; suggests a minimum perimeter to area ratio, compact planning and a longer façade facing north-south to address building form and massing in the composite climate of India [4]]. According to parametric analysis performed by A. AlAnzi et al., the effect of building shape on total building energy use is essentially determined by three factors: relative compactness (RC), window-to-wall ratio (WWR), and glazing type [5]. The relationship between building energy consumption and climate variables is studied by Z. Wang et al. to predict future building energy consumption [6]. It has been observed that limited studies establish the relationship between building energy performances - climate variables and building energy performances – plan form.

This paper evaluates the relationship between the plan form and climate loading for a composite climate as per the National Building Code of India (NBC). The composite climate overlaps monsoon-influenced humid subtropical (Cwa) and semi-arid (BSh) as per the Köppen climate classification. The selection of composite climate type is based on the fact that it has the most varied climate types along the year, with none exceeding six months.

The two objectives of this study are:

a) To identify the built-up area threshold up to which the energy demand is driven by climate loading.

b) To establish the relationship between climate variables and energy demand for different plan-form configurations.

The utilization of space cooling and heating accounts for over half of all final energy use in buildings. Therefore, the impact of climate variables is measured against energy demand for different plan forms.

2. METHODOLOGY

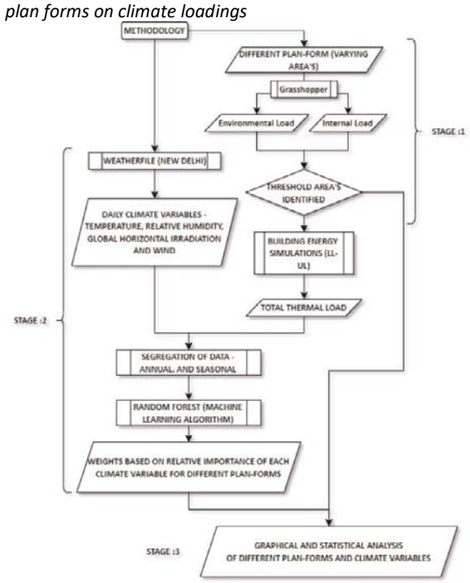
The methodology is performed in three steps, as shown in figure 1:

a) The first step establishes the threshold built-up area up to which the climate variables dominate the energy demand over the internal load.

b) The second step establishes a relation between the climate variables and energy demand with respect to different plan form configurations.

c) The third step includes analyzing the relationship between the different plan forms and each climate variable.

Figure 1: *Methodology to study the impact of different plan forms on climate loadings*



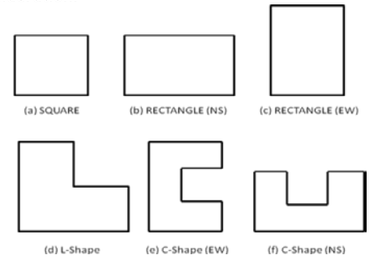
The grasshopper software tool creates 3D models of the four small to mid-size office building plan-form configurations that comply with Energy Conservation Building Code (ECBC) guidelines [7].

The plan forms considered for this study are square, rectangle, L-shape and C-shape, having fixed orientations as shown in figure 2. These plan forms are typical layout plans for mid-rise office buildings.

a) Architectural conditions

The building material considered for the simulation models of wall construction are bricks and cement mortar, having a U-value OF 2.28 ($W/m^2.K$) in compliance with SP-41. The floor and roof are considered adiabatic as mid-rise office buildings have intermediate floors, where the roof and floor are not exposed to the outdoor environment. Window wall ratio (WWR) is consistently distributed in all cardinal directions. The WWR for vertical fenestration is taken at 40%, having a U-factor of 2.2 ($W/m^2.K$) as prescribed under ECBC guidelines. The modelled mid-rise office plan forms were assumed to have the same function, material and typical floor area.

Figure 2: *Plan forms and the orientations under consideration.*



b) Engineering conditions

Two models for each plan-form are simulated – one for environmental thermal loading having a cooling set point at 25°C and heating set point at 23.5°C and dehumidification at 50% as per ASHRAE standards. Ideal loads air system to obtain sensible and latent thermal loads is considered. Further, infiltration of 0.3 $L/s{\cdot}m^2$ is used. Another model having combined environmental and internal thermal loadings is simulated. In this case, in addition to the conditions mentioned above, the interior lighting and equipment loads increased constantly based on the occupant load of 10 people per 100 sq. meter as per NBC general building requirements. The operational schedule is from 8 am to 6 pm, with Saturday and Sunday as holidays.

2.1 Threshold built-up area identification

Each shape is simulated, taking into account both environmental and internal loads. The resultant – sensible and latent loads for heating and cooling are added to obtain total thermal loads. The threshold area is selected at the cross-section where internal loads dominate the total thermal loads compared to environmental loads.

2.2 Random Forest Regressor

Random Forest is a supervised learning algorithm which uses ensemble learning methods for regression. It applies multiple decision trees and bagging techniques. This model uses two concepts:

1. A random sampling of training data points when building trees.
2. Random subsets of features are considered when splitting nodes.

The random forest is based on hundreds or thousands of decision trees. A decision tree is an intuitive random forest building block model that trains each one on a different set of observations at random, separating nodes in each tree based on a restricted number of attributes. Averaging the forecasts of each decision tree yields the final predictions. Each tree in a random forest learns from a random selection of data points during training. Because the sample is drawn via

replacement or bootstrapping, certain samples will be utilized numerous times in a single tree. The theory is that by training each tree on various samples, even if each tree has a lot of variance with regard to a specific set of training data, the overall variance of the forest will be minimized, but not at the expense of bias.

At test time, predictions are made by averaging each decision tree's predictions. However, in this study, we are not concerned with the predictions; thus, 100% of the dataset is used as a training dataset for determining the coefficient of determination (R-sq). Unlike linear models, random forests can capture nonlinear interactions between the feature and output.

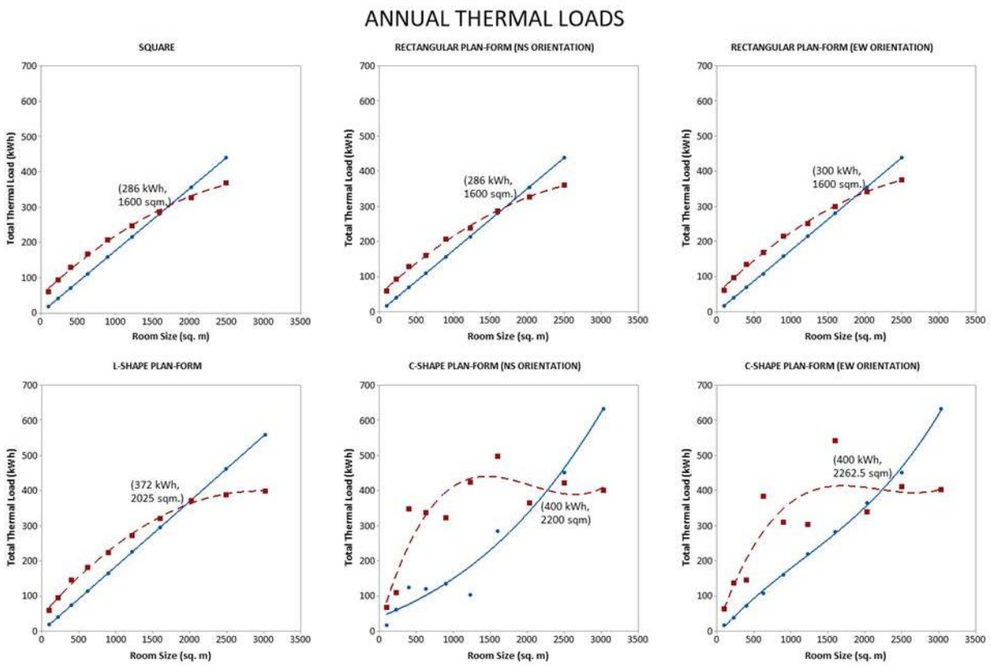
2.3 Graphical and Statistical Analysis

In this section, the threshold area of each plan-form is identified under which the impact of environmental climate loadings is still more significant than the internal thermal loads.

Further, to derive the relative importance of each climate variable for each plan-form, a random forest algorithm is used. The lower limit (LL) presents the minimum plan-form area, and the upper limit (UL) presents the threshold area at which the internal loads start to dominate.

3. RESULTS AND DISCUSSION

Figure 1: *Comparison of annual Internal and environmental thermal load for different plan forms.*



3.1 Annual thermal load

For each plan form under consideration, the thermal load due to environment boundary conditions and internal load is simulated to find the threshold value up to which the impact of climate loading is dominant. Figure 4. presents the average annual results of the simulations for various plan forms under consideration. The environmental load peaks at 286 kWh with 1600 sqm for a square plan form. Whereas for an L-shaped plan form highest environmental load is 372 kWh with a 2025 sqm floor area. Thus, despite the same surface area-to-volume ratios for both cases, the L-shape plan form has 30% higher environmental loading than the square form. Figure 2 shows rectangular and C-shape plan forms having two orientations. The rectangular plan form (NS) has a 286 kWh environmental load with a 1600 sqm floor. Square plan form and rectangular(NS) plan-form simulate similar results as rectangle form short side is exposed east-west orientation. The rectangular plan form (EW) has a 300 kWh environmental load with 1600 sqm. Thus, the rectangular form (EW) orientation has a 5% higher environmental load than the rectangular (NS). In C-shape (NS), the environmental load dominates the total thermal loads up to a floor area of 2200 sqm, beyond which the internal load influences the total thermal load. For a C-shape (EW), the environmental load dominates the total thermal load up to 2262.5 sqm, beyond which the internal load dominates. In C-shape, at 625 sqm and 1600 sqm, they exhibit relatively higher environmental load (350-390 kWh and 500 - 550 kWh, respectively). Both these areas have the minimum depth compared to all the other areas under consideration.

Among all the shapes considered, the square plan form has the least environmental loading, followed by a rectangle. The l-shape plan form has the same surface-to-volume ratio as the square and has a threshold area and environmental load of 2025 sqm and 400 kWh, respectively. The C-shape plan form has a maximum threshold area ranging between 2200-2262.5 sqm, with approximately 400 kWh environmental loading.

3.2 Seasonal thermal load

In this section, the seasonal thermal loads are simulated to identify the floor areas in which the environmental loads dominate the total thermal loads. The environmental loads are dominant for larger floor areas during the summer season compared to the winter season for all the plan forms. The loading during the monsoon season is similar to that of summer. The environmental loads and floor area for the summer month- May are higher when compared to the average annual environmental loads and floor area, as shown in figures 4 and 5. The average annual environmental loads for square form are dominant till 1600 sq.m floor area as shown in figure 4 whereas, for the summer month-May, it is more than 2500 sqm as shown in figure 5.

The environmental load for the square plan form at 1600 sqm for the summer month is 404 kWh, whereas the annual average is 286 kWh (41.26% lesser). The threshold area up to which environmental loads are dominant in square form is still not achieved at 2500 sqm—having 519.16 kWh as environmental load. The rectangular plan form follows a similar trend. L-Shape annual environmental load is 372 kWh for a floor area of 2025 sqm, whereas for the summer month – the value exceeds 589.45 kWh having a threshold floor area of 3025 sqm. As indicated in figures 4 and 5, the C-shape form has an average annual environmental load of around 400 kWh for a floor area spanning 2200 - 2262.5 sqm. Still, for summer, the environmental load increases to 636.81 kWh with a threshold floor area of 3025 sqm. Thus, a 59.2% increase in environmental load and a 33.7% increase in the threshold area during summer are observed. Amongst the studied plan forms, it is observed that the square plan form exhibits the highest variation in the environmental load of 81.52%.

Figure 5: *Comparison of Internal and environmental thermal load for different plan-forms during summer month –May*

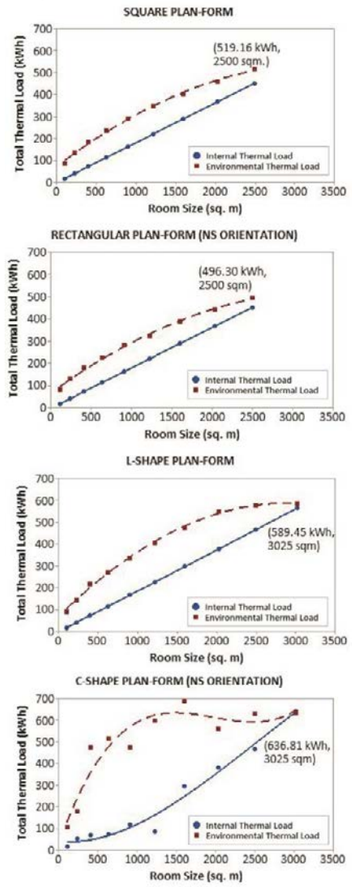
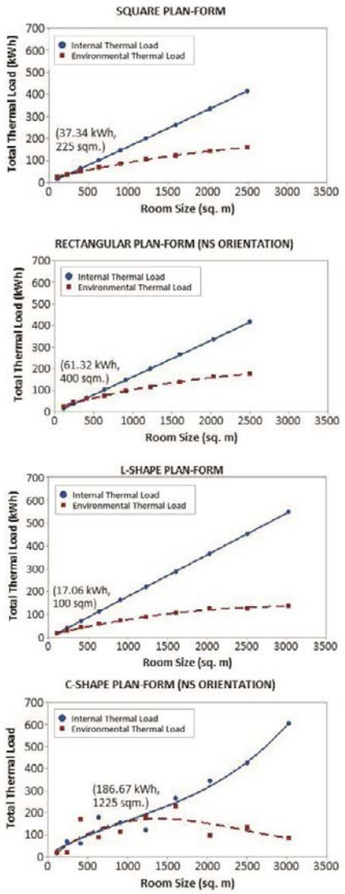


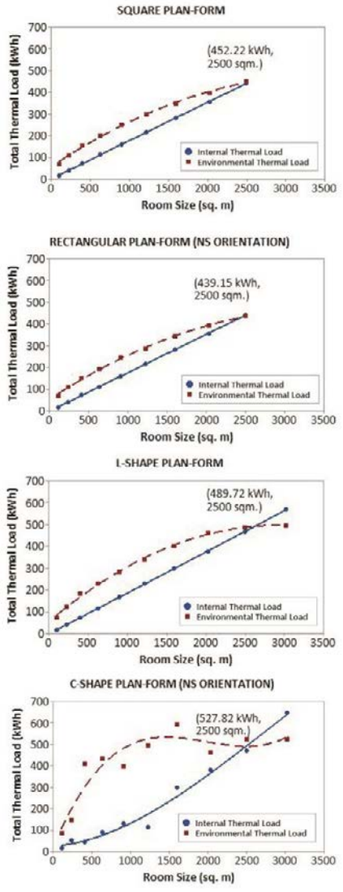
Figure 2: *Comparison of Internal and environmental thermal load for different plan-forms during winter month –December*

The winter month – December is plotted for all the plan forms, as shown in figure 6. This month is least impacted by the environmental loads having a minimum threshold area across each plan form.



Environmental load is 37.78 kWh with a floor area of 225 sqm for square form during winter, 86.94% and 85.94% less than the average annual environmental loading and area, respectively. Similar results are observed in rectangular plan form (NS) as equivalent side length is exposed to an east-west orientation. L-shape plan-form has the least environmental loading of 17.06 kWh having a floor area of 100 sqm, which is 95.4% and 95% less than the threshold average annual environmental loading and threshold area, respectively. C-shape plan-form has an environmental load of 186.67 kWh with a threshold area of 1225 sqm for the winter month, which is 48.9% and 44.3% less than the average annual threshold environmental load and threshold area, respectively. Thus, it is concluded that during winter, L-shape is the most and the C-Shape is the least impacted plan-forms.

Figure 3: *Comparison of Internal and environmental thermal load for different plan-forms during monsoon month –August*



The monsoon month - august, is plotted for all the plan forms under consideration, as shown in figure 7. This month also has higher values for all plan forms than the average annual threshold area and thermal loadings. For square plan-form, the rise in the monsoon month threshold area and thermal loadings is 56.25% and 58.12%, respectively, compared to the annual threshold area and thermal loadings. L-shape and C-Shape plan-form show threshold area for monsoon month at 2500 sqm, which is 23.46% and 13.64% more than the average annual threshold area, respectively. The rise in thermal loading of L-shape and C-Shape plan-form in comparison to annual is 31.65% and 31.96 %, respectively. Thus, it concludes that the square is the most impacted plan form in monsoon month, whereas the l-shape is the least.

3.3 Relation between the climate variables and energy demand

Under this section, statistical analysis of climate variables compared to total thermal load is performed for the annual data. A random forest regressor algorithm calculates the climate variable's relative importance in building thermal performances. The coefficient of determination (R-sq) is studied for each plan form to evaluate the data's fit. Since the target is to extract the feature importance and not a prediction, 100% of the data is taken as training data. Relative weights are evaluated for the lower limit floor area (LL) and the upper limit floor area (UL). Environmental loads dominate for LL, and internal loads dominate for UL.

Table 1: *Relative weights for different plan-forms are computed using a random forest algorithm*

WEIGHTS	T-MEAN	T-MAX	T-MIN	RH-MEAN	GHI - mean	GHI-max	Wind-mean	Wind-max
SQUARE (LL-UL)	0.53-0.18	0.33-0.18	0.02-0.09	0.03-0.11	0.03-0.17	0.02-0.10	0.02-0.09	0.01-0.08
RECTANGLE – NS (LL-UL)	0.65-0.18	0.73-0.19	0.01-0.10	0.07-0.10	0.04-0.18	0.07-0.10	0.02-0.08	0.01-0.07
RECTANGLE – EW (LL-UL)	0.45-0.17	0.40-0.16	0.02-0.10	0.04-0.12	0.03-0.18	0.02-0.10	0.02-0.09	0.01-0.07
L-SHAPE (LL-UL)	0.63-0.18	0.23-0.17	0.03-0.09	0.02-0.11	0.03-0.17	0.02-0.11	0.02-0.09	0.01-0.08
C-SHAPE – NS (LL-UL)	0.74-0.23	0.17-0.22	0.01-0.09	0.02-0.10	0.03-0.14	0.01-0.09	0.01-0.08	0.01-0.06
C-SHAPE – EW (LL-UL)	0.57-0.24	0.31-0.22	0.02-0.08	0.03-0.10	0.02-0.13	0.02-0.09	0.02-0.08	0.01-0.06

Mean temperature followed by maximum temperature is the most crucial feature contributing to the environmental loading, as shown in Table 1. At the UL of each plan-form, the relative importance of mean-relative humidity (RH-mean) and mean-global horizontal irradiation (GHI-mean) are higher, followed by maximum global horizontal irradiation (GHI-max), minimum temperature and wind. In contrast, the relative importance of mean temperature (T-mean) and maximum temperature (T-max) is lesser.

C-shape, the least impacted plan-form in every season, has the highest relative importance of 0.74 for T-mean due to environmental loadings, while the rectangle (EW) has the least. T-max for environmental loads impact the rectangular plan-form(EW) the most, followed by the C-shape plan-form(EW). T-min has risen significantly for rectangular (NS) plan-form when internal loads become dominant. Change in orientation from NS to EW changes the significant climate variable from T-mean to T-max under environmental loadings.

4. CONCLUSION

This study concluded that the environmental loads and their corresponding threshold floor area vary significantly seasonally for a composite climatic location compared to average annual conditions. Among all the plan forms considered C-shape plan-form performs best in every season with the least variation in environmental and threshold areas. In comparison, the square is the most impacted plan-forms in summers and monsoons, and L-shape in winters.

In this study, it has also been observed that the critical attributes of plan forms that impact the climate loadings are the depth of the plan form and surface-to-volume ratio.

Quantifying the impact of climate variables helps determine the significant contributor to the environmental loadings. C-shape might be the most consistent plan-form for all the seasons but has the highest environmental impact due to T-mean followed by T-max. Further investigation is required related to the impact of different plan-form on climate loadings as it varies quite significantly under different seasons.

5. ACKNOWLEDGEMENT

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Historical Building Retrofitting Based on Brazilian Energy Efficiency Legislation:
Evaluation of Energy Consumption Reduction

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This paper presents the results of a retrofit proposal to improve the energy efficiency of a historical university building based on a previously obtained Brazilian National Energy Conservation Label (ENCE) that evaluated the building envelope, lighting and air-conditioning systems. The study was based on improvements proposed to these systems respecting the building's historical character. For the envelope, as most of the building is naturally ventilated, the percentage of thermal comfort hours was evaluated. The façade painting was revitalized and the roof received insulation which resulted in an improvement from 69% to 84% in thermal comfort hours. For the other systems a simple payback analysis was carried out. Results indicated that an artificial lighting renewal presented a predicted reduction of 28% of electric energy consumption for this end-use, with a 9-month payback. In the few artificially air-conditioned rooms an update of 50% of the installed devices to more efficient ones allowed a predicted reduction of 32% on energy consumption for this end-use with a 7.5-year payback. It is considered that significant improvements were achieved in the three systems and the ENCE analysis propitiated an objective diagnosis of the possible interventions to enhance energy efficiency that suits a historical building.
KEYWORDS: Retrofit, Energy Efficiency in Buildings, Heritage Retrofit, University Building, RTQ-C

1. INTRODUCTION

Energy related CO2 emissions have risen in recent years (IEA, 2020), therefore, the retrofitting of existing buildings is highly necessary so Sustainable Development Goals can be reached (UN, 2021). In Brazil, the Technical Regulation on the Quality of the Energy Efficiency Level of Commercial, Services and Public Buildings, RTQ-C, emits a National Energy Conservation Label (ENCE) that varies from A to E, rating 3 systems: envelope, artificial lighting and air conditioning (PBE EDIFICA, 2021). The adoption of the labelling system is mandatory for new federal public buildings since 2014 and voluntary for other typologies. From its implementation in 2009 until September of 2021, RTQ-C culminated in the publication of 275 ENCES, from which 64 are of federal public buildings.

Public universities can play a crucial role towards sustainable development goals as they form future decision-makers (Mohammadalizadehkorde and Weaver, 2018). Furthermore, buildings retrofitting can decrease its operational costs. In Brazil, in the last few years it became common that public universities go through budget contingencies, therefore, energy consumption reduction is relevant for their building administrators. However, there is still little research on the retrofitting possibilities of this type of buildings in the country, especially when there is an additional challenge regarding restrictions due to the historical value of such building.

Previous work shows that different Brazilian public universities present heritage protected buildings in their campuses (Ramos and Rego, 2021; Anzolch and Giralt, 2019). Hence, the relevance of studying energy retrofitting of historical university buildings is reinforced.

Garcia *et al.* (2019) employed RTQ-C regulation to analyse the energetic efficiency of the envelope of a public higher education building in Joinville, Southern Brazil (Brazilian bioclimatic zone, BZ, 3), built in 2019. The envelope classification of the building was verified as level D. Although the roofing contained sandwich tiles, windows presented no shading devices. Authors suggested retrofitting strategies such as the implementation of solar protection on windows, the usage of reduced solar-factor glasses and lighter colours on the façade. No analysis of energy efficiency considering the adoption of retrofitting strategies was presented.

Quevedo, Baumann and Versage (2017) conducted an envelope classification of a public high education building in Florianópolis (BZ 3) according to RTQ-C. Authors showed that the studied building reached level A on envelope energy efficiency by the adoption of architectonic strategies well suited for the local climate.

Ferraz et al. (2018) analysed the energy efficiency of artificial lighting and air conditioning systems of a public university building in Ilhéus (BZ 8). The diagnose indicated level C for the lighting system, that was composed by fluorescent light bulbs with light power of 32W. The replacement of the light bulbs for LED was suggested. A payback time of 10.5 months was cited. The air conditioning system was diagnosed with level C. The update for more efficient devices was suggested. No study of the new energy efficiency classification after the adoption of LED and new air conditioning systems was presented.

Previous work (Garcia, 2022) showed that 27 academic buildings from the Brazilian Federal University of Minas Gerais in Belo Horizonte (BZ 3) presented an average energy use intensity (EUI) of 33 kWh/m²/year. The encountered EUI was considered low compared to international higher education institutions. Authors conducted a thermal comfort survey indicating high levels of heat discomfort in classrooms. It was highlighted that thermal comfort should be accounted for energy efficiency studies, mostly in buildings with mixed or natural ventilation, because low EUI could be coupled with low thermal conditions.

The Architecture and Design School (EAD) of the Federal University of Minas Gerais (UFMG) is located in Belo Horizonte (BZ 3). Its main building (Fig. 1 and number 0 in Fig. 2), originally from the 1950's, is representative of the Modernist Architectonic Movement in Brazil and it is listed as a heritage asset, which restricts changes in its facade characteristics. The first expansion project (number 1, Fig. 2) was built shortly after the original building. This area has an intermediate restriction level, in which the relation between the architectonic volumes and the spatial organization around the inner patio must be preserved. The second expansion (number 2, Fig. 2) consists of a free intervention zone (DOM, 2009).

Figure 1:
EAD original building. Source: UFMG (2018).

In 2012, the school received an ENCE reaching the rates B for artificial lighting and C for the building envelope by a prescriptive (simplified) method. No classification for air conditioning was obtained as it required a thermal simulation, not possible to be carried out at that time. Afterwards, a simplified thermal comfort assessment tool was developed and it is used in the present study. This tool was then incorporated in the new Brazilian energy efficiency labelling, the INI-C (INMETRO, 2018).

Figure 2:
Heritage protection areas

This paper presents then the results of a retrofit proposal to improve the energy efficiency of this historical university building based on the methodology of the Brazilian rating systems RTQ-C and INI-C (for the thermal comfort evaluation). Optimization proposals were developed respecting the historical character of the building. Also, a payback time analysis was verified to build grounds for future decisions regarding financial investments in the building.

2. METHODOLOGY

The method was based on three steps: at first, a verification of each system considered in RTQ-C was made once the existing label is from 2012 and could be outdated. Then, optimization strategies were proposed to reach lower energy consumption and better thermal comfort for the building. There is a chance that naturally ventilated buildings present low energy consumption but poor thermal comfort conditions, so this paper developed an integrated analysis of the retrofitting alternatives using a simplified tool for thermal comfort assessment described by Rackes et al. (2016). The entrance data included aspects such as: building form and layout; window geometry and shading; construction properties; internal gains and schedules and natural ventilation and air flow network.

This step was followed by a calculation of a simple payback time, which does not consider the variation of money value though time. Simple payback time formula is shown in Equation (1). Materials prices and needed services for the optimization solutions implementation were obtained through local stores websites, telephone and emails.

Payback time = initial investment / savings. (1)

2.1 Envelope

The diagnosis was developed through photographic registration to verify if façade and roof solar absorptance (α) levels were the same as the ones described in the ENCE. Thermal transmittance (U) values were obtained by the existing ENCE report (CERTI, 2012) and then checked through on-site visits. Current α and U values were compared against RTQ-C limits for energy efficiency levels.

A renovation of each of the façade's finishes was proposed respecting the original design specifications to obtain level A. The area of each material was calculated based on technical drawings, and its solar absorptance value was obtained from Dornelles (2008) considering the materials as new/renovated according to the original design. The retrofitted building's weighted average absorptance was then calculated and compared to the RTQ-C parameters.

Roof U was verified to be different from the ENCE report and then calculated based on the Brazilian Thermal Performance in Buildings Regulation - NBR 15220-2 (ABNT, 2003). Two optimization solutions were proposed, the first consisted of existing materials renovation and adequation and the second of new roofing material implementation.

The effects of envelope retrofitting were also analysed considering gains on building's thermal comfort. Evaluations of diagnose and retrofitting possibilities were simulated with the ComfortTool, described by Rackes et al. (2016). Thermal comfort analysis considered simulations both for the entire building and for the upper floor individually, so it would be possible to evaluate the retrofitting effects on rooms with exposed roofing as well.

A thermal comfort analysis was also made based on the possibility of installing ceiling fans in some rooms regardless of any envelope alterations. The rooms with long hours of occupancy were selected (library – reading area – offices, laboratories, dining area, cafe, classrooms, waiting room/living area and conference room), adding up to a total of 152 spaces. A model of ceiling fan was selected based on its energy consumption, then it was possible to determinate an average number of units to be installed, average energy consumption per month and an estimated investment value.

2.2 Artificial Lighting

This analysis was made through on site visits. Rooms were listed and separated into 15 categories according to their activity (auditorium, bathroom, library – reading, shelf and filing area – circulation, deposit, offices, laboratories, dining area, cafe, classrooms, waiting room/living area, conference room and entrance hall), according to the Brazilian lighting standard NBR/ISO CIE 8995 (ABNT, 2013). To each of the rooms, the following aspects were analysed: room geometry, number of lamps, type of light bulb, light power density (LPD), daily energy consumption and attendance to RTQ-C's guidelines to level A. Additionally, lighting levels were verified against the normative (ABNT, 2013), so to analyse existing lighting levels adequacy according to the requirements for the distinct visual activities. After lighting levels verification, a retrofitting proposal was developed with the exchange of florescent light bulbs for LED (light-emitting diode) ones.

2.3 Air Conditioning

EAD is mostly naturally ventilated with air conditioning units present in few spaces. In the air-conditioned spaces the devices specifications were obtained: model, units per ambient, BTU value, power consumption (W), energy consumption (kWh/month), usage hours, and daily energy consumption (Wh). Ambient area was also taken into consideration. The replacement of outdated units for more efficient ones was then proposed.

3. RESULTS

3.1 Envelope

The finishing of most walls is paint and some are covered with tile pastilles. All 12 present façade materials were listed along with their solar absorptance values obtained from Dornelles (2008). The present materials in EAD's facade were in poor condition due to weather action and lack of maintenance (Fig. 3), therefore, wall solar absorptance (α) was considered 0.9 in the diagnose.

This leads to a maximum level for the envelope, classified then as C, thus maintaining the existing classification. This classification is in line with the one found in the work of Garcia et al. (2019) in the same BZ, where dark colours on envelope contributed to poor classification. To improve ENCE classification and the aesthetic aspect of EAD, a renovation proposal for the facades materials was made (Fig. 4).

Figure 3:
Current state of EAD's West and South facades materials due to weather action and lack of maintenance.

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Figure 4:
EAD's West and South facades materials after renovation proposal (photographic simulation).

Based on the area of each façade material and its solar absorptance, the building's weighted average absorptance reached 0.41 after the renovation proposal, shown in Table 1. The reference value to obtain an ENCE A is α lower than 0.50.

As EAD is a building listed by the historical heritage, a request must be submitted to the local responsible organ to evaluate and approve the façade renovation. The proposal focused on the renovation of existing materials whilst maintaining the original characteristics of the historically protected facades, therefore, the renovation request process should be simple to be approved.

Table 1:
Envelope α and U mean values for walls.

	α - wall	U – wall (W/m²K)
ENCE limit	0.5	3.70
Diagnose	0.9	2.16/1.78
Retrofitting	0.41	2.16/1.78

Note: Wall U values correspond to the type of wall built in the first and second construction phase respectively.

A total of 80% of EAD's roofing is composed of fiber cement tile and 20% is composed of flat slab. As the roof is not renovated and present very dark surfaces, solar absorptance (α) was considered as being 0.9.

According to RTQ-C standards to reach ENCE limits, for building's roofs located over naturally ventilated rooms, the thermal transmittance (U) should be between 1.0 and 2.0 W/m²K. In air-conditioned rooms the maximum U value is 1.0 W/m²K for a classification A (Brasil, 2010). Most of EAD's rooms endue natural ventilation thus reaching U value of 2.0 W/m²K would be enough for ENCE's good results. However, to provide better thermal comfort for the users, the goal was to reach U value of maximum 1.0 W/m²K.

The diagnose demonstrated a U value of 2.06 W/m²K for the roofing area composed of flat slab and U of 3.74 W/m²K for the one composed of cement tiles, presented on Table 2. Two different optimization solutions were proposed. The initial roof retrofit propose was to renovate the existing roofing by preparing and painting the fiber cement tiles in a light colour, a white with α of 0.158, according to Dornelles (2008). In the areas composed only by flat slab it was also necessary the installation of new white cement tiles, since the transmittance value was much higher than the demanded in these areas. However, this process was not enough to obtain an adequate U value, so the implementation of a layer of foil insulation was proposed, reaching a U value of 1.13 W/m²K. In order to obtain a value lower than 1, it was proposed the installation of plaster lining layer underneath the slab, accomplishing U of 0.87. The first retrofitting proposal presented an estimated investment cost of R$120,000.00 (Brazilian currency), approximately $25,300.00 American dollars considering the current exchange rate of the dollar, 4.74. The second retrofitting proposal consisted of the installation of white sandwich tiles, composed of two thin metallic layers and a thick thermal insulation layer, in all roofing extension. With this feature, it was possible to reach a thermal transmittance of 0.81 W/m²K. The estimated price of the optimization proposal is R$175,000.00, approximately $36,900.00. It was not possible to calculate a payback time because the building is mostly naturally ventilated, so envelope retrofit would endure more influence on thermal comfort than on energy consumption. Diagnose and retrofitting roof values are presented in Table 2.

Table 2:
Envelope α and U mean values for roof.

	α - roof	U – roof (W/m²K)	Investment
ENCE limit	0.5	1.0	-
Diagnose	0.9	2.06/3.74	-
Roof proposal 1	0.158	0.87	R$120,000.00 (app. $25,300.00)
Roof proposal 2	0.158	0.81	R$175,000.00 (app. $36,900.00)

Note: Roof U values for diagnose correspond to fiber cement and flat slab parcel respectively.

Both solutions reached ENCE A and U values under 1 W/m²K, providing good thermal comfort. However, the second proposal presented an easier, faster and simpler implementation since it implicates renovations only on the roof area, presents easy maintenance and high durability, even though it is more expensive than the first option.

Thermal comfort diagnose developed from simulations made with the ComfortTool demonstrated that the building as whole presented 69% of total occupied hours in thermal comfort

(OHTC), considering ASHRAE-55 (2020) 80% acceptance level. It indicates an ENCE level C according to RTQ-C (Table 3). The association of envelope renovations considering the second roofing retrofit proposal resulted in an improvement from 69% to 84% of OHTC. According to RTQ-C, a level A for the ventilation aspect of naturally ventilated rooms require a minimum of 80% OHTC, hence, envelope retrofitting proposals endured rate A for the ENCE's ventilation aspect.

An alternative option was also evaluated, the addition of ceiling fans in some of the school's rooms. Rooms that presented long occupancy hours were selected, adding up to 152 spaces. Based on the ventilation area provided by the selected device and specified by the manufacturer, it was possible to account an average of 291 units to be installed. This represents an investment in the order of R$55,000.00 (approximately $11,600.00) and an approximate increase of 9.000 kWh in the monthly energy consumption. This option presented the raise of 14 percentual points on the total occupied hours in thermal comfort (OHTC) of EAD's building, going from a 69% of OHTC to 83%.

Considering the simulations run for the upper floor individually (representing the rooms with exposed roofing), the diagnose showed 60% of OHTC. With the first envelope retrofitting proposal, OHTC level reached 80% and the second proposal provided an OHTC of 89%. Hence, the renovations on both scenarios (whole building and upper floor) endured an envelope rate A according to RTQ-C, with OHTC levels higher than 80% (Table 3).

Table 3:
Occupied hours in thermal comfort (OHTC)

	OHTC Building	OHTC Upper floor	ENCE (RTQ-C)
Diagnose	69%	60%	C
Roof proposal 1	81%	80%	A
Roof proposal 2	84%	89%	A
Fans usage	83%	---	A

The thermal comfort analysis performed in the present study indicated results in accordance with the survey conducted in the same university by (Garcia, 2022), which indicated heat discomfort. With the adoption of retrofitting strategies, the situation could be mitigated.

3.2 Artificial Lighting

Diagnose demonstrated that the existing ENCE, classified as B, was accurate, with a light power density (LPD) of 8 W/m². However, 30% of EAD's 280 rooms did not reach minimum illuminance levels determined by ABNT (2013). Among these rooms 81% were composed by high illuminance demands, such as laboratories, offices, and classrooms, which must present 500lux. Adapting these ambient illuminances to the normative levels while maintaining the same fluorescent lamps generated an increase in energy consumption as expected, reaching a LPD of 10 W/m², which brought the ENCE to classification C. The retrofitting proposed the exchange of the existing lighting bulbs to LED technology with the maintenance of the existing lighting fixtures, to minimize retrofitting costs. This strategy led to an energy consumption decrease keeping the luminous flux and illuminance levels indicated by ABNT (2013), with an LPD of 6 W/m² and an ENCE A. Table 4 summarises the artificial lighting analysis and retrofitting proposals.

Table 4:
Artificial lighting values for diagnose, adequation to the illuminance levels by ABNT (2013) and LED usage proposal.

	LPD (W/m²)	Energy consumption (kWh/month)	ENCE (RTQ-C)
Diagnose	8	12.000	B
Adequation to ABNT (2013)	10	15.800	C
LED	6	8.600	A

The existing bulbs presented light power of 16, 20, 32 and 40W. Two types of tubular LED bulbs were utilized: 166 units of 13W and 564 units of 25.2W. The renewal presented a predicted reduction of 28% of electric energy consumption, with a 9-month payback time.

The lighting bulbs found in the diagnose of EAD were similar to the ones presented in the diagnose of Ferraz et al. (2018). The use of tubular fluorescent lighting is a common practice in Brazilian public higher educational buildings. The substitution of existing lighting bulbs for LED ones was a solution also suggested by the work, and a similar payback time of 10.5 months was cited.

3.2 Air Conditioning

From the 280 listed rooms, 16 of them have an air conditioning device, with a total of 18 installed devices. Diagnose demonstrated that 9 units were outdated models, categorized with an approximated energy efficiency level C or D. To reduce the building's energy consumption, the exchange of these devices was proposed. The Coefficient of Performance, COP, of the outdated devices varied between 2.7 to 3.3 W/W, and the devices selected for the exchange presented a COP of 7.2 W/W. Four daily hours of usage for 24 days a month were accounted for the estimated energy consumption calculation. The estimation was considered because there is no end-use measurement in the building. The renewal of outdated air conditioning devices allowed an estimated annual energy consumption reduction of 32% for this end-use with a 7.5-year payback.

Previous work (Ferraz et al., 2018) also showed a level C for air conditioning diagnose in a public higher educational building in Brazil. The exchange of outdated devices for more efficient ones was also proposed. The necessity of this strategy may be common for other public buildings of this typology, as budget contingences can lead to the purchase of low efficient equipment and poor maintenance.

4. CONCLUSION

The paper presented results from a retrofitting analysis based on the Brazilian labelling system RTQ-C and INI-C (for thermal comfort analysis) applied to a historical university building also providing estimated payback time. It was seen that measures such as changing the existing light bulbs and outdated equipment along with good maintenance of the façades finishing can significantly decrease energy consumption and increase thermal comfort. The ENCE analysis propitiated an objective diagnose of energy efficiency retrofitting possibilities. The use of a simplified tool to assess thermal comfort in naturally ventilated buildings favoured the measurement of thermal comfort gains on envelope retrofitting. Authors believe the use of RTQ-C guidelines along with the integrated consideration of thermal comfort improvements, energy consumption reduction and payback time were adequate to develop a retrofitting proposal for the analysed building. Further works can contribute with the creation of guidelines to maintain the quality of the roof and facade materials, more complex comfort and lighting simulations and the use of a complete payback time analysis. As the national energy efficiency regulation is not extensively applied, it is expected that the present results could strengthen its use, not only for labelling but also to assist retrofitting analysis.

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Towards a new compliance methodology for Ireland

Informed by studies of nZEB housing, its fabric and technologies

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ABSTRACT: Similar to many countries around the world, the Irish domestic or residential building sector is the major energy demand sector. The sector is responsible for 47% of Ireland's built environment related Greenhouse Gas emissions total. The method of evaluating compliance with building regulation, and technical guidance, in Ireland through the national assessment methodology software DEAP is often criticised. Building performance in reality is often widely different from that returned at time of assessment. This performance gap is often due to building underperformance, but also due to inaccuracies in the assessment method. These include an unrepresentative set of default values, which often are representative of only a subset of construction type, technology performance, building use condition etc.
KEYWORDS: Energy efficiency, nZEB, compliance

1. INTRODUCTION

In 2021 Ireland released the Climate Action and Low Carbon Development bill outlining the strategy by which Ireland will play its part in the just transition to a climate resilient and carbon neutral economy.

A key strategic component to deliver these targets is the building and retrofitting of homes to near zero energy building, (nZEB) standard. This standard is now compulsory for all new buildings in the European Union, and encompasses very low operational energy requirements for buildings, with this energy provided to a large extent from renewable resources. This paper reports on results from studies that are part of the nZEB101 project carried out by University College Dublin and funded by the Sustainable Energy Authority of Ireland (SEAI) [1,2,3]. This project evaluated a large cohort of housing in Ireland newly built, or retrofit, to the new nZEB standard. The project compared the estimated energy use of the houses to in-use data, assessing the achievement of energy efficiency targets related to the nZEB standard.

2. REVIEW OF NATIONAL CONTEXT

Compliance with Irish building regulations relating to energy use and energy conservation is governed by Technical Guidance Document Part L, and demonstrated at design stage using the Domestic Energy Assessment Procedure (DEAP). The DEAP software allows design data to be inserted to a spreadsheet that calculates a Building Energy Rating (BER) for the building. Through an analysis of the national database of BER calculations, Passive House+ magazine monitored the impacts of the new regulations over the course of the first year of their operation. In January 2021, the magazine reported 1862 homes had been built to the new 2019 guidelines up to 8 December 2021 [11]. Of those, 91.8% were A2 rated, 1.2% A1, and 6.7% A3 rated. The average primary energy score was found to be 41kWh/sq.m/year, compared to 51.3kWh/sq.m/year for homes built to the previous regulations. 95.1% of new homes now featured heat pumps, increasing from 48.7% of homes built to the 2011 guidelines. There was a corresponding decline in the number of homes featuring gas boilers. In terms of ventilation, 55.4% of the homes used mechanical extract ventilation, 17.5% natural ventilation, and 17.4% heat recovery ventilation.

In terms of compliance, this early assessment of the impact of the regulations found that 25.5% of naturally ventilated homes had a q50 result of less than 3m3/hr/sq.m, lower than the ventilation building regulation document TGD Part F recommendation for naturally ventilated homes. Naturally ventilated homes were also found to have the highest primary energy scores. A further analysis in March 2021 found similar results, adding that there had been a considerable drop in rates of solar PV installation [12]. This decline is the result of the rise in heat pumps, which fulfil the renewable energy requirement under the new regulations. PV installations were found to be associated with the provision of gas boilers in gas grid areas. Air tightness was found to have improved in new homes from an average q50 of 2.81 to 2.55m3/hr/sq.m. at 50 Pascals.

Writing in October 2021, Jeff Colley [6] raised concerns that almost a quarter of new homes may be not be in compliance with Part L, failing to meet one or more of the targets set to demonstrate compliance. Colley reports strong compliance in the energy performance coefficient (EPC), carbon performance coefficient (CPC) and renewable energy ratio (RER), however found non-compliance in evidence in areas such as airtightness testing and U-values. 10.5% of homes failed to meet the backstop U-values for external walls. Colley again notes the failure of 24.5% of naturally ventilated homes to comply with Part F of the building regulations, with airtightness results of below 3m3/hr/sq.m.

Also in October, Passive House+ reported endemic regulation breaches regarding ventilation, with only 12% of NZEB homes having been subject to independent ventilation validation, despite this being a requirement of the new regulations [10]. Validators report poor awareness of this requirement among clients and assigned certifiers. The report notes a suggestion by Gary O'Sullivan of the National Standards Authority of Ireland (NSAI) that a validation number for such a test should be a required to be entered into the DEAP calculations. At the 2NZEB & Beyond conference organised by Ecological Building Systems, Antonella Uras from the Sustainable Energy Authority of Ireland (SEAI) outlined a number of forthcoming additions to the DEAP software relating to cooling and overheating calculations [15].

3. RESULTS INFORMING THE NEW METHODOLOGY

The paper includes both new results and those from recently published studies [1,2,3,17]. These studies of existing and retrofitted homes can help inform a new methodology by highlighting the discrepancy between operational conditions of buildings in use and parameter constraints and approximations of the DEAP methodology.

3.1 Studies of buildings in use

A cohort of 12 social housing dwellings retrofitted to nZEB standard were evaluated [1]. Of these 12 dwellings, results from 8 dwellings were judged to be sufficiently reliable and robust for analysis. POE study of the dwellings and their occupants evidenced high levels of satisfaction amongst occupants of comfort conditions and indoor environmental quality. However, the dwellings are seen to perform with much lower energy efficiency than expected.

Further insight is gleaned when the dwellings are considered with reference to the national assessment methodology (DEAP), for evaluation of compliance with the Technical Guidance Documents, for calculating the building energy rating (BER), Key findings include:

All of the dwellings are consuming more energy than predicted by DEAP (> 400% in some cases). This leads to actual in-use BER ratings which are worse than the original predicted BER ratings.

The majority of the dwellings record consistently higher median temperatures than that expected, with some exceeding DEAP assumed temperatures by >7°C.

Recorded winter and summer interior temperatures are considerably higher than the assumed set point temperatures of 21°C (living) and the rest of dwelling assumed set temperature of 18°C (bedrooms).

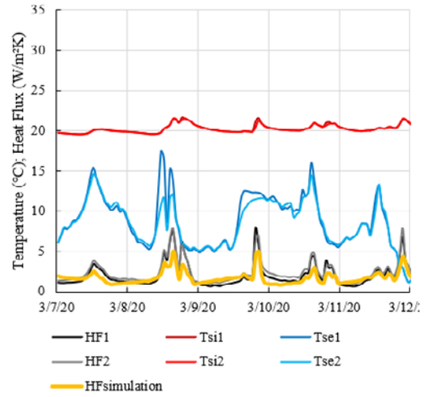
The DEAP-assumed two hour heating period in the morning and six hour heating period in the evening were not reflective of the typical use of the dwellings.

The combination of consistently high temperatures and extended heating season resulted in heat losses in excess of twice that expected by the DEAP software.

3.2 Studies of building fabric

Building fabric performance was evaluated through in-situ U-value testing, augmented with finite element modelling [2]. The U Values were measured using heat flux and temperature sensors indoors, outdoors, and in test setups, on interior and exterior surfaces of the building's fabric. Experimental data of this testing from the 8 successfully measured dwellings is presented in Figure 1. The U-value in-situ is often worse than the design value and depending on the building type and construction method a correction factor is being considered for inclusion in the compliance methodology.

Figure 1:
Experimental and simulated study of the thermal resistance performance of the building envelope [17]
Note: Tsi = Internal surface temperature; Tse = External surface temperature; HF = Heat flux



3.3 Studies of building heating technologies

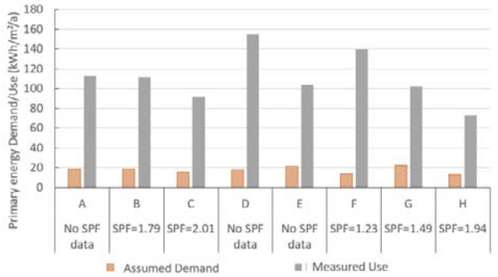
Heat pump underperformance is commonplace, and the nZEB101 study has added to this worrying finding. This is globally concerning as transition from fossil fuel heating to electrically powered heat pumps is central to many national strategies for mitigation of climate change. Figure 2 shows results of analysis of the heat pumps installed in the 8 successfully measured retrofit dwellings earlier described with obvious underperformance evident.

The metric used for evaluating heat pump performance – the Seasonal Performance Factor is given as:

$$SPF_{H1} = \frac{\int P_H}{\int P_{COMP}} = \frac{Q_{HP}}{Q_c} \quad (1)$$

where *SPF* – Seasonal Performance Factor (◦C);
P_H - power (W);
P_{COMP} – power of compressor (W);
Q_{HP} – heat energy output of heat pump (J);
Q_c – energy consumed by compressor (J).

Figure 2:
Heat pump performance in use vs. assumed/expected performance.



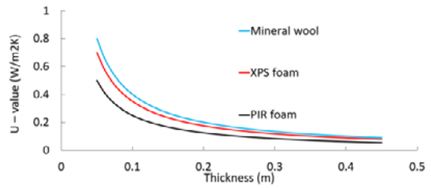
Based on current emission factors, the *COP* of an air source heat pump in Ireland would need to fall below 1.43 to be more carbon-intensive than a natural gas boiler. Some are shown to do so [3].

With regard to the compliance methodology correction multipliers or characteristic functions representing installation factors such as pipe length, emitter sizing are being proposed for inclusion in a revised methodology.

3.4 Building U-value focus and lack of representation

The central strategy of Ireland's building regulations is the reduction in fabric U-value. As was shown by O'Hegarty et al. [2] it is uncertain if this is a worthwhile strategy for achieving significant aims of energy efficiency. Figure 3 points to a case of diminishing returns for insulation inclusion in wall build ups.

Figure 3:
The case of diminishing returns of insulation thickness in building fabrics.



However, the bigger issue with regard to compliance, is the lack of well tested, validated characteristic U-values for traditional buildings in Ireland that make up a significant portion of the stock – estimated at 1 in 6 buildings. This gap in knowledge is the focus of ongoing work by this research group through the *FabTrads* project [18].

In a review of the wider stock, a recent paper showed that 42% of BER/EPC (Building Energy Rating / Energy Performance Certificate) entries in Ireland were characterised with "unknown" wall types relate to dwellings constructed between the year 2000 and 2009 [19]. This lack of true representation of the building stock is worrying. Default values are a necessity where invasive work is impossible but, excessive defaulting is found in many research studies and found to be a major contributor to the thermal energy performance gap. Policy and strategy developed based on inaccurate representations of the stock will create inappropriate policy and strategy.

4. WHOLE LIFE CARBON FOCUS LACKING

The regulatory infrastructure fails to assess a building's impact in terms of embodied carbon (EC)-energy used in the manufacture, transportation and assembly of building materials. Embodied carbon in the construction industry is estimated to account for 14% of Ireland's total emissions, at ~9 MtCO2e/ annum [5]. While savings of operational carbon through legislation and technology are ongoing and steadily improving, the construction of NZEB buildings requires large amounts of embodied carbon generating substantial emissions [13]. The importance of considering embodied energy in the overall reduction of emissions is highlighted by Pat Barry of the Irish Green Building Council, who queries how new home construction of up to 50,000 units per year can be accommodated while the government aims to reduce national carbon emissions by 7% per annum [4].

At the moment there is no regulatory oversight of embodied carbon, with some voluntary measurement and mitigation for individual projects in the construction industry. The professional body for Irish architects, RIAI, has launched the 2030 Climate Challenge which suggests a number of strategies for addressing embodied carbon in building that aim to reduce levels of embodied carbon by 40% [16]. These include:

- Prioritise retrofit, minimise demolitions, repurpose existing structures.
- Avoid sites requiring deep piling foundations; avoid basements/ underground car parks.
- Avoid building redundant unnecessary spaces or non-functional architectural features.
- Avoid oversizing homes, including low-density homes (133sq.m suggested limit).
- Use measuring tools, as they become available, to assess embodied carbon.
- Use low-carbon, healthy, responsibly sourced materials.
- Offset remaining embodied carbon emissions.
- Design buildings for adaptability to other uses and for disassembly to reuse components.

These measures could be incorporated into a programme of regulatory oversight of embodied carbon. The EU Commission is taking a cautious approach to regulating embodied carbon, recognising that consistent measuring standards are required before regulations can be considered. The Commission is currently considering a requirement to measure the carbon emissions associated with construction materials throughout their whole lifecycle as a first step in this process [9]. In France, where carbon intensity of electricity generation is relatively low due to high levels of nuclear power, embodied carbon in the construction industry has been given a higher priority. The French Environmental Regulation RE2020 address this issue, regulating the carbon impact of a building from construction to demolition phase, with the intention of increasing the use of materials with a low carbon footprint (Ibid.). One of the challenges faced by countries will be the harmonisation of calculating methods used in each country.

In terms of end-of-life carbon implications, the Environmental Protection Agency [8] note that construction and demolition activity is the largest waste stream in the EU, with 6.2m tonnes of C&D waste managed in Ireland in 2018. Previous regulation in this area failed to emphasise waste prevention and circular design. The EPA's draft 2021 guidelines address these deficiencies in several ways. The document calls for incentives to use recycled construction materials (possibly including a levy on virgin aggregates). Project developers will prepare a Resource & Waste Management Plan, to be submitted as part of a planning application, refined during the tender process, and submitted as part of the commencement notice. This plan will aid resource optimisation through the application of established principles of prevention of waste, reuse, recycling, green procurement, flexibility and deconstruction. This proposal will serve both to reduce construction waste and to improve the levels of material recycling and reuse at the end of a building's life.

Research by University College Dublin [15] estimates that should government regulations reduce embodied carbon in residential construction by 50%, combined with the provision of 25% of estimated housing demand in repurposed currently non-residential buildings, a saving of approximately 5MtCO2e occurs to 2030 from this sector in Ireland.

Table 1:
Summary of regulatory framework, Ireland, referencing the construction stages defined in EN 15978.

Stage	Category of carbon emissions	Current regulatory situation	Regulatory/ compliance issues/ proposals
A1-A3	Embodied	Unregulated	Measurement and limitation of embodied carbon at design stage.
A4-A5	Embodied	Unregulated	Technological improvements to reduce emissions.
B1-B5	Operational	Building Control legislation including TGDs, BERs, DEAP measurements.	Performance gap to be addressed; in-use post-occupancy performance to be evaluated and regulated.
C1-C4	Embodied	Irish Government waste guidelines, 2006	EPA preparing revised guidelines incorporating circular economy principles

In 2021 the UK Green Building Council published a report envisioning a pathway to net zero carbon in the construction industry in the UK by 2050 [14]. The report addresses both operational emissions (currently regulated in the UK) and embodied emissions (currently unregulated), envisaging a scenario where the built environment emits net zero emissions by 2050.

The roadmap notes that there is currently no regulatory oversight of embodied carbon in the construction industry in the UK. Some voluntary measurement and mitigation measures are taken in certain projects. The roadmap proposes mandatory embodied carbon measurement, tracking, reporting,

and limiting. A minimum standard for embodied carbon would be introduced, and gradually reduced as technological and infrastructural changes allow. To allow for this, data management and collection systems will need to be developed, including a freely available national embodied carbon assessment tool. Materials manufacturers should be required to/ supported in providing the necessary Environmental Product Declarations (EPDs).

The roadmap also suggests measures for the planning process, including a requirement for planning applications to demonstrate actions taken to reduce embodied carbon, and a requirement for a Circular Economy Statement which would critically appraise the need for any demolitions involved in the proposal.

The report notes that technological advances have decreased the carbon intensity of construction by 40% from 2000 to 2018, however these carbon savings have been absorbed by a corresponding increase in building. While the report expects further efficiencies in materials prediction and supply changes to be developed, reduction in demand for new building will be required in order to achieve a net zero scenario. One suggestion the report makes is that 25K new homes could be provided annually through change-of-use of existing non-residential buildings. Other measures to improve the circular economy potential of the construction industry are the removal of VAT on refurbishment works, and the establishment of a second-hand materials database.

4. DISCUSSION

Irish Government policy commits to a reduction of 51% of carbon emissions by 2030, and net zero emissions by 2050. In order to truly achieve these aims across all of society – and all of the built environment - the whole life carbon in construction and the built environment should be accounted for and regulated. The focus areas for new regulatory and compliance goals and strategies outlined in this paper will help to bring these outcomes about.

Focus on the operational carbon only, as is presently the case, can have significant impact but will not result in full sector decrease. However, given the scale of the sector and its continued dependence on fossil fuels for heating and resultant high emissions, strict regulation and accurate performance characterisation could bring considerable efficiencies with considerable emission savings. When it comes to revision of the methodology, a lead can be taken from the UKGBC roadmap. The roadmap recognises that a ‘performance gap’ exists between design intent and real-world energy outcomes. The document proposes that the current system of designing to a ‘notional building’ standard and demonstrating compliance in this hypothetical stage of the construction process should be replaced with an ‘outcomes-led’ energy performance approach. This can be achieved by adopting Energy Use Intensity (EUI), measured in kWh/m2/year, as a consistent, outcome-focused metric that can measure both design and in-use energy performance. The roadmap proposed EUI assessments be carried out at three stages of a project, as follows:

- Design stage (using EUI to forecast energy use)
- Completion (EUI forecast using as-built data)
- In-use (EUI measurement with in-use data)

The roadmap notes that setting EUI targets for different building types (residential, office etc.) would require a body of work to establish standards for each type.

Results from the nZEB101 project are informing a new residential building compliance methodology in Ireland. Proposals for inclusion in a new compliance methodology, will include revisions to setpoint temperatures, heating and occupancy schedules as well as the inclusion of a range of correction factors. This paper presents a wide range of POE nZEB in use results that are informing national policy and compliance to energy efficiency standards and targets.

ACKNOWLEDGEMENTS

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Developing a rating system for a net zero community

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ABSTRACT: Net zero communities are becoming widely popular at the global scale. However, there is often ambiguity in its understanding and application. Different countries around the world have varying perceptions of net zero, each having their own standard of evaluation. Hence, it is crucial to generate a rating system that can act as a starting point in designing large scale net zero developments. The aim of this study is to select, analyse and compare five globally acknowledged energy rating systems for large scale developments and develop an amalgamated rating system that will act as an international guide to design and test net zero communities around the world.
KEYWORDS: Energy Rating systems, Net Zero Energy, Sustainable Communities

1. INTRODUCTION

Net-zero energy and net-zero carbon are terms that have gained popularity over the past two decades, to such an extent that their usage is being expanded to the scale of communities and cities. Despite the subject's growing momentum there is ambiguity in its definition and understanding. Principles for net-zero have been defined for the building scale and energy systems that analyse and rate the sustainability of large-scale developments exist [1]. However, there isn't a set of defined benchmarks for testing the authenticity of net zero in larger scales of development.

This study aims to develop a system that can be used to test a prototype net zero community. For this, five globally acknowledged energy rating systems that are pioneers in building energy rating have been selected. These systems have been shortlisted as their application has been expanded to test large scale developments. This paper aims to bridge the gap between the principles of net zero buildings and energy rating systems, thereby developing a global rating system for a prototype net zero community.

2. ENERGY RATING SYSTEMS AROUND THE WORLD

Five globally acknowledged energy rating systems have been studied. Table 1 lists the selected rating systems, when these were launched, total credit points under each system and the certifications awarded by these.

Table 1:
Selected energy rating systems and their specifications

Rating system	Launch	Credit points	Awards
BREEAM Communities [3]	2008	126	Outstanding /Excellent//Very good/Good /Pass /Unclassified
IGBC Townships [7]	2010	200	Certified/Silver/ Gold/Platinum
PEARL Community Rating system [9]	2010	159	1 Pearl/2 Pearl/3 Pearl/4 Pearl/5 Pearl
Green Star Communities [6]	2012	110	One Star/Two Star/Three Star/Four Star/Five Star/ Six Star
LEED Communities and Cities [8]	2016	110	Certified/Silver/ Gold/Platinum

These energy rating systems have been devised for large scales of developments like communities and neighbourhoods. The study found that systems such as LEED and Green star are not specific to geographic location and are used around the world (see Fig. 1). Some key examples that have used these systems include BedZED in Sutton, UK (see fig. 2) which was compared with BREEAM's system (Beddington zero energy development case study, 2007) and Dubai Sustainable City and MASDAR City (see Fig. 3,4) which use PEARL.

Figure 1: *World map showing selected energy rating systems and their use in different geographic locations (by author)*

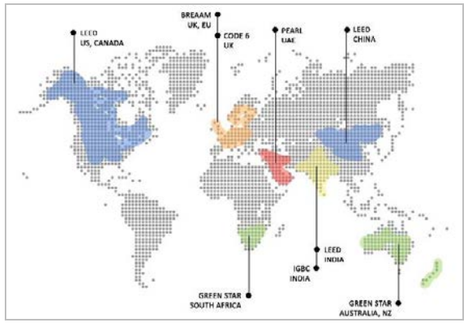


Figure 2: *BedZED in Sutton, UK - 'Excellent' BREEAM certification [4]*

Figure 3: *Dubai Sustainable City, UAE [5]*

Figure 4: *MASDAR City, UAE aims to achieve 3-4 Pearl rating [12]*

3. COMPARITIVE ANALYSIS OF ENERGY RATING SYSTEMS

Each of the selected rating systems was studied in great detail. The technical guide for each rating system was thoroughly analysed and the rating systems were tabulated as Code – Category – Points for each criterion of the five rating systems. Also, the systems were tabulated in parallel to enable comparative analysis between them. This helped identify similarities and differences in categories and weightings (in points) under each criterion. Based on the comparisons the following broad criteria were deduced for the new rating system.

- Social, economic and environmental wellbeing
- Ecology
- Site
- Urban planning and design
- Transport
- Energy and emissions
- Materials
- Water
- Waste
- Innovation
- Accredited professional
- Other

3.1. Criteria and Categories

The study indicated several similarities in categories such as energy, materials, urban design, water and waste, making it possible to establish a pattern between the systems and thereby, group them under similar criteria. However, some categories were moved from one criterion to another where it seemed fit. Table 2 indicates the comparison between BREEAM and PEARL rating systems for the 'Energy and Emissions' criterion [3,9].

Table 2:
Rating systems assessed in parallel to identify similarities and differences in criteria – sample showing comparison of Energy and emissions criteria for BREEAM and PEARL

PEARL		BREEAM	
Code	Category	Code	Category
RE R1	Community energy strategy	RE 1	Energy strategy
RE R2	Building energy guidelines	SE 10	Adapting to climate change
RE R3	Energy monitoring and reporting		
RE 6	Renewable energy: onsite		
RE 7	Renewable energy:		

	offsite		
RE 8	Energy efficient buildings		
IDP 1	LC costing	RE 7	Transport carbon emissions
LC R5	Minimum Pearl rated buildings within communities		
LC 11	Pearl rated buildings within communities	RE 4	Sustainable buildings
IDP R2	Sustainable building guidelines		

Note: Code RE under Pearl implies criteria 'Resourceful energy' and in BREEAM criteria 'Resources and energy'

'LC (life cycle) costing' and 'Sustainable building guidelines' have been moved from 'Integrated development process' to the 'Energy and emissions' criteria in PEARL (Code RE for Resourceful energy). Secondly, 'Adapting to climate change' which falls under the 'Social and economic wellbeing' category in BREEAM has been repositioned in this criterion. Also, Pearl rated buildings within communities from 'Liveable communities' is part of 'Energy and emissions' now.

3.2. Weighting of criteria

Once, the categories were repositioned to fit the appropriate criteria, the weighting (%) for each criterion was calculated as shown in Equation 1 below [3,6,12]. Note that 'High priority sites' falls under 'Land use and ecology' in LEED and 'land use' under 'Transport and land use' in BREEAM. These are now categorised under 'Site'.

$$\text{Weighting (\%)} = CP_{category} / CP_{total} * 100 \quad (1)$$

where, $CP_{category}$ – Total credit points under criteria
CP_{total} – Total rating system credit points

Example a: BREAAM

Criterion 'Site' has one category 'land use' (code LE2) and is weighted at 3 credit points. Total credit points for BREEAM are 126. By using equation 1, the weighting for site as percentage can be calculated as follows:

Weighting (%) for site = 3/126*100 = 2 (approx.)

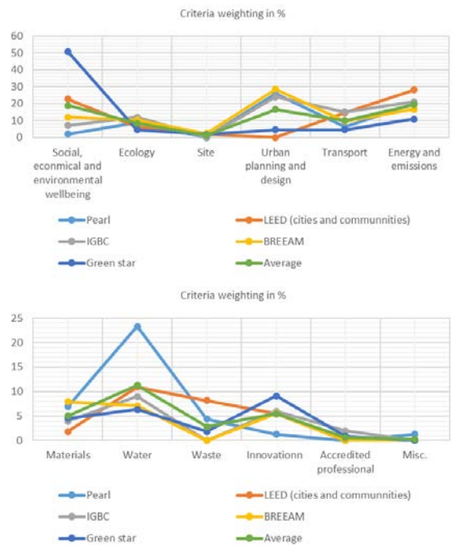
Example b: LEED

LEED too has only 'High priority sites' (code TR6) with 2 credit points under criterion 'Site'. Total credit points for LEED are 110. Using the above equation, the weighting percentage for LEED – 'Site' is as follows:

Weighting (%) for site = 3/126*100 = 2 (approx.)

To understand how the weighting system for the same criterion can vary vastly for different rating systems, the graphs shown in Figure 5 were developed. The graphs represent the percentage contribution of each criterion for the five rating systems. Some key findings are evident from the graph. Four of the five systems (except IGBC) highlight strategies on emissions. Urban design has been thoroughly strategized for most systems bar Green Star with Energy being prioritised in all systems along with socio-economic strategies. Of all criteria, Green Star prioritises Social, economic and environmental wellbeing with a weighting of 51%, followed by LEED at 23%. On the other hand, PEARL weights this criterion at 2%. Ecology had an average weighting between 6-16% in all systems. Two of five systems did not analyse site indicating a weighting of zero for the 'Site' criterion (PEARL, IGBC). However, this was compensated for in the urban planning and design weighting of approximately 25% in both systems. Other anomalies include PEARL's weighting of water at 23% compared to the average 7-11% of other systems, possibly due to location being linked to a scarcity of water and IGBC and BREEAM weighting waste at zero.

Figures 5 a, b:
Comparative analysis of criteria weighting in % (by author)



The data from the above analysis was used to arrive at the average weighting (as a percentage) for each of the criteria (see section 4, Table 4). 'Social, economic and environmental wellbeing' averaged to 19%, which is the highest weighting and 'Ecology' came to an average weighting of 8%. Site was at 1% which is the lowest weighting, possibly because two of the three rating systems have not addressed this criterion. 'Urban planning and design' came to 17% putting it as the second highest weighting. 'Transport' rounded to an average weighting of 10%. 'Energy and emissions' also had the highest weighting of 19%. 'Materials' rounded to a weighting of 5% with 'Water' at 11% and 'Waste' at 3%. 'Innovation', 'Accredited professional' and 'Miscellaneous' (accommodation for construction workers) criteria had averages of 5%, 1% and 0% respectively.

4. DERIVED RATING SYSTEM

Based on the detailed analysis of each rating system and comparisons between them a combined rating system has been developed. As described, the weighting of each of the above criterion was measured and an average weighting was calculated for each criterion to develop a weighting scale for the amalgamated rating system. The criteria for the derived rating system and their weightings are detailed in Table 4.

Table 4:
Derived rating system criteria, average weighting from comparative analysis and derived weighting

Criteria	Average	Derived weighting
Social, economic and environmental wellbeing	19	15
Ecology	8	10
Site	1	20
Urban planning and design	17	
Transport	10	10
Energy and emissions	19	20
Materials	5	5
Water	11	10
Waste	3	5
Innovation	5	
Accredited professional	1	5
Misc.	0	

A few changes have been made to the criteria in the derived rating system. Environment has now been paired with 'Ecology', leaving 'Social and economic wellbeing' as one criterion weighted at 15% and 'Ecology and environment' as one, weighted at 10%. Likewise, 'Site and urban planning and design' have been combined and weighted at 20% together. 'Transport' and 'Materials' weighting has remained the same. 'Energy and emissions' criterion is rounded to 20% with 'Water' at 10%. 'Waste' is weighted at 5% and 'Innovation', 'Accredited professional' and 'Miscellaneous' are now grouped together as the 'Other' criterion. It has a percentage weighting of five too. It can be noted that 'Energy and emissions' and 'Site, urban planning and design' now have the maximum weighting. This seemed appropriate as the aim is to design and test a net zero community, where energy and sustainable design are key. Although the new system's weighting has been changed, this is not drastic to the findings from the comparative analysis and average weightings.

4.1. Criteria categories in detail

The comparative analysis of the five rating systems showed many similarities between them. The consolidation of these systems helped group the various categories under the eight broad criteria listed above. The final step of the study involved detailing out categories included in each of these criteria. The categories for each criterion described below have been reiterated from the existing criteria of the five rating systems studied.

Social and economic wellbeing (15%):

- Integrative planning where stakeholders, especially the community are encouraged to engage in planning
- Adhering to local regulations
- Affordability of developing such a community and its economic impact
- Economic resilience and growth involving employment opportunities and community growth in terms of skills
- Heritage preservation, local vernacular is maintained, the community is encouraged to engage in socio-cultural initiatives

Ecology and environment (10%):

- Assessing ecosystem and conserving and restoring natural resources like water bodies and agricultural lands where appropriate
- Remediation of contaminated sites
- Preserving existing landscape, both hard and soft
- Assessing site topography and making best use of this
- Air, noise and light pollution control during construction

Site, urban planning and design (20%):

- Site selection and analysis which includes assessing solar and wind access, urban heat island, microclimate, outdoor thermal comfort
- Site zoning, layout, planning and sustainable urban design strategies developed based on site analysis
- Responsive planning that addresses needs of the community, to have a mixed-use development and services dedicated to the community
- Incorporating urban landscapes and local food production within the development
- Diversity in housing design based on demographic needs with accessible community facilities and inclusive design
- Energy infrastructure located within site to address lighting, heating and cooling needs

Transport (10%):

- Connectivity of community to public transport systems
- Sustainable transport and movement within community including pedestrian and bicycle networks and alternate fuel vehicles
- Adequate parking facilities

Energy and emissions (20%):

- Energy strategy to minimise energy demand at the building and thereby site scale
- On-site and off-site renewable energy supply planned
- Energy efficient building by incorporating sustainable design strategies and addressing thermal comfort
- Carbon emissions involved in operation and transport and analysing embodied carbon
- Include certified green buildings within the community

Materials (5%):

- Responsible sourcing of materials
- Recycling and reusing materials where feasible

Water (10%):

- Water strategy including assessing and reducing demand, efficiency in terms of supply, using smart water systems to assist with this
- Managing wastewater by addressing treatment and reuse of storm, grey and black water and harvesting rainwater

Waste (5%):

- Managing construction waste
- Solid waste management in terms of segregation and recycling

Other (5%):

- Innovation in design and technology
- Involvement of energy accredited professional
- Providing appropriate facilities for workers during construction

4.2. Application of new rating system

There is often ambiguity in starting a project that constitutes a large-scale net zero development. There is credible literature on net zero energy/carbon buildings and there are notable case studies around the world that claim to achieve net zero energy/carbon (see section 2). However, in-depth study on net zero communities is insufficient given the growing popularity of this term. It therefore proved essential to develop a guide for the same. The aim of this study was to develop a rating system that can be used as a guide/benchmark that would assist in designing and testing a prototype net zero community. This rating system is currently being used to design a community on the BedZED site as part of a larger study (PhD thesis of author). Developing this rating system proved useful as a starting point and guide to design and test a net zero community that will be situated in Sutton, UK.

The starting point for this was to identify existing benchmarks or rating systems that assess sustainable design and energy for large scale developments. The five rating systems selected are renowned for this and have therefore been used as base cases. While each of these systems is excellent in its own terms, combining these helped develop a rating system that acknowledges all the crucial aspects of sustainability. Criteria like waste, water and site that were addressed in detail in some and not so much in others would now be addressed thoroughly in the derived rating system thereby creating a guide that is more detailed.

It is to be noted that rating systems are often used from the conceptualisation stage, through the design and construction stages and into the operational phase of the development. Most criteria such as transport, site, urban planning and design, water and waste strategy, energy and emissions and materials can be controlled during the concept and design phases. Hence, if a hypothetical community was to be designed for say, the BedZED site, almost all of the criteria can be addressed during the design phase bar the ones marked in red in section 4.1. Hence, this rating system acts as a genesis to design a net zero community.

5. CONCLUSION

This paper compared five important energy rating systems for large scale developments. A comparative analysis was conducted to identify a pattern of similarities between these energy rating systems. Based on this analysis a rating system that would be applicable for a large-scale net zero development was derived.

The five rating systems were tabulated in parallel to assess similarities and differences in categories and also their respective weighting in points. 12 broad criteria were evident in all five rating systems. These included social, economic and environmental wellbeing, ecology, site, urban planning and design, transport, energy and emissions, materials, water, waste, innovation, accredited professional and miscellaneous categories such facilities for construction workers and inclusive design. Simultaneously, the average weighting for each of these criteria was derived. Some categories were reallocated to criteria where appropriate. For instance, TR 6 – 'High priority sites' was moved to site from transport for LEED Cities and Communities.

The findings from the comparative analysis of the five rating systems helped derive a rating system that has eight broad criteria. Energy and emissions and site, urban planning and design have maximum weighting. It is to be noted that rating systems are applied from the conceptualisation of a project till the end of construction and even during the first year of operation. The amalgamated rating system considers the categories from conceptualisation till operation. Hence, when designing a net zero community some of these categories may not be applicable at the design stage but can be addressed only during construction. Overall, this derived energy rating system will act as a guide or benchmark that can be used to develop a net zero community in any location around the globe.

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November 22 - 25, 2022

SUSTAINABLE URBAN DEVELOPMENT

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16TH PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Impacts of city morphology on the microclimatic conditions of consolidated urban areas in São Paulo during hot days

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ABSTRACT: This research carried out an evaluation of the potential impacts that different morphological compositions of consolidated urban areas can cause on the local microclimate conditions during hot days perceived on the pedestrian scale. The analysis was based on simulations of the thermal conditions of open urban spaces exemplifying neighborhoods in the city of São Paulo, using the ENVI-met software, calibrated from empirical measurements of microclimate variables collected in an existing environment of the city. The results of the evaluation of five different models, comparing their different occupation aspects, allowed to verify that the morphological conditions are capable of contributing to the alteration of the main thermal variables of the open urban space and pedestrian thermal comfort indexes. In the studied models, it was found that, the greater the density and the verticalization, the milder the thermal conditions of open urban spaces during the daytime, due to the shading caused by the buildings, and the higher the air temperature values at night, due to the higher emission of long-wave radiation by the urban canyon at night.
KEYWORDS: thermal conditions, open urban spaces, urban microclimate, urban morphology

1. INTRODUCTION

This research carried out an evaluation of the impacts that different morphological compositions of consolidated urban areas can cause on the local microclimate conditions during hot days perceived on the pedestrian scale, based on simulations of the thermal conditions of open urban spaces in the city of São Paulo, using the *ENVI-met* software, calibrated from empirical measurements of microclimate variables collected in an existing environment of the city.

Different models of urban planning can show how cities adapt to their growth, through horizontal expansion, densification, or both. They are relevant, among other reasons, because the bigger and more spread the urban occupation spots, the more they impact the environment, and further they intensify the effects of climate change and urban heating phenomena [3].

In this scenario, recent researches have started looking for correlations between the formation of urban microclimates and urban morphology, which is defined by the volumetry of the urban environment and its transformation over time [8], and their results in terms of the aspects of buildings, roads, and open urban spaces [2].

The conception of urban morphology can contribute to increase or decrease the effects of urban heating phenomena [7], considering that the thermal ambience of the urban space is very sensitive to the volumetric changes of city environment [12]. Studies have shown that urban morphology is decisive for the insolation and ventilation conditions of urban spaces and buildings [9]. The morphology can influence heat gain in the urban space during the day and heat loss during the night. Plus, it can change the speeds and the directions of the winds between streets and buildings [15].

For example, urban canyons can perform thermally better during daytime than regions with lower buildings, as the shading of taller buildings helps to reduce the heat gain of urban space by direct radiation and these help to increase speed at the pedestrian level [12], However, at night, urban morphology has a major impact on urban heat islands, as radiation is reflected diffusely in different directions by the surfaces of buildings over the other surfaces and, this way, urban canyons can help to trap radiation [11].

In Israel, it was found that the wide spacing has a heating effect, while the deepening of the urban canyon has a cooling effect [13], similar to a study in Sri Lanka that found more comfortable conditions on narrow streets with tall buildings [6]. Also, a study in Netherlands revealed that different urban geometries led to different thermal situations, with Mean Radiant Temperature and Wind Speed as the most influenced variables [15], and studies in Bangladesh revealed Air Temperature and Mean Radiant Temperature maximum differences of up to 6.2°C and 10.0°C between irregular and regular urban forms [12].

In this context, the objective of this research was to verify the impacts of different urban morphological compositions in thermal conditions of urban areas during hot days. The evaluation of five different models, with different occupation aspects, allowed to verify that the morphological conditions are capable of contributing to the alteration of the main thermal variables of the open urban space and pedestrian thermal comfort indexes. In the studied models, it was found that, the greater the density and the verticalization, the milder the thermal conditions of open urban spaces during the daytime, due to the shading caused by the buildings, and the higher the air temperature values at night, due to the higher emission of long-wave radiation by the urban canyon at night.

2. METHODOLOGY

This work consisted in the comparative analysis of five models through the simulations of the thermal conditions of five models representing neighborhoods with different morphological aspects in São Paulo, using the *ENVI-met* software, calibrated from empirical measurements of microclimate variables presented on the site of one of the simulation models representing a real city environment. All models were submitted to the same microclimate data and the analysis compared the main thermal variables results (air temperature, Mean Radiant Temperature, relative humidity, wind speed, direct, reflected and long wave radiation, daily hours of sunshine) over a 24-hour period of evaluation from a 36-hour period of simulation. Furthermore, thermal comfort was studied through Perceived Equivalent Temperature (TEP) [10], a thermal comfort index for open urban spaces in São Paulo.

2.1 *In loco* measurements of microclimatic data

The measurements were made in a two-story house in Mirandópolis, South Zone of São Paulo, between December 6th 2018 and January 14th 2019, in a residential neighbourhood predominantly occupied by two-story houses, as shown in Figure 1.

Figure 1:
Measurement location in São Paulo.

Even though in São Paulo the summer is characterized by frequent rainfalls, this period was chosen as the most suitable time for measurements, reflecting greater possibilities for days with high temperatures. The 40-day measurement period, accompanied by daily records of weather conditions, made it possible to choose an evaluation hot day period after 4 consecutive days with high temperatures, low humidity, sunny conditions and stable weather.

The data collected during the measurements were Wind Speed (WS) and Direction, Global Radiation (Ig), Globe Temperature (GT), Air Temperature (AT), Relative Humidity (RH), in 10-minute intervals. The measurements included the use of two *Hobos* and a *Campbell Scientific Station*.

There were two fully open-sky external measuring subpoints. Figure 2 shows a subpoint where control data were collected, located on the lower covering slab enclosed by sidewalls and, therefore, protected from the wind and with a partially obstructed sky view. In this case, the sensors were located approximately 4.5m above the ground, with the body of the *Campbell Scientific Station* and a *Hobo*, with 2 thermohygrometers and 2 globe thermometers.

Figure 3 shows the main subpoint located on the roof slab of the two-story house, above surrounding constructions, in a location vertically and laterally unobstructed, with no sky masking, and fully exposed to sunlight and wind. With the sensors approximately 7.5m above the ground, where the data used for calibration of the simulation model were collected, the equipment of the *Campbell Scientific Station* and a *Hobo* were installed, containing 1 thermohygrometer, 1 globe thermometer, 1 pyranometer and 1 ultrasonic digital anemometer.

Figure 2:
Lower subpoint.

Figure 3:
Main subpoint in the roof slab.

2.2 Analysis period and climatic model calibration

December 12th 2018 was chosen as the object day of evaluation, as it was the 4th consecutive day

without precipitation, with clear and sunny skies, an AT ranged from 22°C to 35°C and RH from 20% to 68%, featuring a hot dry day with high temperatures. The predominant wind came from the Southeast (SE) direction and the weighted average wind speed was 1.5m/s.

The measurements made on the roof slab were used for the calibration of the *ENVI-met* climatic model, while the measurements of the lower slab were used for comparative analysis. Simultaneously, measurements data were obtained for the same period from IAG/USP meteorological stations in Cidade Universitária and Água Funda. The calibration of the *ENVI-met* model was carried out through successive simulations of a section of the Mirandópolis neighbourhood, with the adjustment of the software operational and input data, comparing the results obtained in the models with the data measured for the same point where the measurements were made, with volumetric and spatial characteristics modelled as in the real place.

It was found as the optimum configuration for the calibrated climate model the insertion of input data from the climate file of the Congonhas Airport for the whole year overwritten between December 9th 2018 at 00:00am and December 14th 2018 at 06:00am by the *in loco* measured data: AT and RH in 30-minute intervals from empirical measurements; wind direction 138.7° (Southeast) and speed 2.2m/s at the edge of the model to obtain the wind speed 1.5m/s at the measurement point, according to empirical measurements; and cloudiness recorded at 60-minute intervals by the IAG/USP Água Funda Meteorological Station. The period of analysis is a 24-hour cycle between December 12th 2018 at 06:00am and December 13th 2018 at 06:00am. Seeking for the adequate stabilization of the models before the analysis period and to guarantee that there are no influences on the model's initialization, the simulation time before the beginning of the analysis period was maximized and initialization during daytime period was avoided to obtain neutral atmosphere condition. This way, a 36-hour simulation period was adopted, starting at December 11th 2018 at 06:00pm (18:00).

The final calibrated model showed great adherence to the measurements within the established criteria, with maximum differences of 1.5°C (4.9%) for AT (Figure 4), 5.4% (12.4%) for RH (Figure 5), 0.1m/s (7.7%) for the WS, and 0.4° (0.3%) for the wind direction. The calibrated model achieved a Mean Absolute Error (MAE) of 0.4°C in AT, 1.4% in RH, 0.1m/s in WS and 0.2° in wind direction, when compared to the measurements.

Figure 4:
Comparison between ENVI-met calibrated model and measurements: Air Temperature (AT).

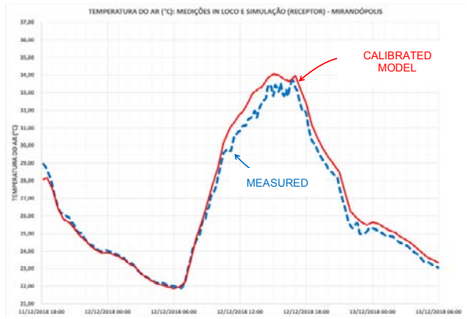
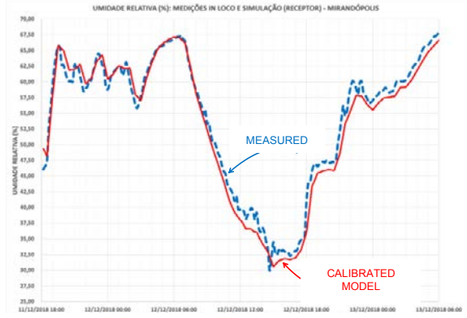


Figure 5:
Comparison between ENVI-met calibrated model and measurements: Relative Humidity (RH).



Also, the Root Mean Square Error (RMSE) was evaluated comparing the calibrated model and the measurements, achieving 0.5 in AT, 1.7 in RH, 0.1 in WS and 0.2 in wind direction.

2.3 Simulated urban models and simulations

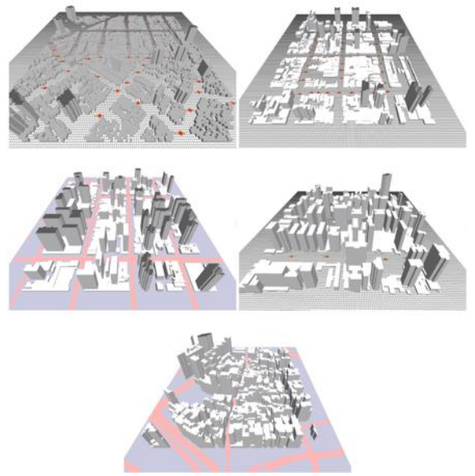
The five models represent neighborhoods in the expanded center of São Paulo (Mirandópolis, Ipiranga, Moema, Itaim Bibi and República), as shown in Figures 6 and 7, with different morphological typologies, selected from consolidated urban areas of dense regular occupation, with mixed use, approximately flat topography, ranging from low to high verticalization high to low Sky View Factor (SVF), buildings spaced apart and twinned buildings, distant from water bodies, without significant vegetated areas, and with similar relationships of floor surfaces (asphalt and concrete).

The geometries of the models, with a building area of 400x400m, wrapped in a surface area of 500x500m, and total height at least twice the height of the tallest building, were developed to reproduce the place with its streets and buildings, extracted from the digital map of the city, using *QGIS*.

Figure 6:

From left to right and top to bottom, aerial photos of the regions of the Mirandópolis, Ipiranga, Moema, Itaim Bibi and República areas.

Figure 7:
From left to right and from top to bottom, three-dimensional views of the models from Mirandópolis, Ipiranga, Moema, Itaim Bibi and República.



To ensure comparability between the models and that the differences in results were due exclusively to the morphological differences, all models have the same characteristics, varying only the morphological aspects of the urban typology, adopting the same materials for sidewalks, streets, soil, facades and roofs of buildings.

This way, all models used the same materials for the surfaces of sidewalks, streets and soil and for the facades and roofs of buildings, and they were created without topography, and, to maintain greater likelihood to reality, only approximately flat areas were selected. Also, all models were created without vegetation, thus avoiding microclimate impacts linked to soil permeability or vegetation.

The models adopted common asphalt as the surface of the roads and the "dirty" concrete pavement for the sidewalks and interior of blocks [4] and the clay and sandy soil, best representative of São Paulo [14]. For all buildings, masonry facade walls of concrete blocks and waterproofed concrete slab roofs were adopted, with normative and bibliography values for thermal and physical properties [1, 5].

2.4 Results analysis method

Maps with spatial distribution at 1.50m height (pedestrian scale) were extracted for Air Temperature (AT), Relative Humidity (RH), Wind Speed (WS), wind direction, radiation (direct, diffuse and long-wave) and Mean Radiant Temperature (MRT). Graphs, tables and spreadsheets of results were also extracted at the central point of each model, at the most central crossing of roads, and at strategic points, all of them at 1.50 m in height for the same variables and for the Perceived Equivalent Temperature (TEP). The results were analysed by comparing the models with each other in view of their different morphological characteristics.

3. RESULTS

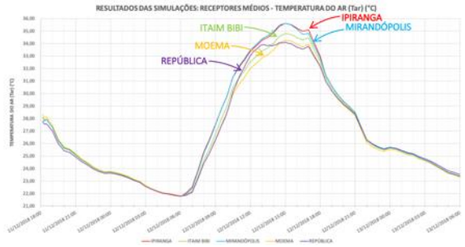
The simulations allowed to verify that the urban morphology is able to change the thermal balance of open urban spaces and the amount of radiation received by different points of space, including daytime and night-time, also changing the speed of the winds and, consequently, the thermal variables and the thermal comfort indexes.

According to Figure 8, during daytime, there was a maximum difference of Air Temperature (AT) of approximately 1.5°C between the central points of the less and more dense models. The models with less verticalization, less constructed volume and higher SVF values (Mirandópolis and Ipiranga) were the ones that presented the highest AT values during daytime period, since open spaces are more exposed to direct sunlight, allowing greater surface heating.

On the other hand, the densest model (República) was the one with the lowest AT during the daytime, due to its urban canyon configuration, causing greater shading of open urban spaces. At night, the most verticalized models and with the highest constructive volume (Itaim Bibi and República) presented the highest AT values, which is mainly due to the greater accumulation of heat in the built masses and to the trapping of heat by the reflection of radiation in the urban canyon.

Figure 8:

Air Temperature (AT) results at the midpoints of the simulation models.

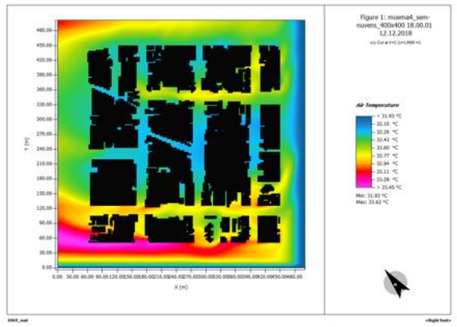


The less dense the models (Mirandópolis and Ipiranga), the more responsive they were to the daytime and night-time AT variations, with a greater and faster AT increase during the day, due to the greater exposure to direct radiation, and with a greater and faster loss of AT during the night, due to the lower emission of long-wave radiation due to the smaller amount of heat accumulated by the built masses.

Thus, the differences in response between the models also refer to the different conditions of exposure to sunlight, shading and radiation emitted by the buildings, analysed under the perspective of the Mean Radiant Temperature (MRT), whose maximum difference reaches 2.2°C between the models.

Even within the models, inside the area of one model, there were great differences between the various spaces, as the greater the building height variability (Moema and Itaim Bibi), the greater the differences between thermal conditions among the various spaces of the models. This happens mainly because the building height variability also causes different conditions of shading and exposure to the sun at different times in different spaces.

Figure 9:
Air Temperature (AT) result of the Moema simulation on December 12th 2018 06:00pm (18:00).



For example, in the Moema model, with greater height variability, at some times, the difference of AT between different sections of the same model reached 3.3°C (Moema), as shown in Figure 9.

It is also natural that the positioning and geometry of buildings can alter the directions and speeds of circulation of the winds, and in this case, the models with the greatest spacing between buildings and the greatest variability in heights were the most susceptible and permissive to the circulation of the winds.

The orientation of roads in the north-south and east-west directions forming regular blocks (Ipiranga) was the one that showed the best performance from the point of view of the permeability to the circulation of the winds coming from the southeast, which is the most common wind direction in São Paulo. This allows better distribution and greater speed of the winds in the streets.

The building height variability, besides interfering in the access to sunlight and shading, also creates differential wind conditions between the models, therefore, the models with greater spacing between buildings and with greater building height variability (Ipiranga and Moema) were the most permissive for the circulation of winds between spaces.

The good circulation of the winds made the environment more susceptible to thermal variations, which helps to remove heat and, consequently, at night, brings milder conditions. Thus, when there are mild and high AT values, the wind circulation has a positive impact on Perceived Equivalent Temperature (TEP), reducing its values, and therefore bringing better thermal comfort conditions for the pedestrians during this hot and dry period daytime. This way, the variability of building heights and the formation of urban canyons also showed a tendency of beneficial impact of reducing TEP during the day, which is associated with the shading caused by the buildings.

There are some important points to consider related to the positive impact of the wind speed in the thermal comfort of the pedestrians. First, the winds speed is beneficial to the pedestrians' thermal comfort when temperatures are mild and high but higher than the human body temperature, and wind speed can potentially reduce the effects of the radiation over the body, facilitating heat loss by the body. If this analysis were conducted in a winter cold day, or in a rainy day, with lower temperatures and lower radiation, wind speed might have had negative impacts in the pedestrians' thermal comfort index.

Secondly, the excess of wind speed might also cause discomfort, thus, creating obstacles that reduce the wind speed in the urban space, but do not integrally block wind circulation, such as buildings spaced from each other (not twinned buildings), walls, vegetation, might be a good solution. Also, we must remember that long street canyons with high twinned buildings can cause wind "corridors", helping to increase wind speed in the urban canyon direction.

To illustrate, there is a difference of up to 2.5°C in the TEP values between the central points of the models, and, with the exception of the República (most of the time with shaded roads), Ipiranga was the model that presented the best performance in terms of to TEP, which is understood to be associated mainly with the distribution of buildings and medium-to-high building height variability, which allowed alternation in the conditions of sunshine direct radiation and shading, and the regular layout of north-south and east-west roads, allowing better circulation of winds from the southeast to remove heat.

Also, during daytime, the most exposed areas of the models – which are more present in the less dense model (Mirandópolis) – showed higher values of TEP, related to the higher direct radiation in the spaces with higher SVF, contributing to reduce thermal comfort. This way, strategies to improve thermal comfort might include obstacles to sun direct radiation, mainly vegetation and also other shading tools.

4. CONCLUSION

The studies in this work corroborate results found in the referred researches [3, 4, 6, 7, 9, 12, 13, 15], as it was found that different morphological models of the city morphology can cause great impacts on the thermal conditions of open urban spaces. This happens mainly because the morphological conditions of the urban space can change the amounts of direct, diffuse and reflected radiation received by the spaces, the wind speeds and, consequently, the Air Temperature and the Mean Radiant Temperature, and subsequently the thermal comfort indexes and the demand on the artificial air conditioning systems of buildings.

The models with less verticalization, less constructed volume and higher SVF values presented higher values of Air Temperature during the daytime, with an air heating that occurs more quickly because the open spaces are more exposed to sunlight and, at night, the more verticalizes and dense models showed the highest temperatures, due to the greater accumulation of heat in the built masses and the trapping of heat by the reflection of radiation in the urban canyon.

These results can contribute to the composition of urban planning guidelines (urban parameters, building regulations), supporting measures that can contribute to achieve better thermal conditions in urban open spaces and buildings, and a greater resilience to the scenarios of aggravation of urban heating and global climate change phenomena.

ACKNOWLEDGEMENTS

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The effect of the building's density on the air temperature within urban neighbourhoods in hot, dry cities

Case study three neighbourhoods in city of Biskra, Algeria

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ABSTRACT: Since the first sight of human habitation in a desert environment, the strategy of urbanization, it was compact urban fabric where a high building density, streets and narrow alleys, it's in order to reach a maximum of protection of climatic factors, especially protection of high air temperatures, the research methodology of this paper is based on three main axes: which are 1- a survey of Climatic factors 2- the second axis, it was regression analysis 3- the third axis, which is the discussion of the results of the survey and regression analysis, we conclusion is the six times which analyze indicated a existence regression significant for one period, which is the daytime of the summer only, where sig =0,00, sig ≤ 0,05, also the field survey analysis indicated an difference in air temperature within neighbourhoods (F1,F2,F3) at the daytime of the summer only, where the difference reached 4,2 co.
KEYWORDS: Buildings Density, Air Temperature, Neighbourhoods, Linear Regression, Biskra City.

1. INTRODUCTION

The public spaces play a large role to define the quality of life experienced by citizens. For this reason, it is essential that urban public spaces be comfortable and attractive(Qaoud & alkama 2017). The outdoor spaces in the neighbourhoods are fundamental for the social life due to their capacity to serve as meeting spaces and interactions among the public (Boukhabla et all 2014), especially in cities of desert, the environmental quality conveys a sense of well-being and satisfaction to its population through characteristics that may be physical, social or symbolic (Theodore et all 2003) also the environmental quality is a complex issue involving subjective perceptions, attitudes and values which vary among groups and individuals(Krüger et all 2010) the environmental conditions influencing well-being in the built environment: thermal, visual and acoustic, as well as air quality (Monika, & Pawel,2010).

2- MATERIALS AND METHODS

2.1. Study area.

The city of Biskra is located in the southeast of the country's capital with a distance of 430 km Biskra city is a link between the north and the south of Algeria, its called through the ages the gate of desert.

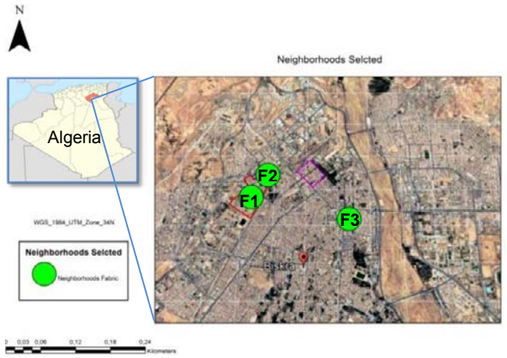


Figure 1. *The neighbourhoods selected.*

, the city is located in the northern part of the state according the coordinates, east of the greenwich line, longitude 5°,43 east and northeast latitude 34,51° north (Qaoud & alkama 2019), the sample study included a three urban fabrics of neighbourhoods in the city center area, with different types of buildings density, the neighbourhoods called , 1- al istqulala(F1), 2- al-nassr(F2), and 3- al-zamala(F3), its representing all patterns building density in neighbourhoods across the city according to the density indicators, the sample will be arranged in ascending order from the smallest to the largest density.

2.2. The measuring stations.

There were 30 measuring stations as flowing figure, 10 stations for each neighbourhood to measure climate factors, the measuring stations were distribution in serial order a central of each neighbourhood, and in different directions in order to get the average values of climate factors be correctly and confirmed from each fabric of neighbourhood the measurement was taken every two consecutive hours throughout 24 hours a day, so the measurement was taken a 25-26/07/2021the summer season, 15-16/05/2021the spring season, 27-28/02/2021 the winter season. As table N° 1 where the average of Technical parameters of each neighbourhood.

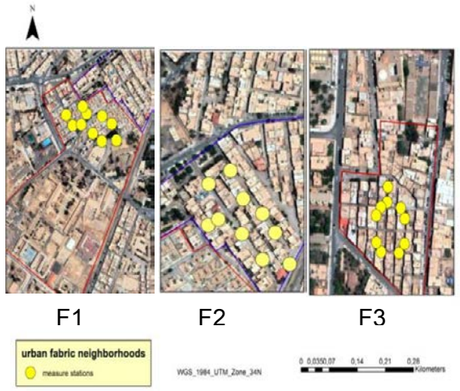
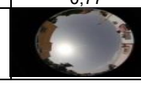


Figure 2. *The measuring stations within urban fabric.*

Table 1.*The Technical Card of Neighbourhood data.*

average	Al-istquala Neighbourhood N1	Al-Nasr - Neighbourhood N2	Al-Zamala Neighbourhood N3
BD	12/ha	35.51/ha	59.52/ha
floor	1	2	*2+TR*
H	3,6	8.33	*8.33*
W	9	8.16	*3,8*
H/W	0,40	1,02	*2,1*
Dir-tion	Nw/Se	Nw/Se	*N/S*
S,V,F	0,77	0,42	*0,22*
FICHE EYE			

2.3. Literature review.

There are some literature which related to the research work in the study area, we mention the works of b, mofidah, k, hamel, and m,al-hadi, their study focus on studying the effect of street engineering and urban fabric morphology on thermal comfort and the heat island in city of Biskra among those works, we mention the following 1- (k hamel, & mazouz 1997) where the study of the compact city an urban shape for sustainable city, in arid areas, 2- (Hamel khalissa, et all 2021) this study show the impact of the palm grove and the built density on the urban microclimate in Ossian environment, 3- (Boukhabl & alkama2012)where study of the impact of vegetation on thermal conditions outside, thermal modelling of urban microclimate, case study, the street of the republic Biskra, 4- (Boukhabla, et all,2014) the energy balance behaviour in open street case study city of Biskra, Algeria, 5-(Al-hadi et all,2021) prediction of climate change effect on outdoor thermal comfort in arid region, through the previous literature review, we can shed light on the research gap of this paper, it was represented in the fact that none of the previous research works had previously addressed the relationship between variable of buildings density of urban fabric and air temperature, as most of the literature of studies in the region dealt with street architecture or the openness or closure of the street and its relationship to indicators of thermal comfort and the heat island.

2.4. Research objectives

The objectives of the research is a good understanding of the reasons how the buildings density of neighbourhoods affects in the air temperature within the outdoor urban space, defining the statistically relationship which links the urban fabric morphology and air temperature, determine the best type of building density of neighbourhoods in hot cities which can affect and reduce of the air temperature.

2.5. Methods

The research methodology of this paper is based on three main axes: which are 1- a survey of climatic factors (air temperature, relative humidity, wind speed) during three seasons of the year, which are winter spring and summer and the sample analyzing according to building density indicators, 2- the second axis, it was regression analysis this in order to infer statistically the effect of the density of buildings of neighbourhoods on the air temperature which is the H/W as an independent variable and the air temperature as an dependent variable, 3- as for the third axis, which is the discussion the results of the survey and regression analysis.

2.6. Examined variables

In this research paper, we studied and analyzed several variables related to building density and climate factors, these variables were classified on the basis of independent and dependent variables.

2.6.1. The independent variable

They represent the independent variables which responsible of the effect that occurs on the phenomenon, here in this study, the independent variables was represent the building density of the fabric, for example the sky view factor variable(S,V,F). it's a coefficient of sky view factor, its a fractional number is limited from 0 to 1(Khaled,2008), H/W variable it's the ratio of the height of the buildings to width of street, the building density variable (BD), which expresses by the number of building/ha(Roberts,2006), the building coverage ratio (BCR) which expresses by surface of building /ha(Omar et all,2020). In this context, the previous literature review conducted at similar goals and locations, it's relied on (H/W)(S.V.F) variables (Roberts,2019) so hence, in this paper, we use variable that represent the density urban form which is (H/W) specified as the independent variable.

2.6.2. The dependent variable

The dependent variables which is the variables affected of the phenomenon, in this study, it's was represent by the climate factors , for example. The air temperature variable is great interest to studies that charge the thermal comfort in the outdoor (R, Compagnon,2004), the most studies are interested of thermal performance in the outdoor spaces focus on the variable of the air temperature (You Peng,2021), it's the result of a interaction between the natural component and the built component, in this paper, the air temperature variable (AT) as the dependent variables.

2.7. The survey.

The field survey, More than 360 measurements of air temperature were taken during three seasons of the year, summer, spring and winter, through 30 measurement stations, each 10 measurement stations in each neighbourhood.

2.8. The regression analysis.

We applied the regression analysis with a simple linear regression to analyze the relationships between independent H/W variable with dependent AT variable (Air temperature) at three seasons of the year during the daytime and night-time of each season.

3. RESULTS

3.1 Aspects of comparison

3.1.1. The survey data

In the winter season as figure N°3 the difference in air temperature values did not exceed 0.6°C at daytime and 0.4C° at night-time which indicates the weak effect of the building density of fabric on the air temperature. Where the average of values of air temperatures recorded - neighbourhood (F1) 23.1C°, neighbourhood (F2) 23.3C°, neighbourhood (F3) 22.7C° at day-time, also the average of air temperatures recorded neighbourhood (F1) 11C°, neighbourhood (F2) 11.1C°, neighbourhood (F3) 10.7C° at night-time .

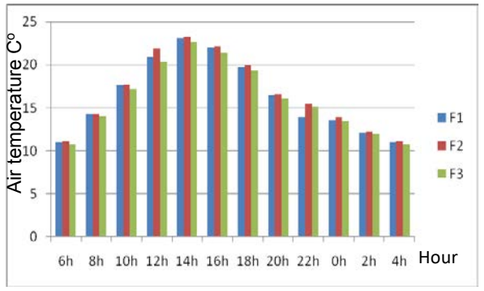


Figure 3. *The histogram of survey data during the winter season.*

In the spring Season figure N°4 the average of values of air temperatures are recorded at day-time in neighbourhood (F1) 33.8C°, neighbourhood (F2) 33.6C°, neighbourhood (F3) 34C°. also the air temperatures are recorded at night-time in neighbourhood (F1) 22.4C°, neighbourhood (F2) 22.3C°, neighbourhood (F3) 22.5C°. Thus the air temperature difference reached 0.4°C at day-time and 0.2 C°, at night-time, the data indicates the weak effect of the building density of fabric on the air temperature.

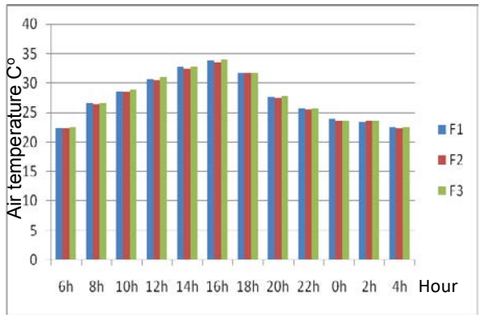


Figure 4. *The histogram of survey data during the spring season.*

In the summer season as figure N° 5 the results clearly showed the difference in air temperature values reached 4.2°C at day-time, where the effect of the building density of fabric on the air temperature, the average of air temperatures values at day-time within neighbourhood (F1) 46.1°C, neighbourhood (F2) 44.43°C, neighbourhood (F3) 41.87°C, also the air temperatures values at night-time within neighbourhood (F1) 32.1°C, neighbourhood (F2) 31.9°C, neighbourhood (F3) 32°C. where the difference reached 0.2 C° of the air temperature reached at night-time which indicates the weak effect of the building density.

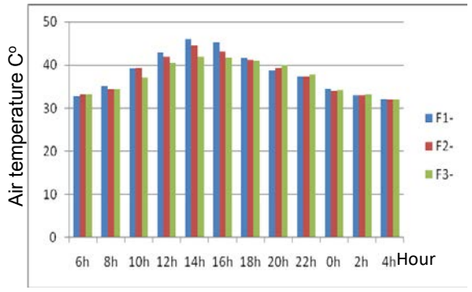


Figure 5. *The histogram of survey data during the summer season.*

3.1.2. The regression data

According the results of the regression analysis, the results indicated a existence statistically significant for one period, which is the day-time period of the summer only, where sig =0.00, sig ≤0.05. Through table N° 2 too the (B) is a negatively sign at day-time for all seasons, and positively sign at night-time for all seasons.

Also the highest values of (B) was in summer season where B=-0.213, (R2) =0.68, (sig)=0.00, the relationship between the two variables is an inverse relationship , and the independent H/W variable has a strongly effects on the dependent variable AT during the daytime of the summer, on anther hand the values in the rest of the periods is low or almost non-existent.

Table 2.*The statistically significant data.*

Season	*Time*	*R2*	*constant*	*B*	*SIG*
Summer	Da-time	0,68	41,43	- 0,213	0,00
	NI-time	0,004	33,98	0,004	0,737
spring	Da-time	0,059	30	- 0,023	0,198
	NI-time	0,003	23,38	0,006	0,758
winter	Da-time	0,11	19,25	-0,021	0,001
	NI-time	0,000	12,48	0,001	0,944

3.2. Aggregation of results.

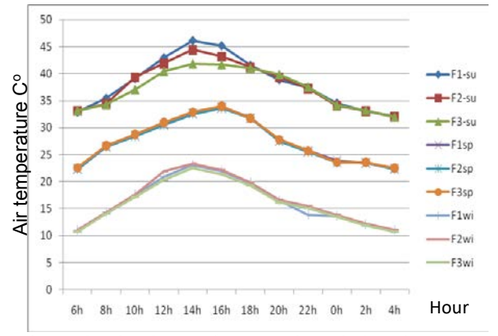


Figure 6. *The Curve of survey data during the summer season.*

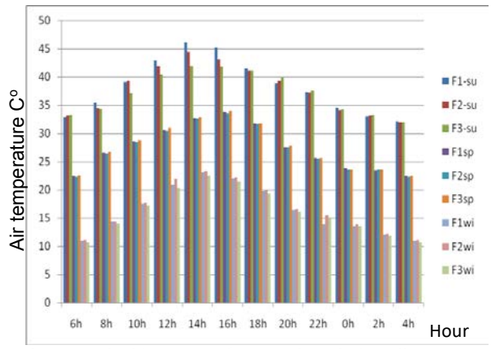


Figure 7. *The histogram of survey data during all seasons.*

Table 3. *The results of the regression with the air temperature difference,*

	summer season		spring season		winter season	
	D-time	N-time	D-time	N-time	D-time	N-time
sig ≤0,05	0,000	0,737	0,198	0,758	0,063	0,944
AT-dif	4,2	0,2	0,4	0,2	0,6	0,4

By data collection of the survey and regression, as fig N° 6 , 7 and table N°3 there is a correlation of the statistical function and variance in air temperature during the daytime of the summer, where ***B=0.213-, R2=0.68, sig=0.00, variance of AT=4.2 °c.*** Also, by comparing the results between the different seasons of the year, it's the variance which was in the day-time in summer season.

So the actual effect of the building density on the air temperature was during that period, which is what the survey and regression results indicated.

4. DISCUSSION

The discussion is based on study of the phenomenon from the physical side, where the study depends on evaluating the impact of density of urban fabric on the physical environment factors Without addressing the aspect of thermal comfort or comfort indicators or introducing the human element into the variables which studied. Therefore, the frame built of fabric which is the effective effect on the air temperature to protection from direct solar radiation and providing more hours of shade, through the results obtained in the previous section, shown in Figure N° 7, 8 . We can say that dense fabric has the lowest of air temperature compared to other fabric in the sample. Therefore, the density of the neighbourhood had a strong role in protecting from solar radiation load in the built environment and the air during the peak time of the year, where the difference of air temperature between dense and less dense neighbourhoods =4.2 c° at summer.

4.1. suggestions of urban density of neighbourhoods

The high urban density is a good way to provide shade in the open spaces, this strategy was mainly in the construction of ancient cities.

Therefore, it is better for the residential neighbourhoods to be a high density in order to provide shaded during the daytime especially in the summer where the alternating shade via the height of buildings.

5. CONCLUSION

The shade which is the technique of built environment to influence on air temperature by a series of simultaneous effects thus, the buildings density is provide the shade which a lower of air temperature values , the surveying of literature, has been proven that shading lower the air temperature and increases the rate of thermal comfort, therefore, the increase in the buildings density of urban fabric can be increased in the number of hours of shade and lower the air temperature within outdoor spaces of the neighbourhood.

There is also a statistical function between the building density variable and the air temperature variable, therefore there is a strong relationship between the two variables, and the reason of variation in air temperature is the building density of neighbourhoods, this relationship could predicted mathematical, in final, we can say that the building density of urban fabric of neighbourhoods can improve the air temperature of the outdoor space in hot, dry cities .

6. Further study

Maybe there is a future study regarding of the behaviour of the buildings density towards the physical factors of the nature environment such as the sound variable, natural lighting and wind, a future study of relationship of buildings density with air temperature according to type of climate different, also the relationship between building density of neighbourhoods and social phenomena such as social interaction within the outdoor space of neighbourhoods.

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How density affects energy demand in urban grids
The case study of the *Eixample* district of Barcelona

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ABSTRACT: High density and compact urban morphology are usually considered prerequisites for sustainable development. This paper explores the effect of density on the air-conditioning demand of urban grids in the Mediterranean climate, based on the case study of the Eixample of Barcelona. Representative periods in the district's history are selected to create four urban energy models. We calculate their annual heating and cooling demands through dynamic thermal simulations in Honeybee. Results show that the denser the block, the lower the total air conditioning demand for cooling and heating. Since the energy demand of the dwellings on the top floors significantly exceeds those of intermediate floors, increased densities achieved with taller buildings allow for reducing the air-conditioning needs at the block scale.
KEYWORDS: Air-conditioning energy demands, Urban grid density, Urban regulations, Eixample, Barcelona

1. INTRODUCTION

Cities play a central role in climate change since they are responsible for more than 70% of global CO_2 emissions. A significant share of these emissions is due to the buildings' energy consumption for heating and cooling, which is heavily dependent on urban form [1-3].

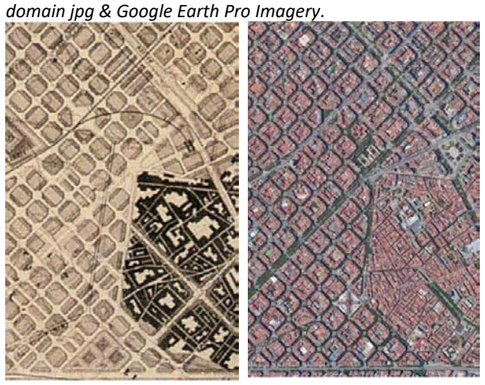
The evolution and shaping of cities are extraordinarily complex, resulting in multiple urban forms. However, most cities in the world use regular grids as the basic growing structure for allowing rational development and guaranteeing minimum quality levels to citizens. Thanks to its flexibility and capacity to adapt to diverse uses, the grid layout has been described as the closest thing cities have to a universal language, able to produce infinite variations in different cultures and times.

Among urban grid layouts, those with high density and a compact urban form are often considered sustainable developments because of their capacity to promote diverse and vibrant urban spaces, foster energy efficiency, and limit environmental impacts [1]. In this framework, it is crucial to understand how this specific archetype of urban form interacts with the energy balance of the compact city.

Selecting the most efficient urban form to limit air conditioning demands in a particular location requires accounting for the local climate. In extremely hot regions, highly compact and dense cities perform better than those following sprawl-like patterns [2]. In temperate zones, where cooling and heating are both necessary (e.g., Mediterranean climate), it is desirable to find a compromise because excessively high densities can limit winter solar gains, increasing hence heating needs [3, 8-10].

Our study aims to explore the impact of built density on energy demand for cooling and heating of urban grid layouts in the Mediterranean climate. To do so, we select the Eixample district of Barcelona (Spain) as the case study. In this fabric, there have been different urban proposals and regulations over the same grid for more than 150 years [4], making it a compelling example where study the energy effects of density changes.

Figure 1:
Plan Cerda (left) and actual aerial views of the Eixample of Barcelona (right). Source: The authors, based on public domain jpg & Google Earth Pro Imagery.



2. METHODS

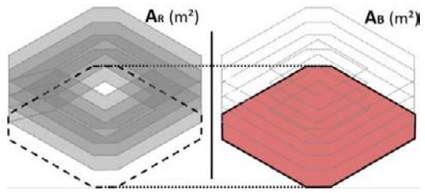
First, we carried out a bibliographic review of the urban regulations of the Eixample from its origins to the present. Based on this, we selected four representative periods in Eixample history and created four geometric urban models using Rhino/Grasshopper (Fig. 1). Then, we computed their annual heating and cooling demands through dynamic thermal simulations in EnergyPlus/ OpenStudio using Honeybee 1.1.0 [5]. Finally, we discussed the link between energy demand for air conditioning and built density, here expressed in terms of "Residential Floor Space Index" (Eq. 1):

$$FSI_R = A_R / A_B \quad (1)$$

where FSI_R - Residential Floor Space Index (m^2/m^2);
A_R - Residential built-up area (m^2);
A_B – Block area (m^2).

FSI may refer to different spatial scales (lot, block, fabric, district, or city) and generally reflects the building intensity independently of the programmatic composition [6]. In this study, the focus is on the residential energy demands at the block scale. Therefore, we exclude the ground-floor area, usually used for commerce and other facilities, from the computation of FSI (Fig.2).

Figure 2:
Graphical definition of FSIR.



3. CASE STUDY

3.1 Urban layouts

The *Eixample* plan emerged as a solution to the demographic growth and poor sanitary conditions experienced by the city in the first half of the 19th century, one of the prominent periods of urban expansion [4]. The plan is based on a regular grid of streets 20 m wide, whose basic unit is a square block (113x113 m) with chamfered corners, oriented 45° North [7, 8]. In this paradigmatic grid, urban form and building shape evolved over decades: from the original *Plan Cerdà* based on open blocks permeated by open spaces to the following closed blocks, more compact and with fluctuating values of building density (Fig. 3).

For this study, we defined and analysed four urban layouts, which are representative of different urban planning ordinances [4]. Fig. 3 describes the configuration of the basic block for each layout, specifying their height, the number of floors, FSIR, and Ground Space Index (GSI [6]).

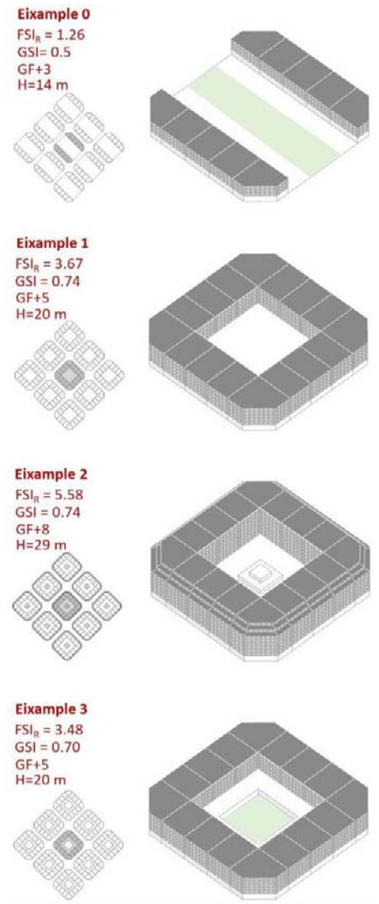
Eixample 0 represents one of the blocks of the original plan of 1859. The main limitations of the ordinance were a plot GSI of 0.5 and a maximum height of 16 m (Ground Floor + 3).

Eixample 1 is the classic Eixample block of 1891 urban regulation (GF+5). Then, the maximum GSI was 0.74, which allowed 27.9-m-depth buildings. Also, one-story buildings were allowed in the block courtyard.

Eixample 2 reproduces the time of highest built density allowed by 1958 urban regulations. GSI and building depth remained the same, but an FSI increase was allowed (up to GF+8, counting attics).

Eixample 3 corresponds to the current urban planning regulations (1976-2002). The floor area and the building depth are reduced, taking up features of the classic block (GF+5).

Figure 3:
Urban models according to the four urban regulations.



3.2 Simulation settings and building features

To investigate the link between urban density and air-conditioning demand in the Eixample, we analysed the four urban models in Fig. 3 through energy simulations.

Each urban model comprises nine blocks distributed in a 3x3 array. The one in the middle is the target of the thermal analysis, while the rest act just as the built environment that casts shadows and creates reflections. The target block comprises a set of buildings made up of several 3-meter-height residential floors over a 5-meter-height commercial ground floor. All the interior partitions and intermediate floors allow for thermal exchanges, except those separating residential and commercial units, considered adiabatic. All buildings have a 30% window-to-wall ratio [7] and thermal properties corresponding to the typical construction system in Spain before the arrival of thermal regulations in 1979 (non-insulated, medium-weight, low air-tightness). Tables 1 and 2 summarise the main building features and settings used for the energy modelling in this work.

Table 1:
Building features of the urban energy models.

Parameter	Value
U-façade wall (W/m²K)	1.5
U-roof (W/m²K)	1.8
U-window (W/m²K)	5.7
U-interior floor	2.0
U-interior walls	2.1
Window-to-wall ratio (%)	30
Infiltration rate (m³/s per m² façade)	0.0006
Façade & roof reflectance [-]	0.30
Ground reflectance [-]	0.30

Table 2:
Simulation settings.

Parameter	Setting
Heating set-point & schedule (1 Oct – 31 Apr)	20°C from 8:00 to 23:59 17°C from 00:00 to 07:59
Cooling set-point & schedule (1 May – 31 Sept)	25°C from 16:00 to 23:59 27°C from 00:00 to 07:59
Free cooling (1 May – 31 Sept)	Whenever Tint > Text If: Tint>21 & Text>16
Ventilation rate	0.63 ach 0.036 people/m²
People density & schedule	**Mon to Fri** 100% from 23:00 to 07:59 25% from 08:00 to 15:59 50% from 16:00 to 22:59 **Sat, Sun & Holidays** 100% all day long
Internal gains & schedule • Lighting • Appliances	4.4 W/m² 10% from 0:00 to 07:59 30% from 8:00 to 18:59 50% from 19:00 to 19:59 100% from 20:00 to 22:59 50% from 20:00 to 22:59

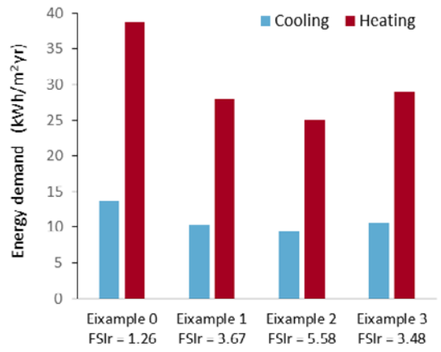
Using Honeybee 1.1.0 [5], we compute air conditioning energy demand to achieve the heating and cooling set-point temperatures at each residential unit, as scheduled in Table 2. These settings, along with internal gains (people, lighting, appliances), follow standards from the Spanish thermal regulation (CTE [11]). Our simulations do not account for shading devices but include a free-cooling strategy to avoid excessive indoor overheating during the cooling season.

4. RESULTS

Though the majority of the regions with Mediterranean climates have relatively mild winters and warm summers, temperatures may vary significantly among regions and, thus, air-conditioning demands. In the case of Barcelona, both heating and cooling are necessary, but the first is far more significant (Fig. 4). For the *Eixample* layouts studied here, normalized heating demands range between 25 and 39 kWh/m², while the cooling ones vary between 9 and 14 kWh/m², which means that heating requirements are 2.6 to 2.8 times higher than the cooling ones.

Our simulations show that the density changes in the *Eixample* have a direct impact on air-conditioning demands. The denser the urban tissue, the lower the energy needs for cooling and heating. The normalized heating demand of the block faithful to Cerda's original idea (*Eixample* 0) is 35% higher than those of the densest block ever allowed by regulations (*Eixample* 2). Regarding cooling, this decrease is slightly smaller, 31%.

Figure 4:
Annual heating and cooling energy demands per floor area for the four layouts of the Eixample block analysed.



To investigate the reasons behind this behaviour, we conducted a spatialized analysis of the simulation results. To this end, we coloured the dwellings of each model according to their heating, cooling, and total demands (Fig. 5, 6, and 7).

Figure 5:
Annual heating demands per floor area for different Eixample models: E0, E1 , E2 and E3.

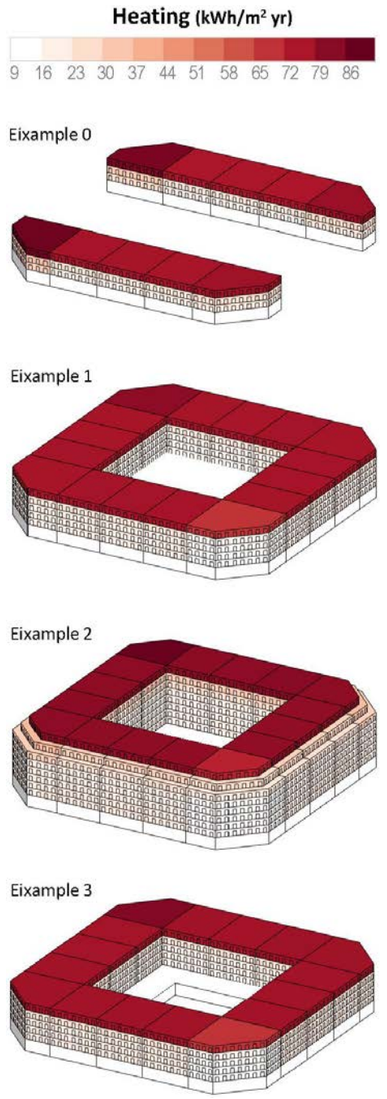
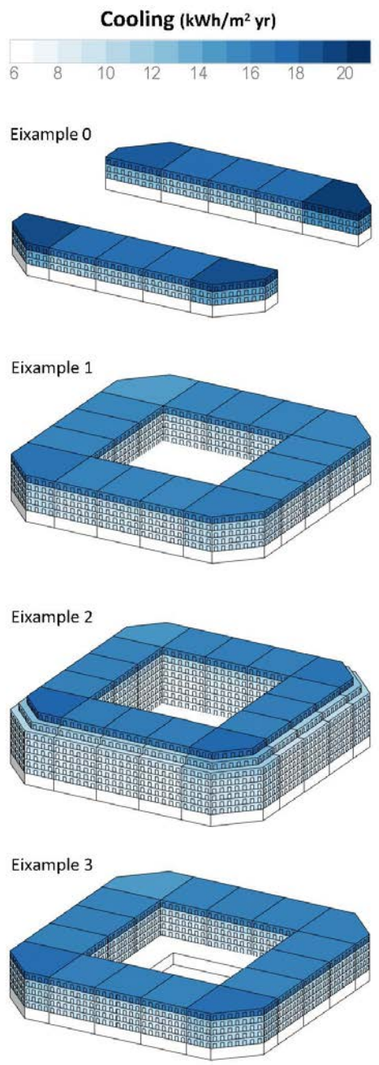


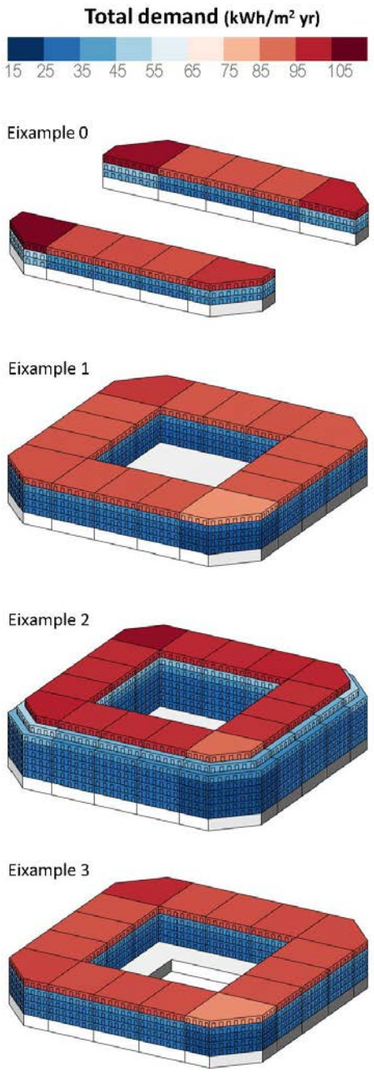
Figure 6:
Annual cooling demands per floor area for different Eixample models: E0, E1 , E2 and E3.



Heating demands range between 10 and 86 kWh/m² per year among the studied urban models. In all the cases, the highest heating demands locate on the last floor of the block, with values between 65 and 86 kWh/m² per year. In contrast, dwellings located at mid-level have lower heating needs, which vary between 10 and 42 kWh/m² depending on their orientation and floor. These results evidence the significant variation in heating demand that can exist among the dwellings of a single block, which may arrive up to 800%.

As for cooling demands, values range between 7 and 19 kWh/m² per year among the studied models. Like for heating, top-floor dwellings have the highest cooling needs in all urban layouts, with values between 14 and 19 kWh/m² per year, while in the rest of the building, they vary between 7 and 15 kWh/m² per year. Cooling needs are more evenly distributed between levels than heating ones because solar gains over façade are more homogenous in summer than winter due to a higher sun elevation.

Figure 7:
Total air-conditioning demands per floor area for different Eixample models: E0, E1 , E2 and E3.



The addition of heating and cooling demands brings total air conditioning demands ranging between 20 and 103 kWh/m^2 per year (Fig. 7). Again, top floors present the highest demands, with values over 81 kWh/m^2, while mid-level dwellings have much smaller demands, below 52 kWh/m^2. Two factors explain this behaviour: the higher exposed-to-air surface of top-floor dwellings and the significance of heat losses/gains through the roof. Differences in demand among block sides are less noticeable than among floor levels because most buildings in this study have symmetrically oriented façades (except in the chamfers).

5. DISCUSSION

To discuss the impact of urban density on energy demand, we analysed the normalized total air-conditioning demand of the blocks by Residential Floor Space Index for the four *Eixample* layouts (Fig. 8).

Figure 8:
Air conditioning demand (kWh/m^2 per year) by Residential Floor Space Index (FSIr) for the Eixample layouts analysed.

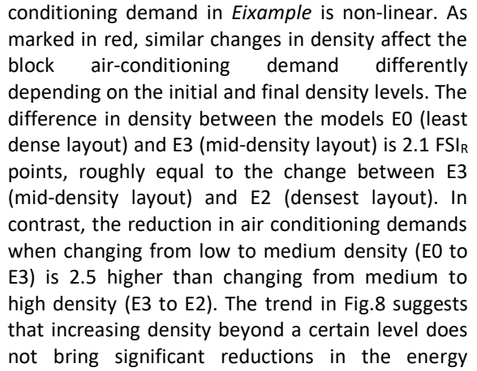


Fig. 8 shows that the denser the tissue (↑FSI$_R$), the lower the total air-conditioning demand per floor area. The main reason for this behaviour is that the density increase in the *Eixample* is mainly due to a rise in the building height. In taller buildings, the roof represents a lower proportion of building skin. Similarly, the top-floor dwellings represent a lower share of the total block surface. Consequently, the high air-conditioning demand of these dwellings is divided by a larger built area, giving lower energy demands per area at the block scale. These results highlight the crucial role of roofs in the energy performance of tissues, pointing to them as a target for urban refurbishment policies.

The relationship between density and block air-conditioning demand in *Eixample* is non-linear. As marked in red, similar changes in density affect the block air-conditioning demand differently depending on the initial and final density levels. The difference in density between the models E0 (least dense layout) and E3 (mid-density layout) is 2.1 FSI$_R$ points, roughly equal to the change between E3 (mid-density layout) and E2 (densest layout). In contrast, the reduction in air conditioning demands when changing from low to medium density (E0 to E3) is 2.5 higher than changing from medium to high density (E3 to E2). The trend in Fig.8 suggests that increasing density beyond a certain level does not bring significant reductions in the energy demand at the block scale and might be counterproductive.

Another aspect worth discussing is that density increase may have different effects at dwelling and block scales. In this study, the increase in urban density leads to decreases in cooling and heating demands at the block scale. However, not all the dwellings in the block follow this trend individually. Results show that those on the lower floors present higher heating demands as urban density increases due to poorer solar access in winter, especially from the street.

Except those in the chamfer, we modelled dwellings as spaces with two opposed façades (SE&NW, SW&NE), one overlooking the street, the other, the inner courtyard. Two-façade dwellings were one of the main ideas of the original *Eixample* plan and are still quite frequent in the district. Due to speculative urban pressures, single-faced dwellings are also recurrent. From the simulation point of view, choosing two-façade dwellings over single-façade ones is expected to have minor repercussions on the results at block and building levels, which ultimately was the focus of our study. However, this approach limits the possibility of studying certain local behaviours as it provides an average demand between orientations.

Future works could explore the sensitivity of the results to the level of insulation in buildings and other density-related aspects, such as the intensity of the urban heat island effect.

6. CONCLUSION

This paper explores how changes in the built density of urban grids affect their demand for air conditioning in a Mediterranean climate, taking the *Eixample* district of Barcelona as a case study.

Our simulations show that increasing density reduces the air-conditioning demand per floor area at the block scale, both for heating and cooling. The reason is that the densification in the *Eixample* is mainly due to an increase in the building height, that is, to growth in FSI$_R$ while maintaining GSI. Since the top floor has significantly higher demands than intermediate floors, the taller the building, the more intermediate floors that offset the energy demand of the top floor, thus resulting in lower air-conditioning needs per area. This decrease in block-scale energy demands might be associated with an increase in the heating needs of dwellings in the lower levels. Spatialized analyses like the ones in this work can help find strategies to minimize the urban demand without excessively affecting the performance of lower-floor dwellings.

Urban density affects cities' liveability and performance in multiple ways. Among them, the air-conditioning need is an aspect rarely considered by policy-makers when developing urban regulations. Our study helps to overcome this limitation. Finally, the findings in this work can also help prioritize retrofitting interventions targeting the energy efficiency of the built environment.

ACKNOWLEDGEMENTS

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Urban verticalization

Predicting the effect of a Master Plan on microclimate in Bagé, Brazil

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ABSTRACT: Many factors constantly modify the urban morphology, such as the urban density and buildings' height. Those changes generally occur without a proper analysis of their future effects on the microclimate and resulting thermal comfort in open spaces. We simulated three urban scenarios in the CFD model ENVI-met for Bagé, a Subtropical city in the Southern Brazilian State: a) the current scenario; b) a prediction of the density growth by 2060; and c) the maximum height allowed by the Master Plan. As for the boundary conditions, we averaged the summer and winter extreme days from a TMY file. For scenarios a) and b), we considered changes in the global temperatures from 2021 to 2060. The results showed that higher and denser squares improved thermal comfort in the summer. Although the cooling effect was less pronounced in the winter, it cannot be ignored in subtropical climates because it can result in colder mean radiant temperatures and, consequently, discomfort by cold. In the scenarios that we considered the increase in air temperature input by climate changes, the T_{mrt} results increased compared with the current scenario, except on the Sidewalk in the highest scenario due to the biggest shading from the buildings.
KEYWORDS: Urban Densification, Thermal Comfort, Open Spaces

1. INTRODUCTION

The effect of urban density on microclimate has been studied by researchers over the last decade. Qualified and healthy open spaces can ameliorate the impacts of urbanization. Master Plans have a crucial role in the urban density increases due to the constructive limits allowed. The modifications of the urban fabric have consequences on microclimate, which can happen at different scales [1]. Changes in the urban morphology impact climate variables such as wind speed and direction, air temperature, air relative humidity, and medium radiant temperature.

Studies of winter and summer seasons in locations with extreme temperatures have shown that, for both seasons, vertical buildings influence outdoor thermal comfort. The Physiological Equivalent Temperature Index (PET) showed that tall buildings reduced the daily thermal amplitude for both summer and winter [2].

In warmer climates, high-rise buildings promote better thermal comfort at a pedestrian level due to the shading, which decreases the mean radiant temperature (T_{mrt}) [3,4]. In addition, progressive building setbacks imposed by Master Plans contribute to achieving better outdoor thermal conditions in tropical cities, mainly with semi-arid climates [5].

A Study in Bandung, a dense city with a hot-humid climate, simulated six squares with Podium, Tower, and Courtyard typologies with a floor area ratio of 2.2 in the existing scenario and 5.6 in the five proposed scenarios, diversifying the building coverage ratio between less than 0.40 and 0.74 [6]. The results demonstrated a direct correlation between the building coverage ratio with the air temperature and relative humidity and a direct correlation between the floor area ratio and relative humidity. Indirect correlations were found between the building coverage ratio, wind direction and speed, and between floor area ratio and air temperature.

In extreme cases, the verticalization of buildings intensifies the adverse effects of climate change, increasing the air temperature, particularly at night, accentuating the urban heat islands [7].

The verticalization of Brazilian urban centres leads to discomfort in open spaces such as the edge of Copacabana, Rio de Janeiro [8]. The urban morphology was simulated for January 1930, 1950, and 2010. The results demonstrated an increase in air temperature from 1930 to 2010.

The high-rise buildings change the wind speed, resulting in canalization or wind shade[1] [9]. Another consequence of the rise in buildings' height is the creation of urban canyons such as the ones in Fortaleza, Brazil [10].

Besides the verticalization, the geometry of street grids can interfere with thermal comfort in open environments at pedestrian level [11]. Similarly, studies that analyse building typologies, such as perimeter block, slab, and tower buildings, observed different microclimate results due to the geometry and characteristics of the sites. In São Paulo, Brazil, tower buildings (with fourteen storeys) showed better thermal performance (on April 27th, at 3 p.m.) than perimeter blocks (with eight-storey and ten-storeys) [12]. Conversely, a study in The Netherlands showed that perimeter blocks resulted in better thermal comfort in the centre of the square in June if compared to singular and slab blocks (both scenarios with 9 meters in height) [13].

This study integrates broader research about the effect of densification on outdoor thermal comfort in the South of Brazil. We analysed the effects of urban densification on microclimate variables, for an urban centre. The studied city was Bagé, a Southern Brazilian city with Cfa climate (warm temperate, humid with a hot summer) [14]. In this clipping, we analysed the central block within the studied area. We compared three scenarios for this square: the current, medium, and maximum verticalized as allowed by the Master Plan, predicting the microclimate at the pedestrian level through computer simulations.

2. METHODS

This study analyses three urban scenarios with different built densities and verticalization for summer and winter. We ran 24-hours simulations in the software ENVI-met 5.0.2. The parameters were the mean radiant temperature (Tmrt), wind speed, and relative humidity.

2.1 Case study

The studied city is Bagé, in the Southern Brazilian part (31°19' South, 54°6' West; altitude of 232m). In that region, medium-sized cities have mainly low-rise buildings. The subtropical climate with high thermal amplitude represents a challenge to city planners from the point of view of thermal comfort. The weather often requires different architectural and urban strategies to respond to the opposite hot temperatures in the summer and cold temperatures in the winter.

To select the studied location, we have adopted the following criteria: an area where higher densification and verticalization occurred in recent years; high permissiveness for verticalization, according to the master plan; few historical buildings (which would not allow an increment in height); few urban voids and low-rise in most existing buildings. In this paper, we simulated the central part inside nine downtown squares.

2.2 Parametric scenarios and modelling

We have established three configurations for the buildings within the square. Whereas the first scenario represents the current square densities of the studied area, the second scenario predicts the density growth by 2060. The increase in the density rate was 10% from 2011 to 2021. We have applied this rate progressively by decade to the current densities of each square, as shown in Table 1. In this study, we analysed the square number 5. We conducted a random selection to establish which buildings would be modified due to the density arising, as projected by 2060.

Table 1:
Square density rates - current vs. by 2060

	Square density rate			Square density rate prognosis by 2060
Square	2011	2021	increase	
1	0.57	0.65	0.08	0.94
2	1.15	1.15	0.00	1.67
3	0.91	0.94	0.03	1.36
4	0.48	0.48	0.00	0.70
5	0.64	0.88	0.24	1.27
6	0.39	0.41	0.02	0.59
7	0.68	0.89	0.21	1.28
8	0.94	1.02	0.08	1.48
9	0.52	0.54	0.02	0.78
total	6.28	6.96	0.68	10.07

The third scenario reflects the maximum verticalization of the city's Master Plan (24 meters in height, or eight storeys). We kept buildings with three or more storeys in their original versions (for the three scenarios). We applied the same rule to the historical buildings. Table 2 shows the height of buildings, square density, and building coverage rates of the scenarios. The square morphologies are demonstrated in Figure 1, which shows the receptors points used to collect microclimate variables.

Table 2:
Height of buildings, square density, and building coverage rates of the scenarios

	Majority height of buildings	Square density rate	Building coverage rate
S.1	1 to 2 storeys	0.88	43%
S.2	3 storeys	1.28	47%
S.3	8 storeys	3.13	46%

Figure 1:
The square morphology in the current scenario (S.1), density growth by 2060 (S.2), and maximum verticalization (S.3) scenarios.

[1]Wind is blocked by some barriers, like buildings.

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We raised the square densities and building heights successively among the three scenarios. While the first scenario (the current one) has a low total density, the second has an intermediary density (buildings until three storeys), and the third scenario has the highest density of them (buildings until eight storeys height - until 24m). For scenarios 2 and 3, the new buildings respect the minimum side retreat to parcels of land whose widths are bigger than seven meters (2.5 meters). To be consistent with the current scenario (S.1), we kept free spaces in the centre of the square.

The weather data was averaged from the representative extreme summer week (22 to 28 December) and the representative extreme winter week (6 to 12 July) of the Test Reference Year (TRY) file [15]. Table 3 presents the boundary conditions in ENVI-met. Table 4 shows the surfaces' materials within the squares.

Table 3: *Initial input data in the ENVI-met simulations*

Current Meteorological data

Configuration Data	Summer	Winter
Initial simulation hour (24 hours)	5 a.m.	5 a.m.
Max T_{air} of the atmosphere (°C)	31.1	13.1
Mini T_{air} of the atmosphere (°C)	20.5	1.4
Diurnal T_{air} amplitude (°C)	10.6	11.6
Max relative humidity (%)	82.7	96.3
Min relative humidity (%)	53.4	65.1
Wind speed at 10m above ground level (m/s)	3.2	2.8
Wind direction (°)	45	45

Table 4:
Characteristics of the surfaces' materials within the squares

Element	Material	Colour	(α)	(ε)
Roofs	Ceramic tiles	Terracotta	0.5	0.9
External Walls	Brick: burned	Terracotta	0.6	0.9
External floors				
Pavement	Concrete	Gray	0.7	0.9
Pavement	Granit	Gray	0.6	0.9
Pavement	Asphalt Road	Dark	0.8	0.9

(α) Absorptance. (ε)Emissivity

Lastly, we simulate S.2 and S.3, increasing 3.1°C in the air temperature inputs at all times for the summer. This increase represents changes in global surface temperature from 2021 to 2060 [16].

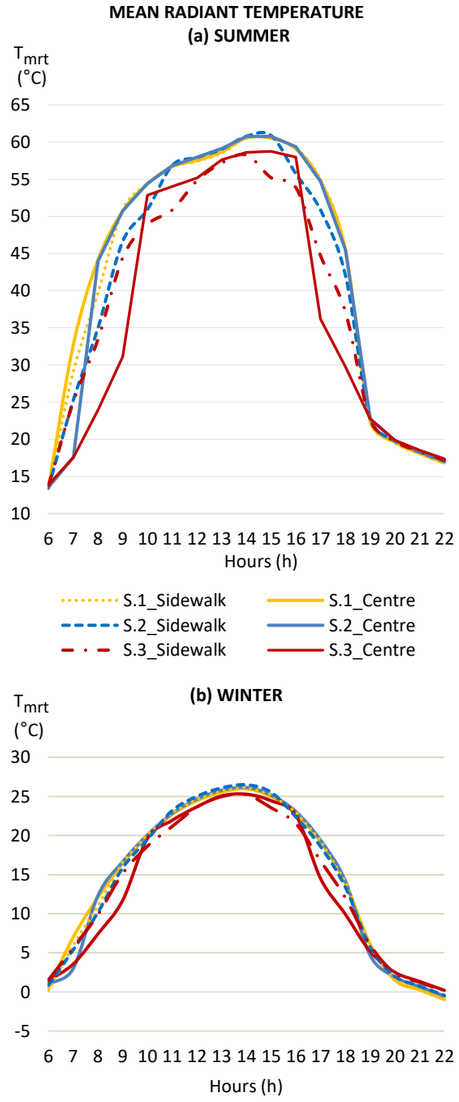
The scenarios originally had a one-metre grid and five receptor points. However, as the simulation was too slow (more than a week-long), we changed the grid value. Thus, we used a three-metres grid with receptor points. The results named "sidewalk" are the medium of the four receptors located in the sidewalks.

3. RESULTS

The changes in T_{mrt} and wind speed results confirmed the improved thermal comfort in the summer, as shown in studies in hot climates. Conversely, the winter results showed moderately adverse effects caused by more extensive shadows, as expected in high latitudes.

Figure 2 shows Tmrt from 6 a.m. to 10 p.m. (warmest daily time), at 1.5m height in the summer and winter. In the summer, the highest Tmrt was at 3 p.m. in all scenarios. An exception was Scenario 3, on the sidewalk, where the highest Tmrt was at 2 p.m. In the winter, the highest Tmrt was at 2 p.m. in all scenarios and analysed points. We observed a drop comparing extreme scenarios (S.3 to S.1) up to 0.97°C in the winter and 5.35°C in the Summer. S.2 compared with S.1 showed a decrease in the highest Tmrt of up to 0.32°C in the summer and 0.28°C in the winter.

Figure 2:
Results of T_{mrt} in the summer (a) and the winter (b) for scenarios 1, 2, and 3.



For Scenario 3, in summer, the urban density raising dropped the Tmrt up to 10.25 °C on the sidewalk and up to 20.17°C in the centre's square. In the winter, results showed a Tmrt increase of 1.18°C on the sidewalk and 1.28°C in the centre at night. The most significant decrease occurred at 5 p.m. on the sidewalk and 8 a.m. in the centre for the two analysed seasons. Besides, the summer simulations showed a discreet increase in Tmrt up to 0.71°C, and winter results showed an extreme decrease of 4.73°C, at 9 a.m., in the centre of the square.

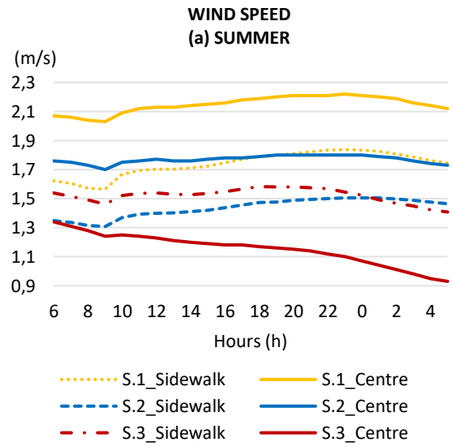
In the summer, the Tmrt from S.2 to S.1 dropped 4.73°C (at 8 a.m.) on the sidewalk and 15.05°C (at 7 a.m.) in the centre of the square. It occurred because of the long shadow from the buildings in S.2.

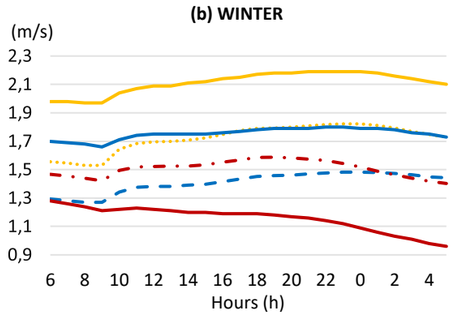
In the winter, the Tmrt was slightly warmer (at most times) in S.2, increasing at most 0.35°C on the sidewalk (at 1 p.m.) and 0.44°C (at 8 p.m.) in the centre. Although shadows from S.2 buildings are more extensive than S.1, S.2 has more facade area exposed to solar radiation. Therefore, the heat absorbed is reflected forward near open spaces, increasing the Tmrt.

The T_{mrt} results showed that for the studied case, the increase in density reduces the thermal amplitude for both the summer and winter. Our results align with a study in Campinas, Brazil [2]. The more expressive influence of density (and verticalization) was observed in the summer when the largest decrease in T_{mrt} happened.

Results indicate that for warmer climates (as in the Cfa), the increase in verticalization can promote thermal comfort at pedestrian level in open spaces. However, it's crucial to pay attention to the temperature decrease in the winter. In general, results showed a beneficial effect of shadings due to a T_{mrt} reduction in the summer. In addition, other effects of the verticalization should be considered, such as the drop in wind speed and modifications in wind direction. Figure 3 presents the results from wind speed, on 24 hours, for the summer and winter seasons.

Figure 3:
Wind speed on the sidewalk and in the centre of the square, for Scenarios 1, 2, and 3, in the summer (a) and winter (b) seasons





The wind speed in the winter and the summer had similar behaviour and values. The increase in building density and verticalization decreased wind speed. It can promote better thermal comfort in winter while contributing to thermal discomfort in the summer. The wind speed dropping was more intense in the centre of the square than on the sidewalk in all scenarios. S.2 to S.1 decreased up to 0.34m/s on the sidewalk and 0.42m/s in the centre of the square. S.3 to S.1 dropped 0.34m/s on the sidewalk and 1.19m/s in the centre.

On the sidewalk, the wind was speeder in S.3 than in S.2. It happened because, on S.3, the wind was channelled through the side clearances, accelerating it. Comparing the same scenarios in the centre, S.3 showed a lower speed due to the tower buildings' effect of partially blocking the wind flow. This effect of wind shading and canalization also was identified by Nogueira et al. [9]. Besides, S.3 was the one larger daily wind speed amplitude in the centre in the summer and winter. On the sidewalk at 1 a.m., the wind speed was the same in S.2 and S.3. Conversely, in the centre, they had the most expressive difference: 0.80m/s in the summer and 0.77m/s in the winter at 5 a.m.

The RH from S.1 to S.3 increased up to 1.2% on the sidewalk and up to 2.8% in the centre of the square in the summer. Similarly, in the winter, the RH increased up to 1.3% on the sidewalk and up to 3.6% in the centre. Thus, there is a direct correlation between RH and higher building density, similar to that identified in the study in Bandung, Indonesia [6].

Table 5 shows the Tmrt (24 hours averaged) for scenarios S.1, S.2, S.3, and two more: S.2.1 and S.3.1. (the initial air temperatures were increased by 3,1°C) that represents the climate change scenarios predicted by IPCC (2021) to 2060 [16].

Table 5:
Medium T_{mrt} (°C) for Scenarios S.1, S.2, S. 3 and the scenarios with an increase in their air temperature inputs (S.2.1 and S.3.1) in the summer

	S.1	S.2	**S.2.1**	S.3	**S.3.1**
Centre	34.02	33.08	**35.81**	31.60	**34.23**
Sidewalk	34.37	33.93	**36.65**	30.42	**33.15**

The S.2.1 and S.3.1 had a T_{mrt} increase compared with S.1, except on the Sidewalk in the highest scenario due to the biggest shading from the buildings.

4. CONCLUSIONS

This study analysed simulations of a current square for a city in Southern Brazilian and two scenarios denser and higher. We simulated all scenarios for the winter and summer seasons. We also run simulations considering the increase of climate change to 2060 in the summer.

The effect of density and verticalization to T_{mrt} was more expressive in the summer, improving the thermal comfort at the pedestrian level, as demonstrated in studies in hot climates. Although results for the winter had a less expressive effect on the variables, they cannot be underrated in subtropical climates. Higher verticalization can result in significant thermal discomfort in open spaces in the winter. Wind speed decreased from the current scenario to verticalized scenarios, mainly in the centre of the square, which can contribute to thermal comfort in the winter and discomfort in summer. In most results, the decrease by higher-rise was smaller than the increase by changing climate in the summer. Predicted studies are crucial to improving thermal comfort in open spaces.

We had a limitation in the configuration of clouds in the software ENVI-met 5.0.2. In this recent version, the software does not allow changing the value of high clouds. It did not commit the results. Furthermore, it is crucial to consider that verticalization affects other comfort aspects, such as the natural light and the thermal conditions inside the buildings. Also, other factors should be looked at, such as the landscape vegetation and surface materials. The further steps of this investigation will apply a thermal index to complement the results and simulate a larger area (nine squares).

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Micro-climatic aspects of Barcelona's Superblock strategy
A computational case study

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ABSTRACT: Warming trends in the cities and the Urban Heat Island Effect represent negative environmental impacts of urbanization, which, combined with increased air and noise pollution, can contribute to the deterioration of physical and mental health of its inhabitants. In the city of Barcelona, urban planners proposed the Superblocks project as a mean to decrease car usage, improve urban microclimate conditions and the overall comfort of adjacent public spaces. By the conversion of side streets into public spaces that prioritize pedestrian use, the traffic of motor vehicles inside the Superblocks is reduced to a minimum. The overall impact of this ground-breaking urban renewal in the metropolitan scale is yet to be seen but the urban microclimatic effects could be already evaluated using state-of-the-art computational simulation. The tool Urban Weather Generator was also used to evaluate the influence of the implementation of the Superblocks in the metropolitan microclimate. These two tools for the study of urban climate were used to assess the impact of Superblocks in the urban climate, and the applicability of the two employed computational methods were compared.
KEYWORDS: Microclimate, Urban Climate, Built Environment, Urban Heat Island Effect

1. INTRODUCTION

As heat waves in temperate regions become stronger and more frequent, the effect of Urban Heat Island (UHI) exacerbates it in urban areas and propels the use of air conditioning to unprecedented levels. The International Energy Agency [1] predicts that, by 2050, 5.5 billion households will have air conditioners, rising from under 1.8 billion in 2018. The growing dependency on active cooling devices and health hazards caused by heat waves have attracted a growing interest of research in ways to mitigate these effects on an urban scale [2].

In Barcelona, between 18% to 28% of the current cooling loads in residential buildings could be suggested to be the result of warming trends and UHI effects [3].

Urban noise pollution is also seen as a main concern by the Catalonian capital as over 40% of its inhabitants are exposed daily to noise levels over 65 dB(A), which is a threshold established by WHO [4].

Moreover, each of Barcelona's residents have, in average, less than one third of the 9 m² of green area per person recommended by the World Health Organization (WHO). There is a massive imbalance regarding the space reserved for individual transportation in the city, even in the central areas. While responsible for only 25% of the journeys within the city, cars take up about 50% to 70% of the street space [4].

The implementation of the Superblocks project in the city of Barcelona focuses on mitigating some of the above-mentioned issues. Thereby, key issues of interest pertain to the project's impact on the thermal comfort at street level and the reduction of energy consumption for space cooling.

To this end, simulation-based comparison of the conditions before and after the implementation of Superblocks can yield useful insights. Thereby, the implementation's effect on the urban microclimate and on thermal comfort of pedestrians and neighbouring inhabitants can be assessed.

The Superblock is a unique structural urban renewal plan that involves the urban agglutination of traditional squared blocks into large areas within which the use of automobiles is decreased to a minimum. The freed space is allocated to green areas and pedestrian zones. The estimated final areal gain amounts to 6 million square meters of public pedestrian and green space. Furthermore, a reduction of 21% in car usage is predicted, encouraged by the implementation of more public transport lines [5]. This represents a massive structural change in the way the city works and how the environment is impacted. The Ecology, Urbanism and Mobility Commission of the City of Barcelona described it as a change in the urban planning paradigm intended to prepare the city to face new environmental challenges and a great opportunity to improve the quality of life of its inhabitants [4].

Given this background, the main objectives of the present study can be summarized as follows:

- Evaluate the microclimatic implications of the urban renewal plan Superblock through simulation of various weather-related variables.
- Assess pedestrian comfort via calculation of the Physiological Equivalent Temperature (PET).
- Estimate related UHI mitigation effects.
- Comment on the usability of the employed computational applications ENVI-met [6] and UWG [7,8].

2. METHODOLOGY

Two of the completed Superblock projects, in urban districts with contrasting urban fabric attributes, were selected for this study. The first Superblock consists of four urban blocks and is in a more consolidated area around the Sant Antoni Market, adjacent to the old city. During the urban renewal, the two streets that separated the four blocks and the area around the market were transformed into pedestrian zones. They were levelled with the sidewalk and covered with a new light grey pavement. Multiple flowerbeds with vegetation of different heights, as well as new large trees were included. Permanent metal structures, which cover temporary usages and events (e.g., weekend markets), were also built around the market.

The second studied area was the Poblenou Superblock, implemented in a former industrial area that has been attracting new usages since the 1992 Barcelona Olympics. The Superblock is formed by the union of nine urban blocks and, even though planned to be permanent, is implemented using solutions that have a temporary character. Flowerbed and tree planters consist of large plastic pots and the separation between pedestrian and cars was implemented by painting the asphalt, not leveling the original street path.

2.1 ENVI-met simulation model and calibrations

Efforts were made to run the ENVI-met simulations in an efficient and effective manner. This involved the fine-tuning of model resolution, the length of the "warm-up" period, boundary conditions, and simulated solar radiation.

The first step was to determine the ideal 3D model resolution, which could be expected to yield reasonably detailed results while not demanding excessive processing time and computational resources. According to the ENVI-met technical manual, a typical horizontal resolution for the 3D model should be between 0.5 m and 10 m [9]. The grid resolution was determined by comparative simulations in both modelled areas with cell dimensions of 2.5, 3.0, and 4.0 meters. The simulated temperature at the centre of the model at a height of 1.5 m above ground was used for comparison purposes. The results of the simulations with the medium-sized and largest grid were compared to those of the smallest grid, and the root mean square error (RMSE) and coefficient of variation (CV) were calculated. This represents a modified version of the method adopted by Tsoka et al. [10] to simulate parts of the city of Thessaloniki with ENVI-met. Given the small divergence in the simulated results in both Sant Antoni and Poblenou areas and the long duration of simulation runs, which exponentially increases with the size of the model, the 4 x 4 m grid was selected. This choice was deemed to provide sufficiently detailed results within reasonable running times.

The second calibration step considered the consistency of the simulation results with reference to the length of the respective warm-up periods. Analog to the methodology described above, identical 3D models and boundary conditions were calculated with warm-up phase lengths of zero, 24, 48, and 72 hours. The simulation length of 48 hours and a 24-hour warm-up was found sufficiently consistent.

To evaluate the most adequate type of boundary condition input for air temperature, relative humidity, as well as wind speed and direction, an approach similar to the one by Vuckovic et al. [11] was followed. Thereby, either full forcing every 30 minutes or only minimum and maximum daily values were compared. As only measured data was available for Sant Antoni, only this area was used for this step. Thereby full forcing every 30 minutes yielded the best results and demanded only slightly longer simulation times.

Finally, simulated solar radiation was also adjusted using the measured global solar radiation as proposed by Mendes [12]. This is necessary as solar radiation is in this case a calculated value and not an input variable from the weather-station measurements.

2.2 Simulation period

For the simulations, the chosen period was from 30th of July to 1st of August of 2019. The days in this period were sunny, with little to no cloud cover, no precipitation, and with maximum temperatures between 26.1 °C and 28.7 °C. As such, these represent average July days in Barcelona. The average temperature in the last decade (2010-2019) for this period was 28.1 °C. The data was downloaded from the Raval weather station from the Catalonian Meteorological Service website [13].

2.3 Virtual sensors

ENVI-met stores the data from the simulations in hourly steps for each of the climate variables of atmosphere, soil, and building surfaces. To obtain data with a finer time resolution it is necessary to create, prior to the simulation, virtual sensor in the 3D models. The virtual sensors monitor the conditions in 10-minute steps.

2.4 3D models

Using ENVI-met version 4.4.3, both Superblocks, Sant Antoni and Poblenou, were 3D-modelled in their current state (i.e., after the completion of the planned urban renewal, as seen in Fig. 1 and 2) as well as in their previous state. The latter 3D-models were elaborated with information from older aerial imagery extracted from Google Earth History tool. Note that the ENVI-met 3D model for Sant Antoni, before and after the renewal, were named *EM-SA$_0$* and *EM-SA$_1$*, respectively. Likewise, the ENVI-met 3D model for Poblenou, before and after the renewal, were named *EM-PN$_0$* and *EM-PN$_1$*, respectively. The triangles in Fig. 1 and Fig. 2 represent the virtual sensors inside the implementation area while the circles are outside the Superblock´s perimeter.

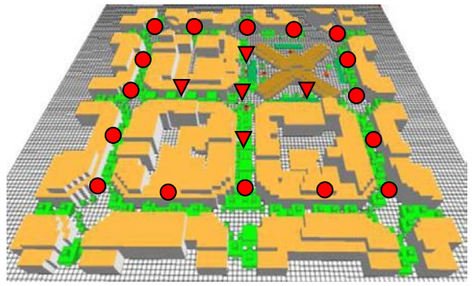

Figure 1: 3D model for ENVI-met from the Sant Antoni Superblock at its current state.

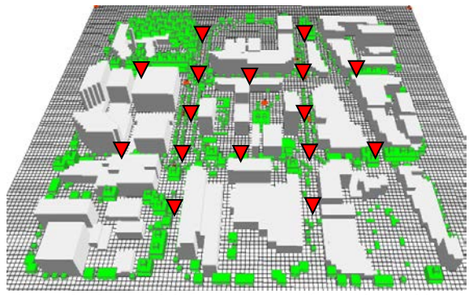

Figure 2: 3D model for ENVI-met from the Poblenou Superblock at its current state.

The assumed material albedos were 0.5 for walls, 0.53 for roof, 0.29 for light concrete pavement, 0.33 for painted asphalt and 0.13 for asphalt road. These assumptions are based on measurements of standard materials by Prado and Ferreira [14] and Richard et al. [15].

2.5 Urban Weather Generator (UWG)

The Urban Weather Generator (UWG) was developed by Bueno et al. [16] to assess the urban canopy temperature within an urban area. It uses as input the weather data from a nearby rural meteorological station and the topology and materials of a limited urban area, such as a neighbourhood. The output is the predicted average hourly air temperature in the urban canyon. The difference between this output and the rural temperature is the calculated increase in temperature due to the Urban Heat Island Effect.

The Rhino Grasshopper plug-in was employed for geometry import and the MATLAB version of UWG for calculation. The urban characteristic values calculated using Grasshopper based on buildings' footprint and height were exported to UWG MATLAB. Moreover, additional information about pavement albedo, proportion of green areas, and tree canopies was included. The same albedo values and the same simulated period from the ENVI-met model were used. The weather data was taken from a rural weather station near the main city airport.

2.6 Anthropogenic heat gain

The heat generated by traffic was taken from Bueno et al. [16] for a mixed used area of Toulouse, because of the similarities between both urban areas. Thereby, 8 W.m^{-2} is suggested to be a good approximation for the heat emitted by motor vehicles. The waste heat generated by air conditioning was calculated with a setpoint cooling temperature of 26 °C, and the schedule according to building usage. The fraction of waste heat into the canyon was estimated by the number of visible air-conditioning units on the roof, facades, or balconies of each Superblock, resulting in a value of 0.8 for Sant Antoni and 0.5 for Poblenou.

2.7 3D models (UWG)

Both Superblocks, Sant Antoni and Poblenou, were 3D-modelled for UWG using Grasshopper software tool for Rhino both in their current (Fig. 3 and 4) and their previous states: Thereby, the same sources were used as those for the ENVI-met model. The model contains the building volumes clustered in groups with similar characteristics, such as usage and age. The size of the modelled areas to be evaluated as one Local Climate Zone (LCZ) comply with the suggested dimensions (i.e., 400 to 1000 meters) [17]. The UWG 3D model for Sant Antoni, before and after the renewal, were named UWG-SA$_0$ and UWG-SA$_1$, respectively. Likewise, the UWG 3D model for Poblenou, before and after the renewal, were named UWG-PN$_0$ and UWG-PN$_1$, respectively. The colours represent different building usages.

Figure 3: 3D model for UWG of the Sant Antoni Superblock (current state).

Figure 4: 3D model for UWG of the Poblenou Superblock (current state).

3. RESULTS

ENVI-met simulations suggest that the implementation of the Sant Antoni Superblock might decrease the air temperature at the pedestrian level during peak heat hour by up to 1.4 K (Fig. 5) and the surface temperature by up to 20 K [18]. A small decrease in wind speed was observed but it was not enough to balance out the decrease in air temperature and radiative temperature due to shading. The resulting local PET mitigation at the pedestrian level is as high as 12 K at certain positions (Fig. 6). The average global PET decrease reached 6 K (Fig. 7). At a height of 10 m, which represents roughly half of the height of the surrounding buildings, the air temperature difference was mostly under 0.4 K (Fig. 8).

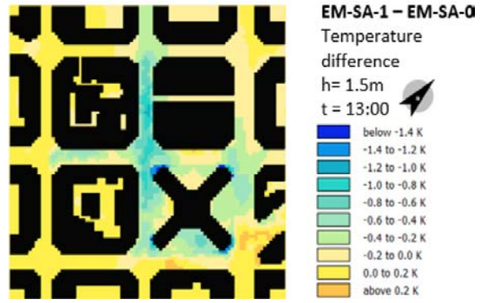

Figure 5: Calculated air temperature difference (using ENVI-met) at 13:00 at pedestrian height between models EM-SA$_1$ and EM-SA$_0$.

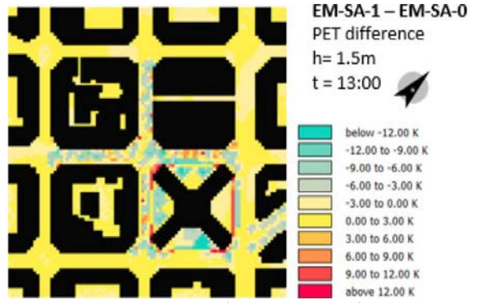

Figure 6: Calculated PET (using ENVI-met) at 13:00 at pedestrian height between models EM-SA$_1$ and EM-SA$_0$.

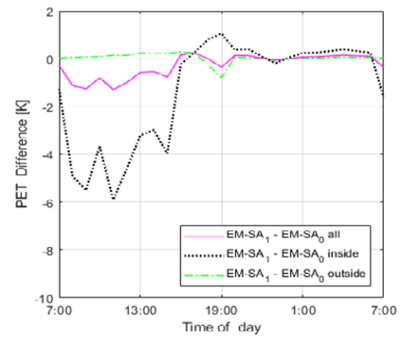

Figure 7: Calculated PET difference (using ENVI-met) at pedestrian height between models EM-SA$_1$ and EM-SA$_0$.

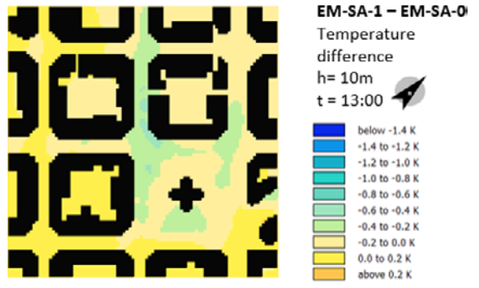

Figure 8: Calculated air temperature difference (using ENVI-met) at 13:00 at 10 m height between models EM-SA$_1$ and EM-SA$_0$.

As for the Poblenou Superblock implementation, it mitigates air temperature at pedestrian level at a peak of 0.3 K (Fig. 9) during the day and it decreases the peak PET to almost 4 K (Fig. 10) where extra shading is created. However, average global PET difference is only about 0.5 K (Fig. 11). At the height of 10 m temperature differences are around 10 times smaller than those from Sant Antoni (Fig. 12).

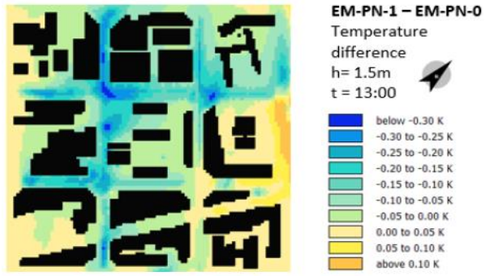

Figure 9: Calculated air temperature difference (using ENVI-met) at 13:00 at pedestrian height between models EM-PN_1 and EM-PN_0.

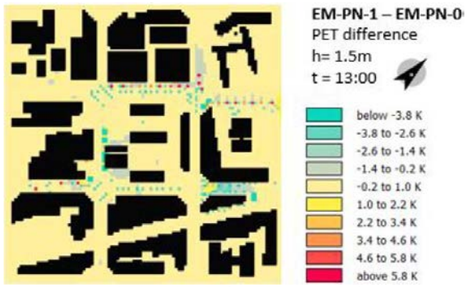

Figure 10: Calculated PET (using ENVI-met) at 13:00 at pedestrian height between models EM-PN_1 and EM-PN_0.

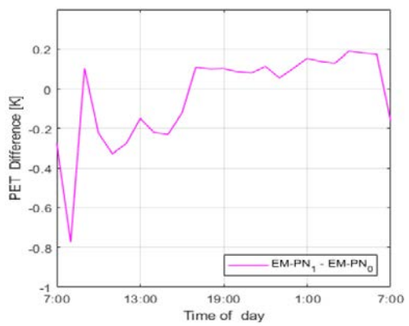

Figure 11: Calculated PET difference (using ENVI-met) at pedestrian height between models EM-PN_1 and EM-PN_0.

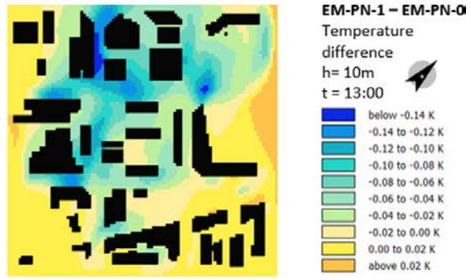

Figure 12: Calculated air temperature difference (using ENVI-met) at 13:00 at 10 m height between models EM-PN_1 and EM-PN_0.

Regarding the UWG results, the decrease in temperature of the urban canopy temperature decreases during the day due to the implementation of the Superblock was found to be negligible. Specifically, the estimated temperature decrease was in average only 0.02 K (Fig. 13) and 0.01 K during the summer (Fig. 14), for Sant Antoni and Poblenou Superblocks, respectively.

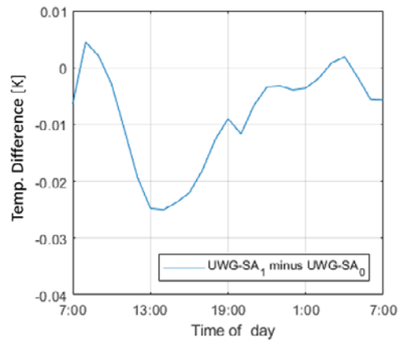

Figure 13: UWG calculated urban canopy temperature difference at 1.5 m height between models UWG-SA_1 and UWG-SA_0.

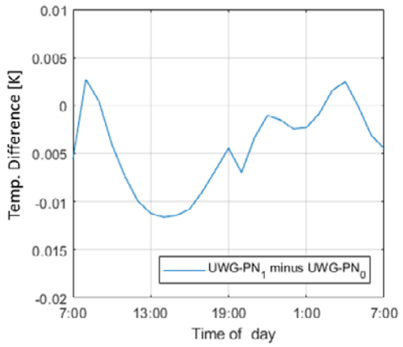

Figure 14: UWG calculated urban canopy temperature difference at 1.5 m height between models UWG-PN_1 and UWG-PN_0.

4. CONCLUSIONS AND FUTURE RESEARCH

Two very different tools were used to assess the micro-climatic implications of the implementation of the studied Superblocks. These tools have very different methodologies and complexities of implementation, and the output variables are also distinct.

ENVI-met simulation results point to a noticeable decrease in perceived temperature at the pedestrian level in both Superblocks, mostly due to a reduction of direct sun radiation and despite the increase in relative humidity and decrease in wind speed.

The more robust and permanent new infrastructure of the Sant Antoni Superblock as well as the distinct typologies of both neighbourhoods might have played a role in the different levels of impact. However, even with a measurable effect at ground level, the studied Superblocks did not display a measurable impact on the more elevated layers beyond the urban canopy. Hence, a reduction potential in cooling demand cannot be inferred from this investigation.

The UWG results regarding the urban canopy temperature imply that the limited implementation of Superblocks may not have a pronounced effect on UHI and air temperatures throughout the day.

The Superblock is an urban solution that gained momentum in the last two years as the COVID-19 pandemic brought the urge for more open public spaces as means of avoiding dense public gatherings. This motivation further underlined the already critical need to address UHI and climate change. Additionally, the city of Barcelona is determined to expand the size of the Superblock project to the scale of the whole metropolis as the pilot projects were deemed successful.

In this context, it is important to mention that, in the year 2020, similar urban renovations were undertaken around the world in cities such as Cordoba (Argentina) and Montreal (Canada). Hence, future studies should explore the impact of large-scale (specifically, metropolitan scale) implementation of Superblocks on the cities' micro-climate in general and the Urban Heat Island Effect in particular.

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Urban Climate map proposal for small town

Mamanguape, Brazil

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Abstract: Most Brazilian cities are considered small (87.79%) and few have studies that assess their urban climate. Thus, practical and easy-to-understand bioclimatic analysis methods are needed to help urban managers in their decision making. The main objective of this work is to develop a thematic map that represents thermally uncomfortable regions of the Center of Mamanguape, a small town in the state of Paraiba/Brazil. For this, it was used the German methodology of production of Urban Climate Maps that characterizes urban areas considering the energy balance, influenced by the aspects of thermal load and dynamic potential. The analyzed areas were identified, classified, and received a climatic valuation according to the relation in the temperature elevation and wind flow capacity, influenced by constructions, topography, vegetation, and open spaces, making use of a Geographic Information System (GIS). With the Urban Climate Map, it was observed that consolidated areas contribute negatively to the thermal comfort of the population, and that areas classified as favorable to comfort are located mainly in peripheral areas. Therefore, the preliminary results obtained can collaborate with the beginning of a climate awareness not only of public managers, but of all those involved in the production of urban space.
Keywords: Small towns, Urban Climate Map, Thermal Comfort.

1. INTRODUCTION

The application of climatology in urban planning has attracted great attention from researchers since the mid-20th century (Arnfield, 2003; Hebbert, 2014), however, it has focused mainly on medium and large cities. Few studies assess the impacts of urban characteristics of small towns (i.e., cities with < 50,000 inhabitants) on their local climate (Kopec, 1970; Cardoso, 2017).

In Brazil, the importance of small towns is reflected in the socioeconomic expression they have taken on in recent decades, as well as in the rapid territorial expansion. Estimates from the Brazilian Institute of Geography and Statistics (IBGE) show that 87.79% of cities in the country are considered small, with a population of fewer than 50,000 inhabitants (IBGE, 2021). In this context, it is essential that these cities draw up urban development plans that ensure less environmental impact and that avoid or minimize the negative effects of urban expansion on the environmental comfort of the population, recurrent in large cities.

In Brazil, it is noted that many of these cities do not have an administrative structure that has professionals specialized in the elaboration of master plans or urban climate studies. Therefore, a climate analysis methodology focused on supporting municipal decision-making must be practical and easy to understand not only by public managers but by the population in general (Eliasson, 2006).

An urban planning tool for this purpose is the Urban Climate Map (VDI 3787, 2015). In the 1970s, the idea of representing the urban climate through maps arose in Germany as a way of evaluating urban plans (Hebbert, 2014). This method has been adapted and applied in several cities around the world, including Amsterdam, Barcelona, Lisbon, Tokyo, Hong Kong, and Singapore (Ren et al, 2011). In Brazil, several studies were developed in different Brazilian regions, however, they were designed for large cities (Nery et al, 2006; Shimomura et al, 2015; Ferreira et al, 2017); Souza & Katzschner, 2018; Freitas et al, 2021; Anjos et al, 2021).

Recognizing the importance of small Brazilian cities and their role in the future of a more urbanized country, this research aims to present a case study of the application of urban climate maps methodology adapted to a region of northeastern Brazil, located in the city of Mamanguape, Paraiba state.

2. METHOD

Since the objective of this paper is to facilitate the elaboration of an urban climatic map (MCU) for small cities, it has been decided to synthesize the methodology, facilitate the obtaining of local geographic data, and employ free geographic information systems (GIS) software.

Within this context, the following data were used in this study: 1. Orthophoto chart with 5-meter spectral resolution; 2. Digital Elevation Model provided by the Brazilian Agricultural Research Corporation (Embrapa); 3. Climate data provided by the government website Projetee (2016).

Thus, the elaboration of the urban climate map for the central region of Mamanguape consisted of 04 steps: 1. data collection and processing; 2. evaluation of aspects of the urban structure in the thermal comfort of the population; 3. analysis of thermal load and dynamic potential; 4. elaboration of the Urban Climate Map.

2.1 Urban climatic map methodology

The methodology for elaborating the urban climatic maps is based on the concept of Climatopes (homogeneous spaces with similar climatic characteristics), focusing on human thermal comfort and atmospheric air quality. For this, a multi-criteria approach is used, with a qualitative and quantitative approach. Two aspects are evaluated: the thermal load and the dynamic potential.

The Thermal Load (TL) is related to the intensity and storage of heat by the city influenced by buildings, topography, and the availability of green spaces. These aspects act directly on the increase in air temperature. The Dynamic Potential (DP), in turn, is related to the possibility of wind flow through the city, considering the built density, the natural landscape and the existence of open spaces. A synthetic description of the MCU analysis structure can be seen below in Table 01.

Table 01:
MCU Analysis Layers

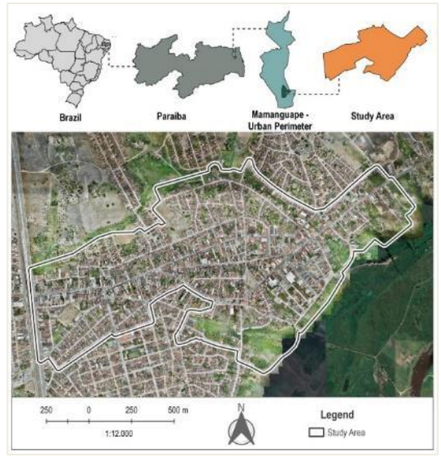
Energy balance	Urban characte. / Layer	Urban Climate Aspect	Thermal Comfort Effect
Thermal Load	Volume Construção	Armazena calor	Negative
	Altitude e elevação	Resfriame-to do ar	Positive
	Vegetação arbórea	Resfriame-to do ar	Positive
Dynamic Potential	Cobertura do solo	Obstrução dos ventos	Negative
	Paisagens Naturais	Movimento do ar frio	Positive
	Espaços abertos	Trocas de massa de ar	Positive

An orthophoto chart of the city center of the year 2019, provided by the Federal Public Ministry of Paraíba (MPF-PB), was used to extract the spatial data of the study area. The elements that make up the image were vectorized using the free software QGis v 3.10. Additionally, other spatial information was collected using the free software Google Earth Pro and on-site visits.

2.2. Study area

The study area is located within the urban perimeter of Mamanguape city (Figure 02). The town was founded in 1855 and is located 45 km from the state capital (6°50'20"S, 35°7'33"W). It is considered a small city with an estimated population of 45,385 inhabitants and a population density of 124.23 inhabit/km² (IBGE, 2021).

Figure 02:
Study Area Location



According to the Köppen-Geiger classification, the climate of Mamanguape is characterized as Aw'i type (tropical climate), that is, hot and humid with rains of fall and winter. The average annual temperature is around 27°C. The annual thermal amplitude is very small due to the low latitude, oscillating between 5° and 6°C. The average rainfall is 1,634.2 mm.

For many small Brazilian cities, wind information is not available. In this case, wind data were taken from the nearest weather station located in the city of João Pessoa (Projetee, 2022). The city's proximity to the equator provides a predominantly daily wind regime, characteristic of coastal areas. In this way, it remains throughout the year within the range

corresponding to the southeast trade winds, which characteristically blow in the cooler months with greater frequency and speed. During the warmer months, its frequency is altered by easterly and northeasterly winds coming from the equatorial areas in the displacement current, towards the south of the Intertropical Convergence Zone (ITCZ). The winds assume distributions in the southeast quadrant between 150° and 180° and speeds ranging from 0 to 9m/s, with an average of 3.6m/s.

The study area analyzed is the Centro district, the oldest in the city, which is spread over an area of 1.4 km². It has a high building density, a greater concentration of services and shops, and a greater dynamic and flow of people in the city.

3. RESULTS

The spatial data vectorization process used the information contained in the orthophotochart, complemented by satellite images from the Google Earth Pro application. Over 4 weeks, 4132 polygons (buildings) were vectorized. In order to collect information on the height of the buildings, on-site visits were carried out, finding that most of the buildings have a height close to 3m, and the tallest with a height close to 12m.

The main biomes found are remnants of the Atlantic Forest, in areas of environmental protection, in addition to the Cerrado, which extends over a greater extent of the municipality, with grass and shrub species.

For the location and delimitation of water bodies, the same material and method were used for vectorization.

After processing the spatial data, the analysis layers related to the CT and PD of the MCU were elaborated, namely: 1. Building Volume; 2. Topography; 3. Green Spaces; 4. Ground cover; 5. Natural Landscapes; 6. Open spaces. Each layer was evaluated and classified according to its impact on thermal comfort based on the study developed by Souza & Kaztschner (2018) for the city of João Pessoa, a region close to the city of Mamanguape. All layers were converted to a raster format, with a spatial resolution of 30m x 30m.

Layer 01 corresponds to the relationship of building volumes with heat storage. Buildings store solar energy during the day and gradually release it at night. Depending on the amount of built-up area, the heat may not properly dissipate into the atmosphere. In the climate classification, areas with a high volume of constructions receive positive classification values for contributing significantly to the increase in air temperature and, conversely, areas with little or no construction receive value. Table 2 shows the impact on the thermal load of city areas according to the percentage of building volume and the respective valuation of climate classes on a scale of 0 (No construction), 1 (low concentration) and 2 (medium concentration).

Table 02
Description of layer 01

Thermal Load	Building Volume	Value
NONE	0%	0
LOW	1 – 4 (%)	1
MEDIUM	4 – 10 (%)	2

Layer 2 is based on the concept of adiabatic cooling of the air concerning altitude. Thus, the topography contributes to the decrease of air temperature due to changes in altitude and relief. The values assigned to the layer are negative, as they do not influence the Thermal Load, and decrease depending on the altitude variation (Table 03).

The digital elevation model file (DEM) was generated from the interpolation of dimensioned points, which consists of using known dimensions to estimate unknown values. Subsequently, this file was converted into a raster format file and reclassified according to the impact of topography on Thermal Load.

Table 03
Description of layer 02

Thermal Load	Topography (m)	Value
YES	> 50m	-1
NONE	0 – 50m	0

The evaluation of vegetation makes up layer 3. The presence of large vegetation formations (forests and woods) favors the cooling of the air temperature, contributing to the reduction of heat storage in the city.

No large area full of trees were identified in the study area, only small arboreal clusters. However, these can contribute to the localized cooling of the local temperature. Thus, negative classification values were assigned to this concerning climate classification (Table 04).

Tabele 04
Description of layer 03

Thermal Load	Vegetation	Value
YES	EXISTENT	-1
NONE	NONEXISTENT	0

The buildings have a direct impact on the flow of winds in the urban environment, that is, the higher the percentage of the occupied area, the lower the urban permeability to ventilation. This is the concept applied to layer 4.

Therefore, the vectorization of buildings was used to classify areas with the highest concentration of constructions, classifying them according to the effects caused on the dynamic potential. Areas with occupancy greater than 50% received a null classification, as they do not favor the dynamic potential, and less dense areas received negative values (Table 05).

Table 05
Description of layer 04

Dynamic Potential	Ground Cover (%)	Value
VERY FAVORABLE	0 – 30	-2
FAVORABLE	30 - 50	-1
NONE	> 50	0

In layer 5, natural landscapes that may favor the flow of winds in the urban space were considered. Thus, areas with undergrowth, fields and pastures received negative classification values. The tree clusters, on the other hand, received a null value, since, in terms of roughness against the winds, they present characteristics similar to the buildings (Table 06).

Table 06
Description of layer 05

Dynamic Potential	Natural Landscape	Value
FAVORABLE	FIELDS, PASTURES	-1
NONE	URBAN	0

In the last layer, areas close to bodies of water and open fields were taken into account, which, due to their low roughness, favor the circulation of winds, benefiting air exchanges. Therefore, the layer was elaborated from the identification of these areas.

For each space described above, a map was prepared with its classification values, called water bodies layer and open spaces layer. Subsequently, they were superimposed, using the map algebra technique (sum operation), and the Open Space Proximity Layer was generated as new classification values (Table 07).

Table 07:
Description of layer 06

Dynamic Potential	Open Spaces	Value
YES	YES	-1
NONE	NO	0

Through the GIS map algebra technique again, performed in the QGis software, the thermal load map was generated by adding the values of layers 1, 2 and 3, which resulted in a map with 5 climate classification values. Similarly, the dynamic potential map was created by superimposing layers 4, 5 and 6, resulting in six new climate classification values. In Figure 03, the structure of the MCU layers can be observed.

As can be seen in Figure 3, the central regions of the study area already have a significant concentration of areas favorable to the Thermal Load, while peripheral areas have few areas that favor the flow of winds.

Finally, for the elaboration of the Urban Climate Map (Figure 4), the map algebra technique (sum operation) was used again in the values of the CT and PD maps, resulting in 6 values of climate classification. The classified areas were evaluated according to characteristics that influence the energy balance of the study area (Table 08).

Figure 03:
Structure of the Urban Climate Map layers.

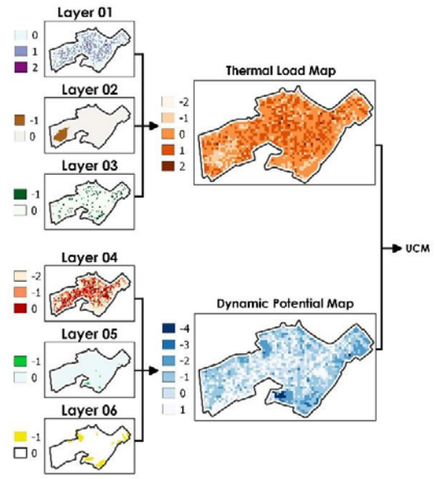


Figure 04:
MCU Mamanguape downtown.

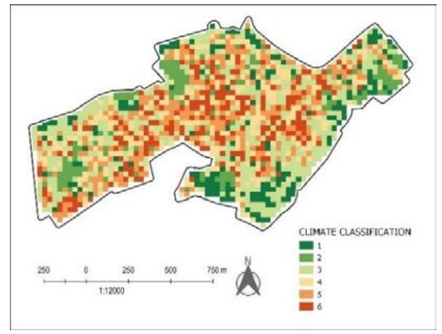


Table 08
Description of the MCU climate classes

Class	Description	Thermal Comfort Impact
1	HIGH MITIGATION	VERY IMPORTANT FOR CLIMATE ITIGATION
2	MODERATE MITIGATION	CONSIDERABLE CLIMATE MITIGATION
3	LIGHT MITIGATION	IMPORTANT FOR WIND FLOW
4	NONE	LOW INCREASE IN TEMPERATURE
5	LIGHT ELEVATION	NO HIGH THERMAL LOADS
6	HIGHT ELEVATION	THERMAL COMFORT AFFECTED

Class 1 represents regions with high climate mitigation, that is, they benefit natural ventilation and reduce the increase in air temperature. In these regions, there is a predominance of vegetation, which in turn favors humidity and the reduction of air temperature, important for reducing the thermal load. The highlighted regions are mainly rural areas, with large extensions of pastures and water bodies, used for irrigation. There are also peripheral, poorly developed areas, with a process of expansion at the beginning and natural landscape still preserved.

Class 2 depicts areas with moderate climate mitigation, characterized by a low building density, a mix of few residential buildings and large open spaces of pastures, which benefit the dynamic potential of the area.

Regions with the presence of buildings and reduced vegetation represent class 3 (light climate mitigation), demonstrating the beginning of urban expansion to peripheral areas and the beginning of the de-characterization of the natural landscape, with the removal of existing vegetation, soil sealing and constructions that can obstruct the flow of winds.

Class 4 shows urban spaces with significant urban density, low-rise buildings, with low impact on thermal comfort, with a predominance of the use of construction materials with low thermal absorption, unpaved streets, and the presence of vegetation, which work with a thermoregulator for temperature.

Class 5 represents areas with a high building density, little vegetation, and few open spaces, impacting the rise in air temperature. They are located mainly in the central region, which have strong characteristics of the urban layout of the 19th century, with few setbacks between the buildings that do not favor the circulation of winds, causing barriers that prevent the winds from entering the urban fabric, in addition to the use of materials with high absorption capacity.

Finally, class 6 (high elevation) depicts regions with affected thermal comfort, characterized by the absence of vegetation, high density and the presence of large equipment, aspects that act as a barrier to ventilation and/or absorption and storage of radiation. These are places that present greater difficulties in intervention, as they are already consolidated areas, in addition to a greater concentration of commercial equipment.

Figure 05 presents some examples of classified areas through the MCU. As can be noted with the increase in the class value, there is a sudden reduction in vegetation and a significant increase in dense and impermeable areas.

Figure 05*:*
Examples of MCU classes.

4. CONCLUSION

Like most small Brazilian cities, the municipality of Mamanguape/PB does not have an urban planning sector, in which it could assess current climatic conditions and propose climate-conscious urban development solutions. The responsible sector, the Secretaria de Obras, focuses only on projects and the construction of buildings for the municipality.

Interventions have already been observed in the studied area. Based on the classical literature, they are known to aggravate human thermal discomfort. The removal of trees from public spaces, asphalt paving of streets and the use of low-albedo materials are recurrent strategies in the city.

In this sense, a practical and easy-to-understand method of climate analysis is urgently needed to help decision-making by public managers in Mamanguape city.

The proposal of an Urban Climate Map, based on the analysis of local physical aspects, was effective to identify and understand how these aspects act in relation to the quality of the urban environment, with the identification of areas where they already present a high thermal discomfort, result of urbanization and the expansion process of recent years. However, the measurement method presented is not fully effective, and the results need to be deepened and constantly updated.

In any case, the Urban Climate Map can collaborate with the beginning of a climate awareness among city managers, as well as professionals who deal with urban planning and design.

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PLEA STGO 2022

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1133 / 1101

17TH PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Economic feasibility of a system to reduce waste of water in hot water building systems

A case study in multifamily buildings

MARCELO DALMÉDICO IORIS [1] ENEDIR GHISI[1]

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ABSTRACT: In homes that have instantaneous gas heaters to heat water, cold water is wasted in the first seconds of using hot water fixtures. The objective of this work is to verify the economic feasibility of implementing an automated system integrated to the hot water fixtures of buildings that reduces the waste of water from the initial moments of use. A comparative economic analysis between the installation of the proposed automated system and an individual recirculation system was performed for a case study for a multifamily building. Altogether nine different economic analyses were carried out, varying the water saving potential and the type of recirculation system to obtain the Net Present Value, Internal Rate of Return and discounted payback. It was verified that the proposed system is more viable than the traditionally used individual recirculation system. The proposed system reduces waste of water in domestic hot water systems, proving viable by providing a daily water savings potential of at least 5.6%. The use of the system is strongly dependent on requirements observed in the building where it would be installed. Costs for installation-related services must be carefully budgeted for the system to be economically feasible.
KEYWORDS: Instantaneous gas heater, Water savings, Water storage tank, Cold water, Hot water

1. INTRODUCTION

In homes that have instantaneous gas heaters to heat water, cold water is wasted in the first seconds of using hot water fixtures. The Brazilian Standard NBR 5626 [1] advises that the residential hot water distribution systems must be sized by reducing as much as possible the hot water arrival time from the heating point to the farthest water fixture with hot water consumption. The Brazilian standard NBR 13103 [2] recommends that gas heating appliances be installed in places with appropriate ventilation. This recommendation means that homes must be designed so that the heaters are installed in the laundry rooms or outside the buildings. Accordingly, this leads to longer hot water pipe lengths from the heating source to the water fixtures.

Through a flow trace analysis of 26,000 bathing events, Lutz [10] concluded that, on average, 13.17 litres of water (3.48 gallons) are wasted per bath. Data were obtained from homes in twelve cities in the United States and Canada during the summer and winter months. For the analysis of waste through taps, it was found that, on average, 4.31 litres of cold water are wasted. Lutz [11] was one of the first researchers to collect data on water waste directly at the place where hot water is used. By monitoring flow and temperature during bathing events in three single-family homes in California during the winter months, it was found that 30% of water was wasted.

Sherman [12] identified an average behavioural waste of 47 seconds in bathing events in homes in the state of California in winter months. That is, the hot water has already reached the water fixture and users start the bath 47 seconds after the flow of hot water. Wood and D'Acquisto [13] found in a sample of 574 baths in homes in the state of Pennsylvania, that the behavioural waste was, on average, 59 seconds and the structural waste was, on average, 64 seconds during the winter months. For a single-family building, for a shower with an average flow equal to 0.157 litres/second, the annual water waste can be approximately 3,774 litres. Ally and Tomlinson [3] conducted a study in five houses in the municipality of Palo Alto in the state of California to verify the efficiency of the water recirculation system using Metlund D'MAND © system technology. In one of the houses, it was possible to estimate savings of approximately 11,500 litres of water per year through a bathroom tap.

As for researches carried out in Brazil, Gonçalves et al. [8], in a specific analysis in a given case study, obtained a time of 70 seconds for the hot water to reach the farthest water fixture, wasting approximately 13 litres of cold (formerly hot) water. Chaguri Junior [4] conducted a similar case study in a flat located in the city of Ribeirão Preto (São Paulo, Brazil) and identified that 76 seconds was the time to get hot water in the farthest water fixture, wasting 10 litres of cold (formerly hot) water. Ioris and Ghisi [9] verified the waste of cold (formerly hot) water that occurs before the flow of hot water in seven showers in three different buildings in Florianópolis (Santa Catarina, Brazil) in summer months. A comparison was made between the waste estimated by means of floor plans and waste obtained by means of in situ measurements. For the flats analysed, the average found for wasting water until the water coming out of the shower suffered some variation in temperature was 6.3 litres. And for the water to come out of the shower at a temperature equal to 30ºC, 9.3 litres of water were wasted on average.

When compared to the electric shower, the most used system in Brazil today to heat water [6], instantaneous gas heaters have a high initial installation cost. Thus, for these systems not to incur expenses and to be effective in providing hot water, it is of great importance to have an integrated water recirculation system, associated or not with thermal insulation of the pipes, which is economically viable.

The objective of this work is to verify the economic feasibility of implementing an automated system integrated to the hot water fixtures of buildings that eliminates the waste of cold (formerly hot) water from the initial moments of use.

2. METHOD

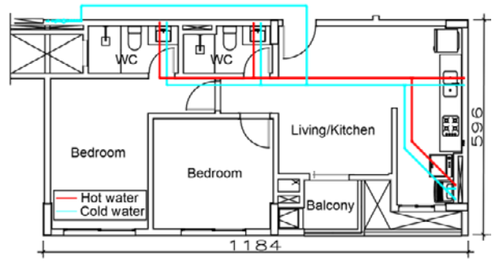
The method was divided into two parts. The first part explains how the installation of the automated system in multifamily buildings is proposed, as well as additional installations and adjustments to the usual building systems for its correct functioning. The second part explains how the economic analysis of the proposed technology was carried out.

2.1 System operation

The system operation consists basically on directing the water to its appropriate destination according to the amount of cold (formerly hot) water inside the pipes between the heater and the fixtures. It can be done with a solenoid valve located at the end of the main pipe of the plumbing system in the house. This valve has the function of directing to its proper destination the amount of cold (formerly hot) water that would be wasted through the use of a certain fixture. By means of a radiofrequency signal sent when a button is activated near the hot water fixture, the system recognises which fixture was activated and the approximate amount of cold (formerly hot) water that must be released through the valve until the arrival of hot water from the heater.

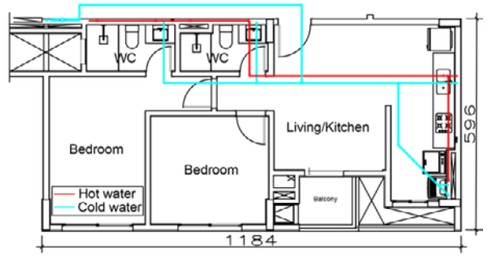
In multifamily buildings with instantaneous gas heaters (with no boiler), the water fixtures are usually supplied by a cold water pipe connected to the building's main water tank, and another hot water pipe connected to the heater (Fig. 1).

Figure 1:
Floor plan of a usual plumbing system of a flat.



To increase the efficiency of the automated system proposed herein, the main hot water pipe must be as close as possible to the hot water fixtures (Fig. 2).

Figure 2:
Plumbing system floor plan for the automated system.



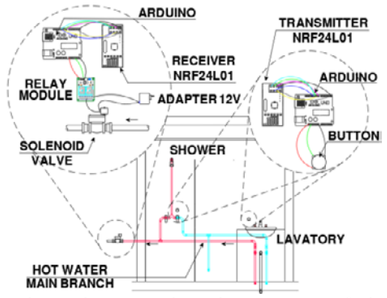
The activation buttons that send the radiofrequency signal must be installed close to the hot water pressure valves. In addition, close to the hot water fixture farthest from the heater, the system must have a solenoid valve. Finally, there must be a system to collect the water from the fixtures. First, there must be a pipe to collect the water that passes through the solenoid valve. Then this pipe will be connected to vertical pipes, responsible for collecting the water from all flats and directing it to the underground water tank of the building with the aid of larger diameter pipes, when necessary.

The diameters of the pipes that direct the water to the water tank will depend on the number of hot water consumption points in the building. All other recommendations made by Brazilian standard NBR 5626 [1] for the correct functioning of the building distribution system must be followed for the installation of the water collection system of the proposed automated system.

The button next to the hot water fixture is connected to an Arduino microcontroller that connects to a radio frequency module transmitter (Fig. 3). The transmitter therefore sends the opening time information from the solenoid valve to the receiver that is connected to another Arduino microcontroller that is also connected to the solenoid valve. The receiver receives the information packet

from the transmitter, transfers the information to the Arduino, which in turn commands the opening of the solenoid valve.

Figure 3:
Electronic circuit of the system proposed herein.

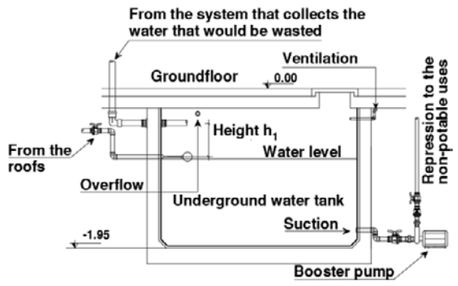


To show the user that the opening of the hot water valve must be started, the Arduino activates a red LED lamp that indicates that all cold water has been drained from the pipe towards the water tank.

The water tank in which the water is stored may be the underground water tank for rainwater harvesting from roofs for non-potables uses. Cold (formerly hot) water from the proposed system could be directed to such water tanks, which already have booster pumps and pipes to direct the water to non-potable uses such as flushing toilets.

The connection of these pipes to the water tank must occur at a height h_1 above the water inlet of the water that comes from the roofs (Fig. 4). This height varies according to the maximum volume of water that will be collected, that is, simultaneous use of all hot water fixtures in a building. This volume is, therefore, the total amount of water that is at rest in all pipes of hot water in the building.

Figure 4:
Connection between the proposed system's pipes and the underground tank.

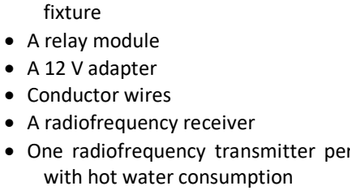


2.2 Economic feasibility

To assess the economic feasibility of the proposed automated system for water systems, a comparative analysis of the economic feasibility between the installation of an individual recirculation system and the installation of the recirculation system proposed in this work was carried out. Both installations were configured, as a case study, for the same multifamily building, however, in separate projects. The analysis is composed of the initial outlay for the implementation of the systems, maintenance and operation costs, and the total revenue from the water savings that the systems provide over a ten-year time horizon.

To predict the initial costs for the entire system in a building, the architectural and water pipes design of the Palmas Central Building were used as a basis (Fig. 5).

Figure 5:
View of Palmas Central Building.



The individual recirculation system is characterized by having a return pipe that connects the end of the main branch of the hot water sub-branch back to the instantaneous gas heater of the flat.

For each flat in the Palmas Central Building, the following were required:

- Additional PP-R (polypropylene random copolymer) piping and connections to return the hot water main branch to the heater
- Hot water pipe insulation
- A recirculation electric pump
- A digital control panel with thermostat

And for the proposed recirculation system, for each flat in the Palmas Central Building, it was necessary:

- Additional PP-R piping and connections to direct cold (formerly hot) water, that would be wasted, to the water tank
- A solenoid valve
- A microcontroller
- One activation button for each hot water fixture
- A relay module
- A 12 V adapter
- Conductor wires
- A radiofrequency receiver
- One radiofrequency transmitter per room with hot water consumption

The total initial cost for installing the recirculation systems throughout the building is the sum of the total cost of materials and the total cost of labour plus 25% of BDI (Budget Difference Income).

To obtain the cost of operating the recirculation systems, the monthly energy consumption must be multiplied by the rates charged by CELESC (Santa Catarina Energy Company. Maintenance costs include expenses over the analysis horizon to keep systems intact and fully operational.

Manufacturers of the individual recirculation system suggest that system maintenance be performed every six months. The cost of semi-annual maintenance for both systems was budgeted with three specialized companies located in the region of Florianópolis. The minimum of the three budgets makes up the system maintenance cost for the economic analysis.

The positive inflows of cash flows are represented by the financial savings provided by the reduction in water consumption through the recirculation systems. Therefore, it is first necessary to estimate how much water the entire building would spend without the recirculation systems and then estimate the volume of water that the systems would be saving. Thus, it is possible to convert this amount of water savings into financial savings in monthly water tariffs.

The individual recirculation system directly reduces water consumption in the water meter of each flat. The proposed recirculation system reduces water consumption in the building. Therefore, in the case of the proposed recirculation system, even if the system does not directly reduce the amount charged individually for each flat, it guarantees global savings for the building, thus reducing the cost of water consumption for future budget forecasts. Thus, the financial savings with the reduction of water consumption is linked to a possible reduction in future fees.

For residential occupation, the building code of Florianópolis [7] guides as an estimate of daily water consumption the value of 200 litres/person.

Altogether, three scenarios of potential water savings through recirculation systems were calculated according to the demand for recirculation. The demand for recirculation was estimated through the daily cycle and the frequency of use of hot water through the hot water fixtures.

The frequency of hot water use, mainly for taps, was based on the final household water use report for North American countries. According to the report, 13% of water consumption events through taps are carried out using hot water. According to DeOreo and Mayer [5], there is a frequency of twenty tap uses per person per day, therefore, the frequency of use for calculating water savings through taps will be 2.6 tap uses with hot water per person per day.

The latest report of the Survey of Ownership and Habits of Use of Electrical Equipment in the Residential Class [6] indicates that, on average, Brazilian households have 3.5 inhabitants and that the average number of times a day the shower is used is 3.95. Therefore, for the use of hot water in the shower, a frequency of one shower per person per day was considered. Total revenue from water savings was calculated through the water tariff of CASAN (Santa Catarina Water and Sanitation Company).

For the comparative economic analysis between the individual recirculation system and the proposed recirculation system, three indicators were used: Net Present Value (NPV), Internal Rate of Return (IRR), and Discounted Payback.

3. RESULTS

The total initial cost for the installation of the individual and proposed recirculation system in the Palmas Central Building was, respectively, R$ 61,013.78 and R$ 18,887.57.

The water saving potential of scenarios 1, 2 and 3 correspond to, respectively, 5, 6 and 7% of the daily water consumption for the Palmas Central Building, which is 17.2 m³.

Table 1 summarizes the results found for the three economic indicators for each water saving potential scenario for the different recirculation systems analysed.

In all flats, the water heater is located in the laundry room. Therefore, the return piping of the individual recirculation system runs from the piping point farthest from the heater to the laundry room, returning to the heater (Fig. 6). Unlike the individual recirculation system, the proposed system conducts the water to the water tank (Fig. 7).

Table 1:
Economic indicators.

# Analysis	System	Water saving potential (%)	NPV (R$)	IRR (% per month)	Discounted Payback (months)
1	Individual recirculation	5	- 69,205.24	N/A	N/A
2		6	- 50,806.58	- 4.8	N/A
3		7	- 34,460.84	- 1.0	N/A
4	Proposed system	5	- 13,740.29	N/A	N/A
5		6	4,658.38	0.7	96.7
6		7	21,004.11	1.8	60.6

Figure 6:
Isometric plan with the return piping and the control panel installation point of the individual recirculation system.

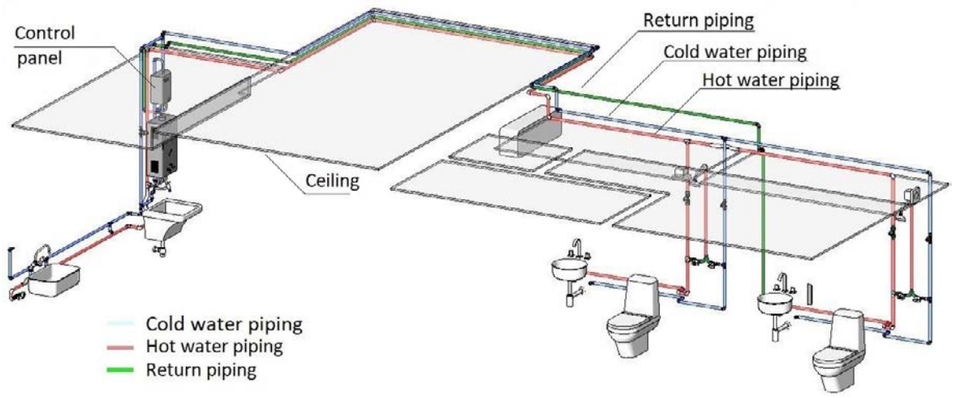
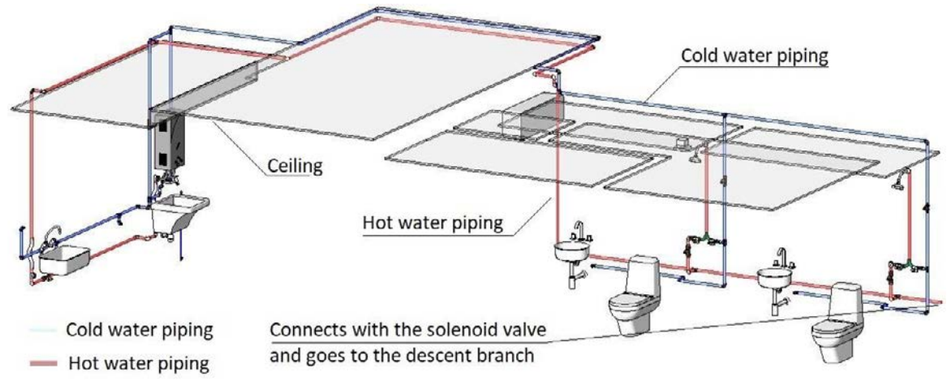
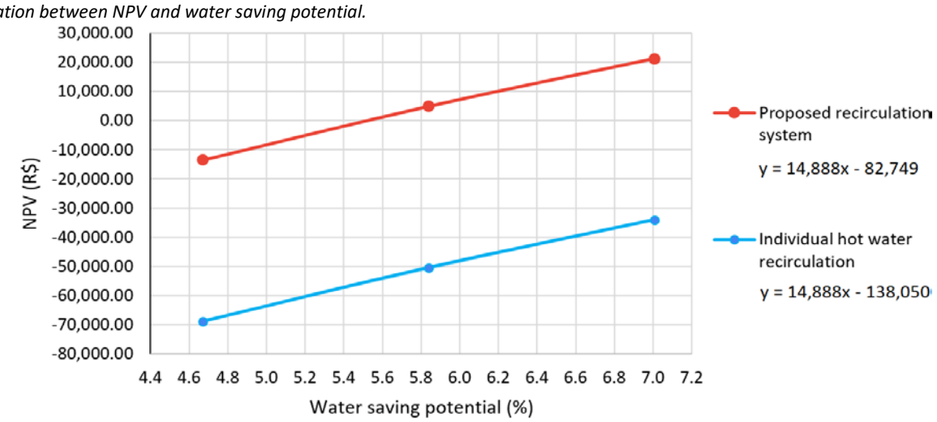


Figure 7:
Isometric plan with the proposed automated system.



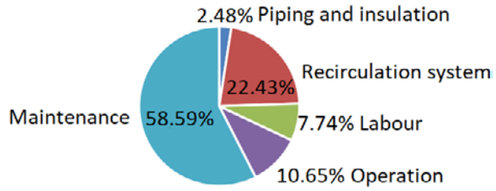
Analysing the behaviour of the NPV as a function of the water saving potential of the recirculation systems, it was possible to obtain the minimum water saving potential in the recirculation activations so that the NPV is positive (Fig. 8). A NPV greater than zero is verified for both the individual recirculation system and the proposed recirculation system, when the minimum water saving potential is, respectively, 9.3% and 5.6%.

Figure 8:
Relation between NPV and water saving potential.



It is observed that the cost of preventive maintenance of the systems every six months represents 58.59% of the expenses with the system over the ten years of the analysis horizon (Fig. 9). Therefore, no matter how great the potential savings provided by the system, the amount of return obtained with water savings hardly exceeds maintenance expenses.

Figure 9:
Expenses of the individual recirculation system (maintenance every six months).



4. CONCLUSION

The economic analysis of the proposed automated system was made in a comparative way with a traditional individual recirculation system. It was found that for the same building, the total initial cost of installing the proposed system could be 69% lower than the initial cost of installing the individual recirculation systems currently used.

It was found that the minimum water savings potential for the individual recirculation and proposed recirculation systems to have a NPV greater than zero is, respectively, 9.3 and 5.6%.

Therefore, the proposed recirculation system with radiofrequency transmission is economically viable and can be an alternative to reduce water waste in the residential sector. The proposed system also proved to be more economically viable when compared to the traditionally used individual recirculation systems. According to the case study, the individual recirculating systems are designed exclusively to solve the problem of the technology itself in not immediately providing hot water at the water fixtures, and not as an alternative for saving water from an economic point of view.

ACKNOWLEDGEMENTS

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Thermal mass study

Investigation of the thermal mass performance of adobe walls in Saudi Arabia

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ABSTRACT: The energy consumption of residential buildings in Saudi Arabia is high due to the harsh weather condition. This high energy consumption is consumed to control the interior temperature to suit the building occupants' thermal comfort. This research focuses on studying the impact of thermal mass on the energy consumption of adobe walls building. It investigates external wall behaviour against the harsh external temperature of Riyadh, Saudi Arabia. The research's results show that the adobe walls' internal temperature behaviour is strongly related to the wall thickness. Also, there is a minimal impact of thermal mass on energy consumption. Furthermore, the TER method does not reflect the thermal mass effect in situations where the temperature difference is too small (one or less). Moreover, a proper internal set-point could reduce yearly energy consumption by 8% (from 66.57 KWh/m²/year that suggested by literature to 61.17 KWh/m²/year). Finally, the wall material properties play a significant role to control the temperature behaviour.
KEYWORDS: Thermal mass, vernacular building, Energy consumption, building envelope, Thermal comfort

1. INTRODUCTION

The use of electrical energy increased rapidly in Saudi Arabia over the last decade. According to the Saudi general authority for statistics, the electricity demand in Saudi Arabia increased from 218 TWh in 2010 to 300 TWh in 2018 [1]. Buildings (residential, governmental and commercial) in Saudi Arabia consumed over two-thirds of the electrical energy generated in the country [2]. The residential building only globally consumed about 22% of the final global energy used in 2018 [3]; however, it consumed about half of the total electricity used in Saudi Arabia [4]. The Saudi government implemented a new building code (Saudi Code 2018) to regulate the high energy demand [5]. However, until January 2019, 33% of a new residential building was built based on the previous building codes (Saudi Code 2007) [6]. Moreover, until June 2021 (Saudi Code 2018 becomes compulsory for residential buildings), new homes could be built using the Saudi previous building codes (Saudi Code 2007). Besides, more than 70% of current residential buildings lack thermal insulation, according to the Saudi Energy Efficiency Centre (SEEC) [7].

The vernacular buildings in Saudi Arabia were built with local materials from the surrounding environment, depending on their location. For example, buildings in Saudi Arabia's central region were made of a mixture of mud and hay (bricks), while those in the southern region were made of stone or a combination of stone and mud. Even though, the adobe walls have high thermal transmittance (0.225-0.75 *(W/(m·K)* see studies reviewed below), they have a high thermal mass (high thermal capacity) that slow down the heat transfer and regulate the temperature fluctuating. Also, adobe buildings usually have thick walls, which helps to store more heat [8]. The lack of using such sustainable materials on the new Saudi residential building caused an increase in the energy consumed.

Mud or adobe has been used in buildings for centuries and is still used in many countries worldwide [9]. It operated as the primary construction material for walls and roofs and is also used as mortar and plaster. Adobe is commonly used because of its widespread availability, low cost, and straightforward construction techniques. It also has additional characteristics such as durability, fire resistance, low sound transmission levels, and non-toxic and sufficient thermal mass. However, the construction techniques and the material properties are varied.

It has been indicated that adobe can be categorised as a sustainable material due to the raw materials' availability and low embodied energy [10]. However, the maintenance embodied energy of the adobe was found to be significant, about 12% of total embodied energy as discovered by Shukla, Tiwari, and Sodha [10]. Also, Eben-Saleh [11] found that adobe is a thermal regulator material that can maintain a yearly natural thermal comfort.

Thermal mass is defined as the fabric's energy storage and delay heat transfer or, in more detail, the wall's materials to absorb, store, and release heat energy [12]. For instance, in a hot and warm climate, thermal mass stabilises daily temperatures by absorbing heat during the daytime and releasing it at night, resulting in indoor thermal comfort to the occupant and reducing the need for HVAC, especially in the summer season [13]. Moreover, external walls constructed from materials with high capacity to store heat are described as high thermal mass and vice versa, but it does not mean that high thermal mass is more effective than low thermal mass, as proven in previous research [12]. Although several researchers described thermal mass by thermal diffusivity *(α)* of the building material [14], [15], however, Reilly and Kinnane showed that thermal diffusivity is an unsuitable parameter to describe thermal mass [16]. Moreover, the impact of using insulation layers with varying thicknesses and distribution to improve the thermal performance is also investigated [17]. Finally, the thermal mass effect appears as a transient heat transfer function and is never shown in steady-state conditions based on the material's thickness and thermal conductivity only.

This paper analyses and investigates the impact of thermal mass on the traditional building's external walls and tries to reduce the building's energy consumption by controlling the effect of thermal mass, which is being consumed due to the hot and deserted weather conditions. Furthermore, examining the best combination between thermal mass and the internal set-point. Finally, understanding the effect of different material properties on the internal temperature behaviour.

1.1. Research Objectives

The main objective of this research is:

a) Investigating the temperature behaviour of the adobe walls.
b) Investigating the impact of thermal mass on the energy consumed in these adobe walls.
c) Controlling the thermal mass effect by applying different indoor temperature set-points for each month.
d) Understanding the effect of different material properties on the internal temperature behaviour.

To address objective a), two models (shown in Figure 1) were evaluated using the evaluation parameters listed in Section 3.1. Moreover, to address objectives b and c, the methods listed in Section 0 are (the energy consumption and the Transient Energy Ratio (TER)) used to evaluate the impact of thermal mass on the buildings. Finally, to address objective d, the Finite Element method was used to analyse the 27 wall alternatives.

2. METHODOLOGY

The methodology used in this paper is focused on three main subjects. The first one aims to understand the temperature behaviour in the adobe walls. The second investigates the impact of thermal mass on energy consumption for adobe walls using several internal set-point schedule alternatives.

The Finite Element Method (FEM) is used to solve the heat equation using COMSOL Multiphysics 5.5, and the boundary conditions were applied as shown in Figure 1. Weather data for Riyadh, Saudi Arabia, is used in this study and were taken from ASHRAE handbook-fundamental SI 2017 [18]. The material used in the model and its associated property is listed in Table 1.

Table 1|Material properties used in Finite Element Modelling

Materials	Density (ρ) kg/m³	Design thermal conductivity (k) W/(m·K)	Specific Heat Capacity (c) J/(Kg·K)
Mudbrick (Adobe)	1730	0.75	880

2.1 Understanding the temperature behaviour

Two scenarios were studied for this part of the study, as shown in Figure 1. For each scenario, six wall thicknesses were investigated (from 0.20 m to 2.1 m (that meets the Saudi code requirement for Zone 1 of U-value = 0.34)).

a) examining the temperature behaviour of the external walls with no heat transfer through the walls into the internal.

b) examining the temperature behaviour of the external walls with a continuous air-conditioning operation, and the set-point is set at 24°C for internal temperature.

Models a and b were analysed using July 2017 climatic conditions, and the analysis ran for a day, a week and a month.

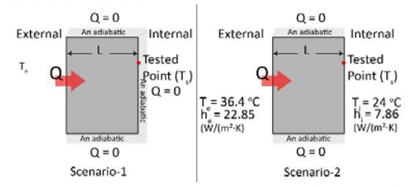

Figure 1: Understanding the temperature behaviour scenarios

2.2 Evaluation parameters

3.2.1 Time lag (Ø)

The time lag is defined as the time difference between reaching the peak temperature of the external surface and the wall section's internal surface's peak temperature and can be calculated using Equation 1.

$$A = \begin{cases} tT_o^{max} > tT_e^{max} \Rightarrow tT_o^{max} - tT_e^{max} \\ tT_o^{max} < tT_e^{max} \Rightarrow tT_o^{max} - tT_e^{max} + P \\ tT_o^{max} = tT_e^{max} \Rightarrow = P \end{cases} \quad (1)$$

tT^{max}, tT^{min} is the time in hours when the temperature reached the maximum or minimum for

the inside, and outside surface (◦C), P is the wave period (h).

2.2.2 Decrement factor (D*f*)

The D*f* is the difference between the maximum internal surface temperature and the external temperature. The decrement factor result is between 0 and 1 and can be calculated using Equation 2.

$$Df = \frac{A_o}{A_e} = \frac{T_i^{max} - T_i^{min}}{T_e^{max} - T_e^{min}} \quad (2)$$

As reported, a low decrement factor and a significant time lag could increase energy-saving and enhance thermal comfort [19].

2.3 Investigates the impact of thermal mass on energy consumption

The second part of the study investigates thermal mass effects for the model shown in Figure 2 using the new metric introduced by Reilly and Kinnane Transient Energy Ratio (TER) [12] on the Saudi traditional adobe building. It has been indicated that the human comfort zone led between 18 °C to 26 °C [20]. Therefore, the internal temperature will range within the comfort zone as listed in Table 2. The first set-point group is indicated in the literature as an appropriate monthly set-point for Riyadh, Saudi Arabia [17]. The other four groups test a monthly variation within the human comfort zone (18-26 °C).

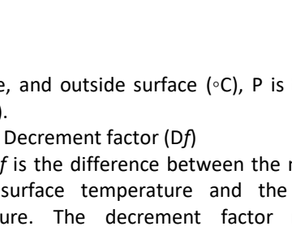

Figure 2| Model used for studying the impact of thermal mass on energy consumption.

Table 2: Models' external and internal boundary conditions.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ave. external temperature (°C)	14.6	17.5	21.4	27.1	32.7	35.5	36.4	36.4	33.2	28.2	21.4	16.6
Set-point G-1 (°C)	21	21	21	24	26	26	26	26	26	24	21	21
Set-point G-2 (°C)	18	21	24	25	26	26	26	26	26	25	24	18
Set-point G-3 (°C)	21	21	22	24	25	25	26	26	25	22	22	20
Set-point G-4 (°C)	21	22	23	24	25	26	26	26	24	21	20	23
Set-point G-5 (°C)	21	23	25	24	25	26	26	26	23	20	23	22

External and internal heat transfer coefficients (h) are calculated according to ISO 6946 [21].

2.3.1 Transient Energy Ratio (TER).

Transient Energy Ratio (TER) is a new metric introduced by Reilly and Kinnane and used to evaluate the impact of thermal mass on energy consumption [12] and can be calculated using Equation 3.

$$T.E.R = \frac{Energy\ used\ in\ a\ transient\ model}{Energy\ used\ in\ a\ static\ model} \quad (3)$$

2.3.2 Energy consumption

The daily, weekly or monthly energy consumption is calculated for the data resulting from the finite element model or using Equation 4.

$$E = \int_0^n q_w\, dt \quad (4)$$

E is energy consumption for the dedicated time (W), n is the period studied in hours (h), and q_w is the average heat flux calculated using Equation 5.

$$q_w = U \cdot A \cdot \Delta T \quad (5)$$

Where q_w is the average heat flux over the period studied, U is the U-value of the wall section, A is the area of the wall section, and ΔT is the temperature difference (T_o-T_i).

2.4 Effect material properties on internal temperature behaviour.

Material properties of adobe in previous studies reviewed by the authors have varied depending on the study location or the adobe mixture. For instance, an experimental measurement carried out by Babé et al. shows that using 4% fibre in an adobe mixture decreases the thermal conductivity by 23% from 0.96 to 0.74 W/(m·K), compared to adobe without fibre [22]. Also, in the literature, the wall density varied from 1698 to 1922 (Kg/m³), thermal conductivity also ranged from 0.283 to 0.75 (W/(m·K)), and the specific heat capacity ranged from 559 to 1005 (J/(kg·K)) [9], [11], [23]–[27]. Therefore, for simplicity, three values for each property have been chosen (highest, middle, and lowest). 1660, 1730, 1920 for density, 0.255, 0.52 and 0.75 for thermal conductivity, and 600, 800, 1000 for specific heat capacity. These values are mixed and resulted in 27 alternatives. These 27th alternatives are analysed using FEM, and the internal temperature behaviour is compared.

3. RESULTS

This section presents the result by first outlining the internal temperature behaviour results in the two scenarios shown in Figure 1. The second section presents the impact of thermal mass on the energy consumption for the model illustrated in Figure 2. The last section of the result is elaborate the result of investigating the impact of material properties on the internal temperature.

3.1 Internal temperature behaviour

The temperature response of the wall sections is studied in the first scenario with no heat transfer through the building. This scenario helps determine how these wall sections respond to temperature. The wall sections' time lag and decrement factor are presented in Table 3. The wall section shows a time-shifting effect on the peak external temperatures, long time lag, and deficient decrement factor due to a thick wall section and high thermal capacity, close to a previous finding by Asan [28]. The time lag for these wall sections varies between 7.30 hours to over 24 hours, and the decrement factors also vary between 0.37 to 0 depending on the wall thickness.

Table 3| Model-1 Time lag, Decrement factor for all wall thicknesses.

Wall section	Time lag (Ø) (hours)	Decrement factor (D*f*)
0.20 m	7.30	0.37
0.30 m	11.00	0.17
0.45 m	19.15	0.02
0.60 m	23.30	0.004
1.00 m	> 24	0.00016
2.10 m	> 24	0

The results of a dynamic models analysis for one week and one month (July) are presented in Figure 3. As shown, the wall sections' interior temperature is increasing due to boundary conditions with no heat flow inside the building. However, Bahadori and Haghighat [29] indicated that the room temperature change would continue for about seven days. Similarly, the increase continues growing for about nine days and then remains stable except for wall sections with a thickness of 1.00 m and 2.10 m. In the high thicknesses wall, the internal temperature increase continues for about 50 and 65 days for walls sections with a thickness of 1.00 m and 2.10 m, respectively.

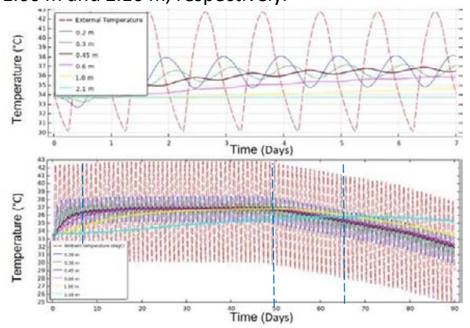

Figure 3|Temperature distribution for wall sections for one week (Up) and one month (Down)

Table 4| Scenario-2 time lag and decrement factor.

Wall section	Time lag (Ø) (hours)	Decrement factor (D*f*)
0.20 m	6.15	0.15
0.30 m	9.30	0.06
0.45 m	10.00	0.003
0.60 m	20.00	0.001
1.00 m	> 24	0.0
2.10 m	>24	0.0

The second scenario of this part investigates the temperature behaviour while air-conditioning operates. As listed in Table 4, the wall section with a thickness of 0.20 m has the lowest time lag with 6.15 (h), and the highest time lag was over 24 (h) for the wall sections with a thickness of 1.0 m and 2.1 m. However, all the wall sections are in and over the recommended time lag range (between 6 to 12 hours) to reduce the summer overheating effect [30]. The high time lag and low decrement factor for these wall sections significantly increase energy-saving and enhance thermal comfort [30].

The temperature distribution for these wall sections shows more stability in the internal temperature than in the first scenario. Also, there is no increasing trend, as shown in Figure 4.

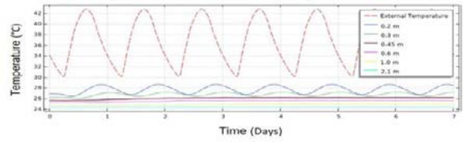

Figure 4| Temperature distribution for scenario-2 for one week.

Figure 5 shows the relationship between wall thickness and other factors. As shown, time lag has a direct relationship with wall thickness. On the other hand, the decrement factor has an inverse relationship with the wall section. Also, it is shown that the decrement factor after a thickness of 0.45 m became very small, almost zero.

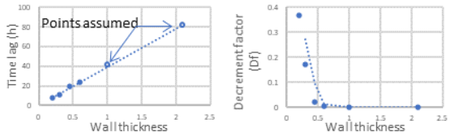

Figure 5| Relationship between time lag, decrement factor, wall thickness.

3.2 Investigates the impact of thermal mass on energy consumption

The effect of thermal mass on the energy consumed is shown here as the ratio between the energy consumed in transient conditions and the energy consumed in a steady-state condition using the TER method. Figure 6 shows the TERs resulting for the five set-point groups listed in Table 2. The TERs for all months except for March and November is very close to 1, which means the impact of thermal mass on energy consumption is minimal, which can be neglected. The high TERs in March and November in group-1 and group-3 are due to the small energy consumption in steady-state conditions resulting from multiplying the U-value by a small temperature difference, less than 1 (0.4 in March and 0.6 in November for group-1).

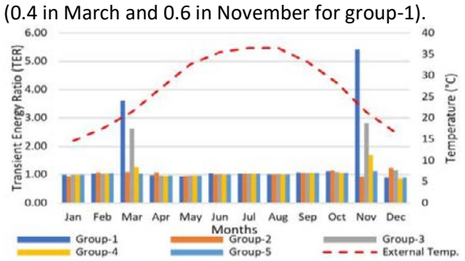

Figure 6 |Monthly TERs results for the five set-point groups.

As a result of multiplying the U-value by these small numbers, a small amount of heat enters the building in a static state that is not reflecting the

actual amount of heat energy. Also, as discussed earlier, the TER is the ratio of energy used in a transient model divided by energy used in a static model with the same boundary condition. Therefore, the TER method failed to represent the impact of thermal mass in situations where the temperature difference is too small (one or less).

The monthly energy consumption for these five groups is presented in Figure 7. From the graph, energy consumption is affected directly by the monthly internal set-point. Therefore, the yearly total energy consumption is affected too. Total annual energy consumption varied for these groups from 61.61 (KWh/m²/year) in group-2 to 79.14 (KWh/m²/year) in group-5.

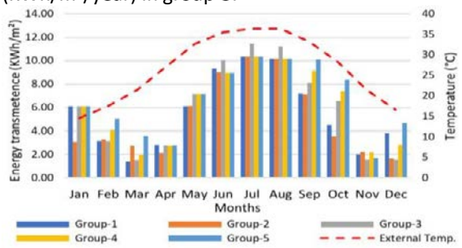

Figure 7 | Monthly energy consumption results for the five set-point groups.

3.3 The impact of different material properties on the temperature behaviour

The impact of thermal properties on the internal temperature of the 27th wall sections is illustrated in Figure 8. In general, high thermal conductivity indicates a faster and higher heat flow (heat loss/gain), while high thermal capacity (ρCp) indicates a large amount of heat storage per unit mass, resulting in a longer time lag. Also, the ratio between these parameters represents the thermal diffusivity (α). However, according to Raily and Kinnane, thermal diffusivity is an unsuitable parameter for activating the thermal mass since materials with different thermal properties may have equal thermal diffusivity [12]. For instance, in our case, wall sections W13 (k=0.52, Cρ=800, ρ=1660) and W27 (k=0.75, Cρ=1000, ρ=1920) have different material properties; however, they both have the same thermal diffusivity of 0.39 (mm²/s).

Although high thermal conductivity leads to high thermal diffusivity (for constant ρCp), it also increases heat flow to the interior. Also, a wall section with high thermal conductivity and low thermal capacity *(ρC_p)* had a high thermal diffusivity (0.753 mm²/s), resulting in a higher internal temperature change and shorter time lag (wall section 19). Alternatively, a wall section with low thermal conductivity and high thermal capacity (ρCp) had a low thermal diffusivity (0.133 mm²/s), resulting in a lower internal temperature change and longer time lag (wall section 9). Also, high thermal conductivity and high thermal capacity result in a low internal temperature fluctuation (low decrement factor) (wall section 27).

Finally, walls 1-9 have low thermal conductivity (0.255 (W/(m·K))) which contributed to a low thermal diffusivity, resulting in a higher internal temperature. Also, walls 19-27 with high thermal conductivity (0.75 (W/(m·K))) contribute to high thermal diffusivity, resulting in lower internal temperature.

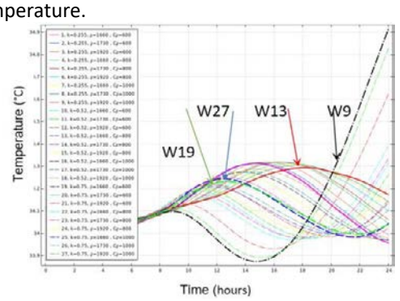

Figure 8|results of the impact of thermal propriety on the internal temperature for the 27th wall sections.

The results also show a strong relationship between the material parameters (time lag and decrement factor with thermal diffusivity and heat capacity). As shown in Figure 9, there is an inverse relationship between thermal diffusivity and time lag and a direct connection between heat capacity and time lag. However, an opposite relationship appears with the decrement factor.

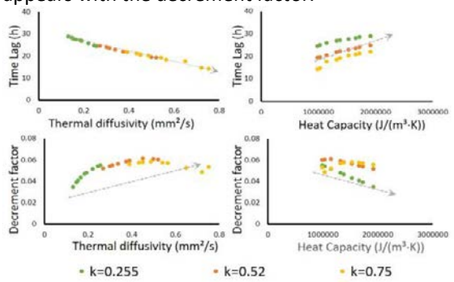

Figure 9| Relationship between time lag and thermal diffusivity, time lag and Heat capacity, decrement factor and thermal diffusivity, and decrement factor and Heat capacity.

4. CONCLUSION

This study has investigated the adobe wall thermal behaviour using different investigation parameters. The investigation was conducted using the FE method for two scenarios. Results show that adobe walls' internal temperature behaviour is strongly related to the wall thickness. Also, the TER method failed to reflect the thermal mass effect when the temperature difference is too small (one or less). Moreover, a proper internal set-point could reduce yearly energy consumption by 8% (from 66.57 KWh/m²/year that suggested by literature to 61.17 KWh/m²/year). Furthermore, adobe cannot be classified as an insulating material; it may describe as a thermal regulator material that can maintain a yearly natural thermal comfort. Finally, the wall material properties play a significant role to control the temperature behaviour.

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Envelope variables evaluated in multi-objective optimization using the genetic algorithm NSGA-II to improve the efficiency of energy

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ABSTRACT: The envelope of the buildings has a great influence on their energy consumption. Analyzing and designing the external envelope of a building requires the decision-making of many variables, whether constructive, design or climate-related. Genetic algorithms, as in biology, cross-reference various constructive or design parameters, in the search to maximize or minimize one or more specific objectives, and thus find the best solution for the specified purposes. Allied to energy simulation software, they can perform a large number of simultaneous simulations, reducing decision-takers working time and reducing the need for expensive and robust equipment. With genetic algorithms it is possible to make the appendment of many variables at the same time, assisting the final decision of the project, which could be extremely exhaustive if done prescriptively or one simulation at a time. In this sense, this article seeks to identify the publications that used multi-objective optimization evaluations to improve the building envelope energy efficiency using the NSGA-II genetic algorithm as a calculation engine, and, from these, verify which architectural and construction variables were analyzed in the research.
KEYWORDS: NSGA-II, Genetic Algorithm, Building Envelope, Energy Efficiency, Multi-objective optimization.

1. INTRODUCTION

With the global energy crisis, experienced in the 70s, there was a need to improve and adapt the buildings' energy standards. As a result, new laws and regulations on the subject were created to minimize the buildings' energy impacts. Since then, designers and builders have had to adapt to this new reality, looking for ways to build with greater energy efficiency [1].

Building construction requires a large initial study and analysis of many variables so that it can be built with adequate energy performance. There are countless constructive, climatic, and design variables that influence the project.

This systematic literature review (SRL) intends to evaluate publications that optimize the building envelope, using multi-objective analysis and the non-dominated sorting genetic algorithm, known as NSGA-II, to seek energy efficiency.

2. BACKGROUND

The genetic algorithm was introduced by Holland (1975) and is based on a natural selection and adaptation process that mimics biological evolution (Darwin), including aspects of inheritance, crossover or combination, and mutation. It stands out for the diversity of the solutions it presents and the efficiency in optimizing the building's performance, due to its elitist classification that accelerates the convergence of the solutions [1].

In addition, Kheiri and Attia et al., point out that the NSGA-II algorithm, proposed by Deb et al. (2002), is best suited for solving multi-objective optimization problems, which are common in architectural design. This variant uses crowding distance, which means that it seeks the convergence of the fittest genes after the first random generation [1, 2].

On the other hand, multi-objective optimization is the use of two conflicting objective functions that will generate a Pareto curve. The best solution will be the one closest to the utopia point, in the search for minimization or maximization of the selected objective functions.

3. OBJECTIVE

This article has as main objective to identify the publications that used multi-objective optimization evaluations to improve the building envelope energy efficiency using the NSGA-II genetic algorithm as a calculation engine, and, from these, verify which architectural and construction variables were analyzed in the research.

The main focus of this SRL is to answer the following question: "Which were the literature variables used in the multi-objective optimization for building energy efficiency, with a focus on envelopment and with NSGA-II genetic algorithm application?"

4. METHOD

To find the premises indicated in the objectives of this article, a search for productions were conducted on the ScienceDirect and Scopus databases. Primarily, the keywords were delimited, according to Table 1, and later on, used to form the search string.

Table 1:
Keywords used to form search strings.

Keywords
Multi-objective optimization OR Multi-objective optimisation
Genetic Algorithm
Non-dominated sorting genetic algorithm
NSGA-II
Building Envelope OR Building Envelops
Energy Efficiency

From the keywords, the production's general string search was created with an approach to optimization, building envelope, genetic algorithms, and energy efficiency. In the Scopus database, the Boolean keyword was used in this form: optimi*ation and envelop*, to find all possible word endings. In the ScienceDirect database, the selected words were: *("multi-objective optimization" OR "multi-objective optimization") AND ("genetic algorithm" OR "non-dominated sorting genetic algorithm" OR "NSGA-II") AND (" building envelope OR building envelopes") AND ("energy efficiency").*

The criteria inclusion used to evaluate the works are: published in journals (review articles, indexed proceedings), publications in Spanish, English, or Portuguese, being a multi-objective analysis, and the use of the NSGA-II genetic algorithm. As a result of the searches carried out in the databases, Table 2 presents the final database results.

Table 2:
Total productions identified and filtered by the search databases.

Science Direct	418
Scopus	27
Duplicates	13
Total	432

Furthermore, in the articles selection process and identification, the open-source software, developed by the Federal University of São Carlos, StArt v. 2.3.4.2 was used as a knowledge organization tool, adjusting the duplicated publications. A total of 445 works were identified; of these, 13 were duplicates, ending in 432 publications for evaluation.

Initially, the extraction and selection of articles were carried out by reading the abstract, where the use of genetic algorithms in the research was verified. At the end of this stage, 176 articles were selected for analysis. Of which, only 47 used the NSGA-II as an analysis engine to assess the building envelope. At the same time, from the 176, only 14 review articles related the themes of the envelope to the use of artificial intelligence as a way to achieve energy efficiency of buildings.

5. PUBLICATIONS ANALYSIS

As a quantitative result of the research, it can be highlighted that the publications were increasing from 2013 to 2021, with 13 articles published in 2021. The countries with a major number of studies were China (24.5%) and Italy (13.2%). The authors with the higher number of studies were Chen, with 4 articles, Ascione with 3, Bre and Kerdan with 2 publications each.

The Journal Energy and Buildings had the higher number of publications, with 33.3% of the selected articles, followed by Applied Energy (10.4%), Journal of Building Engineering (6.3%), Energy (6.3%), Journal of Cleaner Production (6.3%), Solar Energy (6.3%), and Sustainable Cities and Society (6.3%).

The majority of the papers evaluated residential buildings (68.8%), followed by offices (16.7%) and institutional buildings (14.6%). In 43.8% of the studies, a hypothetical case was assessed. Real case studies were present in 39.6% of the articles and retrofit strategies were evaluated in 16.7% of the studies.

As the energetic calculation engines for the simulations, EnergyPlus was used in 62.5% of the studies, followed by TRNSYS (14.6%), IDA ICE (6.3%), others (8.3%), and a total of 8.3% did not mention the software used in the simulation. The optimization engines used were Matlab (26%), jEPlus (14%), jEPlus + EA (10%), Python (10%), MOBO (10%), GenOpt (4%) and others (4%). A total of 22% of the articles did not mention the tool used for the optimization.

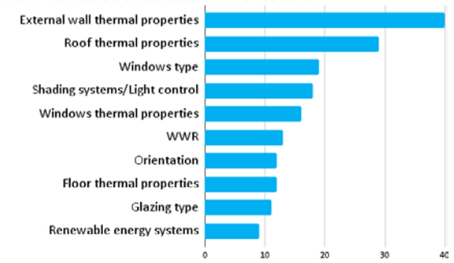
In regards to the NSGA-II settings, there is not a pattern related to the population size and number of generations. A total of 12.2% of the selected articles did not mention the population size and 13.5% did not mention the number of generations. It can be

highlighted that, although there is no pattern, the population size of 50 was the most used between the articles, as well as 100 for the number of generations.

As for the main multi-optimization objectives functions searched in the publications, the most common objectives for the optimizations are the maximization of thermal comfort, present in 26.9% of the studies, and the minimization of the energy consumption (22.6%) and energy demand (11.8%). The cost function is frequently seen in the optimizations, as in for the Life Cycle Cost (LCC) (10.8%) or the investment cost (7.5%). The minimization of heating and cooling loads is present in 9.7% and 7.5% of the studies, respectively.

As the main objective of this study, to achieve the optimization objectives, several variables are evaluated, as illustrated in Figure 1.

Figure 1:
Main variables evaluated in the research.



It can be highlighted that the thermal properties of the wall and the roof are present in 37.2% of the selected studies. Windows types and their thermal properties were evaluated in 19.7% of the analyses. Other variables were present in the following sequence: shading systems/lighting control (9.9%), window-to-wall ratio (WWR) (7.6%), building orientation (7%), floor's thermal properties (7%), glazing type (6.4%) and renewable energy systems (5.2%).

6. MAJOR FINDINGS

The 7 articles utilizing the Artificial Neural Networks (ANN) coupled with the NSGA-II the authors find for a house in Morocco, a reduction of 74.5% in the energy demand (cooling and heating) and an improvement of 4.32% in the internal comfort [4]. The optimization of the envelope of a Tourist Center in Nanjing, China resulted in the 8.3% reduction in the annual energy demand and 11% annual average predicted percentage dissatisfaction [5]. Also in Nanjing, the comparison between multi-objective particle swarm optimization (MOPSO) and NSGA-II optimization of an institutional building, showed the suitability of the algorithm for complex constructive problems [6]. A residential building in Shangai reached 27.86% to 33.29% reducing energy demand with the optimization of 20 variables [7]. A three-story residential building in Chongqing, China, achieves a reduction of almost 50% in energy consumption and an increase of 1.5% in indoor thermal comfort [8]. For south Italy, a study of retrofit of office buildings achieved a reduction in energy consumption, discomfort hours, and polluting emissions, producing global cost savings of around 42.4 €/m² [9]. Evaluating two different climates of France, the main highlight of the study describes the climate as a major impact in the search for the optimal envelope solution [10].

In China, several articles optimized the envelope buildings. For an institutional building in Wuhan, it can reduce 10.6% of the energy consumption and increase in 32.2% the thermal comfort [11]. For a residential building, there was a reduction of 39.6% in the energy use intensity (EUI) [12]. For Tianjin, it was found that the window ventilation could compensate for the overheating in 85.2% and 62.1% for high-performance buildings [13]. The analysis of the Institute of Green buildings in Tianjin shows that the photovoltaic system can produce more energy than the consumption of the building in half-year [14]. For an office building in 4 cities, a slight increase in the energy consumption was achieved for Hohhot, while a reduction of 27% to 8% was found for the other cities, as well as a decrease of 2.53% to 0.81% for the discomfort hours for the case studies. [15].

For Hong Kong, Chen et al. evaluated in 3 occasions a typical high-rise residential building, achieving the results of a decrease of 35.73 kWh/m² [16, 17] and, when coupled with particle swarm optimization (PSO), reached 71.36% of reduction in the energy demand [18]. For an apartment, it was increased by 31.95% the thermal comfort [19].

The envelope optimization of a hypothetical office building in Taiwan, resulted in the reduction of 58,3% of the CO2 emission while increasing 5.3% of the construction cost [20].

For Turkey, a hypothetical office building in Izmir had a decrease of 14% in annual energy consumption with envelope optimization [21]. For the cities of Omaniye and Erzurum, the results of a residential building evidenced that envelope optimization can help to achieve buildings ZEB [22].

A passive solar building evaluated in Niˇs, Serbia, conclude that the triple low-emissivity argon-filled glazing, the isolation, and a higher thermal capacity of the materials are the more suitable strategies for the climate [23]. A typical room was analyzed to all climates of Iran and it was found a 55.8% to 76.4% decrease in the cooling demand [24].

In London, UK, Kerdan et al., applied retrofit measurements to an office and a school building, and the optimization performed achieved 50% and 53% improvement in the annual energy use, as well as, 66% and 80% of thermal comfort, respectively [25]. A retrofitted Passivhaus community center was analyzed by the same authors to find the difference of 32.4 kWh/m².year in the energy use intensity comparing the energy/economic and the exergy/exergoeconomic approach [26].

The retrofit measurements for a single-house are analyzed in two articles, in Portugal. In the first, in Amarante, the study of the cost-optimal and the investment return evidenced that the use of biomass system has a negative return of investment and the photovoltaic panels are not profitable for this case [27]. For Lisbon, Évora, Porto, and Bragança the set of retrofit strategies achieved the payback period of 3.79, 2.51, 3.44, and 2 years respectively [28].

For Finland, the study of a residential building in Helsinki shows the use of efficient strategies to achieve 23% to 16% of the Life Cycle Energy (LCE) [29]. A daycare evaluated in Tampere, concludes that the best solutions to achieve energy efficiency in the building is to improve the ventilation system, use modern lighting, and use solar energy [30]. In Vantaa, a typical residential brick building should focus on the utilization of renewable energies, that have the greatest return investment [31].

A single-family house was optimized in La Rochelle, France and as output, the author highlights the importance of increasing the solar gains to achieve better performance [32]. Comparing the climates of France and Lebanon, it was found a reduction of 6.7% for Beirut to 22.1% for Cedars in the annual thermal energy, while the LCC could be reduced by 0.8% to Limoges and 31% to Cedars [33]. Analyzing 5 building morphologies of Paris, it can be recommended that the first action of retrofit would be the connection of the building with the district heating and in second the envelope refurbishing [34].

For Italy, the researchers showed that, for a residential building in Milan and Messina, the results reached more than 57% energy saving, however, the comfort gets worse [35]. A net-zero-energy house was optimized in Mascalucia and a long-term percentage of dissatisfied comfort lower than 10% for summer and winter was found [36]. For residential buildings in Monza and Trento, the best thickness to the insulation was found in 2 and 3 cm respectively [37]. The window-wall ratio (WWR), of an office building evaluated for Palermo and Torino, Italy, in Frankfurt, Germany, and Oslo, Norway show an increase in WWR compared to Italy, maintained the same percentage to Germany and a reduction to Noway, as to find the best proportions to achieve energy efficiency [38]. Representing the Mediterranean climate, a residential building was optimized to Madrid, Spain, Nice, France, Naples, Italy, and Athens, Greece, showing that, to reduce heating demand it is recommended the use of insulation and robust materials with thermal inertia, for the decrease of cooling demand, it is recommended the use of cool-colored with extremely insulated roof [39]. To Naples, Italy, and Istambul, Turkey, the main findings are that the envelope must have substantial mass, as the use of dense and/or thick masonry [40].

A study of a prefabricated house in Australia achieved 27 to 31% savings in LCC and a reduction of 6 to 55% in the thermal discomfort hours amongst the 6 different climates evaluated [41].

21% of energy savings and 45% of the energy consumption can be covered by renewable systems in all Moroccan climatic zones, for the typical collective residential evaluation [42]. A Mauritius hypothetical house, had a reduction of 10.2% in the energy consumption, just with the alterations applied in the study [43].

In the USA, the envelope optimization of the Philadelphia Business and Technology Center achieved a reduction between 11 to 22% in energy consumption [44]. In the same city, the optimization of an office building reached a 16.7% of reduction in the heating demand [45]. Optimization of the WWR in an office building in Boston indicates that the room on the 29th floor had a 40% of reduction in the annual energy consumption [46]. Evaluating 8 cities in the USA, the author concludes that the potential of reducing the energy consumption varies between 63% to 76% and it is conditioned to the climate [47].

A typical house was optimized in the Argentina Littoral; in the first study, the authors reached a reduction of 91% degree-hours for the living room and 88% in the energy consumption [48]. The same house was assessed by the authors in the sequent year, doing a ventilation analysis that resulted in 95% of improvement in the comfort [49].

In Canada, a comparison of a holistic versus sequential building design approach, in Québec, evaluating 39 different design variables, shows that the first reach 59% of optimal solutions and the other 41% [50]. A three-story residential building was assessed in Toronto, reaching 33% of energy saving in the building, utilizing passive energy efficiency measures [51].

7. CONCLUSIONS

As a result of this SRL, it can be evidenced that multi-objective optimization is widely used in academia, to find the solution for conflicting optimization objectives, noting that the most used energy simulation software is EnergyPlus and the optimization tool Matlab. Furthermore, in all evaluated articles, the main objectives were achieved and the findings are that there is an improvement in the energy efficiency of the assessed buildings.

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Low energy cooling strategies for public housings in the hot and humid climate through window design

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ABSTRACT: Natural ventilation is highly considered to be a simple and cost-efficient solution to promote thermal comfort, energy-saving, and good indoor air quality. Therefore, this ventilation technique is considered suitable for public housing. In order to optimise the cooling and energy-saving potentials of natural ventilation, it is important to properly design the opening configuration, such as opening size, position, and window type. However, this aspect is often overlooked in existing public housing. This study aims to assess the effects of various opening configurations on the ventilation performance and thermal environment of public housing through field measurement and numerical simulation. A typical public apartment in Indonesia is used as the case study. The field measurement result shows that a small operable window can provide better indoor air speed and airflow pattern than larger size window even under single-sided ventilation condition. Nevertheless, one particular window type is not able to provide a uniformed ventilation performance in all units in a single apartment building. Specific window design tailored for particular location of the unit can be one of the solutions to ensure a good and equally distributed ventilation performance.
KEYWORDS: Window design, Opening Configuration, Passive cooling, Thermal Comfort, Apartment.

1. INTRODUCTION

Natural ventilation in the hot humid climate, particularly the wind-driven ventilation, is believed to be a simple and cost-efficient solution to promote thermal comfort, energy saving and good indoor air quality (IAQ). Therefore, natural ventilation is considered suitable to be used widely in public housing. Nevertheless, in order to optimise the cooling and energy-saving potentials of this technique, it is important to properly design the opening, e.g., the opening size, position, and selection of window type.

According to ASHRAE [1], the elevated indoor air speed is able to expand the thermal comfort range to certain degrees. Under the naturally ventilated space, the average indoor air speed of 0.6, 0.9 and 1.2 m/s can raise the thermal comfort acceptability by 1.2, 1.8, and 2.2 °C, respectively. This has been adopted in Singapore's green building guideline [2] where the weighted average wind velocity of 0.2, 0.4, and 0.6 m/s are classified as the 'moderate', 'good', and 'best', respectively. Moreover, the desirable air speed could promote sweat evaporation, thus improving thermal comfort. In particular, the upper body such as the neck, back and chest have higher amounts of sweat [3]. Therefore, the airflow with higher air speed around the upper body is considered a desirable airflow pattern.

Nevertheless, the role of opening configuration to enhance thermal comfort in public housing is often overlooked. Therefore, this study aims to investigate the effects of various opening configurations on the ventilation performance and thermal environment through field measurement and numerical simulation. A typical public apartment in Indonesia is used as the case study building in the numerical simulation.

2. DATA AND METHODOLOGY

2.1 Field measurement in an experimental building

An experimental building in Tangerang, Indonesia, was used to conduct the field measurement. The building has two identical units, namely Room A and B, respectively (see Fig.1). Room B is used as the control unit in which the opening configuration demonstrates the typical opening configuration of a public apartment in Indonesia. Meanwhile, Room A acts as the experimental unit where several opening configurations were examined.

The field measurement in the experimental house was carried out to verify several optimum opening configurations resulting from the numerical simulation. Fig.1 depicts the setting of the experimental building and the measurement points.

2.2 Numerical simulation

This study coupled a Computer Fluid Dynamic (CFD) simulation and building energy simulation using scSTREAM [4] and TRNSYS [5], respectively. Firstly, CFD simulation was carried out under steady-state condition to obtain variables related to the ventilation performance (e.g. air speed, airflow pattern, and air change rate (ACH). The reference wind speed at 10 m above the ground was set to 2 m/s with the wind direction is perpendicular to the outer wall of the unit. Then, the resulting ACH is used as the input data in the TRNSYS simulation.

Moreover, the numerical simulation in this study is divided into two phases. The first phase aims to assess the effects of various opening configurations such as opening size, opening position and window types on the ventilation performance and indoor thermal environment. Then, several opening configurations resulted from the first phase which give optimum results were verified through the field measurement using an experimental building. Both the TRNSYS and scSTREAM simulations employed the same building model that represents a typical unit size of the public apartment (see Fig. 2). The IWEC2 weather data in Jakarta is used for the TRNSYS simulation. In order to reduce the computational time, the simulation period in TRNSYS is conducted for 30 days (i.e., in March).

The second phase of numerical simulation will review the optimum opening configuration obtained from the field measurement. The assessment was carried out under three building configurations (i.e. low-, mid-, and high-rise) (see Fig.3). The distributions of the ACH, indoor air speed, and airflow pattern in the whole units in the building will be analysed. Only CFD simulation was employed in this phase.

2.3 Case design for experiment

In the first phase of numerical simulations, there are 170 combinations of opening size, opening position, and window types at the inlet and outlet, respectively, which were investigated (See Fig.4). The opening position and size follow the 30 x 30 cm for the smallest module. Therefore, as shown in Fig.4, the smallest opening size is 30 x 60 cm, while for the largest opening size is 240x240 cm. In addition, several window types were also assessed. In case of the window type assessment, the opening size was fixed to 120 x 120 cm.

Meanwhile, in the second phase of numerical simulation, the optimum window configuration was simulated under three building configurations, i.e. five-, 15-, and 37- stories buildings that represent typical configuration of public apartment in Indonesia. Furthermore, the building consists of a double-loaded corridor with 15 units on each floor (See Fig. 4). The ventilation performances in the units at both windward and leeward sides were analysed.

Figure 1:
Layout of the experimental house and the locations of the measurement points.

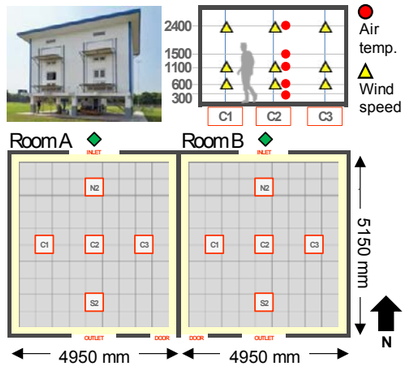


Figure 2:
Layout of the base model in the Phase-1 simulation.

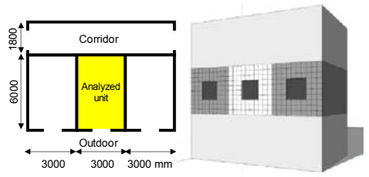


Figure 3:
Setting of the base models in the Phase-2 simulation.

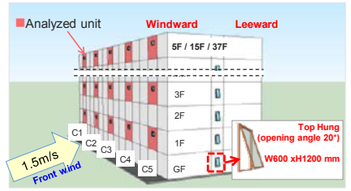


Figure 4:
Opening configurations in the Phase-1 simulation: (a) Opening size, proportion, (b) opening position, and (c) window types.

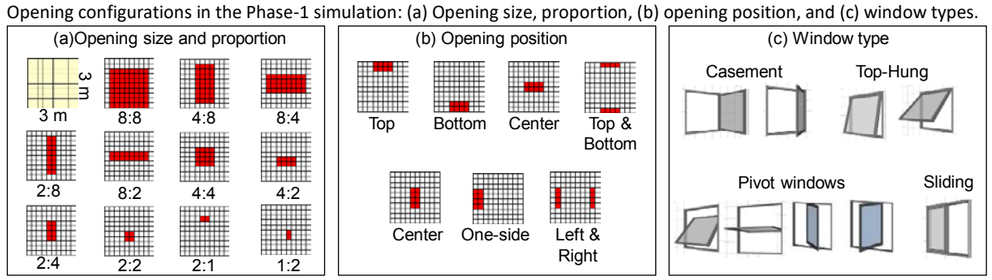
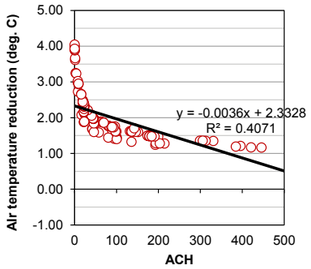


Figure 5:
The ACHs and average air temperature differences between indoor-outdoor resulted from various opening configurations.

INLET \ OUTLET												NO OUTLET
	ρ T (°C)	0.45	0.53	0.52	0.58	0.58	0.54	0.64	0.65	0.72	0.77	0.77	0.98
	ACH (/h)	800	396	385	196	196	193	101	100	58	42	43	17
	ρ T	0.5	0.6	0.6	0.67	0.68	0.68	0.75	0.83	0.86	1	1	1.36
	ACH	446	331	299	184	176	178	96	97	50	27	27	9
	ρ T	0.51	0.6	0.6	0.68	0.68	0.68	0.76	0.76	0.87	1	1	1.6
	ACH	421	313	306	175	176	174	91	92	47	24	25	3
	ρ T	0.56	0.66	0.68	0.73	0.74	0.74	0.82	0.81	0.93	1.1	1.1	1.7
	ACH	215	200	183	152	134	142	87	89	48	25	25	4
	ρ T	0.56	0.67	0.67	0.58	0.74	0.74	0.83	0.83	0.96	1.2	1.2	1.9
	ACH	194	178	179	136	132	135	80	81	42	20	21	1.6
	ρ T	0.56	0.66	0.67	0.74	0.74	0.8	0.82	0.8	0.94	1.1	1.1	2
	ACH	203	191	184	146	136	142	85	86	45	23	23	1
	ρ T	0.62	0.74	0.75	0.81	0.64	0.82	0.89	0.89	1	1.2	1.2	2
	ACH	95	93	90	87	81	83	63	65	39	21	21	0.7
	ρ T	0.62	0.74	0.74	0.8	0.81	0.81	0.88	0.87	0.99	1.16	1.16	2
	ACH	101	100	98	93	88	90	68	70	42	23	23	0.7
	ρ T	0.72	0.86	0.93	0.93	0.94	0.94	0.99	0.98	1.07	1.23	1.22	2.11
	ACH	46	46	45	45	43	44	41	41	32	20	20	0.5
	ρ T	0.87	1.03	1.03	1.12	1.04	1.12	1.13	1.17	1.22	1.31	1.32	2.15
	ACH	22	22	22	22	22	22	21	22	20	16	16	0.3
	ρ T	0.97	1.23	1.18	1.22	1.23	1.23	1.28	1.28	1.3	1.43	1.43	2.2
	ACH	23	23	23	23	22	23	22	22	20	16	16	0.2

Figure 6:
The relationship between ACHs and indoor-outdoor air temperature differences in the daytime.



3. RESULTS AND DISCUSSION

3.1 Parametric study on opening configurations

Fig. 5 shows the ACHs and indoor air temperatures resulting from various opening configurations at the inlet and outlet, respectively. The written air temperature values in Fig.5 are the difference of average air temperature between indoor and outdoor. In other words, the smaller value of air temperature difference means that the indoor temperature becomes warmer due to the effect of opening configurations, vice versa.

Fig. 5 shows that as the opening size becomes larger, the ACH increases. In contrast, when the opening size is smaller, the ACH becomes lower. The highest ACH is achieved when the opening size is 2.4 x 2.4 m, while the lower ACHs are commonly found under single-sided ventilation, i.e., without any openings at the corridor's wall.

Moreover, the changes of the opening size at the inlet is more significant in influencing the ventilation performance than the changes of opening size at the outlet. Meanwhile, under the single-sided ventilation, the changes of inlet size influence the ventilation performance although the ACH under this ventilation mode is generally low. In other words, there is a linear and positive correlation between the opening sizes and ACH.

In contrast, there is a negative correlation between the ACH and the indoor air temperature (Fig.6). As shown, the air temperature reduction decreases as the ACH increases due to the increase of opening size at inlet and outlet. The higher ACH under large opening introduce more outdoor air into the indoor space. This will lead to the overheating of indoor space in the daytime. In contrast, at night, higher ACH will be desirable in order to bring more cool nocturnal air to the indoor space (night purge).

Therefore, in regards to the ventilation performance and indoor thermal environment, the openings should be designed with two functions: First, to limit the warm air penetration in the daytime while still allow desirable airflow required to maintain good indoor air quality. Secondly, to achieve optimum ACH at night in order to enhance the passive cooling through the night purge.

Furthermore, most of recent apartment buildings in Indonesia use double-loaded corridor so it is difficult to secure the opening at the corridor

Figure 7:
The ACHs and average air temperature resulted from various inlet configurations under single-side ventilation mode
The daytime ACH use reference outdoor wind speed of 2 m/s, while the outdoor wind speed of 0.5 m/s is used for the night-time condition.

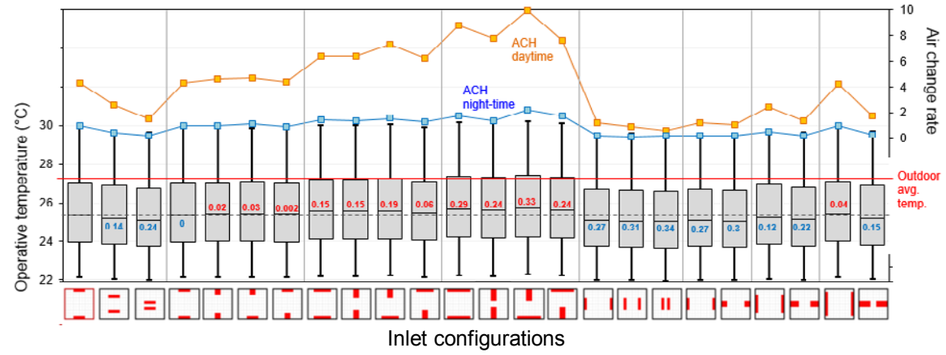
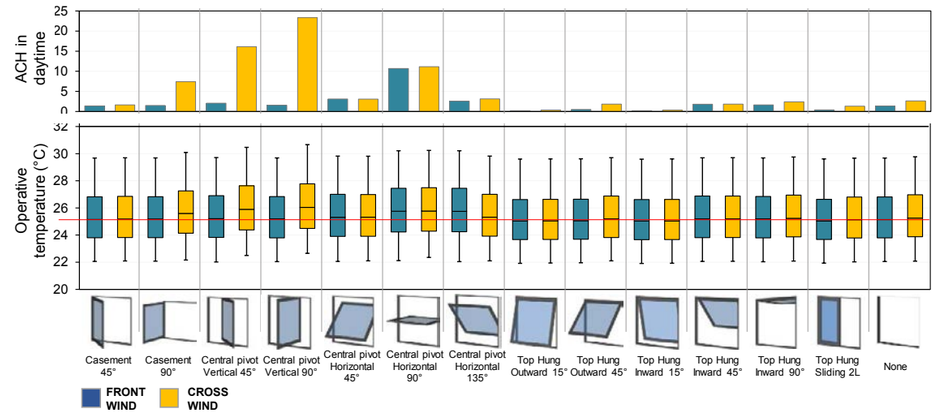


Figure 8:
The ACHs and operative temperature resulted from various window types. The effect of window type was assessed using two wind direction, i.e. front wind and cross wind (45 degree), respectively.



side due the security and privacy issues. Therefore, it is a challenge to design a proper opening at corridor's side by considering the previously mentioned issues. In addition, it is also important to optimize the opening configuration for the apartment unit with single-sided ventilation mode.

Fig. 7 shows the effects of opening position on the ACH and indoor air temperature under the single-sided ventilation mode. As shown, the number of openings and their position at the outer wall significantly affect the ventilation performance. Within the same opening area, the ACH in a unit with two openings (0.36 m^2/opening) at the outer wall is up to 3-4 times higher than the one with only one opening (0.72 m^2). Moreover, two openings with upper-bottom combination provides better ACH than the left-right side combination.

Fig. 8 shows the ventilation performance of some basic window types. As shown, the high ACHs is strongly associated to windows with larger effective opening ratio. The highest ACH is achieved by the vertical pivot window with 90° opening angle, followed by the horizontal pivot window (90° opening angle). Furthermore, the ventilation performance of window is also affected by the incoming wind direction (e.g. front wind, cross wind or side wind). Interestingly, the horizontal pivot window could provide relatively similar ACH under both front and cross wind conditions. Moreover, the lowest ACH is observed under the top-hung window.

3.2 Field measurement

Seven opening configurations were investigated through the field measurement as described in Fig. 9. As shown, the experiment cases were categorized into the single-sided (Cases 1 to 4) and cross ventilation (Cases 5 to 7), respectively. Only the results under northerly outdoor wind direction (+/- 22.5° or perpendicular to the northern wall) were analysed in this study.

Figure 9:
Case design for the field measurement in the experimental building (Room A and Room B).

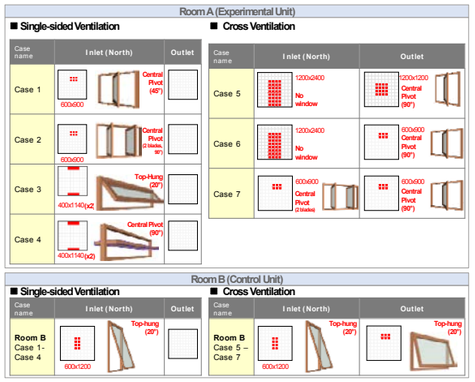


Fig. 10 shows the vertical distribution of average indoor air speed at the centre of the room under four outdoor wind speed ranges for Cases 1 to 4, respectively. As shown, under similar opening configuration, the horizontal pivot window (Case 4) provides slightly higher indoor air speed than the top-hung window (Case 3). Meanwhile, with smaller opening size, the small high position window (Case 2) produces the highest indoor air speed, especially at the occupant's level (up to 0.6 m/s).

Fig. 12 shows the daily average air temperature at 1.1 m above the floor for Cases 1 to 4, and the control room, respectively. As shown, all cases in Room A resulted in lower air temperature than in Room B, especially at night. This was primarily associated with the higher air change rates which allow the relatively cool nocturnal air enter the Room A at night.

Fig. 11 shows the vertical distribution of average indoor air speed at the centre of the room under four outdoor wind speed ranges for Cases 5 to 7, respectively. Cases 5 and 6 demonstrate a large inlet size but with different outlet size. As shown in Fig. 5, the indoor air speed decreases as the outlet size decreases. This shows that the size of the outlet is important in designing ventilation for cross ventilation mode. Meanwhile in Case 7, the resulted indoor air speed is higher than Case 5 and/or 6 although the inlet size is significantly smaller. The indoor air speed in Case-7 even reached 1.3 m/s at the occupant's zone.

Fig. 13 shows the daily average air temperature at 1.1 m above the floor for Cases 5 to 7, and the control room, respectively. The large inlet size of Cases 5 and 6 results in higher air temperature in Room A than in Room B. In contrast, Case 7 was still able maintain lower air temperature.

Figure 10:
Vertical distribution of indoor air speed of Cases 1 to 4 under several outdoor wind speed ranges (0.2~0.5, 0.5~1, 1~1.5, and more than 1.5 m/s)

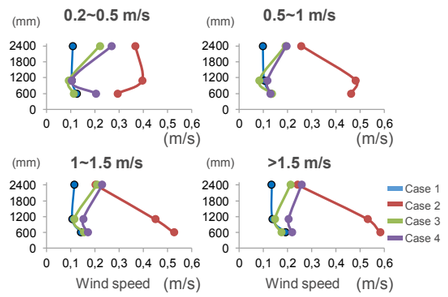


Figure 11:
Vertical distribution of indoor air speed of Cases 5 to 7 under several outdoor wind speed ranges (0.2~0.5, 0.5~1, 1~1.5, and more than 1.5 m/s)

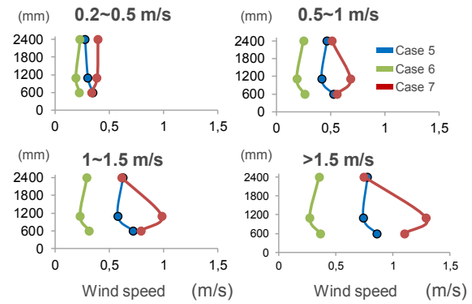


Figure 12:
Daily average of indoor air temperature in Room A and B under Cases 1 to 4 (Single-side ventilation).

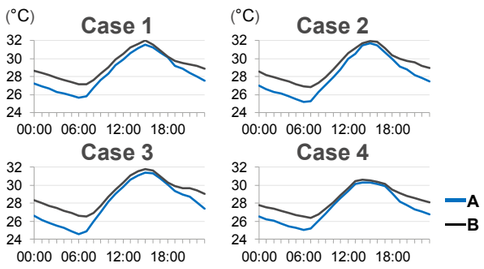


Figure 13:
Daily average of indoor air temperature in Room A and B under Cases 5 to 7 (Cross ventilation).

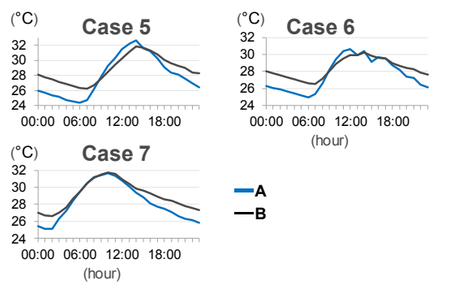
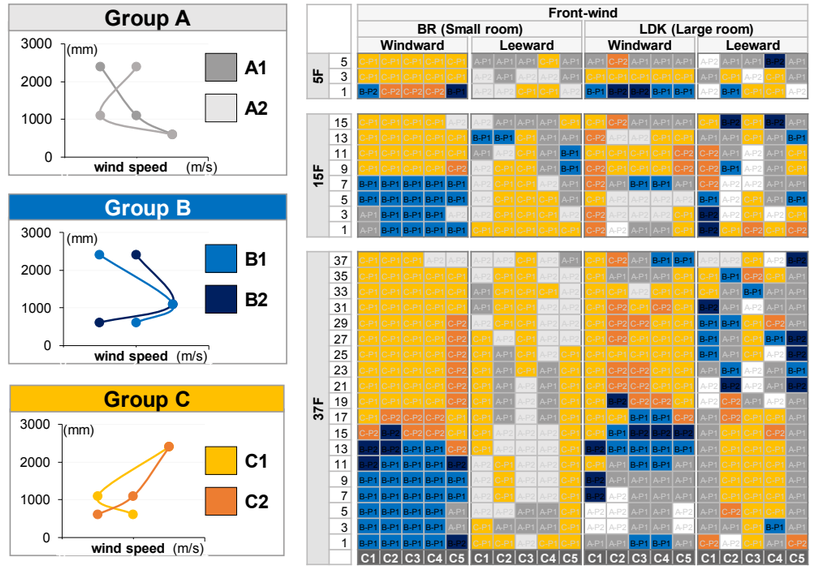


Figure 14:
Distribution of airflow patterns in the windward and leeward in the five, 15- and 37- stories buildings under the front wind condition. There three main groups of wind patterns, namely Group A, B and C, respectively.



3.3 Verification of optimum window configuration

The vertical pivot at the upper position (or "Top Window" was able to provide desirable air flow pattern and indoor air speed for ventilative cooling. In addition, this window type is also able to maintain relatively lower indoor air temperature. Therefore, this opening configuration was selected as the test case in the Phase-2 simulation.

In general, there are three major airflow patterns inside the unit which were observed, namely Group A, B and C, respectively. Group A is characterised by the higher wind speed region at the upper part of the room, while Group B is associated with higher air flow pattern at the middle part of the unit. Last, the Group C has higher wind speed near the floor level. Further, Group B is the observed airflow pattern of the Top Window in the field measurement.

Fig. 14 shows the distributions of the air flow patterns in the windward and leeward units, under five-, 15- and 37- stories buildings, respectively. As shown, the air flow patterns vary depending the location of the units. In the windward side, the units located on the higher floors mostly experience higher wind speed at the upper part of the room (Group A). Moreover, Group B was only observed only less than 26% of the units and mostly found at the lower floor levels of windward side. This shows that the field measurement results could not be used to justify the optimum opening configuration to be used in the actual buildings. Therefore, cross-verification process should be carried out to determine the optimum opening configuration. Meanwhile, the airflow in the leeward unit is mostly dominated by the Group A and C.

4. CONCLUSION

Window position, size and types play an important role for securing desirable ventilation performance. The results also show that even a small operable window can provide good indoor air speed and airflow required for improving the thermal comfort. Nevertheless, one particular window type is not able to provide a uniformed ventilation performance throughout the building.

The opening/window configurations in public apartment have been designed in a way that it should be uniformed throughout the building's facade. Meanwhile, the results show that the ventilation performance varies depending on the location of the unit. Therefore, specific window design tailored for particular location of the unit can be one of the solutions to ensure a good and equally distributed ventilation performance.

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Wood-textile composites for self-shaping material assemblies in architectural scale

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ABSTRACT: Self-shaping materials can be designed for material efficiency, programmable behavior and bespoke performance and enable designers to produce climate sensitive architectures that react in real time to environmental dynamics. However, their implementation in building elements remains challenging in relation with the scale, structural rigidity, and time-dependent responsive behavior of the self-shaping material assemblies. The study presents new design methods to understand, develop and test novel wood-textile composites for environmentally responsive self-shaping material assemblies in architectural scale. Equally concerned with material, environmental, and computational studies, the aim of the research is to contribute with design knowledge on environmental responsive envelope structures that can potentially contribute to reduced operational energy use in buildings. The research includes an experimental case study on inlayed textiles using wood bilayers and provides a systematic comparative review of the dynamic thermal responsive and structural performance of the assembly, in relation to dynamic daylight regulation. By mapping wood and textile properties as well as their synergetic capacities for form change, we investigate the ability to design increasingly larger and physically stronger responsive material systems.
KEYWORDS: self-shaping composites, wood bi-layer, hybrid textiles, adaptive envelopes, responsive behaviour

1. INTRODUCTION

Building culture finds itself in new contexts of environmental crisis, resource scarcity and climate change [1]. This incites research into identifying new material practices that consider the resources, energy consumption and climate adaptation of our buildings.

Self-shaping materials lie at the centre of these emerging material practices, designed for material efficiency, programmable behavior, and bespoke performance [2]. Due to their inherent material properties, self-shaping materials enable sense and response to a range of stimuli, producing responses to changes in heat, light, or moisture levels in the environment. By directly connecting with environmental stimuli, these materials have the ability to act as physical sensing systems, reducing the need for additional electronic control [3]. While many of these active, programable composites are developed with smart and/or synthetic materials [4, 5], there is a class that utilise the inherent properties of natural fibers [6, 7].

The study presents a new class of self-shaping lightweight assemblies that are capable of large geometrical transformations with high activation speed. The self-shaping behaviour lies on the combination of wood bilayers and textile composites for environmentally responsive material assemblies, as an approach to the challenges driven by the current material and environmental crisis for the built environment. The aim of this paper is to develop new design integrated methods for the implementation of active and responsive wood-textile assemblies in architecture and construction. The focus is on application for responsive envelope structures that reduce operational and embodied energy in buildings. The research applies a hybrid design methodology based on material and computational studies through encoding the grain pattern, the geometric layout and thermal expansion properties of wood, strategically coupled with inner structure, elasticity, and tensile strength of bi-elastic knitted textiles.

Through an experimental case study, we investigate the dynamic thermal responsive and structural performance of inlayed textiles using wood bilayers and we provide a systematic comparative review of the assembly, in relation to dynamic daylight regulation. By mapping wood and textile properties as well as their synergetic capacities for form change, we investigate the ability to design increasingly larger and physically stronger responsive material systems, allowing the potential to embed design into active, material-driven, building-scale construction.

Finally, we discuss on advanced design methods for the development of highly specified multi-material textile assemblies, which could introduce new hybrid responsive properties, allowing for local and global control within one thermally driven responsive architectural system.

2. CONTEXT

The ability to digitally map the environmental parameters of temperature, light and moisture, provide us with a better understanding of the environmental flux of both interior and exterior spaces [8] and, as a result, their impact on human body sensation. However, despite the ability to monitor these energy patterns, most of the major energy consuming systems in our buildings including heating, lighting, cooling and ventilation systems, tend to normalize changes in energy behavior and to provide ambient conditions, in which the human body is insensitive, leading to intensive energy consuming solutions [9].

2.1 Energy flux as design tool

Mapping the interior and exterior environmental dynamics provide a unique opportunity to rethink the way we engage with the patterns of energy flow as a spatial design tool. On the one hand, this incites research into the development of new active responsive material systems that have the ability to sense and respond in real time to environmental changes. On the other hand, it allows us to map, understand and specify an interior space from the perspective of discrete environmental stimuli that dynamically change and adapt over time [10].

2.2 Programming self-shaping behaviour of natural materials

As a natural fibrous composite, wood possesses a variety of complex properties and ingrained responsive capacities, related to environmental conditions of temperature and humidity, allowing for embedding sensing, actuation, and regulation within the material itself. Its anisotropic dimensional behaviour lies on its anatomy, and it is directly related to the fibre direction [6]. The key parameters are the relationship between the structure of the material, the grain of wood and the direction of growth, as well as the geometric and dimensional layout of the elements. Current research in self-shaping and self-assembling systems employ wood bi-layer composites [6, 11, 12] that shrink and swell in response to relative temperature gradients due to their high thermal expansion coefficient respectively. However, the implementation and use of self-shaping responsive material systems in architectural assemblies remains challenging in relation with:

1. **Upscale** of the responsive system. Design for and with responsive systems that are adaptive and structurally sound [13].

2. **Robustness** of the responsive behaviour. Address material fatigue and degradation of material's responsive capacity [14].

3. **Steering** of the responsive cycle. Control over the material responsive behaviour as a time-dependent transient phenomena [15].

3. METHODS

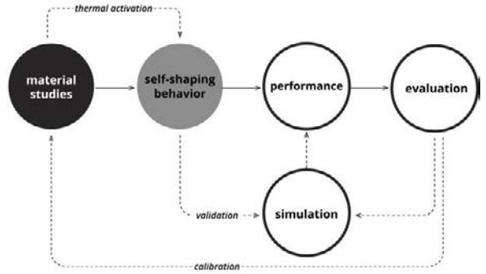

Figure 1: Hybrid design workflow for development and testing of self-shaping wood-textile assemblies in an architectural scale.

The presented research suggests a hybrid methodology coupling material-driven computational and prototyping studies (Fig. 1). The enquiry focuses on steering the macro-scale responsive behaviour of self-shaping components, through an assembly of multiple discrete elements, based on oak wood bilayer composites and bi-elastic knitted textile. Due to its high thermal expansion coefficient tangentially to growth rings, wood transfers thermally activated dimensional changes into responsive bending behaviour [16].

The direction and magnitude of this responsive capacity is ingrained in the material's anisotropic characteristics, which are directly related to the anatomy of wood and specifically the fibre direction. The research follows the hypothesis that the innate self-shaping thermal responsive capacity of timber, combined with textile's material elastic properties present unique opportunities to implement environmentally actuated self-shaping behaviour and can allow for implementation in an architectural scale, by using:

1. Textile as **binder**. Providing a soft assembly space where many small rigid wood elements can be combined into larger structures (as an approach to challenge 1).

2. Textile as **tension force**. Acting across the bending direction of the responsive wood elements can create a shape memory effect (as an approach to challenge 2).

3. Textile as **compression force**. Acting across the bending direction can control the responsive behaviour (as an approach to challenge 3).

3.1 Prototyping methods – *From 2D to 3D self-formed assemblies*

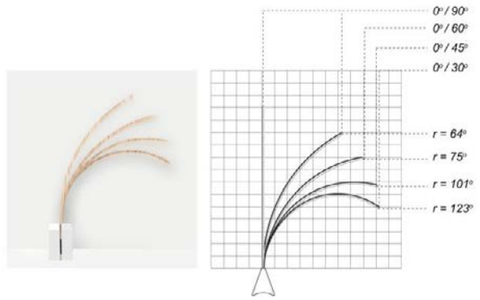

Figure 2: Principal curvatures of thermally actuated oak bi-layer composites of varying grain directionality.

By using the material's inherent properties, geometric shape and formations can be embedded into the material system and conventional forming methods can be replaced with self-shaping. For the experimental prototyping studies, we selected oak veneer for its high thermal expansion coefficient tangentially to growth rings (a_T =11, 9%), its high material strength (E=343 Nmm^2) and homogeneity of samples, presenting an almost linear grain topology. The enquiry uses oak veneer of 3mm thickness for the active layer (tangential cut) and 1 mm for the passive layer (longitudinal cut), pressed and laminated together into bilayer composites. After being thermally activated, composites of different geometric layout vary in bending magnitude (Fig. 2).

The textile used for the presented prototyping studies is bi-elastic knitted polyester (weight 150g/m), presenting high tensile strength (80 MPa) in transverse direction (warp) and minimal strength (55 MPa) in the longitudinal direction (weft) (Fig. 3). The oak bilayer composites are embedded within the textile membrane through stitched channels, in various configurations. After thermal activation, the bending of the oak bilayers combined with the elastic limitations of the textile allow for variations in self-shaping behavior and inner structure of the assembly (Fig. 4).

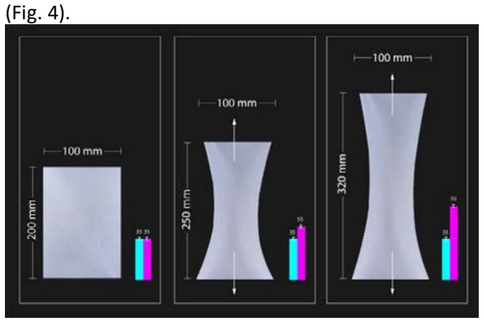

Figure 3: Tensile strength of bi-elastic knitted textile in warp direction.

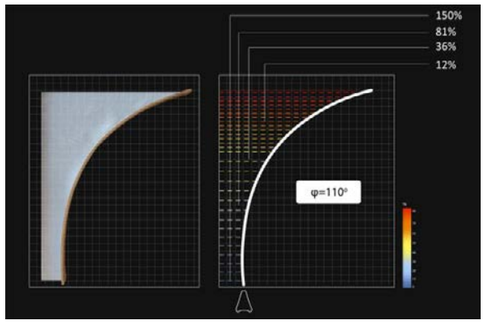

Figure 4: Experimental setup using oak bilayer composite (3mm/1mm) and bi-elastic knitted textile (5 cm x 20 cm). After thermal activation at 15° temperature fluctuation, the textile displays tensile elongation.

3.2 Computational methods – *Tailoring shape-change behaviour*

Computational design is continuously evolving and new tools present new opportunities. However, while self-shaping responsive systems offer an attractive paradigm for architecture today, our computer-aided design (CAD) tools and computer-aided manufacturing (CAM) processes are not capable to represent differentiated properties within solids such as anisotropy, graded density, elastic variations, and non-linear behaviour in response to dynamic environmental transient phenomena, such as temperature and humidity change [17]. The experimental computational setup uses spring-based physics engine, K2 solver in Grasshopper, Rhino, design environment [18], where we map the individual parameters of wood and textile and combine them into a matrix of material, structural and environmental performance synergies.

3.2.1 Steering parameters for wood

The bending curvature of the wood bilayers is calculated using the Timoshenko formula [19], as an implementation in Rhino, Grasshopper environment.

$$\frac{1}{\rho} = \frac{6(1+m)^2}{(3(1+m)^2+(1+mn)(m^2+\frac{1}{mn}))}\frac{(\alpha_2-\alpha_1)(c-c_0)}{h} = k\frac{\Delta\alpha\Delta c}{h},$$

$$m = \frac{h_1}{h_2},\ n = \frac{E_1}{E_2} \qquad (1)$$

The key parameters included in the calculation are the temperature change (c-c_o), the thermal expansion coefficient for the active (a_2) and passive layer (a_1), the thickness ratio between active and passive layer (m), as well as the longitudinal (E_1) and tangential (E_2) stiffness of oak [16]. Through this formula, we can derive the radius (ρ) of the oak bilayer curvature when exposed to temperature flux. This value can then be applied to derive the change in curvature angle.

3.2.2 Steering parameters for textile

For the material and form experimentation of textile elements, the parameters taken into account are the layout, the elastic capacity and the pretension of the samples. In order to compute the differentiated behavioural response of wood-textile composites, we use spring-based simulation. The form finding of the reactive elements occurs by assigning the grain orientation of each fibre into weighted values for hinges, along the internal edges of a triangulated mesh, corresponding to the oak bi-layer layout. The resulted vertex map of graded weighted values is then being informed by the curvature angle as derived from the Timoshenko formula and the pretension and elastic limitations of the bi-elastic textile.

4. DESIGN EXPERIMENTATION

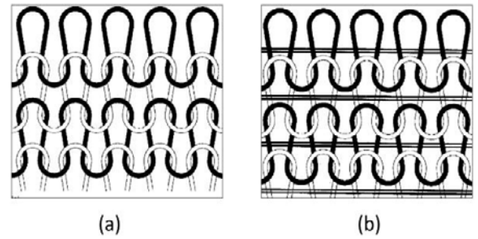

Figure 5: Principal diagram of (a) loop yarn (b) inlay yarn.

The study presents an experimental case study that focuses on inlayed textile using wood bilayers (Fig. 5) and provides a systematic comparative review of the dynamic thermal responsive and structural performance of the assembly, in relation to dynamic daylight regulation. By mapping wood and textile properties as well as their synergetic capacities for form change, we investigate the ability to design increasingly larger and physically stronger responsive material systems. Organized in a reciprocal open topology, the study discusses the development of microclimate-sensitive responsive surfaces, which can be tuned to desired performance related to daylight and thermal sensation.

4.1 Inlayed textile assembly with adaptive luminance

The case study is developed in a reciprocal open topology of 1 x 1 m test membrane, using two layers of bi-elastic knitted textile and ten oak bilayer composites of 20 x 500 mm geometric layout. The bilayer composites are implemented between the two layers through stitched channels. After being thermally activated, the oak bilayers bend in various directions, creating differentiated areas of tension and compression across the textile membrane. This differentiation then leads to areas of high and low luminance.

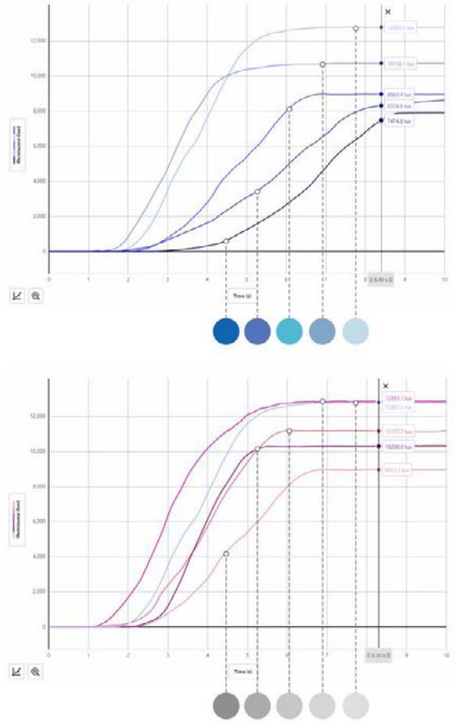

Figure 6: Luminance measurement of textile samples across (top) five colour variation and (bottom) five tensile force variations.

For understanding the adaptive capacities of the luminance performance of the assembly we performed a series of studies that looked into the potentials and limitations of colour and pre-tension of the textile. For this study, we developed an experimental setup with a test area of 30 x 30 cm, where 10 samples were tested in total, including five colour variations and five tensile force variations. The measurements were performed in daylight, on September 10th 13:00 p.m., in Copenhagen. The luminance performance of the samples was calculated using Go Direct Light and Colour Sensor by Vernier and the data were collected and displayed in graphs using Vernier Graphical Analysis (Fig. 6).

These data were then exported and interfaced with a daylight simulation using Ladybug tools in Rhino, Grasshopper design environment [20] for evaluating the performance of self-shaping wood/textile assemblies across various activation states, based on real data. In order to define the topology of the wood/textile assembly, we developed a hybrid model that displays a parallel evaluation of the self-shaping behaviour, structural performance on tensile and compression forces and luminance evaluation of the assembly (Fig. 7).

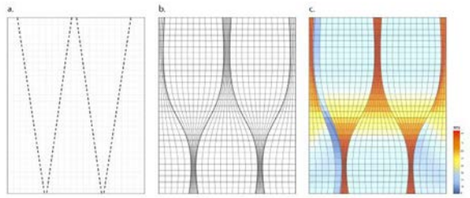

Figure 7: Design integrated model including (a) input values for simulation, (b) modelling of self-shaping behaviour based on wood specification and textile pre-tension, (c) stress map of tension and compression areas of the membrane.

The simulation of the self-shaping behaviour follows the computational methods presented above. In detail, for the material and form experimentation of the assembly, the parameters taken into account are the elastic capacity of the textile and the bending magnitude of the wood bilayers. In order to compute the differentiated behavioural response of wood-textile composites, we use spring-based simulation. After form-finding, we extract the layout cutting pattern of the textile, used for the fabrication.

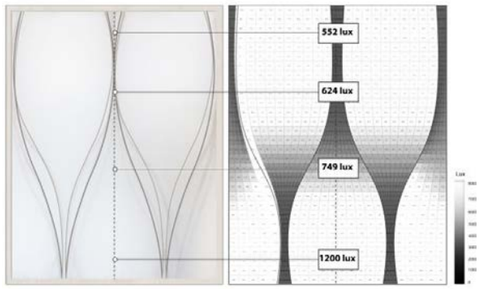

Figure 8: (Left) Overlapping of the different responsive states of the self-shaping membrane during thermal activation. (Right) Measurement of the luminance values of the self-shaping assembly after thermal activation (lux).

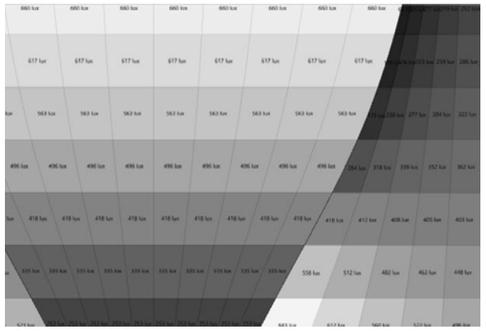

Figure 9: Validation of luminance performance measured with Vernier colour and light sensor on the responsive self-shaping assembly.

The model displays a parallel evaluation study of how the various bending states of the thermal responsive oak bilayers act as tensile force across the textile and affect the amount of solar energy passing through the self-shaping membrane, providing the designer with a direct relation between material behaviour and environmental performance. The experimental responsive specimen is being exposed and activated in a temperature fluctuation of 15°C, maintaining 30% RH.

The responsive behaviour is expressed with variations in magnitude, ratio and bending direction and allows for local changes while addressing consistent global structural and environmental performance. Within these investigations, the textile pre-tension and the anisotropic characteristics of the bi-layer composite is proved to be the driving force of the programmed deformation.

With the use of light sensor, the self-shaping assembly is being real-time tracked and the resulted luminance data are used as validation method for the fidelity of the simulation (Fig. 8). This allows for deviation analysis between the physical and digital studies (Fig 9). The system demonstrates the integration of a responsive material system into a functional, modular, and highly adaptable system in an architectural scale (Fig. 10).

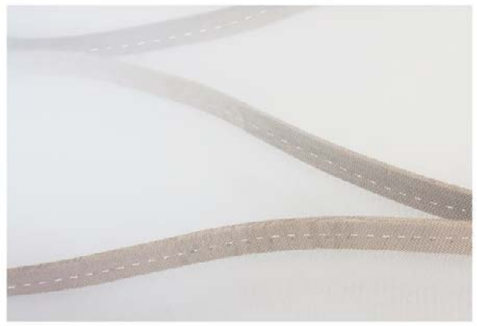

Figure 10: Close-up of wood-textile self-shaping composite after thermal activation.

5. RESULTS

The case study proves that the integration of a hybrid material-driven adaptive workflow that connects material and environmental performance of wood bilayers and bi-elastic knitted textile, can inform the design chain with a series of critical results, allowing for high precision steering of the self-shaping assembly in an architectural scale. Particularly, the research findings suggest that:

1. **Using textile as a binder** can allow the upscale of the responsive behaviour, retaining a response magnitude relevant to the structural capacity of the material elements and the global scale of the material assembly.

2. **Using textile as a tension force** along the bending direction can facilitate the return of the self-shaped composite to its initial state and reduce responsive degradation. However, the selection of uniform knitted textile presented certain challenges in relation with tensile forces caused by the thermal activation of the oak bilayers. While the tensile strength is high in transverse direction, it is relatively low in the longitudinal and as a result, it constraints the bending magnitude of the bilayers, parallel to this direction.

3. **Using textile as a compression force**, along the bending direction, can counteract over self-weight of the responsive wood elements and thus facilitate consistent control throughout the responsive cycle. However, material calibration is directly related to the environmental conditions and therefore, the same control that is being carried out through activation must be also maintained through fabrication process. Thus, it is required diligent measuring of the ingrained moisture content of wood, as well as control over relative temperature and humidity levels during the production of the composites.

6. DISCUSSION

Based on these findings the research speculates and demonstrates future implementation of wood-textile membranes for adaptive building envelopes. As an extension of the current computational and prototyping studies we aim to transfer the presented design knowledge into full scale implementations and that will further investigate the potentials and limitations in field conditions. The ability to differentiate locally textile's structure, elasticity and tensile strength can allow for high-resolution specification, rigorous control and upscale of the responsive behaviour over time. Future development will investigate knitting as a material practice to locally differentiate elastic properties, linking micro behaviour to macro performance. Finally, the research constructs new pathways towards multi material compositions for hybrid self-shaping behaviours and graded performance.

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Adaptive and dynamic façade modules for serial energy-retrofit of residential and office buildings using active and passive building components

A pilot study

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ABSTRACT: The energetic retrofit of existing buildings plays an important role in decarbonizing the building stock, whereby modular retrofit solutions can accelerate the energetic retrofit on a large scale. The combination of passive and active measures in the building envelope offers the possibility to address the energetic performance and thermal comfort through retrofit. Nevertheless, there are no market-ready modular retrofit elements, including HVAC systems, and hardly any research showing the practical implementation in case studies. To close this gap, this study demonstrates the implementation of an active-dynamic modular façade, including active and passive building components, in a case study on an office building in Western Germany. The influence of the retrofit measures on the room climate is evaluated by long-term monitoring data. This study gives planners an orientation in designing and implementing modular retrofit elements including HVAC components. Monitoring results show that adding an additional insulation layer can cause overheating in summer. Especially in buildings with high heat gains, HVAC systems should be considered in the planning of retrofit measures. The case study shows, that the implementation of a reversible heat pump can decrease the indoor temperature in summer about 3.2 K and reduces overheating.

KEYWORDS: Energy retrofit, Adaptive dynamic façade, Modular refurbishment, Thermal comfort

1. INTRODUCTION

The building sector is responsible for approximately 28 % of the world's total energy-related CO_2 emissions (IEA, 2019). According to the International Energy Agency, existing buildings are expected to account for up to 80% of the stock in 2030 in some countries (IEA, 2020). These high CO_2 emissions and large proportion of existing buildings show the need for building retrofit to decarbonize the building stock and reach the emission-reduction targets of each country. In Europe, the European Green Deal (European Comission, 2019) emphasizes the retrofit of public and private buildings as a key initiative to achieve the objective of climate neutrality in the European Union in 2050. In addition to environmental aspects, retrofit in old buildings can improve thermal comfort. In contrast to the need for the retrofit, average annual retrofit rates are currently less than 1 % in most countries worldwide (IEA, 2020). Modular, easy-to-implement retrofit measures offer a promising option to increase these retrofit rates. Therefore, several projects in multiple European countries try to develop serial produced façades for retrofit, e.g., the Energiesprong project (Energiesprong Foundation, 2022) in several north-west European countries or the European funded RenoZeb project (RenoZeb, 2022).

The concept of serial energy-efficient façades has provided an excellent opportunity to accelerate retrofit speed. These partly prefabricated, modular façade systems can enhance energy performance and thermal comfort. Such envelope systems can contain both, passive measures like insulation, and active measures like technical components for energy harvesting.

Adaptive Dynamic Building Envelopes (ADBE) is the term used to describe envelope systems that increase the adaptability of the building skin. ADBEs can adapt toward changing ambient conditions resulting in better energy efficiency and thermal comfort (Mohtashami et al., 2022). ADBEs usually exploit the potentials of active and passive components simultaneously. However, the design of the active components varies significantly among different ADBEs.

A large-scale review study conducted on ADBEs (Mohtashami et al., 2022) reflects that very few ADBE systems are designed for the retrofit of old buildings. In addition, many studies (e.g. Bigaila & Athienitis, 2017; Catto Lucchino et al., 2021) only provide simulation-based results and do not test the ideas in an on-site situation. Besides, the lack of a clear business model for market exploitation was found to be another obstacle toward adopting ADBE systems on a large scale (Mohtashami et al., 2022).

2. BACKGROUND OF THE ADBE SYSTEMS

Researchers have long investigated developing envelope systems to respond to outdoor weather conditions. These responses are either by developing passive solutions that are usually static and do not use any energy source to perform, or they are active solutions that devise HVAC or solar-based systems in order to produce more energy. The concept of ADBE falls in the domain of using active technologies, passive systems, and a combination of both. The level of user controllability and interaction with the envelope is a differentiating characteristic of ADBEs, reflecting how adaptive and dynamic they are.

Researchers have shown a keen interest in using more active systems in their ADBE design in the past years. The use of Photovoltaics (PV) on the envelope has revolutionized the enhancement of the envelope's energy efficiency. More than half of the technologies devised as active measures in an ADBE are PVs, which is then followed by mechanical ventilators and heat pumps (Mohtashami et al., 2022). PVs are often used to produce electricity either as the source for other accompanying HVAC systems in the ADBE, or to store electricity in a battery. Heat pumps are part of air conditioning systems that control airflow and temperatures in the building. As a result, there are a few systems capable of producing cooling energy. The HVAC systems are often combined with PVs (Alessandro et al., 2021). A mechanical ventilator is a cost-efficient technology for air conditioning (Pekdogan et al., 2021) in areas where cooling demand is not very high.

The majority of the aforementioned studies are simulation-based and fall short in experimental and on-site assessments. Examples of experimental works include the study of Lopez et al. (López et al., 2014), where they test two Building integrated PV (BIPV) systems when installed on the façade and the roof. The authors conclude that their monitoring data can predict the behaviour of the modules in real buildings. Mei et al. (Mei et al., 2006) consider a PV roof tile to explore the high-temperature operation of BIPVs. The result of a case-study assessment of a semi-transparent photovoltaic system for an office building (Li et al., 2009) confirms that the proposed system, together with dimming controls, reduces the electricity demand of the building by 1203 MWh and peak cooling load by 450 kW.

However, most of these studies investigate the performance of PV-based ADBEs, and very few reflect assessments of mechanical ventilators and heat pumps. This study focuses on integrating mechanical ventilators and heat pumps as HVAC systems in the ADBE design, which is designed as a retrofit solution.

To address the discussed research gaps, the Plug-and-Harvest (PnH) project was born. It bases on a circular business model with the idea of integrating energy harvesting systems into modular façade frames in order to easily install them on the existing building's façade and speed up the serial retrofit process. This paper shows the implementation of the Plug and Harvest-ADBE on a pilot building located in Germany. This implementation includes the integration of suitable HVAC systems into an ADBE. The results of this retrofit are highlighted by monitoring data before and after the retrofit and by assessing the final influence on the room climate in a non-retrofitted building. The paper demonstrates technical steps in the integration of HVAC in an ADBE, evaluates the ADBE performance through monitoring data, and reflects the lessons learned in this process.

3. ADBE DEVELOPMENT

The case study investigates the retrofit of three office rooms of an institute of the RWTH University in Aachen, Germany. In this section, we present first the pilot building, second the ADBE design and third the ADBE implementation.

3.1 Pilot building

The pilot building was erected in 1975-1979 in a massive prefabricated construction system with flat roofing and interior system fittings. We consider three office rooms on the southern façade of the building in this case study (see Fig. 1).

Figure 1:
South façade of the pilot building, including the investigated rooms

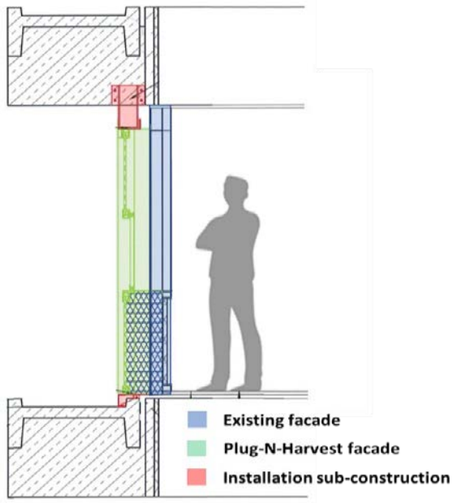
The building has a modular façade with metal elements 3 m high and 1.2 m wide divided into a lower part with balustrade elements and an upper glazing part. Each floor has balconies serving as escape routes in case of fire. After the retrofit, a minimum width of the escape routes of 1 m must be guaranteed. The three investigated office rooms are directly adjacent to one another and have a floor

height of 3 meters. All three rooms are used as four to five-person offices. The occupancy has changed repeatedly during the two-year monitoring phase because of COVID-19 restrictions. The offices are neither specially air-conditioned nor is a ventilation system installed. In winter, flat radiators can heat the rooms. The observed rooms have almost no heating demand because of high solar radiation and internal gains. In contrast, high room temperatures measured over summer lead to low thermal comfort.

3.2 The ADBE Design

A new building skin with integrated HVAC components is implemented in front of the existing façade in March 2021. To maintain a uniform appearance, we decide to use window modules with the same structure as the existing ones. In the upper part of the modules, fixed glazing alternates with openable vertical sliding windows. Below the windows, balustrade elements with the same height as the ones of the existing façade are integrated. Fig. 2 shows a scheme of the implemented façade system that in the following will be called PnH system.

Figure 2:
Design of the final PnH façade system



Existing façade (blue, oriented to the person) and PnH façade system attached to the external balconies of the building

The balustrade modules are partly insulated and partly equipped with technical components. For each of the rooms, one module including HVAC is provided. We select different ventilation devices to ensure good air quality and a reversible monobloc heat pump for heating and cooling, as some rooms' pre-monitoring results show a high cooling demand. In this paper, we present the implementation for one ventilation device and a heat pump. Table 1 compares the façade integrated HVAC devices.

Table 1:
Comparison of façade integrated HVAC devices

	device	Advantage	Dis-advantage
Room A	Monobloc heatpump	Heating and cooling	High electricity consumption
Room B	Central ventilation unit	Supply of several rooms	No active cooling, Large size

4. ADBE IMPLEMENTATION

This section explains the implementation process of the designed PnH facade system on the case study and highlights the challenges during construction, installation, and incorporation of HVAC devices.

4.1 Details of construction and installation

Construction of a substructure construction

The Plug-and-Harvest (PnH) facade is positioned in front of the existing façade. The static situation of the existing building requires the installation of a substructure. A steel structure is fixed between the prefabricated concrete balconies' cantilevered beams. The steel substructure consists of two hat profiles per balcony screwed to the concrete beams. An L-profile is set between the top hat profiles to which the PnH-modules are attached. The L-profile is closed with lugs at the sides and the front.

Structure the of ADBE modules

The ADBE consists of eleven aluminium frames with a total size of 300 cm x 120 cm. A stone wool layer of 23 cm thickness in the modules without technical components ensures an estimated heat transition coefficient (U-value) of only 0.13 W/m²K (pre-retrofit: 1.0 W/m²K). The upper-glazing part has a U-value of 0.71 W/m²K. The modules with technical components are insulated with a thinner insulation layer whose thickness varies in each panel. Aluminium panels similar to those of the existing façade serve as the cladding for the balustrade elements.

Incorporation of HVAC

The minimum width of 1 m for the escape routes allows a construction thickness of maximal 25 cm for the technical components inside the PnH modules. This strongly influences the choice of technical components suitable for the application.

A reversible monobloc heat pump suitable for heating and cooling (device: Olimpia Splendid Unico Air) is chosen for the design of PnH modules dedicated for room A. Room A had the highest measured pre-retrofit temperatures and therefore higher cooling demand (Fig. 3 left). The device positioned in the lower part of the PnH modules, is supported by aluminium profiles for vertical load transfer to the balconies. The remaining volume in the ADBE module is insulated with stone wool. For the supply of outside air as a heat source or sink for the heat pump, two core drillings through the outer façade panel are provided. A plastic construction separates inlet and outlet airflow and leads it into the room. For both heating and cooling, the heat pump can provide a power of approximately 2 kW.

A central ventilation system (device: Lunos Lunomat) is integrated into the PnH module dedicated for room B (Fig. 3 middle). The device is suspended on the inner panel of the façade; the remaining module space is insulated. Fig. 3 illustrates the implementation of the devices and the final external view of the PnH façade.

Figure 3:
Implementation of three different HVAC components in the ADBE

left: monobloc heat pump, middle: decentral ventilation unit, right: external view of the final PnH façade

4.2 Challenges in implementation

In planning and implementation, several challenges occurred that are discussed in the following.

- Escape plan: A minimum width of 1 m for the escape routes on the balconies must be guaranteed. This fact strongly influences the ADBE design. HVAC units with small thicknesses are chosen.
- PV implementation: The implementation of photovoltaics (PV) wasn't feasible in the case study. Fire safety regulations require an emergency turn-off switch for the PV at every building entrance, which leads to high costs in combination with the high number of inputs and long distances for cables. A pre-study shows the benefits of PV to cover the electricity demand of the HVAC units.
- Opening of windows: We choose vertical sliding windows as the positioning of the ADBE layer in front of the existing façade does not allow the opening of horizontal opening windows.
- Maintenance: The integration of HVAC units in the façade complicates maintenance. A click-system for the outer panels, comparable to the insertion of window panes, facilitates the process.

5. PERFORMANCE EVALUATION

Section 5 describes the installed monitoring system and analyses the influences on the room temperature by monitoring data.

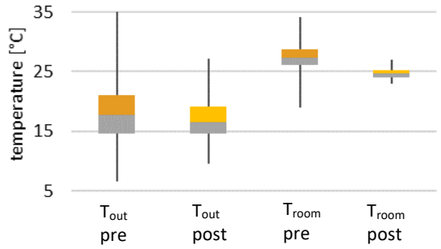
5.1 Monitoring system

To assess the pre-retrofit situation and evaluate the situation after retrofit, a monitoring system is installed 1.5 years before the retrofit. Measurements will be carried out up to one year after the retrofit. The monitoring focuses on energy consumption, user behaviour, and user comfort. The following sensor types are installed in each room: CO_2, humidity and indoor temperature measure, presence & illuminance detector, door and window sensors, heat flow meter, and electricity meter for the ADBE system. For outdoor weather conditions, we use data from the weather station of the German Weather Service, which is located two kilometers away from the pilot building.

5.2 Monitoring data analysis

This section investigates the impact of the external ADBE layer on the room climate through monitoring data. Fig. 4 shows the summers outdoor and room temperature variation for room A.

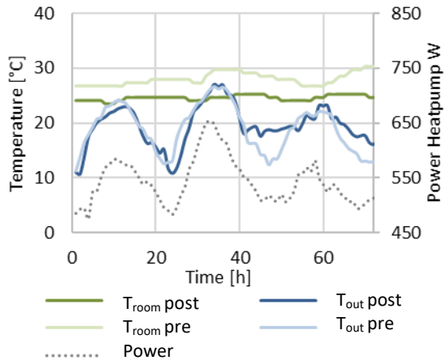
Figure 4:
Variation of temperature pre and post retrofit including a reversible heat pump in summer in room A where Median, 25 % and 75 % quartile are highlighted by boxes



The influence of the external climate gets visible using boxplots of the outdoor temperatures in both years. In 2020, the summer temperatures were hotter and more volatile than 2021. High internal and solar gains on the southern façade lead to high room temperatures with an average of 27.4 °C and peaks up to 34 °C. While the high heat gains are a problem in summer, they result in a low heating demand required in winter. Due to the active cooling with the reversible heat pump in room A in combination with a lower average outdoor temperature (Fig. 4), the median of the indoor temperature is reduced by 3.2 K to 24,7 °C. After the

retrofit, the variation of the indoor temperatures is lower than before retrofit. The lower variation can be attributed to the additional thermal inertia resulting from the additional insulation layer. The reaction to fluctuations in the outside temperature is thus reduced. Furthermore, the smaller fluctuations of the outdoor temperature influence the curve of the room temperature. To evaluate both effects and understand the interactions of the ADBE and the room climate, Fig. 5 compares room temperatures in room A over three days with a similar outdoor climate pre- and post-retrofit.

Figure 5:
Comparison of room temperatures over three exemplary days (01.06. - 03.06.) pre- and post-retrofit including a reversible heat pump in Room A where Median, 25 % and 75 % quartile are highlighted by boxes



The indoor temperature in the retrofitted room is 2 K to 5 K lower than before retrofitting due to the active cooling of the heat pump. To decrease the room temperature and improve thermal comfort, an electrical power of 500-650 W is necessary over the entire period. Compared to the indoor temperature pre-retrofit course, the indoor temperature post-retrofit is less volatile. Pre-retrofit, the influence of the outdoor temperature fluctuations is visible in the indoor temperature course. After the retrofit, the interaction with the outdoor temperature is reduced due to the thermal insulation.

Whereas the indoor temperature in room A is reduced through active measures, the median temperature in room B in summer after retrofit is 0.6 K higher than pre-retrofit (see Fig. 6). As in room A, the indoor temperature variation post-retrofit is lower than pre-retrofit due to higher thermal inertia. The room temperature increase can be explained by the interaction of the thermal insulation and the high internal and solar heat gains. The increased insulation reduces the heat transmission through the outer wall. Therefore, passive cooling on summer nights is reduced, resulting in a higher indoor temperature. In addition, the airtightness of the outer wall has been increased in the course of retrofit, resulting in lower heat losses through infiltration. The additional ventilation flow through the ventilation device is insufficient to compensate for those effects.

Figure 6:
Variation of temperature pre and post retrofit including a ventilation system in summer in room B where Median, 25 % and 75 % quartile are highlighted by boxes

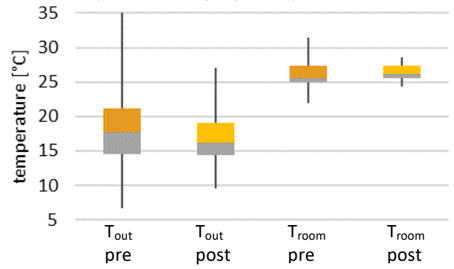
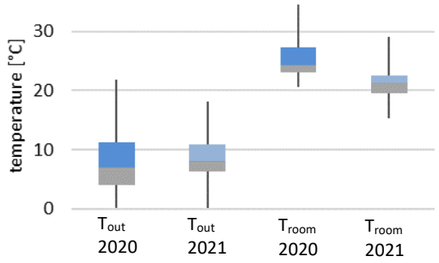


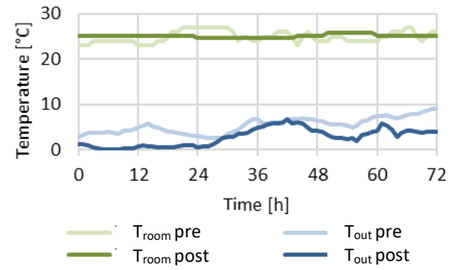
Fig. 7 demonstrates the influence of the ADBE on the room climate in winter in room B. Passive cooling through the ventilation unit reduces the high room temperatures pre-retrofit. For some periods, the room temperature falls below the set temperature of 20 °C that is valid according to the German standard DIN 18599 (DIN German Institute for Standardization, 2018). The undercutting can be justified by a continuous basic operation of the ventilation unit and could be improved by demand-controlled ventilation. However, long-term monitoring data for room A in winter is missing due to a measurement failure.

Figure 7:
variation of temperature pre and post retrofit including a ventilation system in winter in room B where Median, 25 % and 75 % quartile are highlighted by boxes



In winter, without active and passive cooling, the temperatures in room A are in the same range for pre- and post-retrofit (compare Fig. 8). The course of the temperatures post-retrofit is less volatile than pre-retrofit due to the room's higher thermal inertia and airtightness. Regarding the high room temperatures, passive cooling measures, for example, through ventilation as in Rooms B and C, seem reasonable.

Figure 8:
Comparison of room temperatures over three exemplary days (26.01. - 28.01.) pre- and post-retrofit in Room A



Because of the low occupancy of the room due to the Covid 19 restrictions in Germany, it is difficult to derive statements about the air quality. Pre-retrofit, the CO_2 values exceeded a value of 1000 ppm for some periods, showing the need for ventilation. After the retrofit, the level of CO2 is decreased. Due to the rooms' strongly variable occupancy, the authors can't make a statement about air quality. The relative humidity in the observed rooms varies by 30 - 40 % for the central part of the observed period. Due to the high room temperatures, the relative humidity is comparatively low but does not restrict the user's comfort.

5. DISCUSSION AND CONCLUSION

The paper presents an approach to integrate Heating, Ventilation and air conditioning (HVAC) units in an Adaptive Dynamic Building Envelope (ADBE) for modular retrofit and addresses practical gaps in the implementation of ADBE systems. The case study highlights challenges in construction and installation. Monitoring results demonstrate that the implementation of a reversible heat pump can avoid overheating in summer and decrease the indoor temperature about 3.2 K. Therefore, a high electricity power of approx. 600 W is necessary and leads to a high-energy consumption. In rooms without active cooling, we can see higher average room temperatures after installing an additional insulation. The case study shows that implementing an external insulation in rooms with high internal and solar gains can cause a high cooling demand. Therefore, the authors can state that thermal comfort and energy efficiency must be considered together in renovation cases. In the energy retrofit of buildings with high internal and solar gains, HVAC measures should accompany the insulation of the building envelope to ensure thermal comfort.
As the ADBE design takes the specific requirements of the pilot building into account, it cannot directly be transferred to all other building types. The authors see the need for further research in developing ADBE modules with a higher degree of prefabrication and demonstrate the implementation on more buildings.

ACKNOWLEDGEMENTS

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Renovation of old bamboo tubular shaped house in south China

Application of passive energy saving and ventilation methods

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ABSTRACT : Based on the composite design principle, this paper discusses the influence of the chimney effect generated by the stairwell in renovation of "old bamboo tubular shaped house" on the thermal and wet environment and energy consumption of HVAC from a cross-disciplinary perspective. CFD software was used to simulate the effect of active and passive energy saving design. Studies have shown that the wind speed of the room on the first floor is increased from 0m/s to 0.5 ~ 1.2 m/s through transformation. [Conclusion] The result shows that the composite design principle can keep the comfort of the room in the summer while saving energy.
KEY WORDS：Composite Design; CFD; Building renovation; Energy saving

1. INTRODUCTION

The house studied in this paper are located in Guangzhou, China, where the bamboo tubular shaped house is enclosed by buildings, which blocked up 3 sides of the house; the ground water surface rises almost up to the soil surface due to the tide of river nearby; the gap of cling houses is filled with waste and dirty mud, also full of plumbing tubes and every families vented gases directly into the gap. The habitats definitely suffered. As result these houses which play an important part of historical urban area cannot maintain their hygienic conditions and the index of healthy is much lower than that of the requirement in the norm, which include directly sunshine times, luminous, air circulation ratio, etc.

When the former habitats move to the modern city area, leased their houses to the tenants who work in the city, who didn't care about the living conditions too much and even unwilling to paid for addition fee for eject fans. The old Guangzhou city area lost its original vital, and became another kind of Urban Slums, nick named "old, dilapidated and small".

Now, there are two wicked problem of these houses. First, insufficient sunshine times, especially in the ground floor. It's gloomy and moist, which has no directly sunlight all year round. Second, stink. Third, oxygen-poor. These were mainly because of the long rectangular shape plans and minus gap of cling houses, which the gap width is 20-30 centimeters. In order to prevent the stink smell of bathroom and kitchen, the windows which are opening to the gap were shut down, so the indoor air is stagnate. Then the air circulation ratio is much lower than 1 times/ per hour, of which is a requirement of norm. Vitiated air harms people's health.

How came of these problems. Why were these problems not solved in time. For the tube-shaped house has existed even more than one century and the answer is because of the latitude changed of this kind of house, they were originally one floor, with no more than 5 meters' height. A small open atrium inside can cover ventilation & sunlight needs, but now they were rebuilt to multi storey during recently 50 years.

The number of rooms were increasing, but sadly the living quality goes inversely due to shadow of neighborhood houses. The atrium which was believed to be useless has been wiped out of, which is due to too much height & width ratio. The typical tube-shaped house has only 3.8m of front side which facing a narrow street, but it has more than 10 meters deep and 10 meters high. An atrium which is only 1.5㎡ area but 10ms tall and not to mention its safety problemAlso, it's conveniently, especially for the workers who have heavy equipment. The middle floor is worst, for it has no advantage comparing to upper or ground floor. What's worse there were some capillary water even rise up to 2nd floor. The hygienic conditions in these tube-shaped houses need to transformation urgently.

2. BACKGROUND INVESTIGATION

2.1 Investigation one

There are some researchers who concern about adding a chimney at the top of an atrium to enhance the natural ventilation in office building. Hussain added an atrium adjacent to a stair (2015)[1]. Wang[1] concluded that a chimney's opening size in bottom or top need to be equal. Other researchers indicate if blackening the outside of the chimney will warm up the air inside and increase the pressure difference between the top and bottom enhancing the chimney effect. A similar conclusion was draw by Zhang[1]. He add 7 series of hot water diffuser to increase the air temp at the top cube of an office building in Shanghai. There is a case that a fan was cited on top of chimneys in the atrium to enhance the chimney effect.[1]

All of their studies based on a smooth interior chimney, which has not any obstruction inside. How is the one with obstruction? Where to locate the chimney can maximize the chimney effect. These questions will be surveyed next.

2.2 Investigation two

We're going to use the stair as a ventilation channel, for which there have no similar research before. However, there are some basic relevant research. According to Fenghui[1] generally the air flow in a stair is not a positive one. On contrary it is a negative flow that air blowing from roof to ground floor. She surveyed a scissor shaped stair of a resident building in Wuhan city and the survey was taken in hottest summer day. The temp of air was 40℃ on the roof, while it was 32℃ on the ground floor. The result showed that when the air of the roof enters the room at a wind speed of 1.4 m/s, the bottom air flows to the outside at 0.8 m/s. (The total height is 98m). This result is confusing. Because according to the formulation:

$$\Delta P = 3460(\frac{1}{T_0} - \frac{1}{T_s})h$$

Where T0 = indoor temperature at the top; Ts = out-door temperature, h = height from the neutral plane of atrium; and ΔP= pressure difference values. (Zhu et al 2008).

The result of the differential pressure obtained by bringing in the relevant data is 1059Pa. This is a huge pressure which can force the air to form a positive flow; the air shouldn't be pulled back. From this we may know that the slope or even section will play an important role in stair chimney. The △P is not simply determined by formulation [1], also how is the effect of height T0 measured?

2.3 Investigation three

There are studies which concern the case in fire about what is the critical limit of air circulation ratio in a stairi. They found that if controlling the circulation times then we can restraint the chimney effect occur. Their study is based on the dramatic hot air with smoke in fire, that is big different from ordinary daily. Although contrary to the purpose of their research, their research results tell us that some artifice means is still needed to influence the chimney effect. In order to enhance the flow, what position is better for setting an additional fan? It has not been studied in this research.

Just as to prevent fire and disaster caused by fire, a fire smoke detective is set in advance.[2] According to research which concern in fire calamity, if we set a partition to cover the outlet of the chimney, it can effectively stop the chimney effect. Using stairs as a chimney-like air passage, there will be 3 advantages: 1st, to solve the air stagnate problem; 2nd, to save valuable land, because the stair is already there; 3rd, to exhaust the hot air which stack in the ceiling below the roof.

This paper is aim to find out how to deal with the negative impact of chimney effect in ordinary day. This paper aims to find out what technical measures can be adopted, not only to make the chimney effort happen but also to enhance it.

3. SOLUTIONS METHODS

3.1 A case investigation

Moisture has formed a mold on the wall of the room, which can be showed from a red-infrared thermal camera. (Fig. 1,2)

Figure 1: Floor plans and section sketch and photo

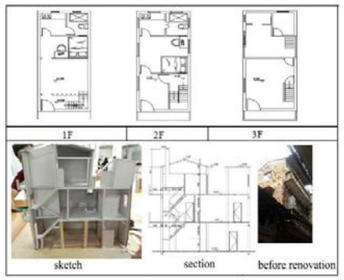
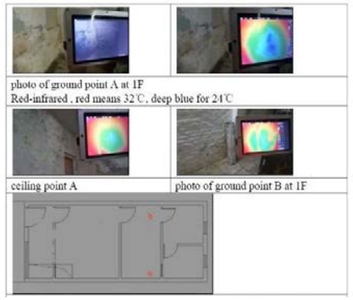


Figure 2:wall temperature of Red-infrared(1st floor and neigbourhood)



Note: The experiment was held by Dajiang thermal imager

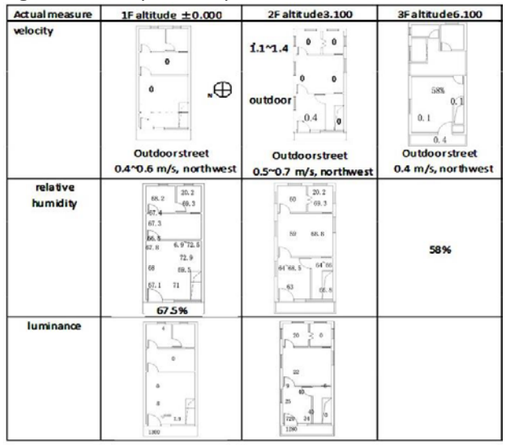
The basic data of the building we studied are shown in the table 1.

TABLE1: building database

Table 2 Building database			
equipments		opening	m
Top fan	150pa	Stair chimney	0.55×0.50×1.85
2F fan	50pa	Back gap chimney	0.25×3.8×11
1F fan	50pa	1F front door	1.2×2
		1F front window	1.85×1.2
human	180W×2		
lamp	34W	1F rear gap window 1	0.4×0.4
		1F rear gap window 2	0.6×0.2
Situation 1 condition			
1F inlet	1m²	Street inlet opening1	1×3
Top outlet	1m²		Velocity 0.5m/s
elevation	11.5m	Street outlet opening2	0.3×0.5
Four wall	38℃		Velocity 0.05m/s

The experiment is composed of three steps: *Step 1*, simulating original condition by CFD, which hasn't any opening on the roof. According to the simulation results of air particle mean age, after air particles enter into the window, they cannot form a smooth upward flow, they form a turbulent flow. *Step 2* is to figure out the reason. From the mean age of air, because the slope section of stair obstructed the flow, the velocity of wind changes with the direction of the stair section. In each section, the process is similar. While air climbing up, the velocity increases from 0 to 0.3m/s, but when the particles hit the wall, they calm down to 0m/s again, then they turn around to begin the next phase again. With this resistance, the chimney effect couldn't occur. None the less, once the external wind speed increases a little bit, suction flow will form and the air will be drawn down to outside. *Step3*, after figuring out the organized of the air flow in the stair, we faced with another exploration. The stair is inside of the house, which means more than one sides are enclosed by functional rooms.

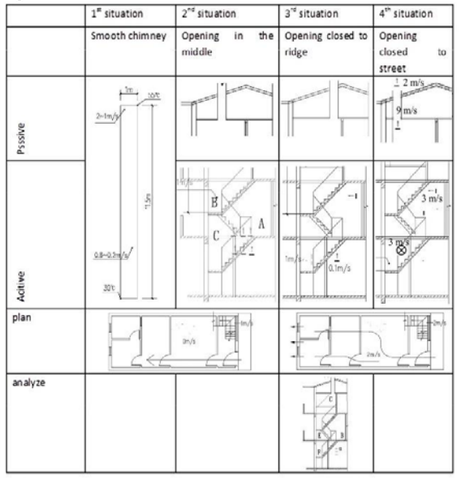
Figure3: velocity humidity luminance



There is no direct sunlight to heat the air. Is the formulation [1] suitable for this stair chimney? Will the difference between To and Ts affects △P or not ?

Next we will assume four situations to stimulate in order to figure out the questions that be presented above.

Figure 4: four situations to simulate



1st situation: the size of chimney's opening at bottom & top are 1㎡ both and the chimney is located outside of the wall.

When without artificial fans, the VT (Top) < 2m/s, positive.

Conclusion: the total air volume is small.

2nd situation: the chimney is set on the middle of the stair's roof.

The simulation result is that VT≦0.5～1m/s.

Conclusion: the chimney at the top of the stairwell is 1.5m high only. Even with the help of several fans separated in the stair, the air flow speed is still small, especially at point A, B & C due to turbulence. The total air volume is small.

3rd situation: The chimney is set closed to the 3F's door.

The simulation result is that VT≦2.4m/s. But if add 3 fans at point αβ& top, The VT≦3.4m/s and △VT≈1m/s.

Figure 5 2ed situation

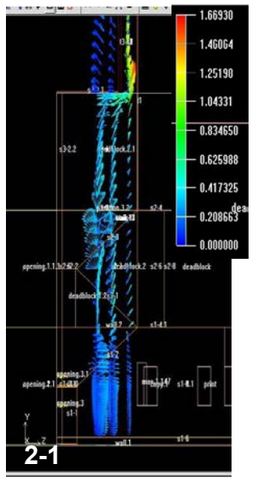
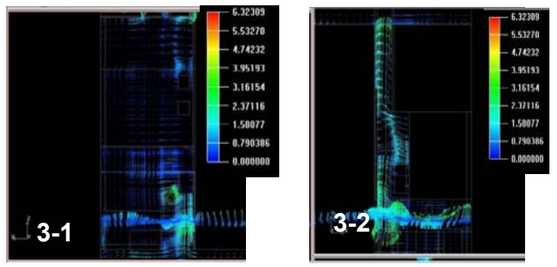
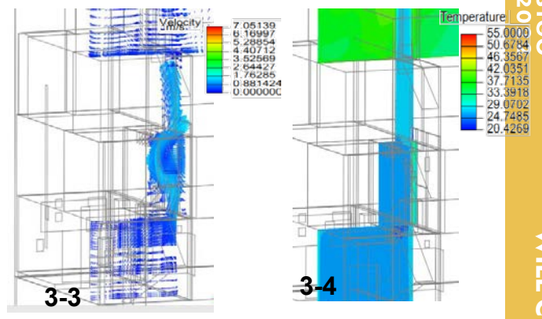
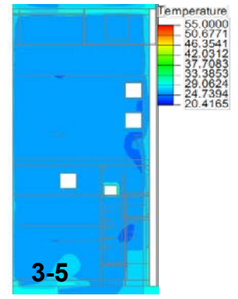


Figure 6 3rd situation



Conclusion : The actually working section is 6.1m high. There is turbulence at point A, the Velocity of air at point B, C, D & E become to 0 due to the wall obstruction. The start point of inlet can be considered under point F.



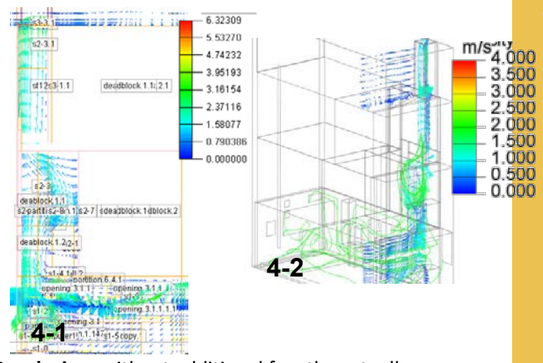


4th situation: the chimney is set closed to the front wall. (Fig. 7). In the 4th situation, when there is no chimney on the roof but an opening that area is 0.8 ㎡ and VT =0m/s. VB=0.04m/s.

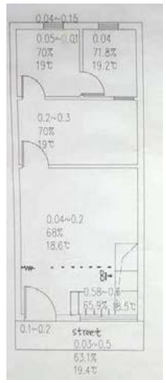
In the 4th situation, when there is no chimney on the roof but an opening that area is 0.8 ㎡ and VT =0m/s. VB=0.04m/s

The stimulation result is the best, only form there is a turbulence flow at point A.

Figure 7 4th situation



Conclusion: without additional fan, the actually section is 7.5m. If adding fans, the height upward to 9.1m and VT=4m/s.



1st floor plan

2nd floor

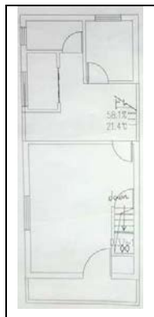
equipment of HD

1st floor plan

2nd floor

equipment of HD

The test is taken in Dem 20. While the temp of outside is 22.9℃，it's hot in the winter of year 2019 in guangzhou city.



3rd floor

4th floor

The data record proves the effective of upward flow. Though the value is small than stimulation, the bad smell of 1st floor has been extracted out.

The conclusion:

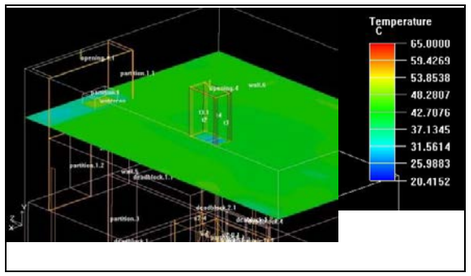
1. The VT will drop down due to size of chimney,

Table 2 The associate fans

1st fan 300cm*300cm	**Max 3m/s**	**2nd fan 300*300cm**	**Max 2m/s**
3rd centrifugal fan	**Max 9m/s**	**3rd fan 110cm*110cm**	**Max 2m/s**

because Radiant heat of the wall drops down due to more air volume.

Fig. 7 twice size chimney



2.Under the resistance of slope section in stair, the height of chimney can only be calculated as starting point while without slope section. A chimney needs at least three sides enclosing continually.

3.When the stair sections converge, the air will form a turbulence flow.

4.After a continual upward flow was formed in the stair, the gap and the stair will work together. Both of two chimneys suck the air from window & door on 1F. A small part of the air blowing across 1F then is ejected out from the back side windows. The VB of air is 2m/s

5.A turbulence flow is formed at point O on 1st floor either in case of natural or in additional fans and V≈0.01～0.5m/s.

3. RESULTS ANALYSIS.

As can be seen from above the best airflow organization is in 4th situation of all, the chimney should be set near the wall which facing the street. A smooth flow with minimize energy can be formed.

The result shows that in this stair chimney, the difference between To & TS is not a determinant factor.

In the backside gap, air will form a upward flow base on the situation while stair chimney is working. The combination pulling pressure of them resists the sucking pressure, which comes from the street.

There are three conclusions can be drawn:

1st, the house is 3.8m width of front elevation and is 9m tall. The distance of the street is 3m width opening to the sky. The total size is 3 x9(27 m^2). When the velocity of street increase 0.1m/s, the total passing by air flow volume increase 2 m^3/s. This means the sucking pressure come from street is huge. The velocity of roof is bigger than that on the ground, so that the air flow in stair is a negative one. This is proved by the stimulation. It shows that there will be upward & downward air flow existing in the stair simultaneously. The upward velocity in the chimney is lower than 7m/s.

2ed, the result shows that the upward flow is formed by two kinds of flow: one is due to buoyancy, another is a lateral flow. The reason is due to air as a flow and it will follow in the stair to climb upward, then to combine with the buoyancy flow together.

3rd, whether the chimney effect occur or not is decided by obstruct in the stair. Each time the stair section's air flow's direction turns 180°, it means that place need a fan to push. the air forward. The fan's static pressure can neither bigger than the VT , nor small than the fan beside it. While the speed is too slow, it can't reach the diverge point and then form a turbulent flow instead.

EPILOGUE

The stair chimney effectively improves the natural flow on 1st floor and then the humid problem is alleviated effectively.

However, there are associated fans have to be set for the air flow. Using fans to combine with natural circulation can force the chimney effect to occur.

While the speed is too fast the air will form a flow jam.

Fig 8 back gap chimney

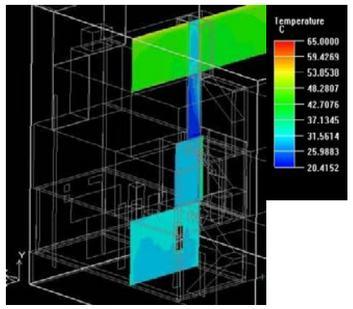


Fig 9 . the photo of stair chimney on the roof

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November 22 - 25, 2022

CHALLENGES FOR DEVELOPING COUNTRIES

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18TH PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Inhabiting industrial heritage as a practice of preservation
Cuareim Housing Complex in Montevideo, Uruguay

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ABSTRACT: Considering the housing deficit and the concentration of idle buildings in Latin America's historical centres, governments at federal, state and city levels propose their rehabilitation through intervention projects to adapt them to Social Interest Housing (SIH) use. In this context, this paper aims at analysing whether the Housing Intervention of the Cuareim Housing Complex preserved the historical and physical remnants of the Cerveceria del Uruguai ("Uruguay's Brewery", a former brewery plant), in the port district of La Aguada (Montevideo, Uruguay). The research method consists of a comparative study between the architecture of the old Brewery and the Housing Intervention through documentary sources (historical data, plans, sections, elevations and photographs), as well as a critical analysis based on Restoration Theories and International Heritage Charters. The results indicate that the Housing Intervention only partially fits the historical-critical restoration theory of Cesare Brandi (1906-1988), but manages to preserve the remnants of the industrial site (the brewery's volumetric scheme and facades). As a contribution to the field of heritage preservation, this paper seeks to highlight housing as a possibility for Latin America's industrial heritage preservation. This kind of intervention should extensively study the pre-existing building, for which this work's methodology is suggested.
KEYWORDS: Housing, Industrial Heritage, Historical Centres, Restoration Theories and International Heritage Charters.

1. INHABITING THE INDUSTRIAL HERITAGE IN LATIN AMERICA HISTORICAL CENTRES

To inhabit means to live a number of spaces: one as residence, another one as workplace, experiencing the neighborhood, and the city. Therefore, one can argue that there is an existential relation between humankind and buildings [1]. Not all buildings are houses, but they all have a shelter function, and architecture must insert people in a territory, providing them social identity and a sense of belonging to a community [2]. Housing is the "expression of the inhabitant's personality and unique living standards" [2] and "an institution created for a complex group of purposes. As the construction of a house is a cultural phenomenon, its form and organization are highly influenced by the cultural environment to which they belong" [3].

Housing is also a Human Right, enshrined in the "Universal Declaration of Human Rights" and in the "International Covenant on Economic, Social and Cultural Rights" [4]. It supports the maintenance of other Human Rights, since "access to safe and healthy housing is essential for people's physical, psychological, social and economic well-being" [4].

In Latin America's historical centres, the existence of many inadequate houses is associated with "poverty, homelessness, poor health, social exclusion, family instability and insecurity, violence, environmental degradation, and increased vulnerability to disasters" [5]. For this social issue one could find solutions within the environment of those sites themselves, and thus tend to adequate housing and a sustainable urban development.

"Historical centres mainly represent the initial outline of cities, they are urban and architectural structures that express the political, economic, social, cultural, and technological manifestations of social formations from different historical periods" [6]. These sites present a diverse set of historical, urban and cultural contexts. Each location has a certain degree of preservation, a community identity and an architectural/urban set of heritage buildings. However, it is possible to identify some issues which are common to them all, and that are verifiable to this day. For example, Latin American historical buildings frequently do not fulfil their social purpose, being often underused.

Between the end of the 19th century and the beginning of the 20th century, Latin America's historical centres went through a migratory process, as their original residents began to move to the suburbs. Concurrently, low-income rural families moved to historical centres, and began to pay high rents to live in the recently turned-idle buildings, which would then become tenements [7]. These sites suffered with the mischaracterisation of buildings and urban layout, causing the loss of heritage and community identity values [7].

Until the late 1970's, laws in Latin American countries were limited to preserving isolated monuments and buildings, without a broader notion of the historical centre as a set of heritage buildings [7]. From the 1990's onwards, the recovery of built heritage for housing use started to gain more prominence. In the 21st century, "the protection and recovery of historical centres is understood as an integral and transdisciplinary action, which encompasses a set of social, economic, cultural and territorial policies, as well as various urban purposes, including housing" [8].

The rehabilitation of idle buildings for Social Interest Housing (SIH) use can bring social and urban benefits (containment of city's horizontal growth and peripheralisation processes, reduction of periphery-centre-periphery pendulum movement and maintenance of the Right to Housing to low-income population) [9]. Having heritage as housing is also an effective instrument for the safeguard of historical centres and their built heritage [10-11].

The recovery of these sites must occur through public policies that consider the physical, social and cultural aspects of each site, also including the housing issue, so the low-income families will not be expelled by real estate speculation and gentrification processes. It is possible to rehabilitate these sites by implementing Social Housing in the built heritage, but it is necessary to preserve their aesthetic and historical values, based on Restoration Theories and Heritage Charters. In the following paragraphs, this paper will address the specificities of industrial heritage.

The preservation of industrial heritage buildings started later if compared to the safeguarding of other architectural typologies. The academic debate around it became more prominent in England and France from the 1960's and 1970's onwards [12]. In 2003, the Nizhny Tagil Charter was published, the first Heritage Charter dedicated exclusively to this type of built heritage. It defines industrial heritage as "the remnants of industrial culture which are of historical, technological, social, architectural or scientific value. These remnants consist of buildings and machinery, workshops, mills and factories, mines and sites for processing and refining, warehouses and stores, places where energy is generated, transmitted and used, transport and all its infrastructure, as well as places used for social activities related to industry such as housing, religious worship or education" [13].

The study of this type of built heritage needs to be extensive, by considering its physical remnants and the cultural values provided by the original use, spatiality and machinery, which must be preserved if it represents great heritage value. Adaptations for new uses are possible, but these must follow restoration practices [13]. The Dublin Principles (2011) states that the study and inventory processes must consider the natural and cultural environment, economic history and productive category [14]. Then, the appropriate strategy for the safeguard of industrial heritage sites should be chosen among conservation, rehabilitation and restoration repertoires.

If the building needs a restoration, one of the suggested theories is Cesare Brandi's (1906-1988) historical-critical restoration theory, considered the most contemporary one for heritage interventions [12]. Based on the principles of distinguishability, reversibility, and minimal intervention, this theory establishes a dialectic between the historical and aesthetic instances of the work of art, respecting its documentary values and historical phases [15]. In this theory, the aesthetic instance must prevail over the historical one. However, there are some caveats for industrial heritage. Due to the documentary values of industrial site facilities (machinery, infrastructure, etc.), the historical instance must prevail over the aesthetic one [12].

It is noteworthy that the study, inventory, preservation and intervention on industrial heritage buildings is very complex. The most common uses are those for large groups of users, such as cultural, commercial and educational uses (museums, cultural centres, shopping malls, university campus, etc.) [16]. However, internationally, housing use has precedents starting in the 1980's, with an increase in the 1990's and a boom from the 2000's onwards. This use presents several advantages, since industrial facilities are "solidly constructed buildings that are easy to maintain, easily adaptable to current standards and lend themselves to multiple public and private uses" [16].

Those buildings generally also have "large open areas with generous natural lighting through large spans, its spatial configuration is quite simple and the construction system is prepared to receive large loads" [16]. In Latin America, there are six projects of this type in Buenos Aires (Argentina), all of them built between 1992 and 2005 [16]:

1) "Silos de Dorrego" (1992): a former mill built around 1920, converted into a single-purpose apartment building.

2) "Puerto Madero - Dock 8" (1993): a former warehouse built around 1889, converted into a mixed-purpose apartment building.

3) "Puerto Madero - Dock 14" (1994): a former warehouse built around 1889, converted into a mixed-purpose apartment building.

4) "Alcorta Palace" (1994): a former vehicle plant, no estimate construction date, converted into a single-purpose apartment building.

5) "Puerto Madero - Docks 5 and 6" (1996): a former warehouse built around 1889, converted into a mixed-purpose apartment building.

6) "El Porteño" (2005): a former mill built around 1902, converted into a hotel.

All the projects mentioned had, as target user, a social stratum with higher purchasing power. Social Interest Housing (SIH) still does not have the necessary relevance. However, there is a Latin American project in this category, the Cuareim Housing Complex, this paper's case study. It is located in Montevideo (Uruguay), in the port region of La Aguada. It was originally the Cerveceria del Uruguai ("Uruguay's Brewery", a brewery plant), which was vacant and degraded in the 1980's. Considering this context, this paper will analyse if the Housing Intervention preserved the historical and physical remnants of the former brewery plant.

2. RESEARCH PROCEDURES

To analyse if the Cuareim Housing Complex Intervention preserved the remnants of the former Brewery, this paper will realise a comparative study between the original building and its intervention, through documentary sources (historical data, plans, sections, elevations and photographs), and a critical analysis, based on Restoration Theories and International Heritage Charters.

This study consists of two phases. In the first one, the historical and political context that conditioned the Housing Complex's project competition is studied through a brief bibliographic review. In the second one, a critical analysis of the heritage aspects of the Housing Intervention is developed. There was use of the theories by Camillo Boito (1836-1914) [17] and by Cesare Brandi (1906-1988) [15], as well the Venice Charter (1964) [18], the Restoration Charter (1972) [19], the Amsterdam Declaration (1975) [20], the Nizhny Tagil Charter (2003) [13], and the Dublin Principles (2011) [14].

In this way, we seek to comprehend the degree of heritage preservation that the housing use provided to the physical and historical remnants of this historical industrial site.

3. CASE STUDY: THE CUAREIM HOUSING COMPLEX

Located in Montevideo (Uruguay), the Cuareim Housing Complex has as historical permanence the Cerveceria del Uruguay ("Uruguay's Brewery") and its surrounding, the port region of La Aguada (old industrial district). Between the end of the 19th century and the beginning of the 20th century, various urban improvements were implemented in that region, consolidating it as part of the "modern city", which had developed bordering the historical centre [21]. From the 1920's onwards, both regions started to undergo a process of urban decay, similar to other historical centres in Latin America [7].

La Aguada is located in the city's west coast and sheltered port services. Its original population later moved to the city's east coast. Between the 1970's and 1980's, the local urban crisis reached its peak, "in lieu of a neoliberal economic context and by a growing deterioration of its urban environment" [21]. As a result, there occurred a "construction boom, fuelled by unbridled real estate speculation and favoured by the fact that several properties ceased to have the character of Historical Monuments, resulting in drastic disappearances of architectural and urban heritage" [21].

In 1988, the BHU, Banco Hipotecário del Uruguay ("Uruguay's Mortgage Bank"), held a project competition for a Social Housing proposal that would replace the old Brewery, founded in 1896 on a block bounded by the "Cuareim", "Lima", "Asunción" and "Acuña de Figueroa" streets. In the 1980's, the industrial site had a heterogeneous spatial arrangement, with towers of four to eight floors, contiguous to the building alignment, in addition to some constructions in the centre of the block. The competition intended for a new building and the urban legislation at the time would allow the construction of only four floors. These factors led the winning team to propose a way to reuse the former Brewery [22-24].

The winning team (Nelson Inda, Horacio Rodríguez Pardiño, Juan Carlos Apolo, Martín Boga, Álvaro Cayón and Gustavo Vera Ocampo), was composed by two generations, one of experienced architects and the other of architecture students. Indeed, this generational clash allowed for multiple critical perspectives on the same object of study. While the architects of the "brick generation" followed an austere and regionalist architectural language, also used in the BHU projects of the 1970's, the architecture students found themselves in the rise of postmodern criticism and the debate about industrial heritage preservation [23].

There was a consensus that a new building would generate a small number of housings units. Despite the idea of requalifying the former Brewery into a Social Housing Complex being a technical-constructive and economic challenge, the winning team ended up convincing the BHU. Taking into account the spatial diversity of the industrial plant, the housing units demanded detailed design solutions, so that each of the towers was comprised of one or more housing types. The Cuareim Housing Complex was inaugurated in 1996 with a 15,000 square meters (m^2) of built-up area, 131 affordable housing units, community facilities, 05 commercial spaces, concierge, library, bar and 90 parking spaces, with the final price per housing unit being 30% lower than the BHU's new buildings prices practiced at that time [22-24]. (Fig. 1-5).

Figure 1: The old Brewery during its rehabilitation.

Figure 2: The Cuareim Housing Complex nowadays.

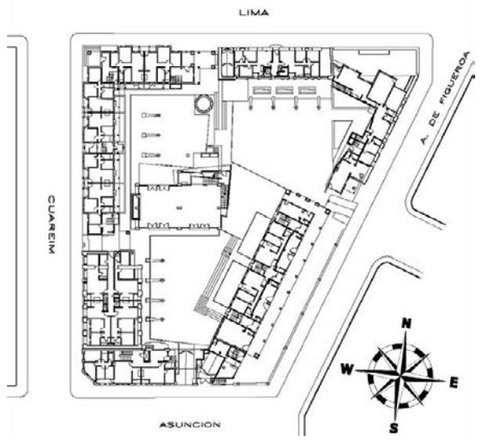

Figure 3: Ground floor Plan of the Housing Complex.

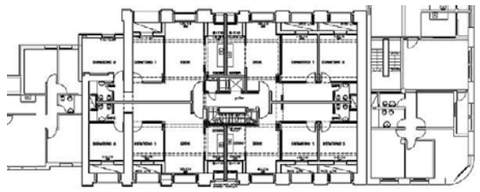

Figure 4: Floor Plan of the Housing Complex (partial), corner bweteen the "Cuareim" and "Asunción" streets.

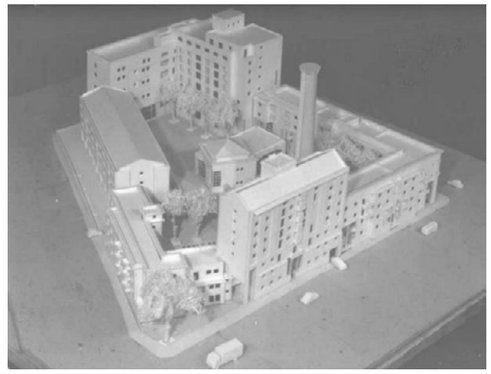

Figure 5: A model of the Cuareim Housing Complex.

By doing a photographic comparison between the former Brewery and the Housing Intervention, it was verified that the corner of the "Cuareim" and "Asunción" streets presents the most preserved volumetric scheme and facades, in Art Deco style. The rest of the intervention, contiguous to the built alignment, resulted in four-story housing towers, in modern style. The same compositional scheme of the original industrial facades (flat facades, vertical spans, symmetrical composition) was used in order to provide a harmonious composition. (Fig. 6). In the centre of the block, the Housing Complex's library (Fig. 5) was established, also in a modern style, but having its volume and facades differing more, if compared to the rest of the Housing Intervention.

Figure 6: Facades in Art Deco and Modern styles.

In a critique of the Housing Intervention, Mario Arana (1933-current), former mayor of Montevideo (1994-2005), claims that the project's success occurred because of the "sensitive and balanced use of some disused manufacturing facilities, resurrecting their buried plasticity, in conjunction with new insertions that do not seek expressive submission". In this passage, the former mayor points to a very effective dialogue between the historical industrial site and its new housing use, that

also considered economic viability and utilitarian housing needs [22].

One of this paper's authors conducted a technical visit to the Housing Complex, which was only possible in January 2022 due to the COVID-19 pandemic. By approaching some of its residents, it was noted that currently middle class families inhabit the Housing Complex. This may be related to the financing model adopted by BHU. Despite being a state bank, it has probably used interest rates that made access to affordable housing more difficult to low-income families.

The architecture team was successful in implementing Social Interest Housing (SIH) into an industrial site, in terms of design and economic feasibility. However, it is necessary to elucidate some aspects about its heritage preservation.

Restoration is an instrument that needs to be used only in extreme situations ("in extremis"), as stated by Camillo Boito (1836-1914) [17]. Restoration practices went through a series of theoretical formulations between the 19th and 20th centuries, which culminated in the historical-critical restoration theory of Cesare Brandi (1906-1988) [12, 15]. The latter directly influenced the formulation of the Venice Charter (1964) [18] and the Restoration Charter (1972) [19].

For both Heritage Charters, restoration is the "methodological moment of recognition of the work of art, in its physical consistency and in its dual aesthetic and historical polarity, with a view to its transmission to the future" [15]. In addition, it is necessary to have "respect for the original material and authentic documents" and its safeguarding must preserve "a scheme in its scale. As long as it persists, the traditional scheme will be preserved, and any new construction, any destruction and any modification that could alter the relations of volumes and colours will be prohibited" [18]. The Housing Intervention of this case study partially fits the historical-critical restoration principles.

At the time of the contest, in the late 1980's, the old Brewery was not formally recognized as Montevideo's cultural heritage, since it was abandoned and in a worrying state of degradation. Since there was no social or state recognition of the industrial site as a work of art, its historical and physical remnants were only partially preserved: facades, built morphology, block design (volumetric scheme), and compositional relation with the port landscape of La Aguada. This Housing Intervention is not a typical historical-critical restoration, also within the Nizhny Tagil Charter (2003) [13] and the Dublin Principles (2011) [14]. In spite of that, this intervention can be analysed as a case of architectural rehabilitation.

According to the Amsterdam Declaration (1975), "the conservation of existing buildings contributes to the economy of resources and the fight against waste, one of the great concerns of contemporary society" [20]. A historical building can be rehabilitated for a new use, but a rehabilitation does not necessarily need to occur through a historical-critical restoration. Therefore, it is of great interest that the old Brewery was rehabilitated — not restored. Even if the maintenance of the historical industrial site was guided by economic viability and utilitarian housing needs, it is clear that the historical and physical remnants of the former "Uruguay's Brewery" were preserved and introduced to a contemporary use.

However, some principles of the historical-critical restoration are verified in the Housing Intervention. The architecture team respected the principle of distinguishability, by establishing style differences between the historical industrial site and the housing use, although these are subtle at first analysis. This fact may be due to its monochromatic facades, since all the Housing Complex is painted white. There was also care as to not creating "analogue style or additions", one of the most important restoration principles, provided by the Restoration Charter (1972) [19].

CONCLUSIONS

The Cuareim Housing Complex is a case of architectural rehabilitation for housing use. The architecture team was successful in converting the industrial site to housing use, by considering design and utilitarian housing needs, as well as economic feasibility. The historical and physical remnants of the old Brewery, its volumetric scheme, and the facades were preserved and restored, being also introduced into contemporary use.

This paper considers this project an interesting exemplary of architectural rehabilitation, but it cannot be considered a "typical restoration". It only partially fits into Cesare Brandi's historical-critical restoration principles. Despite industrial heritage buildings frequently offering adequate structural strength for the insertion of housing use, the intervention considered herein represents a high degree of intervention towards their built structure and heritage values. Therefore, an extensive historical and theoretical contextualization about the Cuareim Housing Complex is necessary to understand its heritage values. This case study is not an "ideal exemplary" of a contemporary restoration, but its pioneering denotes its merit.

In conclusion, this paper aimed to be a contribution to the field of heritage preservation, by highlighting the housing use as a possibility for the preservation of Latin America's industrial heritage. The intervention on this type of built heritage should extensively study the pre-existing building, its historical and political context, as well as Restoration Theories and International Heritage Charters. For that, it is suggested to use this paper's methodology.

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Modifying microclimate by introducing green floor in multi storey buildings in Lahore Pakistan

A review in relation to orientation, microclimate modifiers and built environment

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ABSTRACT: Lahore's economic pull has resulted in a rapid increase in population and city expansion. This research investigates Lahore's commercial multi-story buildings, with an emphasis on the addition of green floors for communal recreational uses. The research demonstrates that permeable facades can utilise cross and stack ventilation for an open planned communal floor. While cross ventilation is critical for removing heat on warm days, stack ventilation serves as an essential supplemental cooling strategy on extremely warm days. The research methodology adopted for this study includes a comprehensive literature review, fieldwork and digital performative analysis. The research investigates the findings from literature and fieldwork for proposing a green floor in an existing building. According to the research, additional mitigation strategies such as evaporative cooling and plantation can help to improve the PMV and PPD. However, the development of a green floor is site specific, but the general findings can guide designers in collaborating with local restrictions.
KEYWORDS: Green floor, Cross ventilation, Stack ventilation, PMV, PPD

1. EMERGING NEW NEEDS:

The city of Lahore dates back to 7th century. The first population censes in 1951 shows a population of 1,130,000 people in Lahore. Today it has approximately 11.1 million people inhabiting it (1)(2). Lahore's population has grown a 4.07% annual rate over the last decade and is expected to reach 14 million by 2025 (2). Currently, Lahore is confronted by the challenges posed by rapidly evolving urban cultures (11). These emerging design trends must be contextualised within contemporary global debates such as climate change, overpopulation, resource and land scarcity, societal imbalance, and pandemics such as COVID-19.

In terms of demographic dynamism, as more and more people make Lahore their home, a parallel experience of inhospitality has been experienced in the city, a paradox currently associated with many major cities in developing countries. The increase in population growth and new constructions in urban areas, very few appropriate areas have been left for recreation and social activities (12)(13).

To arrive at an ideal solution for the city increasingly demands, one needs to understand its demographics, social life and most importantly climate. During pandemic, with the exemption of withholding tax on building material (4), the city has shown an increasingly number of investments in commercial multi story buildings. These buildings can be revitalised, reproduced and designed to respond to public needs of recreational spaces in harsh climate.

Numerous metropolitan areas have successfully implemented the concept of ecologically breathable buildings. The "Royal-park," a vertical garden structure in Singapore, is a living example of a building designed as a garden. Each fourth level of the building is planted with tropical plants (13). While Royal-park has become an urban landmark, the building's green pockets also help to reduce energy consumption (13)

Breathable green buildings have been researched around the world for their environmental benefits. However, fewer studies can be found on impact of an intermediate green floor to combat harsh outdoor climate. This paper investigates an introduction of green floor in a multi storey building with no or perforated walls and plantation to provide a free running space for a warm climate of Lahore. These green floors will become catalysts for sustainable way of social life.

Building form and envelope define the microclimate pattern. Moreover, the microclimate is associated with solar gains, landscapes, plant types, the presence of bodies of water, and human metabolic rates. These factors have an effect on the local microclimate; while they cannot change the prevailing climate within the urban boundary layer, they can significantly modify it locally (Weather and the building industry, 1950).

2. CONTEXT:

The relationship between urban design, architecture, and the city of Lahore has changed significantly over time (Kugelman, 2021), but especially so in the aftermath of the pandemic. Additionally, the city, like the rest of the world, has been experiencing extreme heat, with temperatures reaching 40 degrees Celsius (Munawar, 2021). In this case, the introduction of green floors in multi storey buildings can compensate for the lack of outdoor communal spaces caused by Lahore's hyper transformation.

Lahore is categorised as Bsh (Koppen climate classification) with warm summers from May to mid-September and a short winter from November to February. See Table 1

Table 1

Geography	Climate	Demography
Location:31° North and 74 ° East	Summer: 40° – 25° C	Population : 11,126,285
Altitude: 217 m	Autumn:23-18 ° C	Density:6300/km^2
Area:1772 km^2	Winters: 20 °- 5°C	
	Spring:28-19 ° C	
	Average temp. 30°-32° C	

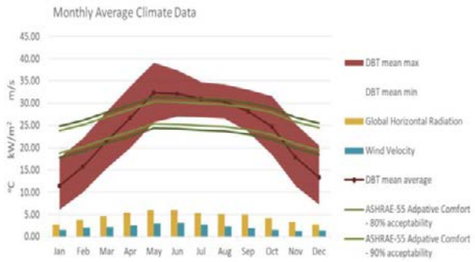


Figure 1: Monthly average Climate data obtained from meteonorm for Lahore

Multi-storey buildings have designated floors for (MEP) services. By designating a green floor in similar way, we can facilitate collective evolution by providing the environment necessary for people to function in today's world of pandemic.

These green floors within a building can function as an open shaded space for people to enjoy outdoor activities even in adverse weather and as Jan Gehl emphasis on life between building and its social interaction , people get to celebrate a variety of sociocultural and natural pleasures such as sun, air, and flora. Due to the fact that the green floor is conceptualised as a free running floor, heat gains can be mitigated through the addition of heat reflective materials, plantation, and evaporation, similar to the ancient Egyptian technique of placing water pots near windows.

3. DEVELOPING CLIMATE RESPONSIVE STRATEGIES

The two common strategies in Lahore households for natural ventilation is cross ventilation and stack ventilation. Usually a combination of both is used. Natural ventilation strategies can draw enough outside air to attain appropriate level of indoor air quality and provide cooling. Cross ventilation occurs where there are openings on both sides of the room (5). Cross ventilation is an effective cooling technique, but when no air is available, the area's effective height can be increased by using the stairwell as a stack chimney and the space can be cooled via stack ventilation (10) and Wind driven ventilation by density differences (5). The extent of pressure differences depends on the wind profile on building envelope.

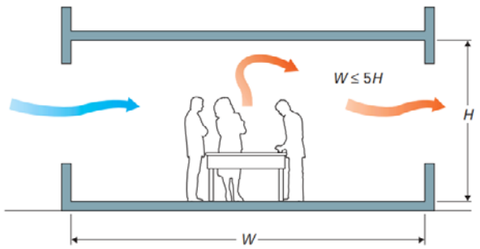


Figure 2: Cross ventilation requirement - CIBSE

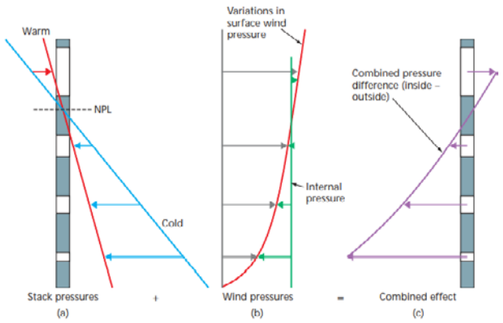


Figure 3: Combined effect of stack pressure and wind pressure - CIBSE

The pressure difference depends on following factors,

1- Wind direction
2- Wind speed (wind driven ventilation)
3- Temperature difference (buoyancy driven ventilation)
4- Combination of wind and buoyancy driven ventilation.

The wind pressure difference Δp due to wind is expressed by Eq. (1) regardless of the type of building [5]:

$$\Delta p = 0.5 \cdot \rho \cdot U\ 2 \cdot \Delta C\rho \quad (1)$$

Where;

U = Wind speed measured at the height of the building

ρ = Density of the air

ΔCp = Coefficient of pressure difference which depends on the factors of building geometry and wind direction.

Equation 1 shows that in a tall building, as the height of the building increases, wind pressure increases with the increased wind velocity [6].

The pressure due to buoyancy effects can be expressed as:

$$\Delta p = \rho \cdot g \cdot h \cdot \Delta T \quad (2)$$

Where;

ΔT= The temperature difference over the height h

g = The gravitation constant.

Lahore suffers a time period of hot air commonly characterised as “luh”, that results in dehydration and casualties during harsh hot days. The rise in heat index results in higher mortality rate, discomfort and heat strokes in humans and animals (7) thus limiting the outdoor activities in Lahore.

Two indigenous methods have been put in place to combat it, use of water and plants. The concept of a water filled pot or hanging wet drapes is a common passive evaporative cooling method in hot arid climates (9). By laws of thermo-dynamics an exchange of heat transfer cools down the temperature of the incoming air. Its advanced counterpart a water cooler is a main source of cooling in middle to lower income houses in city.

Since the cooling capacity of natural ventilation is limited, a key design challenge is to limit heat gains through good solar control and careful management of the internal gains(5). In hot arid climates, evaporation can cool the air temperatures (10).The evaporation in an enclosed open space such as a courtyard depends on the surface area of water, the relative humidity of the air and the water temperature (10) When enclosed through walls or brought in the interior premises, water has the ability to cool the enclosure surfaces, most specifically ceiling, by radiation (10). In order to minimise the used= of any active system and run the floor passively, the evap cool system can be combined with the building envelope. The studies conducted by Schiano-Phan from AA UK (9) show that ingress of fresh air through a wet cavity wall can generate indoor comfort levels. The team (9) developed a porous ceramic components for the non-domestic buildings and showed that the cooling capacity of such systems depend on the surface areas of the ceramic body and dry to wet bulb temperature depressions.

Lastly, plantation has been opted as third strategy for passive cooling of an intermediate green floor. A difference of 5-10 degrees in the mean radiant temperatures can be expected with vegetation to no vegetation. (8)

4. FIELDWORK :

The fieldwork included visit of multi storey commercial building to observe the usage of space by the occupants, brief interviews and collection of temperatures and wind speed at each floor. A standard commercial building of 30’x45’ was used for the development of initial proposal for a vertically exposed floor. For the microclimate study a thermal walk was conducted on 25th September, 2021 from 11:00 am to 1:00 pm and 5:00 pm to 6pm in order to select an appropriate floor level. Spot measurements were recorded in four buildings with facades facing the North, South, East and West orientation for a comparative study. The Lahore weather, was recorded from the nearest weather station at the time of spot measurement (11:00 am, 25th September, 2021) as following,

Dry Bulb temperature 33 ˚C, Humidity, 56% Wind 6 km/h with scattered clouds.

Sky condition scattered clouds/ smog in morning.

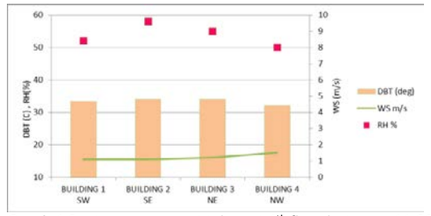
The locations of buildings are marked in the figure-4

Figure :4 Location of Building 1,2,3,4 in DHA phase 6 Lahore

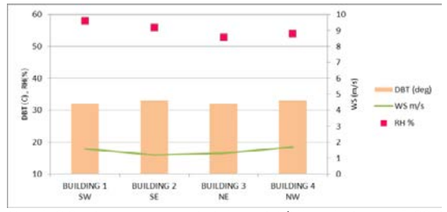
It was observed that the wind speed was higher on mostly top floor but the results also showed higher cooling demands due to higher conductive heat gains from roof. The lower levels experienced less solar gains as indicated by eq 1 & eq 2.

After comparing the wind speed, noise, solar radiations and cooling needs, the intermediate floor level was shortlisted for further development of an exposed green floor.

The measurements indicated a following trend,



Graph 1 Spot measurement taken at 4th floor between 11:00 Am to 11:45 Am on 25th Sept 2021.



Graph 2 Spot measurements taken at 4th floor between 5:00 Pm to 5:30 Pm on 25th Sept 2021.

The initial results from fieldwork forecast that placing the fully exposed side at North West will allow less solar exposure of the green floor. The opposite wall facing in south east will predominately show higher temperature during the day time but as the sun descend to West after noon, the temperatures will decrease. The wind direction is determined by the site conditions however the higher the altitudes, the higher the speed.

4. INTEGRATION IN COMMERCAIL BUILDINGS:

In terms of environmental performance of such a green floor, two key points have to be considered as well

1- Adequate indoor air quality
2- Ventilation with additional strategies can reduce overheating of the space in summer.

A crucial issue that might appear due to ventilation apertures, is a noise transmission from outdoors to interior spaces of a building that may result into a demeaning factor for locations adjacent to busy areas (5) . The placement of plants and a ceramic parapet wall (9) can allow controlling the sound levels. The Lahore climate cannot function only on passive means. The ceiling fans will be needed in order to allow a constant air flow through the room. The proposed floor is ideally placed at level 4 in building 4. The efficiency of green floor was tested for natural ventilation in Optivent for summer, winter and mid-season .

Construction Data:

Glazing:

Solar Transmittance Factor (0-1):	**0.6**
Shading Proportion (%):	**20**

Wall

Surface Absorptance (0-1):	**0.6**
U-Value (W/m²·K):	**0.3**
Ext. Surf. Transmittance (W/m²·K):	**4.0**

Roof

Surface Absorptance (0-1):	**0.6**
U-Value (W/m²·K):	**0.2**
Ext. Surf. Transmittance (W/m²·K)	**4.0**

The Optivent showed comfortable bands with natural ventilation for mid-season days. However, the summer and winter days showed discomfort as per ASHRAE standard. The floor was tested for stack

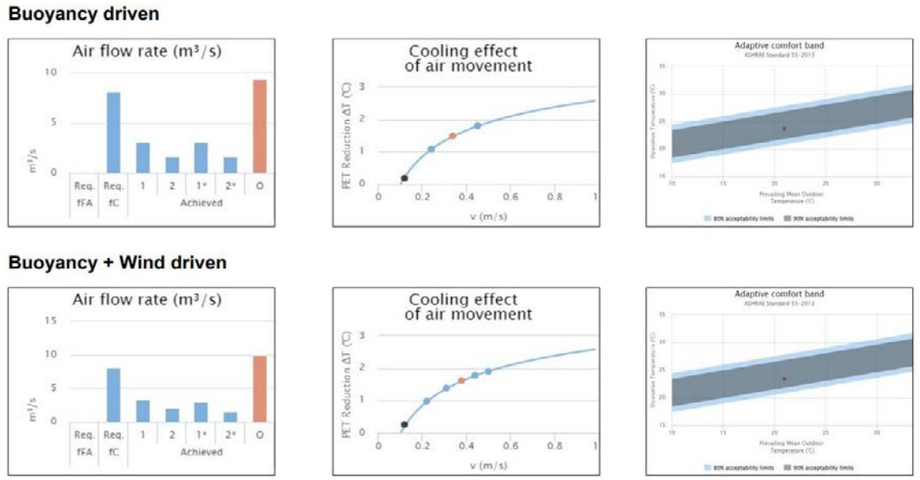


Figure 5 : Effect of stack ventilation through stair well for mid season -Results derived from Optivent for Fourth floor

ventilation using the stairwell as a source of up darft. The results showed that with a normal height of 10 feet per floor, comfort band can be achieved for mid season. see figure 5.

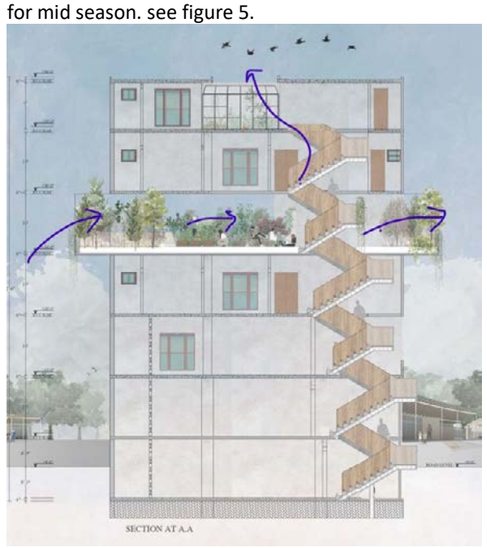


Figure : 6 Proposed green floor in existing building, Phase 6 DHA Lahore

The performance analysis was commenced using a dynamic simulation. The passive strategies used for grasshopper stimulations in order to study the comfort levels were:

1- Evaporative cooling
2- Thermal Mass and night vent
3- Occupant use of fans

As the fieldwork had a major limitation of time and weather, hence digital simulations were run to further extend this research for the whole year for detailed assessment of the material and green features of these floors which affect the microclimate. There are number of tools for investigating microclimates and comfort indices but for this study, following software were used.

- Rhino (Grasshopper and ladybug plugin).
- Optivent

The model looked at the performance of an intermediate floor in the selected orientation. This enabled to investigate the potential of selected strategies for the cooling requirements.

5. PERFORMATIVE ANALYSIS:

The simulations for green floor were run for typical hot day and a typical cold day. Following data was considered as inputs

Human Height = 1.8 m
Human Weight = 75 kg
Human Activity = Sitting, Walking leisurely
Clo = 0.5 summers, spring, fall
Clo = 0.9 winters
Albedo = 0.3-0.5
Plantation height = 0.9-1.5m
Plantation Head crown = 0.9 – 1.8m
Lighting loads = 12 W/m2
Equipment loads = 5 W/m2

The meteonorm weather file provided Dry bulb temperature, relative humidity and wind speed for Lahore through ladybug plugin. The wind speed was generated for floors. The average wind speed at fourth floor is 2.2 m/s annually

The effect of mitigation strategies was translated on psychometric chart,

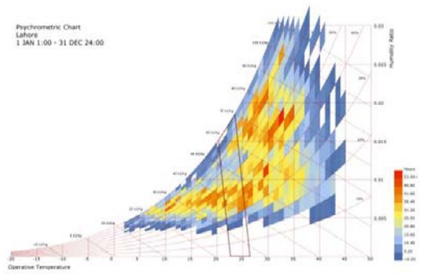


Figure:7 Psychometric chart without mitigation strategy developed on Grasshopper .

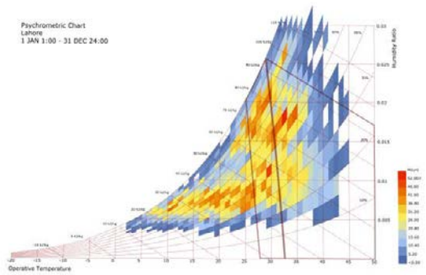


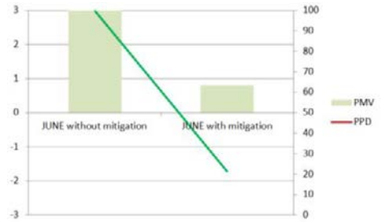
Figure 8 Psychometric chart with evaporative cooling developed on grasshopper

The two graphs show that with the addition of evap cool the comfort band increases for the weather indices of Lahore.

In order to measure the thermal comfort of the space, the data obtained from grasshopper and on site field work was used to determine the Predicted mean value (PMV) and Predicted Percentage dissatisfied (PPD) values for typical hot summer day , typical mid-season day and a typical cold day , following BSEN ISO 7730:2005 : Ergonomics of thermal environment. There is a 7 point thermal scale . The PMV and PPD calculated are shown in the graph below without the use of any mitigation strategy,

Graph 3 PMV and PPD without plants and water for summer solstice , winter solstice , spring equinox and fall equinox .

The data showed that on typical hot days, there is 100% dissatisfaction among the people. In order to improve the indoor temperature the effect of plants and water was taken into account for plotting PMV and PPD values. The graph 3 shows that the addition of these two factors can reduce the dissatisfaction to 20%.



Graph 4 PMV and PPD with plants and water for Summer solstice .

6. CONCLUSION AND OUTCOMES:

A passive semi exposed green floor can be integrated in commercial buildings to improve the quality of life. The ideal placement of this floor is site specific however the according to parametric studies and simulations, the top floors of a multi-storey building exhibit more wind flow but also showed higher temperatures than the lower floors. The primary finding of this research is that an intermediate floor can be converted into an open walls & top shaded green floor with careful placement of bioclimatic features and consideration for permeable and open façade orientation.

The mitigation strategies like plants and evaporative cooling can meet the PMV and PPD requirements in the building. The literature and previous analytical work performed by author on Envi-met showed significant improvements in PMV due to plants.

The north west and south east façades are left permeable to resist solar gain while allowing in the prevailing wind. Planting on the south eastern side can help to reduce the ambient air temperature by allowing for the passage of cool air.

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Surviving overheating
From land surface temperature variations to low-energy strategies

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ABSTRACT: In recent decades, the integration of synoptic visions to comprehend the urban climate critical changes due to the rapid growth of population and the influence of climate change has been one of the main challenges for modern societies. The built environment has been dramatically modified by greenhouse gas emissions, low aerodynamics, and the modification of atmospheric air. Simultaneously, anthropogenic heat loads along with land use and land cover distortions and its resulting green infrastructure reduction have elevated multidimensional human vulnerability due to global warming in the Urban Heat Island (UHI) context. This study highlights cooling energy demands in a critical scenario among 12 different locations based on thermal driver criteria, such as building density, traffic intensity, and green areas. For this purpose, synthetic climatological parameters and remote sensing techniques using LANDSAT 8 thermal infrared sensor bands were used in an automated mapping algorithm to calculate Land Surface Temperature (LST) variations. Results obtained via site analysis under a low-energy approach showed an increase of up to ≈50% of the energy demand in terms of cooling needs of buildings located in dense urban areas compared with those in coastal zones.
KEYWORDS: Climate change adaptation, Urban Overheating, Passive design, Energy demand, Less Developed Regions

1. INTRODUCTION

In recent times, the integration of synoptic visions to comprehend the urban climate complexities under the influence of climate change has been one of the main challenges for modern societies. While the earth´s population has doubled since 1960 and 70% is concentrated in 4,300 cities worldwide (UN Department of Economic and social affairs, 2017) (Population Reference Bureau, 2004), the greenhouse gas (GHG) emissions impact the aerodynamics and quality of atmospheric air daily. Simultaneously, anthropogenic heat loads along with land use/cover change and its resulting green infrastructure reduction have elevated imperviousness and human vulnerability due to global warming and the increasingly recurrent heat waves (Khan et al., 2020).

In the current city-scale trend framework, studying urban tissues to design passive buildings has compelled the experts´ examination -especially in temperate climates- of relevant drivers, such as population, landscape, and climate metrics (Ward et al., 2016) to evaluate economic, social, health and pollution effects, or evaluate the environmental factors on heat-related illnesses (Heidari et al., 2020) to energy fluxes and cooling demands, drawing the attention of risk derived from urban overheating within the Heat Waves (HW), and Urban Heat Island (UHI) context.

2. ANTECEDENTS AND MOTIVATIONS

Thus, to design adaptive measures and study the spatial distribution of different UHI types for multidimensional approaches to low-energy urban countermeasures, and passive design buildings, different data sources, models, tools, and techniques have been studied over the last years. As in the case of satellite remote sensing instruments used to evaluate the Surface Urban Heat Island (SUHI) variations, which represent the difference in Land Surface Temperature (LST) in urban relativity to adjacent non-urban surfaces (Zhou et al., 2019).

However, urban and rural thermal environment differences are usually diverse and more complex, especially in terms of specific morphology, land surface energy and radiation balances, building fractions, land cover, or human activity. These fundamental aspects are observed by experts to characterize the city from another perspective, using field meta-data to define a “Local Climate Zone (LCZ)”, an urban-rural classification system (Stewart & Oke, 2012), that allows the analysis of Spatio-temporal urban patterns and related variables, key factors while designing remediation strategies to address the influence on thermal comfort conditions, among others (Wu et al., 2022).

Hence, this study aims to evaluate cooling low-energy demands amongst different urban locations predefined by: a) Building density, b) Traffic intensity, and c) Green areas within urban LST variations and LCZ classification for a BSk city with a Steppe (semi-arid) climate according to Köppen-Geiger classification system (Chen & Chen, 2013).

3. METHOD

For this research, relevant climate features of Ensenada, Baja California, a compact lowrise port city in the northwestern region of Mexico are estimated via stochastic models (Genossenschaft Meteotest, 2020), an equivalent georeference location of the official weather station (EMA) BC02 (CONAGUA, 2021), located at -116.6, 31.8 and 104 m.a.s.l. was used, the relevant data is listed below:

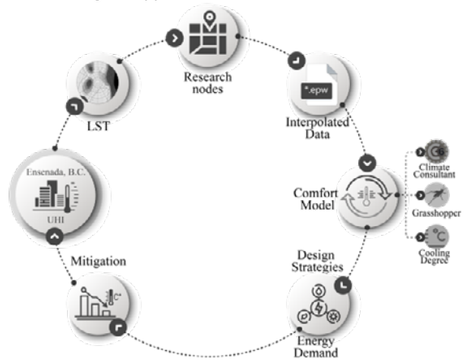
- Average annual temperature: 19.0 °C
- Hottest yearly temperature: 31.8 °C
- Coldest yearly temperature: 7.0 °C
- Annual cumulative horizontal solar radiation: 1948.666 kWh/m2
- Diffuse horizontal solar radiation: 32.7 %

As seen in Fig. 1, an algorithm for automatic mapping of LST variations was conducted using equation 1 (Avdan & Jovanovska, 2016) and the Landsat 8 thermal bands to place 12 research nodes defined by urban overheating criteria and calculate their energy demands based on the thermal zone defined by the California Energy Code Comfort Model (CECCM), Title 24 (California Energy Commission, 2019) via the graphics-based software Climate Consultant (Milne, 2020).

$$LST = BT / \{1 + [(\lambda BT / \rho)] \ln \varepsilon_\lambda\} \quad (1)$$

where BT: Brightness temperature (◦C);
λ: wavelength of emitted radiance (μm);
ε_λ: vegetation/ soil emissivity calculated;
ρ: 1.438 X 10^{-2} m·K.

Figure 1:
Methodological approach conducted.



3.1 Overheating and research node definitions

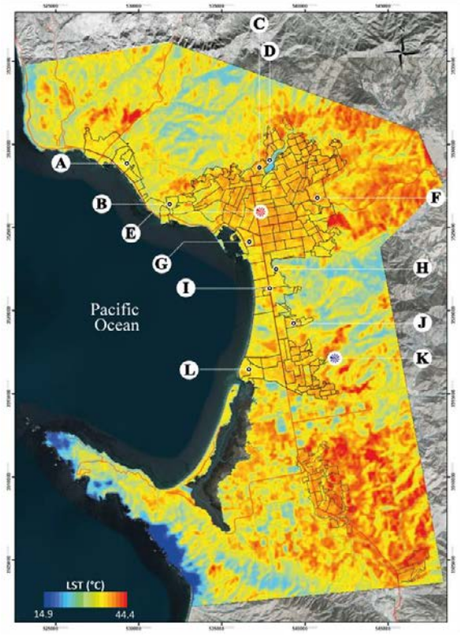
In the context of UHI, this research analyzes thermal implications to highlight the cooling energy demands of built typologies located in different climate zones and Basic Geostatistical Areas (AGEB) oriented to study population vulnerability. AGEB are defined as cartographic and statistical units that contain a complex sociodemographic database clearly outlined by urban blocks and infrastructure, in populations greater than or equal to 2,500 inhabitants (INEGI, 2010). The methodological approach is synthesized as follows:

- A critical scenario was designed with 12 research nodes based on LST and LCZ to outline urban overheating and AGEB to enclose population vulnerability.
- Interpolated climatological parameters of a typical meteorological year were also used to contrast 2 research critical nodes.
- The CECCM was used to define thermal limits for cooling needs.
- The influence of urban overheating on energy demands and passive design strategies were contrasted on research nodes.

4. RESULTS

The LANDSAT 8 TIRS bands were used in an automated mapping algorithm to calculate LST using atmospheric spectral radiance and the NDVI index. The critical research nodes in terms of heat vulnerability can be seen below in Fig. 2.

Figure 2:
Critical research nodes and urban LST (July 3rd 2019).



4.1 Site analysis under a Local Climate Zone

LCZ classification was obtained according to the characteristics of the LCZ classification system given by Stewart and Oke, (2012) in compliance with the World Urban Database and Access Portal Tool project framework (Ching et al., 2018).

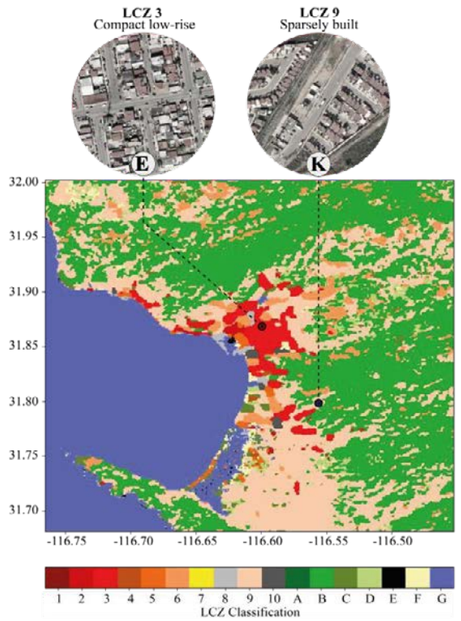
Fourteen classes of 17 possible classes were observed, Table 1 and Figure 3 show the classes found in the study area with a brief description of LCZ.

Table 1:
Local Climate Zones (LCZ) in the urban environment, based on Stewart & Oke (2012) classification.

LCZ	Class	Description
LCZ 2	Compact midrise	Dense mix of midrise buildings (3 stories). Few or no trees
LCZ 3	Compact low-rise	Dense mix of low-rise buildings (1 storie). Few or no trees.
LCZ 4	Open high-rise	Open arrangement of tall building
LCZ 5	Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover
LCZ 6	Open low-rise	Open arrangement of low-rise buildings. Abundance of pervious land cover.
LCZ 8	Large low-rise	Open arrangement of large low-rise buildings. Few or no trees.
LCZ 9	Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting.
LCZ 10	Heavy industry	Low-rise and midrise industrial structures.
LCZ B	Scattered trees	Lightly wooded landscape of Trees.
LCZ C	Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees.
LCZ D	Low plants	Featureless landscape of grass or herbaceous plants.
LCZ E	Bare rock or paved	Featureless landscape of rock or paved cover.
LCZ F	Bare soil or sand	Featureless landscape of soil.
LCZ G	Water	Small bodies such as rivers, reservoirs, and lagoons.

Fig. 3 shows different urban structures in the study area. Although, most of the city's morphology comprises the LCZ 3: compact low-rise buildings as observed in node E. The K node was contrasted due to its sparse morphology. It is important to mention that from these morphology patterns, the cooling requirements were identified and compared.

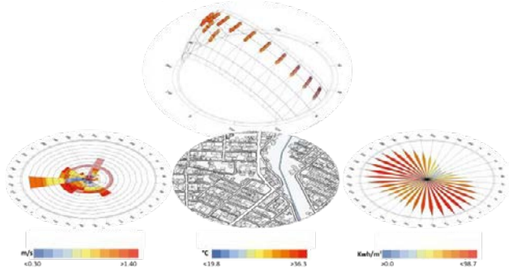
Figure 3:
AGEB[1] analysis based on the LCZ



Once the effect of LST variations was mapped on the urban tissue and the UHI effects visualized, the critical locations (nodes K & E) in the range of variation were clearly defined, from which it was possible to develop a site analysis of the critical case, the following analysis addressing predominant climatic conditions in urban nodes is listed as and shown in Fig. 4 through parametric environmental design (Shahcheraghi, 2017).

- Wind speed/direction distribution (m/s).
- Sun-path regarding temperature (°C).
- Solar radiation (kW/hm2/month).

Figure 4:
Solar and wind analysis for the critical node E.



Note: Based on Shahcheraghi, D. (2017).

[1] AGEB (Basic Geostatistical Area) is part of the National Geostatistical Framework from the National Institute of Statistics and Geography (INEGI) in Mexico.

The local climate features and the intensity of the urban heat island around the city correlate with the impact of the urban climate on thermal comfort and potential energy consumption of buildings from critical urban locations. Notably, the significance of evaluating relevant population factors in terms of the AGEBS can be overstated in Table 2.

Table 2:
Important spatial and demographic features from critical urban locations.

Study node	Lat.	Long.	Alt.	Coast distance (meters)	Pop. (Inhab.)
E	31.86	-116.6	16	1,504	2,522
K	31.78	-116.56	81	5,210	3,537

Note: Population is referred in compliance with AGEB database.

In contrast, Table 3 shows the passive design strategy analysis regarding the thermal comfort zone during the critical warm period, those with the greatest impact on the study nodes are shown, it is important to highlight that the characteristics of urban morphology and land cover play an important role in the behavior of the local climate.

Table 3:
Low-energy strategies in compliance with the California Energy Code thermal zone during the summer period.

Low-energy Design Strategy	Node E (%) and Hours	Node K (%) and Hours
LST		
Comfort	(4.7) 72 h	(7.3) 129 h
Sun shading of windows	(18.5) 285 h	16.0) 284 h
High thermal mass (HTM)	(2.4) 37 h	(4.4) 78 h
HTM night flushed	(4.1) 63 h	(5.8) 103 h
Direct Evaporative Cooling	(2.0) 30 h	(3.3) 58 h
Two-stage Evaporative Cooling	(4.0) 62 h	(4.7) 84 h
Natural Ventilation cooling	(17.6) 271 h	(17.4) 309 h
Fan-forced ventilation cooling	(19.7) 303 h	(18.1) 321 h

Note: Low-energy strategies oriented to mitigate overheating.

Table 4. shows Cooling Degree Days (CDD) and Cooling Degree Hours (CDH) as a range measurement designed to quantify the demand for energy needed to cool buildings in the overheating context for urban locations E & K during summer in the urban environment analyzed.

Table 4:
Cooling energy demand for critical urban locations.

Study node	Min. Avg (°C)	Mean (°C)	Max. Avg(°C)	CDD (°C)	CDH (°C)
E	22.8	26.9	31.0	92.9	2,481.6
K	21.2	25.0	29.2	45.4	1,544.7

Note: Cooling Degree Hours (CDH)

4. CONCLUSION

The present research studied a Land Surface Temperature case through an algorithm for automatic mapping using the Landsat 8 instruments regarding a Local Climate Zone framework along with the California thermal comfort model to explore low-energy strategies to make relevant analysis, and draw the following conclusions:

1. There is an increase in the surface temperature of the earth in urban areas further from the coast, however, the vulnerability of spatial geostatistical zones is influenced by socio-spatial and economic aspects.
2. The city of Ensenada has a significant diversity of local climate zones due to the dispersion of its built environment.
3. A significant number of passive design strategies for low-energy architecture and shown in Table 3 can be applied to avoid urban overheating in the predominant climatic area of the city
4. It is feasible to extend the analysis in a variety of comfort models and local climatic zones.

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PLEA SANTIAGO 2022
Will Cities Survive?

Climate Justice and Sea-Level Rise

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ABSTRACT: Community, climate change, urban and architectural solutions are the focus of this article. The literature review focuses on the history of segregation, climate hazard maps, and mitigations. This article explores different ways to integrate communities and hazard mitigation solutions in the context of an architecture curriculum. The analytical research framework is observing and analyzing student projects in ARC Design II in spring 2021 and an elective course on Climate Justice + Sea-level Rise. The climate section in these courses provides an opportunity to introduce the students to a new realm of discovery. Examples of tangible discourse include flooding and hurricane mitigation methods at the urban and building scale. The project outcomes indicate the ways students perceive community challenges in relation to architecture and hazard mitigation. Hazard mitigation cultivates the idea of the societal class. This work studies the intersection between race, land use, and vulnerability to hazard mitigation to shape a broader scholarly discourse.

KEYWORDS: Equitable Communities, Hazard Mitigation, Climate Justice, Sea-level rise.

1. INTRODUCTION

This article reviews the literature on the issue of race in urban design and its climate vulnerability consequences. Diane Davis, Charles Dyer Norton Professor of Regional Planning and Urbanism at Harvard University, wrote a commentary on "Architecture, Design, Action," addressing the issue of racism in architecture pedagogy based on a series of interviews among Harvard Design Faculty. Toshiko Mori, for instance, reviews Harvard Graduate School of Design's historical viewpoint on a colonial legacy. Rahul Mehrotra addresses the issue of scale and how buildings and pedagogies should reach beyond the community scale.[1]

Carnegie Mellon University and other institutions investigated race and inclusion through the lens of climate change, economy, technology, community, and ethics.[2] Schindler, 2015 discusses segregation through architectural and urban design decisions, such as preventing access to specific neighborhoods.[3] Students examined such examples through community-based projects that ask students to reflect on design values and climate issues in the context of studio projects. Lecture series and guest speakers on Climate Justice provide a valuable contribution to the education of undergraduate students. The discussions connect the dots between different disciplines.

Research by de Gaulmyn and Dupre provides a quantitative analysis of students' performances after being introduced to climate issues and passive strategies on density.[4] The unanswered question is how to implement these learning outcomes within the studio of an architecture curriculum. This article reflects on the attempts towards community and environment-based studio projects.

The NY Times published a series of maps presenting the racial residential patterns of different U.S. cities.[5] The segregation maps by Matthew Bloch, Amanda Cox, and Tom Giratikanon provide a unique resource on how racial groups are dispersed throughout cities. The maps illustrate the segregated living conditions found throughout cities. The maps are valuable tools that help researchers speculate the relationship between different land values to disparities in social status and an underserved community's vulnerability to climate change.

2. CLIMATE JUSTICE + SEA-LEVEL RISE

A cross-disciplinary course was developed to implement hazard mitigation in the curriculum further. The proposal connects the underlying issue of segregation to neighborhood planning and hazard mitigation strategies. This opportunity provides students with an elective course to work on projects through a historical viewpoint with futuristic design solutions.

In this course, students examine the history of African-American landowners and how segregation practices in residential neighborhoods are tied to climate change impacts. The hazard mitigation discussions provided insights and case studies on

flood prevention, sea-level rise, and design strategies for lateral forces. The course provided students with an increased awareness of the relationship between land ownership, geography, and the impact of climate change. Figure 1 illustrates lower prices for land values compared to the lower topography in Tallahassee, FL.

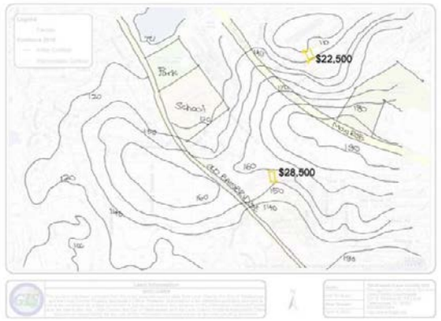

Figure 1:
Comparison of land value and topography, Tallahassee, FL. (Data source: TLH GIS and Property Appraiser)

The relationship between geographical and economic features included topography, land value, rivers, flood zones, etc. The connection is evident in the high concentration of Louisiana's black population and along most of Louisiana's rivers (as shown in Figure 2).

Figure 2:
Comparison of percentage of black population and river, Louisiana. (Data source: US Census and LA Lidar)

Students in this course get introduced to building design solutions, such as amphibious structures by Elizabeth English[6], growing islands by MIT Self-Assembly lab[7], beach restoration, oyster/ coral reefs, open space preservation, bioswales, etc. The hurricane-related strategies and case studies include resilience for roofs, strapping, walls, window protection, and foundations based on FEMA guidelines. The existential significance of this project in the Lower Ninth Ward and the hurricane strappings that are intricately designed are topics for discussion in this class. Students participate in conversations based on articles like "Below the Sill Plate" by Deborah Gans.[8]

The urban planning aspect of this course focuses on studying an overlay of racial disparities, zoning, urban density, and transportation. Students in this class present their demographic, planning, and climate analysis of a selected neighborhood and proposed solutions. This course attempts to bridge the gap between planning and climate issues. For instance, one of the lectures discusses the relation between floor to area ratio and its impact on climate vulnerability and heat islands. To dive deeper into the topic of urban heat, students get introduced to an urban simulation to calculate solar radiation based on the location and the three-dimensional properties of the study area.

The solution section illustrates environmental features ranging from agriculture to policies. The final section focuses on building case studies for African-American communities that highlight their historical origins and purpose, the physical evolution of the neighborhood, its surroundings, and their susceptibility to climate change issues. The reflective and practical work explores waterfront and inland African-American communities (e.g., in North Port St Joe and Tallahassee, FL) (Figure 3).

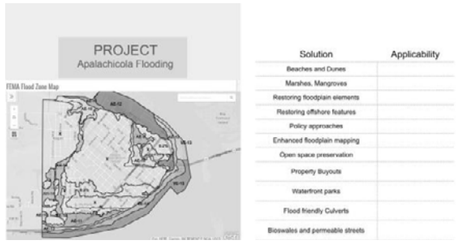

Figure 3:
Climate Justice project template

The final project asks the students to overlay the following maps for their selected neighborhood:

- Demographic (Race. Education. Income)
- Planning (Transportation. Land Use. Walkability)
- Natural (FEMA Flood Zone Map. Urban heat)
- Solutions

Documenting these historic communities and maps provides a foundation to propose innovative solutions for floods or hurricanes. This article introduces ways to include the issue of community design among universities and communities, which is the foundation of climate change.

3. DESIGN STUDIO PROJECTS TIED TO COMMUNITY

This section provides examples that integrate the Environmental Systems course and climate change issues with the design studios within a community context. Environmental Systems in Architecture narrates how sun path and climate conditions affect a designer's decisions. The course introduces the basics of heating load and energy modeling, which allows students to evaluate the thermal performance of their designs in the early stages. The upper division design studio students develop design concepts from climate, community, structures, materiality, etc.

ARC Design studios introduce the students to environmental and community projects, where the results show the extent of thoughts students put on sustainability measures. Resilience and site resources are the main topics included in this studio. Another design studio topic could explore the Timber In The City project with the approach towards community design and the concept of the reuse of materials. Hazard mitigation plays a significant role in the architectural design of the coastal areas; however, it is an issue that is often neglected. ARC Graduate Design in spring 2021 encouraged students to explore passive design strategies for flood mitigation in the Apalachicola River area, FL (Figure 4).

The Coastal design project in Grad design is to introduce the concept of climate and energy in architectural design and consolidate design skills based on passive strategies in Apalachicola, FL. This project considers how culture and river flood/ hurricane resiliency influence design. It considers how the climate affects the buildings' size, height, shape, orientation, and the vernacular methods used. Students learned the differences between using smaller footprints and heights in the cold and coastal climates and explored applying raised structures in the coastal design.

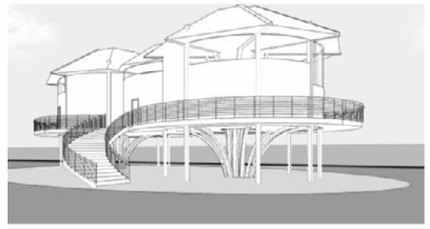

Figure 4:
Grad Design Apalachicola Project 2021 (Florida A&M University student work: Alexandria Robinson)

4. HAZARD MITIGATION SOLUTIONS

Embodied Carbon

The remaining question is how to mitigate through *education* and *policies* towards building resilient neighborhoods. This section discusses urban and architectural solutions for flooding and hurricanes. *Reducing Carbon Emissions* is one of the critical factors in addressing climate change hazard mitigation.

Carbon footprint calculator is an online tool developed by the Environmental Protection Agency (EPA), which provides carbon emission data based on the number of people in a household, location, and fuel cost.[9] The outcomes represent data for home energy, transportation, and waste. The results show pounds of CO2 per year while providing guidelines on reducing emissions.

Flooding

There are different flooding hazards, including coastal or river erosion and stormwater flooding. Preserving coastal lines, beaches, dunes, oyster reefs, and mangroves are examples of protection against erosion floods. In Pensacola, FL. GreenShores completed its first phase on site 1 in 2003 by making acres of offshore restoration and breakwater.

Relocations and moving people out of floodplains is one of the strategies which could mitigate the impacts of flooding. Managing *open space in floodplains, maintaining* waterfront parks, *bioswales*, and *levees* are some of the strategies for flood management at the urban scale.

Hurricanes

There were 86 tornado watches across the US in 2021 based on NOAA's Storm Prediction Center. Strengthening the roof, using hurricane straps, protecting windows, and optimizing the configuration of the building are examples of a resilient design. The shape of the building would be

Triple bottom line redistribution in mixed-income housing through transition spaces

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ABSTRACT: Though the LIHTC promote the presence of sustainability features, they are extremely time consuming, expensive, and competitive to win. Developers tend to build green to increase their chances of winning the tax credits, often overlooking the full potential of the LIHTC. Though scholars and urban planners agree that mixed-income housing benefits people from lower incomes through proximal role-modelling and promotion of tolerance, case-studies show limited economic integration of the middle-income tenants and the poor. Transition spaces are spaces that need community interaction and issues of safety can be addressed through their design. There is a huge opportunity here as developers are willing to implement any positive design change that benefits the community and existing LIHTC talk vaguely about transition spaces and credits are given for improved health and economic growth but how it can be achieved through design is not specified. This research proposes a new model that takes a soon to be developed mixed-income housing development and proposes various design interventions to be implemented in the transition spaces of the housing, by equally distributing strategies for environmental, social, and economic growth thereby increasing their chances of winning the LIHTC that will create an equitable model for social justice.
KEYWORDS: LIHTC, 3BL, mixed-income housing, affordable housing, sustainability

1. INTRODUCTION

Using sustainability as a factor to increase the price of real estate has been used to gain competitive advantage and for developers to improve their portfolio. Though the inclusion of sustainability creates long term value generation and causes short term increase in profits, it is feeding into the corporate system of where only the rich can afford to be sustainable. The Return on Investment (ROI) for green rated buildings is a minimum of 14% but the rent increases by 13.8% for a LEED or an ENERGY STAR building when compared to a non-certified building in the same metropolitan area (Fuerst. et al, 2011). As of 2013, 44 million Americans were burdened by the cost of housing (Metcalf. et al, 2018) and there is a great need to combat escalating rent for good quality affordable housing in the US.

This problem of unaffordable housing and increase in premium of green rated houses is making sustainability inaccessible to the poor. Higher construction costs and formation of new trends related to green features cannot be afforded by the poor. The original intention of sustainable development is to foster equal growth and eco-technologies should not hinder social equity. The term 'sustainable housing' becomes inappropriate if it becomes inaccessible to the lower income public.

This issue is being addressed by the Low-Income Housing Tax Credits (LIHTC). The federal government issues tax credits to the state government and state housing agencies awards credits to developers of affordable housing. The current budget in 9.5 billion dollars per annum and under Biden's administration this is going to increase to 64 billion dollars with extra emphasis on safety, health, and energy efficiency.

Though there are many models proposed for mixed-income development, there are negative social and spatial consequences due to unwillingness to share space and vertical capitalism (Darcy. et al, 2010). The current model will be unpacked to overlap social justice with the real estate development model through a tool that helps architects and developers analyse different sustainability credits available in the LIHTC and select additional design interventions to equally distribute credits in 3 different focuses of environment, equity, and economy. This research presents a hypothesis that this gap can be addressed through the transition spaces of the housing unit. Sustainability used as a different social housing model will reduce class segregation and create an equitable model for the urban space. By creating and analysing this model, developers can promote the value of human health, economic growth, and socialization.

2. METHODOLOGY

To propose a solution to combat inequality in mixed-income housing through sustainability, the process is divided into 2 stages – pre-design and

optimized when providing a smooth and curved path for the wind forces to pass. The US Department of Energy's Building America Solution Center offers best practices to minimize hurricane damage.[10] It covers categories for roof, wall, window, building attachments, site and foundation, operation and equipment, and design. Building America Solution Center provides training images and code briefs on hurricane detailing (Figure 5).

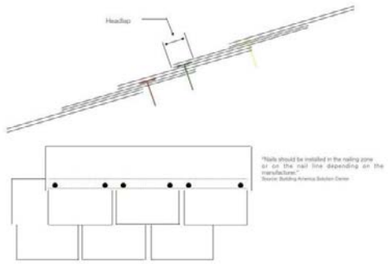

Figure 5:
Detail of shingle roof construction for hurricanes (Building America Solution Center)

Students' final project is a comprehensive analysis of a selected neighborhood regarding race, land use, climate features, site energy analysis, and proposed solutions.

Hazard mitigation solutions in architecture look at the historical roots of communities, precedents, student work, and architectural elements to mitigate such impacts. This article aims to provide ways to integrate socio-economic values and hazard mitigation discussions with students in the architecture program to promote equitable communities.

ACKNOWLEDGEMENTS

This research would not have been completed without the support of Florida A & M University, the Office of Graduate Studies and Research, FAMU Sustainability Institute, and NSF Award HRD-1824267.

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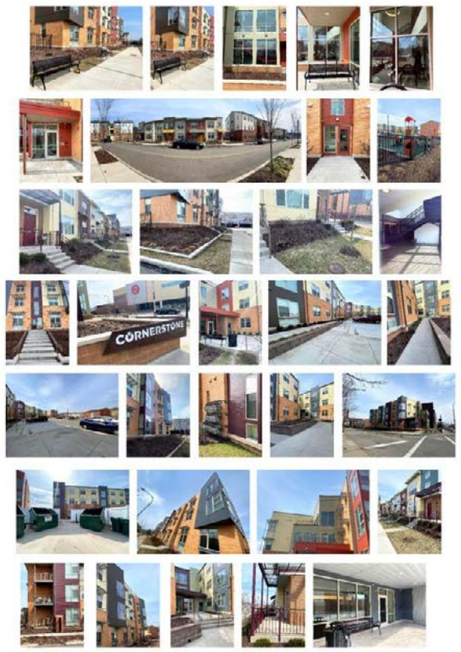
design. The pre-design stage involves contextualizing the research by identifying the LIHTC in Pennsylvania, doing case-studies of existing mixed-income housing units in Pittsburgh, breaking down the existing sustainability rating systems and interviewing the stakeholders involved in affordable housing. The design stage involves developing the design taxonomies based on the stakeholder interviews and developing the final toolkit.

2.1 LIHTC in Pennsylvania

The research is contextualized by studying the LIHTC in Pennsylvania (PA). The current annual state cap is 10 million dollars per year (Novoco, 2021) for PA which is calculated based on population (population x $1.755). The qualified allocation plan (QAP) for Pennsylvania includes 6 sustainability rating systems such as National Green Building Standard, DOE Zero Energy Ready, Enterprise Green Communities, LEED Homes, LEED BD+C (New Construction) and Passive House. The states that are similar to Pennsylvania in terms of sustainability rating systems are Illinois and Virgina (Novoco, 2021). There are also several states in the United States that do not have any LIHTC program enacted yet.

2.2 Case Studies

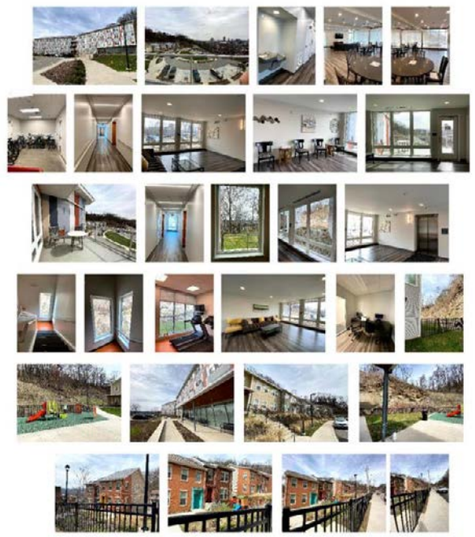
Figure 1:
Images from Cornerstone project case study.



The Cornerstone Project at East Liberty (Tai + Lee Architects, 2021) was designed by Architect Yoko Tai from Tai + Lee Architects and was developed by McCormack Baron Salazar.

The Sandstone Quarry project at Fineview was designed and developed by Trek Development (Trek Development Group, 2021) and was earlier a site to the Old Allegheny Dwellings.

Figure 2:
Images from Sandstone Quarry case study.



2.3 Break-down of Sustainability Rating System

A previous research by Kasper Guldager Jensen and Harpa Birgisdottir breaks down the content of different sustainability rating systems used across the world into 3 focuses – environmental, economic, and social aspects (Jensen et. al, 2019). The break down shows that the focuses in all the rating systems are not equally distributed.

The same concept was used to divide the credits under the 6 sustainability rating systems in the Pennsylvania Qualified Allocated Plan (QAP). Ony credits related to transition spaces were marked.

The LIHTC has compulsory thresholds (Novoco, 2021). The thresholds related to transition spaces were marked and divided into 3 focuses. It is observed that the break-down for the LIHTC and the 6 sustainability rating systems under each focus is not equally divided. The LIHTC thresholds mostly focus on social credits and passive house certification only talks about the environment. The focus on economic growth is very limited in all the rating systems.

2.4 Stakeholder

To propose the design interventions the design had to be ground to reality. For this it was important to know what the stakeholders think about the gaps present and how it can be resolved. To understand who should be interviewed, a stakeholder diagram was mapped out. The stakeholders that have the most influence are the architects, developers, and market rate tenants. The value of a well-structured and well-designed mixed-income housing can be reaped by tenants living at subsidized rate, developers and in the long run, the entire community.

2.5 Interview

The first interview was with an architect, Yoko Tai (Tai + Lee Architects, 2021). Her expertise lies in mixed-income housing. Yoko has been working primarily with a private, not for profit developer – McCormack Baron Salazer and from her personal experience felt that the developer cared a lot about sustainability and social justice. Their designs for mixed-income housing always include colourful and grand lobbies, and utmost care is taken to design the staircases, roof decks and patios. Her project at East Liberty called Cornerstone is tactically designed for sunlight, visibility, and safety.

The second step was to interview both a non-profit and a private developer. Linda Metropolus runs a non-profit called Metropolus Development (Metropolus Org., 2021). In her work experience she always concentrated on making the mixed or low-income housing healthier, quieter and more thermally comfortable. 2 of her projects have community rooms that doubled up as an art space and a computer room. Though these spaces were used a lot by the lower income group, it was noted that there was a lack of interaction between communities of different income groups.

The third interview was with a private developer, Bill Gatti from Trek Development (Trek Development Group, 2021) who hired a director of mission culture and people to overlook all the housing projects. They concentrate on strategically designing spaces for safety by using a lot of glass and windows. They make sure to add luxurious amenities to attract the market rate tenants to use these spaces. They also confirmed that transition spaces are not susceptible to get value engineered and they would rather cut down their budget by changing external cladding, HVAC system, light fixtures, etc.

The last stakeholder interview was with an architectural coordinator who worked with McCormack Baron Salazer (McCormack Baron Salazer, 2021) for years. He talks about the importance of visual connection to outdoor spaces for self-policing and agrees that interaction spaces need more attention.

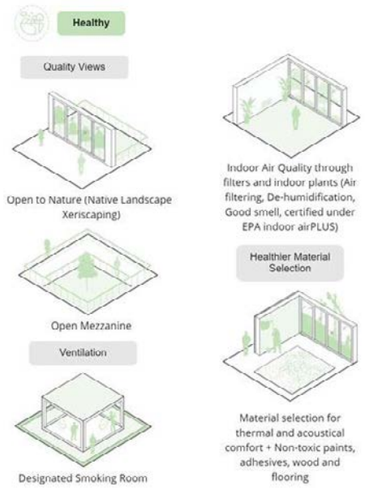
Figure 3:
Word Cloud of words associated with Transition Spaces.

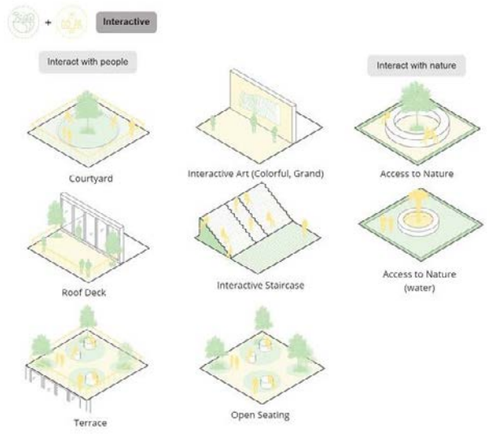
Note: From these interviews, a word cloud of design aspects that the stakeholders felt were related to or important to transition spaces was developed. Some of the words include well-lit, safe, grand. The transition spaces addressed would be staircase, corridor, courtyard, lift lobby, outdoor deck, foyer, and entrance.

2.6 Developing the taxonomies

In the penultimate step, taxonomies were developed for transition spaces and were categorized into 3 focuses – environment, social justice, and economy. 3 other focuses were developed that lied at the intersection of the previously mentioned 3 focuses.

Figure 4:
Environmental Taxonomies.

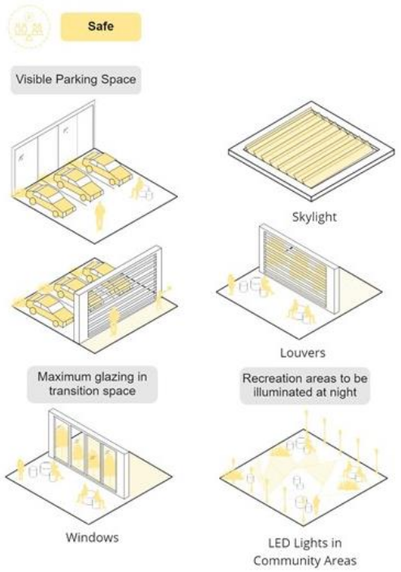


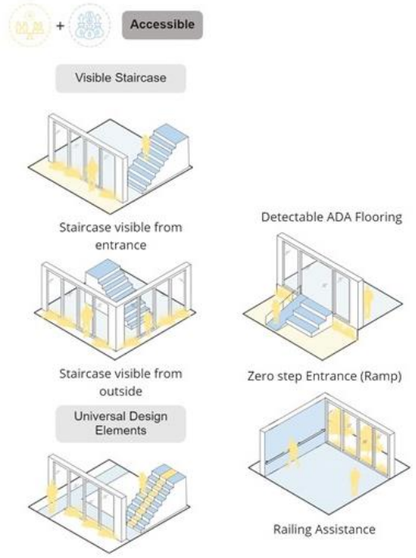


Some of the environmental taxonomies include having access to views, having access to nature, improving indoor air quality, using materials for thermal and acoustical comfort, etc. The taxonomies that have an overlap between environmental and social are places where residents are allowed to interact with each other and with nature.

Social taxonomies address issues of safety and inclusivity. Issues of safety are tackled with visibility and universal design elements are recommended for inclusivity.

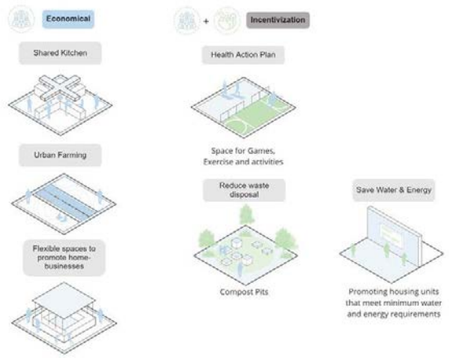
Figure 5:
Social Taxonomies.





To show influence on economic growth through design; shared kitchen, urban farming, and flexible spaces to promote home businesses are proposed.

Figure 6:
Economical Taxonomies.



2.7 Creating the tool

To build the final toolkit, the users were first identified. They were – architects, developers, and sustainability consultants. The next step was to decide the platform on which the tool will be built.

The 3 options were a standalone app, Microsoft excel and a website. Despite having a boring user interface, Microsoft Excel (The Microsoft Corporation, 1985) was identified as the best option as it is used by everybody in the industry and has no learning curve.

The idea was to develop a toolkit that does 2 things – it helps architects of a soon to be developed mixed-income housing unit design transition spaces that negate social and spatial disparities. It will also help the developers propose various design interventions to be implemented in the transition spaces of the housing, by equally distributing strategies for environmental, social, and economic growth thereby increasing their chances of winning the LIHTC. It has 2 parts – analysing the existing green rating systems and understanding the gap and the second part is to fill the gap with design suggestions.

3. RESULTS

3.1 Tool-Kit

The final toolkit developed on Microsoft Excel (The Microsoft Corporation, 1985) currently works only for Pennsylvania, LIHTC and for newly constructed low-income housing units. It is an 8-step process and helps the user analyse different options available to evenly distribute the triple bottom line in the affordable housing unit.

In Step-1 the user must select the state that they are constructing the affordable housing in.

In Step-2 the user must select the sustainability rating system they are opting for in order to increase their chances of winning the tax credits. The credits for the selected sustainability rating system related to transition spaces populate the screen and when the user clicks on each credit, a pop-up window opens that shows the detailed requirements of each credit. Each credit is pre-classified as one focus, either environment, social or economy.

Figure 7:
Step-1, Step-2 and Step-3.

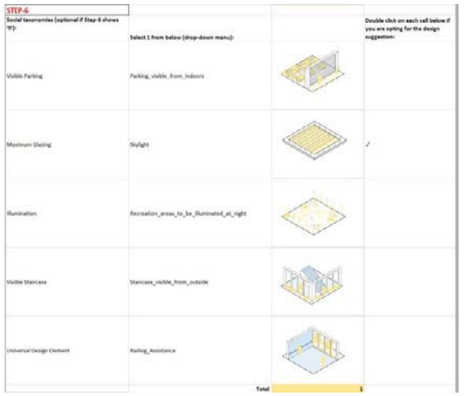
In Step-3 the user must double click on the credit that they want to opt for in their final design.

Based on the number of credits selected in Step-3 and the category of focus it belongs to, the break-up is shown in Step-4 which also includes the LIHTC thresholds.

In Step-5 the user can select up to 5 taxonomies in the environmental category. The drop-down menu shows different options available for design interventions and the taxonomy image changes accordingly. Like Step-3, the user can double click which credit they are opting for.

In Step-6 the user can select up to 5 taxonomies in the social category. The drop-down menu shows different options available for design interventions and the taxonomy image changes accordingly and the user can double click their preferred design intervention.

Figure 8:
Step-6.



In Step-7 the user can select up to 5 taxonomies in the economy category. The user can double click their preferred design intervention.

In the final step, the user can see the updated percentage break down of the triple bottom line that includes existing LIHTC thresholds, selected sustainability rating system and selected proposed new design interventions for the mixed-income housing unit. For better visualization there is a before and after graph. If the user is not satisfied with the break-up, they are allowed to go back and update their selection by selecting or unselecting a certain taxonomy.

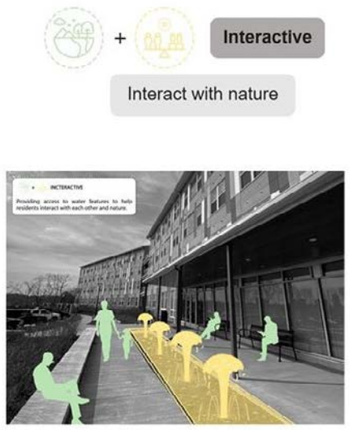
Figure 9:
Step-8.

3.2 Implementation on a case-study

Below are some examples of how the design suggestions or taxonomies are superimposed on an existing site of an already constructed mixed-income house. It shows that the design interventions can be done without much change to

the architectural layout. Some examples are - Views from windows should have access to nature, water features can be added wherever possible and community areas should be illuminated at night for safety.

Figure 10:
Execution on a case study.

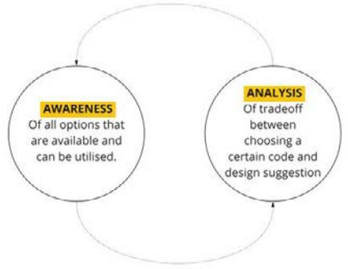


Detectable flooring for the visually impaired, flexible spaces to promote home businesses, encouraging tenants to avoid excessive use of energy and water and space for composting waste are some examples in the economical taxonomy category.

4. CONCLUSION

To reiterate why this tool is important, it creates an awareness of all the options that are available to evenly distribute the triple bottom line by designing for wellness, resilience, and community integration. By analysing the options that are available one can not only increase their chances of winning the LIHTC but also understand the actual potential of its intent.

Figure 11:
Importance of the tool.



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This section, if included, appears right after the main body of the text and is headed “Acknowledgments.” This section includes acknowledgments of help received from associates and colleagues, credits to sponsoring agencies, financial support, and permission to publish. This template has been updated from PLEA 2020 Conference.

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Integrated approaches addressing urban heat

Sustainable urban cooling strategies in Guangzhou

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ABSTRACT: Climate change has posed profound impacts on rapidly expanding cities in developing countries and threatened the survival of vulnerable urban areas. With growing urban population and rapid development, issues associated with excessive urban heat have become more and more prominent, confronted by cities around the globe. For cities in developing countries, addressing climate change while building livable communities are urgent and long-term tasks. This paper summarized strategies of the sustainable cooling pilot project in Guangzhou, and proposed a new model underpinned by an integrated approach to a paradigm shift that incorporates heat mitigation considerations for multiple stages of urban planning and design. This paper introduced multiscale interventions for accelerating sustainable urban transformation, with an operationalized framework to enable “cool cities”. The solutions for cooling issues are highly relevant to 17 Sustainable Development Goals (SDG) toward 2030 by United Nations and can serve as important anchors to promote concerted efforts for sustainable urban development.
KEYWORDS: Urban Heat, Sustainable Urban Cooling, Guangzhou, Cool Cities, Integrated Approaches

1. INTRODUCTION

The unprecedented urbanization with threats posed by climate change makes cities the frontlines to tackle the global climate emergency. With cities heating up at twice the global average rate, the issues associated with excessive urban heat become increasingly prominent, which pose complex and long-lasting impacts on citizens and urban systems[1]. As climate change continues, almost half of global population is exposed to high heat events which increase heat-related morbidity and reduce productivity[2]. The emission and anthropogenic waste heat generated by cities will worsen climate change and the way cities mitigate excessive urban heats is fundamental to determine whether urban transition will succeed or not. This paper summarized the development of sustainable cooling strategies in Guangzhou and proposed a framework of sustainable urban transformation focusing on enabling cooling cities. With comprehensive targets on key issues to mitigate urban heat, this paper will introduce an approach for cities aiming at addressing climate changes and establishing pathways for a cooling environment, to develop integrated solutions, systematic urban policymaking and promote effective implementation through participatory engagement.

2. COOLING CITIES STRATEGIC FRAMEWORK

Guangzhou is a megacity in the southern part of China, located in a coastal area characterized by subtropical monsoon climates. Since 1990s, the annual average temperature in Guangzhou has increased by about 1.4 ℃ due to the intensified urban heat island (UHI) driven by the accelerated urbanization process and global warming.

To address the excessive urban heat issues, a cooling city strategic framework was established, with emphasis on integrating cooling goals, strengthening networks of cooling sources, designing spaces with cooling measures and incorporating green solutions. By connecting technologies on adaptation and mitigation with policies taking natural capital into account, the interventions to improve urban climates can bring extra co-benefits to achieve goals of multiple sustainable initiatives.

2.1 Integrated approach addressing urban heat

Enhancing urban resilience towards the increasing temperature led by UHI is one of the priorities for cities to accelerate adaptation and mitigation to climate change. Mechanical cooling measures lead to a vicious cycle where energy demand increases to satisfy needs of

thermal comforts heightened by urban heat and results in even higher emissions, thus exacerbates global warming issues. Stemming from a small niche of building technologies, the concept of sustainable urban cooling could be scaled up though the collaboration across disciplines and sectors, put forward an initiative to mitigate excessive heat while generating benefits that are closely associated with 17 SDGs[3,4].

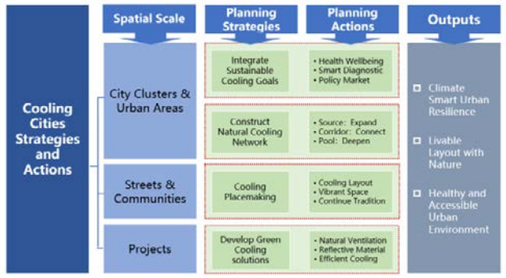
In 2020, Guangzhou initiated pilots for sustainable cooling in select sites piloting for optimizing future urban interventions including scenarios of regeneration, expansion, and restoration. An operationalized framework and technical guidelines for cooling have been established to foster joint efforts across relevant stakeholders. Through extensive consultations between planning and design agencies, research institutions, construction agencies, developers and communities, an integrated approach was developed to combine cooling consideration into land use plans and urban design guidelines by engaging cities at different stages of urban development and across multiple scales.

The pilots emphasized exploring the feasibility of urban cooling interventions, underpinned by the following strategic pillars including: 1) making plans result-oriented: the concerted efforts derived from public consultations that captured both climate experts and residents' opinions through surveys on thermal comforts and temperature-based monitoring and evaluation make impacts of cooling solutions measurable and inclusive; 2) promoting cross-departmental collaboration: the cooling initiatives offered a paradigm shift of thinking from sectoral to integrated urban approach. Through building the ownership to address urban heats in departments including planning, nature resources and buildings, the initiative broke the silos between agencies by enhancing communications; 3) establishing localized pathway: urban cooling initiative helped coordinate action plans tailored to local climates and environmental conditions of specific districts and communities while being aligned with development objectives and social-economic trajectories of the municipality; 4) strengthening human-centric and equitable decision making process: conduct stakeholder engagement through participatory planning to incorporate recommendations from the private sector and target groups.

2.2 Overall framework for sustainable urban cooling

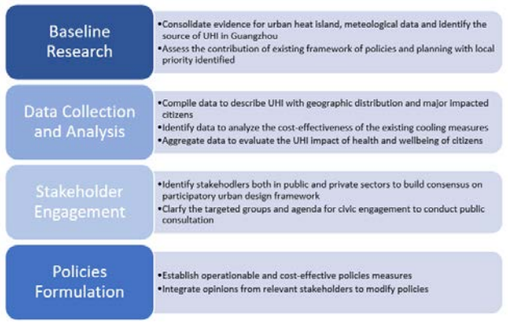
Building upon international best practices on mitigating UHI and the solid foundation to promote urban sustainability in Guangzhou, a framework of cooling cities strategies and actions is operationalized with multiscale building blocks (Fig.1), incorporating an inclusive, comprehensive action plan to address heat mitigation based on the environmental context and urban development path of Guangzhou municipality.

Figure 1: *Schematic for the framework of cooling cities strategies and actions*



An evident-based strategy development process was established. This includes mechanisms that assess the additionality of policies and strategies according to baseline information collected. After conducting in-depth analysis and identification of the key prioritized intervention areas, planning and design policies will be piloted in select sites, following a holistic and participatory framework (Fig.2).

Figure 2: *Process framework of strategy formulation*

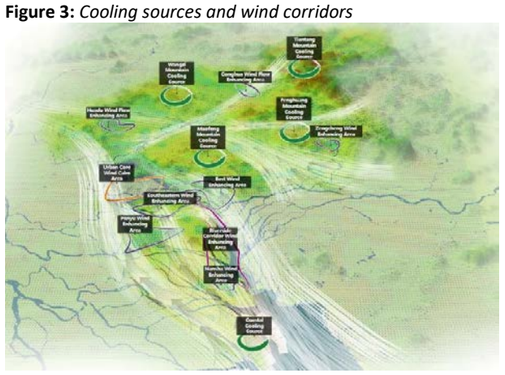


2.3 Urban cooling strategies

The process framework has developed five thematic and mutually supportive strategies that can exert orchestrated efforts to realize urban cooling goals including alleviating heat stress in historical core, avoiding potential excessive heat in new town developments, and fostering cooling sources in natural assets by ecological restoration.

Strategy 1. Optimizing cooling sources and maximizing the benefit of wind corridors: At city level, urban heat needs to be mitigated by enhancing evapotranspiration and ventilation which required policies regulating development intensity and conservation. Based on ecological conservation plans, the strategy proposed to conserve the major source of natural cooling, such as mountainous areas with urban forests and rivers, and connect them by wind corridors with widths proposed to be 80-150m. Strategies for managing the development intensity suggested building density within designated areas for wind corridors to be lower than 25% to ensure sufficient open spaces along wind corridors without slowing down wind flows[5]. Leveraging the green trail system, urban design is suggested to increase the accessibility to natural and man-made green and blue infrastructure so that the cooling effects of natural cooling sources can be maximized.

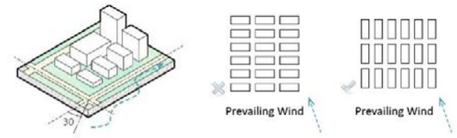
Figure 3: *Cooling sources and wind corridors*



Strategy 2. Enhancing urban surface through integrated greenery and breathable spaces: an adaptive and pervasive framework to connect parks, water features, pervious and reflective surfaces and vertical greenery will enable cities to breath and become resilient against extreme heats. Greenery on the ground and building envelopes have been proved to be an efficient strategy for heat mitigation which can reduce surface temperature as much as 17 degrees[6]. When solar reflectivity at city level increase 0.1, the average outdoor temperature will decrease by 0.3°C and 0.9°C during peak temperature[7]. Adding to the scheme for fifth facades, the strategy proposed to implement green roofs across the city, which will decrease temperature by 1.3°C, shown by studies in the tropical city[8]. The planning actions include developing a network of nature-based cooling, by leveraging green patches along corridors, and accumulating the effects of cooling towards heat centres.

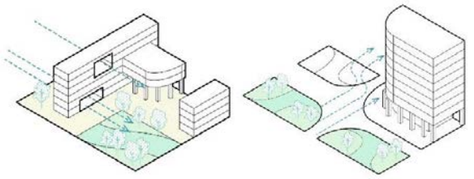
Strategy 3. Improving urban and architecture design with shading and ventilation structures. To fully leverage the prevailing wind in summer, the intersection angle of street networks and the direction of prevailing wind is recommended to be laid out with less than 30 degrees and further align the long side of parcel paralleled to establish wind corridors and avoid slowing down air exchanges. Coordinating green roofs and tree canopies with an optimized layout of urban geometry can contribute to urban cooling and make communities more livable.

Figure 4: *Street layout and prevailing winds*



During the design stage of a new community, building heights are suggested to be less homogeneous to avoid creating wind screens that block wind flows. Designers are encouraged to optimize buildings by terrace layout, enhancing the form of sequential heights conducive to ventilation. If possible, the height of buildings should increase along the prevailing wind direction in summer. The shading by buildings should be considered to minimize the westward sun exposure of the site. Coordination is required between the layout of buildings and urban design of open space, to better construct ventilation corridors conducive for air circulation, and leverage shades by buildings to improve comforts for open space. Architecture design and neighbourhood layout need to enlarge wind flow and lessen heat captured. Large building volume is encouraged to increase porosity and develop rounded façade to facilitate wind flows.

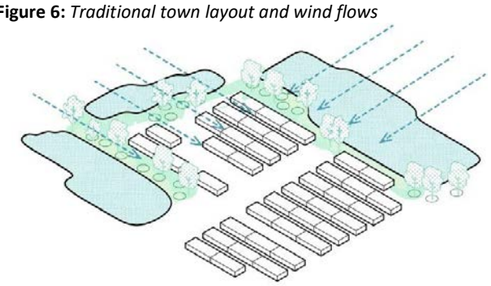
Figure 5: *Building Porosity and Rounded Facades*



Strategy 4. Promoting cooling through urban landscapes and facilities by traditional and localized methods: Inspired by traditional townscape layout in Lingnan area, urban landscapes such as man-made wetlands, ponds and urban rivers can Improving outdoor thermal comfort while revitalizing traditional urban forms. The traditional plan with narrow alleys featured by a comb layout, offer extensive shading that create an enabling environment for passive ventilation caused by the difference of temperature between alleys and ponds. Neighbourhood is recommended to incorporate traditional Lingnan techniques that make best use of passive solutions. This also calls for urban designers to continue the traditions of climate adaptive town

planning characterized by traditional Lingnan styles and encourage passive ventilation with heat insulation featured by Lingnan architectural characteristics such as arcades.

Figure 6: *Traditional town layout and wind flows*



Strategy 5. Reducing anthropogenic heat by green transportation and air-conditioner optimization: Promoting urban design to minimize heat retention and behaviour change on indoor comforts can help keep cities cool. The waste heat generated by active cooling contribute to worsen the nocturnal urban heat island and increases cooling demands[9]. Thus, increasing air conditioner efficiency and reducing cooling demand can impact urban climate directly. For example, studies have shown raising air conditioning temperatures in buildings citywide from 21 to 25 degrees would reduce waste heat from air conditioning units by 20 percent in a tropical city[¡Error! Marcador no definido.]. Urban policies and awareness raising campaign will incentivize urban residents to optimize energy consumption on indoor thermal comfort. Since transportation is one of the sources of anthropogenic waste heat, by promoting transit-oriented development and creating a pedestrian and cycling friendly system requested can reduce the dependence on motor vehicles and weaken the heat retention effects caused by traffic congestion.

3. PILOTING COOLING ACTIONS

The sustainable urban cooling program has piloted cooling solutions across multiple dimensions for urban regeneration and new town design, while exploring implementation in different stages of urban development, including land preparation, urban master planning, implementation, and evaluation.

3.1 Institutional development and policy framework for promoting cooling

A set of guidance has been issued by the Bureau of Planning and Natural Resources in Guangzhou, required relevant agencies to consider and implement cooling strategies during the planning and management process of urban renewal. Key strategies were highlighted for urban cooling across scales of site, architecture, landscape, and urban infrastructure, to leverage open spaces and ecological conservation areas to integrate sources of cooling and cooling corridors. Planners and designers are recommended to optimize site planning and design to consider ventilation, shading and generate an urban "cooling surface" across scales with greenery in building envelopes. Stakeholders participated in urban renewal development are encouraged to propose participatory urban cooling solutions and realize sustainable urban cooling concepts and technologies in the planning and management process.

To support implementing sustainable urban approaches, Guangzhou have published and leveraged the guidelines, including the Guangzhou Urban and Rural Technical Regulations, that provides floor area ratio incentives to public open space in projects verified for green building standards. The public open space that meets the technical requirements, including overhead floors, roof gardens, arcades, urban public passages in buildings, will be exempted in the calculation of the floor area ratio (FAR) as incentives for developers. The additional space due to green building design may not be included in the calculation of the plot ratio after being reviewed by the supervising agencies.

As a part of integrated approaches, urban development incentive policies will play a critical role to mobilize different stakeholders for supporting cooling initiatives. Selected as one of pilot sites, China-Singapore Guangzhou Knowledge City Project explored incentive policies to promote the implementation of urban cooling strategies. FAR bonus policies have been developed to subsidize three-dimensional greenery and shading structures. The examination for project construction will review green roof ratio, building porosity and air ventilation. This integrated measures, through a combination of compulsory urban planning requirements and incentive policies, can facilitate sustainable cooling across multiple development stages from urban planning to project construction.

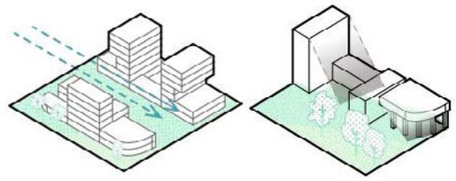
3.3 Incorporating integrated approaches and strategies into localized actions

Establishing wind corridors remains crucial in the site level design. Given the geographic locations of Guangzhou, with proximity to mountains and sea, enhancing natural ventilation is one of the most effective measures to alleviate UHI in the densely built-up area.

To facilitate airflow in urban built-up areas and alleviate UHI effects, the municipality of Guangzhou has developed six primary wind corridors based on the analysis of prevalent winds and the layout of mountainous landscape and pearl rivers, which is promoted through a masterplan with urban design guidelines. The planned wind corridor areas will conserve surrounding green and blue space while controlling the building volumes along the corridor, with requirements on height, density and setback, to avoid creating barriers that slow down the airflow. According to simulation based on urban design optimizing wind corridors, wind speed is expected to increase by 0.5-1m/s[¡Error! Marcador no definido.].

Transforming traditional architectural elements enables contextualized urban climate responses. The traditional Lingnan style architecture has generated a wealth of knowledge to address the major demands in residential buildings to reduce heat and enhance ventilation with open layout and plans. The characteristics of narrow street layout with high walls and narrow streets can be transformed into architectures that are passive to reduce solar gain and facilitate breezes. This is reflected by cold valleys, patios and arcades which have been consolidated as recommended urban forms for cooling strategies and urban design guidelines.

Figure 7: *Building layout for wind corridors and shading*



3.2 Implementing strategies through piloting projects

Pilot projects highlighted the cooling opportunities by urban regeneration design. Yongqingfang, a historic core under renewal in Guangzhou, was selected for sustainable cooling pilot given UHI is concentrated in old neighbourhoods with similar density. The roughness of underlying surface in historic core tends to be higher which results in slower wind speed that exacerbated UHI. To address this challenge while responding to the urban fabric and the architectural context, strategies combining cooling and ventilation with technologies that are affordable have been explored. The pilot tested green roof design with high reflective surface that are feasible for buildings in old neighbourhoods (Fig.9). Transformed from Lingnan style architectural insulation elements, the project applied double layered tile roof and hollow walls to reduce solar gain and heat.

Figure 8: *Piloting cooling actions in urban renewal sites*

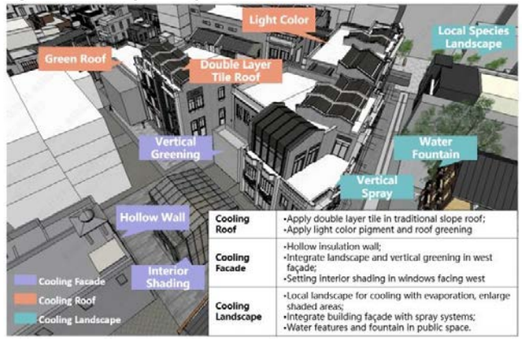
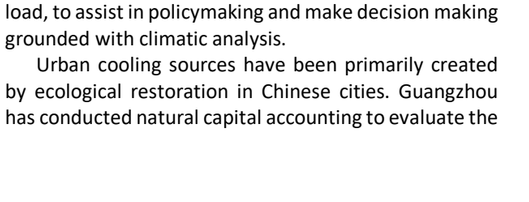


Figure 9: *Multiscale Implementation Framework*



New town development process was streamlined to incorporate lifecycle cooling design considerations. Translating cooling measures to operationalized guidelines required integrating cooling-related optimizations into site level control plans. First, cooling options such as district cooling, cooling pavement and reflective surface have been proposed through expert consultation and collective decision making. Second, cooling options were integrated into detailed control zoning guidelines at neighbourhood level. The implementation of cooling guidelines is further advanced by design scheme in select sites with medium density which require urban designers and developers to consider cooling at communities and buildings. This process has ensured the consistency across scales from planning to architecture design.

Assessing the value and capacity of cooling services provided by green urban infrastructure while translating scientific research to practical urban design guidelines is of great importance to ensure the benefits of urban green infrastructure have been maximized[10]. The site planning will benefit from simulating the impact of land use and urban design plans, while comparing the performance associated with shading, ventilation, heat load, to assist in policymaking and make decision making grounded with climatic analysis.

Urban cooling sources have been primarily created by ecological restoration in Chinese cities. Guangzhou has conducted natural capital accounting to evaluate the

services provided by ecological restoration under the territorial spatial planning through ecological area identification, establishing ecological space zoning. By categorizing natural assets in Guangzhou as areas for improvement, degradation, damaged, restoration policies can be more tailored and targeted to maximize ecosystem services including climate regulations such as cooling. Endorsed by the biggest urban wetland in China and a network of parks and urban forests, this green urban infrastructure has offered UHI mitigation, biodiversity protection and recreation as a win-win solution. Estimating the comprehensive value of climate, recreation, biodiversity can better inform the formulation of cooling strategies that leverage the co-benefits of adaptation efforts.

4. CONCLUSION

The issues of climate change do not respect borders and should be recognized as a global crisis related to a community of a shared future. It is of paramount importance to form a joint force for sustainable cooling across disciplines and departments. As cities in various countries strive to recover from impacts of the pandemic, investment in climate smart urban infrastructure will be key to address extreme weather events, improving local climates and creating livable communities. With the advancement of the pilot sustainable city cooling project in Guangzhou based on integrated approaches, cities in developing countries will be able to establish new pathways to tackle local climate issues while contributing to urban sustainable development goals. The paper presents the conceptual developments behind urban cooling strategies and contribute to rethink urban sustainability by an integrated approach.

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PLEA STGO 2022
WILL CITIES SURVIVE? CHALLENGES FOR DEVELOPING COUNTRIES

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WILL CITIES SURVIVE?

Wellbeing in daylighting studies
A literature review

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ABSTRACT: Daylight conditions throughout an internal space directly impact building occupant health and wellbeing. To design a healthy building, many rating systems that use standards and recommendations are used to achieve this goal. Although daylight is usually perceived as a visual phenomenon, it also affects human physiology, behaviour and mood known as non-visual effects which are considered a subjective assessment. These standards and rating systems share the same consideration to improve users' health and wellbeing; however, different approaches have been taken to achieve this goal related to daylight. This paper review three daylight standards and four building rating system studies that are selected and critically evaluated to extract recommendations and guidelines regarding daylighting comfort and wellbeing targets. The review starts with a chronological overview and presents daylight metrics, as well as their underlying methodologies to define the gap in using these metrics to assess daylighting non-visual effects and illustrate the need to use building rating systems' guidelines and recommendations to enhance these effects. After that, a thematic analysis was conducted to extract the relative recommendation on how building rating systems and daylight standards could contribute to comfort and wellbeing in terms of daylight.
KEYWORDS:, Health and wellbeing, Daylight metrics, Standards and Building rating systems.

1. INTRODUCTION

Daylight has been associated with many physiological and psychological benefits which directly impact building occupant health and wellbeing [1]. Although daylight is more normally perceived as a visual phenomenon, it also affects human physiology, behaviour, and mood, summarized as non-visual effects (CIE, 2008). Daylight visual effects refer to the photometric measurements used to analyse how much light is present in a given space for undertaking tasks. In contrast, non-visual effects are subjective assessments that evaluate how the light affects occupant's perception. Many experiments have been conducted to evaluate the impact of various daylighting conditions- visual and non-visual effects- on occupant, such as melatonin suppression, phase shift, sleep quality, visual interest, and mood [2] by controlling daylight in a way that adequately affect occupant's comfort and wellbeing [3].

In recent decades, a range of standards have been published that outline the ideal theme of daylighting practice that should be used to assess or improve wellbeing. The recommended practices in daylighting design are primarily focused on improving energy efficiency and building occupant comfort rather than on optimizing its role in enhancing the health and wellbeing of occupants [4]. Published literature on the relationship between daylight and wellbeing indicates the challenges to have a healthy environment. This paper examines the measurements used to assess wellbeing associated with the daylighting practice. It is a literature review of specialist academic journal papers published over the last two decades. This paper seeks to identify the current state of knowledge in this field and the best practice guidelines of daylight's comfort and wellbeing. It identifies the gaps in daylight metrics and presents the movement from static metrics to dynamic metrics which known as Climate-Based Daylight Modelling (CBDM). It is a thematic analysis of how wellbeing is defined in both building rating systems and daylighting standards, identifying how the approach, recommended value and metrics can be used to assess wellbeing in terms of daylighting. A conclusion of the implications of the findings is presented to set the health and wellbeing parameters.

2. Methodology

The paper is divided into two parts: the first part is a historical review of daylight metrics used from 1895 to 2016 to illustrate the move from static metrics to dynamic metrics to assess comfort and wellbeing. Numerous databases are widely available online; the most prominent sources such as SCOPUS, Web of Science, and Google Scholar were used in this research. The literature was chosen after systematically searching Google Scholar and SCOPUS for recent daylighting-related articles. The research was limited to journal papers, and the combination of the following keywords was used: Daylight, Health, and Wellbeing. Only articles exploring daylighting effects on occupant wellbeing were selected to form the review sample. The following papers were excluded: studies analysing daylight comfort in terms of specific points such as thermal consumption, energy, and artificial light, the exception were the papers referred to the interaction of occupant comfort and wellbeing. The criteria matched with 13 published papers in essential Daylight, Comfort, and Wellbeing.

Theme of "Wellbeing"	
Scopus & Google Scholar	-(Daylight and Comfort and Wellbeing [Title/Abstract] AND daylight, natural light [Title/Abstract]) NOT Thermal (All Fields) - (Daylight and Visual effects and non-visual effects [Title/Abstract] AND daylight, natural light [Title/Abstract]) NOT Thermal [Title/Abstract] AND daylight, natural light

***Table 1**: Search terms In 'Scopus' and 'Google Scholar'*

The second part of this paper is a thematic analysis to extract the relative recommendation on how daylighting standards such as; [1-British standards/ Europe standards(*BS/EN*), 2-The Illuminating Engineering Society of North America (*IESNA*), 3-The Chartered Institution of Building Services Engineers *(CIBSE*)] and building rating systems such as; [1-Building Research Establishment Environmental Assessment Method (*BREEAM*), 2-Leadership in Energy and Environmental Design (*LEED*), 3-The Living Building Challenge (*LBC*), 4-WELL building Standard (*WELL*)] define comfort and wellbeing in terms of daylight. Regarding daylight standards, the themes used "keyword-in-context" method by identify the word "Wellbeing" and select the related paragraphs to daylight. These paragraphs were analysed to identify the approach, recommended value and metric used to assess wellbeing in terms of daylighting. The same method was used in building rating systems to extract the theme of 'Wellbeing' in terms of daylighting.

Theme of "Wellbeing"			
Daylight standards	**Theme of "Wellbeing"**	**Rating systems**	**Theme of "Wellbeing"**
1-BS/US	1	1-BREEM	65
2-IESNA	14	2-LEED	6
		3-LBC	1
3-CIBSE	1	4-WELL	27

***Table 2** Wellbeing in context by using MAXQDA software.*

The keyword-in-context method was used by the MAXQDA tool [5], as quantitative text analysis, to find the Keyword-in-context feature to display all word locations and their context in an interactive result table was used. A critical evaluation was conducted to extract the most relevant context related to wellbeing in terms of daylight practice.

3. Historical review of daylighting metrics.

Daylight metrics was measured by using two techniques to assess the quantity of the light. Initially photometric measurement was used between (1895 and 1989). Subsequently, the second method which is called Climate-Based Daylight Modelling (CBDM) was used between (1989 until now). In 2001, Thapan et al. [6] and Brainard et al. [7] disputed the evidence of non-rod non-cone photoreceptors. In addition, Prof. Berson from Brown University discovered intrinsically photosensitive retinal ganglion cells (ipRGCs) in 2002, which increased the interest in non-visual effects related to lighting studies. [8]

3.1 Photometric Measurements (1895 to 1989)

Between 1895 and 1989 photometric measurement of lighting was used as a performance indicator of daylight. These two indicators were qualified using Illuminance, and luminance metrics. The Illuminance of a given surface is defined by the amount of light reflected by it; however, luminance plays a significant role in describing visual comfort coming from having some glare issues or high brightness levels in a space. The luminous flux per unit area defines a surface's luminance measured by foot candles or lux. [9]

3.2 Moving from Static Metrics to Climate-Based Daylight Modelling (1989 to 2016)

Metrics and analysis tools have changed dramatically over the past few decades. Thanks to computer simulation methods that allow designers to measure daylight at a definite time at a day with a single condition over a year. Therefore, they evaluate daylight variability for complex façades at definite point-in-time Illuminance per year. There was a shift in using daylight static metrics such as Daylight Factor to be replaced by Point-in-Time measurements. Then the approach was developed to include climatic change and called Climate-Based Daylight Modelling (CBDM), such as Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (SDA), and Annual Sunlight Exposure (ASE) [10].These metrics are still used in many research studies because of its simplicity and stability, unfortunately this approach does not present realistic climate conditions as it does not consider changing date and time, latitude, the orientation of the building and glare [11-12-13-14].

3.4 The introduction of Daylighting non-visual effects (2016 till now)

In 2002, by discovering non-rod and non-cone photoreceptors which increased the interest in non-visual effects of light studies [6, 7]. These non-visual effects are considered subjective assessments which quantify the quality of light, such as daylight colour, intensity, distribution, and uniformity. This type of measurement is essential for measuring the daylight impact on occupants' satisfaction, impressions, and behaviour. Photometric measurements focus on achieving the adequate Illuminance required for a particular task. Subjective assessment assesses the quality of light, such as distribution and uniformity. Using this method gives a translation of daylight's psychological effects on occupant, such as impression and satisfaction. Many experiments have assessed the non-visual responses' impact on daylighting conditions, such as melatonin suppression, sleep quality, subjective and objective visual interest, and mood [9].

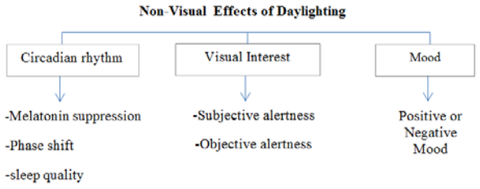

Table 3 *Non-Visual effects of daylighting [10].*

Numerous experimental studies were conducted to understand the non-visual effects and provide recommendations for daylighting designs that positively impact human health and Wellbeing. In 2016, The International Commission released a technical report on healthy interior daylighting recommendations on Illumination (CIE) this provided researchers with a methodology to define the aspects of non-visual effects. The healthy daylight recommendations resulted from the relationship between daylight exposure and its effects to simulate the occupant's circadian system [10-15]. From this introduction of CIE, the main aspects of designing a healthy and comfortable daylighting environment are improving the occupant's circadian rhythm, visual interest, and mood. When using a shading system, which may obscure the outside view's capability to achieve the desired luminance and avoid glare issues, the effects of daylighting are both visual and non-visual; the link between these opposing approaches has remained unclear.

3.5. Linking between visual and non-visual effects

Circadian rhythm, or the Circadian cycle, is considered a natural and internal process that affects our sleep-wake cycle thought out the day [16]. Circadian stimulus (CS) is the average value of Illuminance for each hour and time of a day per year. This value is represented by a numerical score starting from 0 to 2 related to the ratio of CS per year that achieved finally 24 credit score. Therefore, when CS is more than 35 percent, equivalent to 120 Lux, the score will be 2, and a score of zero is achieved when the CS is less than 10 percent [17]. Based on the model of human circadian phototransduction, CS could be measured laboratory by counting the illuminance level falling on the occupant's eye cornea and the duration of this exposure [18]. This value of CS indicates the predicted percentage of melatonin suppression.

In 2005, Rea et al. developed a new model of human circadian response based on the measured value of the neuroanatomy and neurophysiology and the published psychophysical studies results.

A graph in Fig. 1 illustrates this relation recommended to achieve CS between 0.1 and 0.7 [19]. In addition, Figueiro claims that " An exposure to CS of 0.3 or higher for one hour or more in the early part of the morning has been shown to effectively maintain office workers' circadian systems" [18].

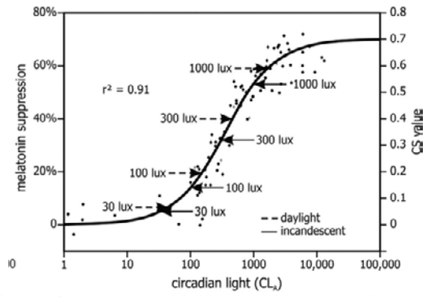

Figure 4*: the relation between Circadian light and Melatonin suppression [18]*

4. Wellbeing recommendations in international Daylight Standards

4.1 British standards/ Europe standards [19]

Recommendation:

Improve the emotional and non-visual (non-image-forming) effects to define the impact on people's performance and wellbeing.

Assessment values:

- Regarding visual interest = the ratio of maximum to minimum luminance within the 40-degree band should be between 10 % and 50 % of illuminance.
- To attain an acceptable level of illumination, 50% of a reference plane must be illuminated for at least half of the yearly daylight hours.
- It is recommended to ensure a uniformity levels on the task or activity area and immediate surroundings similar to those in 5.3.6 of illuminance.

4.2 IESNA [20]

Recommendation01: Not to exceed luminance ratio for visual interest improvements.

Assessment values 01: - Ratio between paper task and screen 3:1

Ratio between a task and remote surfaces 10:1.

Ratio between a task and adjacent dark surroundings 3:1

Recommendation02: Variations in the intensity, distribution, and colour tone of the lighting could affect the occupant's subjective impressions.

Assessment values 02: Ratio between paper and the desk to be 3:1 if illuminance exceeds 500 Lux, and generally, a ratio of 2:1 is the preferred one. The ratio of min to max daylighting illumination falls below 0.7.

4.3 CIBSE [21]

Recommendation01: There are several wellbeing benefits associated with the ability to see outside through openings in the building envelope. View composition is also essential, as it dictates the perceived quality of the view and thus the benefits to the occupant's wellbeing. [21]

Assessment value01: - View composition but without referring to the composition type.

S	Theme of Wellbeing	Approach /Recommended value / Metric
BS / EN	'Improve The emotional and non-visual (non-image forming) effects to define the impact on peoples performance and **well-being**'.	**A01**: Perceived room brightness **R**-Copying (offices) 34.1 Offices 34 -Reading, Typing, Writing (offices) 34.2 -Technical drawing (offices) 34.3 **M:** Ēm
		A02: Mean ambient illuminance **R**: -200 lx < $\bar{E}$ amb < 500 lx - $\bar{E}$ amb / $\bar{E}$ m ≥ 50 % **M**: Ēamb
		A03: Visual lightness and interest - 40 degree band luminance **R**: Regarding visual interest = the ratio of maximum to minimum luminance within the 40 degree band should be between 10 % and 50 %. **M**: illuminance
		A04: Daylight provision **R**: Useful illuminance level is achieved for 50 % of a reference plane for at least half of the yearly daylight hours. - It is recommended to ensure uniformity levels 5.3.6. **M**: illuminance
IESNA	Not to exceed luminance-ratio for **visual interest** improvements.	**A01:** Luminance Ratios **R:** Ratio between paper task and screen 3:1 - Ratio between a task and remote surfaces 10:1. -Ratio between a task and adjacent dark surroundings 3:1 **M:** Luminance
		A01: Variations in the intensity **R:** Ration between paper and the desk to be 3:1 if illuminance exceed 500 Lux, And generally, ration 2:1 is the preferred one. **M:** Luminance
	'By Variations in the intensity, distribution, and color tone of the lighting could have effects on occupant's **subjective impressions'**.	**A01:** Spatial distribution **R**: The ration of min to max daylighting illumination falls below 0.7. **M**: illuminance
CIBSE	'**Wellbeing** benefits associated with the ability to see the outside view and view composition	**A01:** View composition **R: Not found** **M: Not found**

Table 5 *Themes extraction [Author]*

5. Building rating systems to assess Wellbeing.

The following section illustrates the most crucial rating systems components related to the building life cycle, focusing on extracting the relative recommendation on how this rating system or standard matches with term health and wellbeing by daylighting. The following overview presents a selection of the most important and tools and their underlying application. This overview shows the four planning tools and their respective structures, focusing on how this rating system or standard matches with term health and wellbeing by daylighting.

5.1 BREEAM [22]

Daylighting: 1-Average daylight illuminance: not less than 300 lux achieved for 2000 h/year. The daylight factor for 80% of floor space achieves an average of 2%. At the worst lit point, the daylight illuminance is at least 90 lux for 2000 h/year.

Outside view recommendations: 1-View out available for 95% of space away from the wall by 7 m. A building, screen, wall, fence, or other solid object is 10m away. The Window Wall Ration (WWR) more than 20%.

5.2 LEED [23]

Daylighting: 1-Daylight levels between 300 and 3000 lux. Annual sunlight exposure1000, 250. The spatial daylight autonomy 300/50%.

Outside view recommendations: 1-View out available for 75% of space. View Quality for at least 75% includes two elements; (Flora and fauna, or sky; movement; objects away 7 m from the façade).

5.3 THE LIVING BUILDING CHALLENGE [24]
Daylighting: Daylight is available at 75% of regularly occupied spaces.
Outside view recommendations: Views outside achieved by not less than 75% of occupied spaces.

	Daylighting	Outside View
1-BREEM	1-Average daylight illuminance : not less than 300 lux achieved for 2000 h/year. 2- Daylight factor for 80% of floor space achieves an average of 2%. 3- At worst lit point, the daylight illuminance is: At least 90 lux for 2000 h/year.	1-View out available for 95% of a space away from the wall by 7 m at least. 2-A building, screen, wall, fence, or other solid object is 10m away. 3-The WWR must be more than 20%.
2-LEED	1-Daylight levels between 300 and 3000 lux. 2-The spatial daylight autonomy 300/50%. 3-Annual sunlight exposure1000, 250.	1-View out available for 75% of a space. 2-View Quality for at least 75% with including two of; (Flora, fauna, or sky; movement; objects away 7 m from the façade).
3-LBC	1-Daylight available 75% of regularly occupied spaces	1- Views outside achieved by not less than 75% of occupied spaces.
4-WELL	-Visual task lighting min. 300 lux with light intensity of 215 lux. - CIRCADIAN LIGHTING DESIGN: 75% or more of workstations achieve 200 Mlux between 9AM and 1PM day/ year. - The spatial daylight autonomy 300/50%, Annual sunlight exposure1000, 250 achieved for no more than 10% of users.	-Not less than 75% of workstation that from the opining by 7.5m at least has view to outside environment.

Table 6 *Outside view contribution to wellbeing [Author]*

5.4 WELL BUILDING STANDARD [25]
Daylighting: Visual task lighting achieved by min. 300 lux at the work plane with a light intensity of 215 lux. Circadian lighting design: 75% or more workstations achieve 200 Mlux between 9 am and 1 pm day/ year. The spatial daylight autonomy 300 Lux/50%. Annual sunlight exposure 1000 Lux, 250 was achieved for no more than 10% of users.
Outside view recommendations: Not less than 75% of workstations positions from the opening by 7.5m at least have a view of the outside environment.

6. CONCLUSION

6.1 Gaps found in daylighting metrics to assess Wellbeing.

Most scientific studies and lighting standards and recommendations emphasize lighting research related to visual performance and comfort [6-10-11-12]. More qualitative research studies confirm that recommendations and guidelines do not guarantee a well-lit environment and suggest further research on the impact of light on occupant health and wellbeing [1-2-3--6-7-9-14]. Researchers generally divide lighting research into photometric measurements and subjective assessments. Photometric measurements analyse how much light is present for tasks and energy-related studies in a given space. In contrast to this subjective assessments evaluate how the light is perceived (colour, intensity, distribution, uniformity, etc.) and how it impacts occupant satisfaction, perception, cognition, and behaviour.
In contrast to thermal comfort, there is no quantitative method for predicting the quality of light [5-6]. These metrics could quantify the amount and daylight distribution in space, measure the occupant's visual comfort, and controls the presence of adequate daylight to enable task performance.

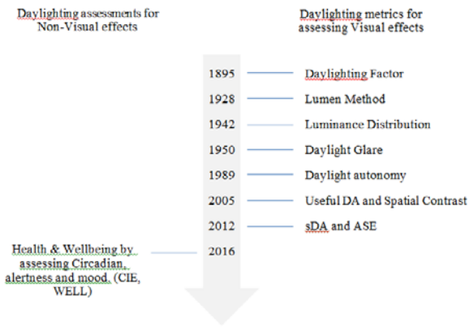

Table 7 *Health and wellbeing in daylighting metrics*

6.2 Gaps found in outside view metrics to assess Wellbeing.

A thematic analysis was conducted to identify the themes of wellbeing in terms of daylight. These themes were anticipated to the outside view quality in many terms related to daylight standards and building rating systems.
In daylighting standards, four themes were founded 1-emotional impact (BS-EN), 2-Visual interest, variations in the intensity, distribution, and colour tone of the lighting (IESNA), 3-Outside view and view composition (CIBSE). However, outside view quality was recommended by CIBSE to improve occupant wellbeing but, no metric was found to quantify the outside view quality. Therefore another thematic analysis was needed to find relative recommendations in building rating systems to daylighting and outside view quality. The outside view was defined in many ways. BREEAM defines the outside view by Window to Wall Ratio to the outside environment to be more than 20% and the internal space looking to the outside to be 95 % of space away from the wall by 7 m at least. LEED and The Living Challenge follow the same strategy as BREEAM except LEED adds outside view features for at least 75% of regularly occupied spaces including two; (Flora and fauna, or sky; movement; objects away 7 m from the façade).
Regarding WELL standards, new metric was added to quantify wellbeing by identify the circadian lighting design. The new metric is called Equivalent Melanopic Lux (MLux). A 75% or more of workstations achieve 200 Mlux) between 9 am and 1 pm day/ year. The spatial daylight autonomy of 300 Lux/50%, Annual sunlight exposure1000, 250 achieved for no more than 10% of users. Visual task lighting achieved by min. 300 lux at the working plane with a light intensity of 215 lux.
Outside view quality was recommended by CIBSI and WELL standards to improve occupant wellbeing but, no metric is found to quantify the best outside view composition. Therefore further research is needed to fill this gap.

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The virtual environments lighting quality assessment using the virtual reality

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ABSTRACT: The computer simulation field opened up new application opportunities in architecture in the last decades. In particular, Virtual Reality (VR) and Immersive Virtual Environments (IVEs) enable to study the subjective experience in-vitro. This paper investigates the ability of VR coupled with immersive devices in providing users with a better spatial lighting understanding. The goal is to reason about the potentiality of VR and IVE on the lighting quality assessment studies involving final users. The research was carried out by analysing and comparing data of the spatial and lighting perception of users using conventional devices frequently used by researchers in the lighting field for running experiments: screens, video projectors, and VR. Three different virtual lighting conditions in a virtual environment were presented, and a survey was administered to twenty-six participants. Results show that immersive VR allows obtaining more significant correlations between lightning variables than the other devices. Besides, the statistical analyses highlight that VR navigation with immersive devices is associated with an overall better lightning perception of the virtual model than the other non-immersive devices tested in the experimentation. The findings also show that users prefer the immersive environment.
KEYWORDS: Virtual reality, Lighting assessment, Survey, indoor environment, ANOVA analyses.

1. INTRODUCTION

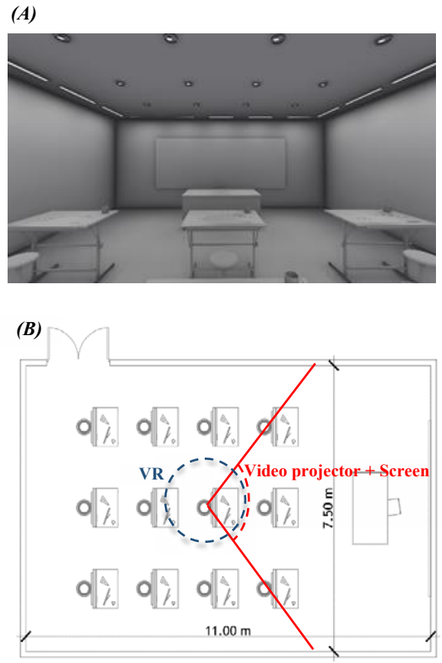
As a result of urbanization and industrialization, people spend more time indoors than ever before. It is estimated that, on average, people spend more than ninety percent of their time indoors (Luongo, 2016). Good lighting plays an important role in safeguarding health in indoor spaces by enabling users to perform their tasks comfortably and efficiently. Accordingly, there should be an appropriate level of light falling on the surfaces that users are working on. For instance, excessive contrast, intense glare, and light flickering in their fields of vision are inappropriate. To assess situations of visual discomfort, architects used two methods. The first one is a subjective lighting assessment: this method evaluates the quality of light in space using surveys (Daich, Zemmouri, Piga, Saadi, & Daiche, 2017; Yacine, Noureddine, Piga, & Morello, 2017; Day, Futrell, Cox, & Ruiz, 2019; Piga, B. E. A., Stancato, G, Rainisio, N, & Boffi, M. 2021). The second one is an objective assessment: this method evaluates the amount of light on the working plane and walls at the users' eyes level. The quantitative method is mainly based on a value obtained through physical measurements on-site using dedicated instruments (typically luminance-meter or luminance-meter) or virtually via computer simulations (e.g. via software such as Radiance, Ecotects, Dialux; Zhu & Rein, 2019). The early 1990s saw several failed efforts by various entities to bring Virtual Reality (VR) technology into widespread adoption in the lighting field, a concept ahead of its time (Lipnack & Stamps, 2008). Some years after, the maturation of key technologies such as lightweight, high-resolution displays and positional tracking improved the possibilities of such an approach. At the time of writing, multiple industries, including cinema, education, defense, design, architecture, and environmental planning, are actively exploring the potential uses and benefits of VR technologies (Portman, M. E & al., 2015; Luigi, Aniello, Gennaro, & Virginia, 2015). This paper investigates the seamless integration of VR technology in architecture and, more precisely, the lighting assessment process. The paper aims to expose the result of a comparative study between three devices frequently used by researchers for lighting assessment purposes: screen, video-projector, and VR (Mahdavi & Eissa, 2002; Newsham, Richardson, & Blanchet, 2005, Saadi,2019). A comparative study on three lighting scenarios of a (virtual) drawing classroom was performed by assessing the users' reactions via a survey administered to twenty-six participants.

2. METHOD AND APPROACH

2.1 Virtual experimental room

The experiment was conducted in a virtual space representing a university design classroom (Fig. 1). The classroom has a rectangular shape (7.50m x 11 m x 4.50m) and a total area of 82.50 M². Three different configurations of artificial lighting have been modeled: 1) overhead lighting, 2) peripheral lighting, 3) mixed lighting (overhead plus peripheral lighting) (Manav & Yener, 1999; Flynn, Hendrick, Spencer, & Martyniuk, 1979; Boyce, 2014).

Figure 1: *A) 3D rendering of the virtual classroom; B) Plan of the virtual room of the experiment showing furniture and subjects' eating location.*



2.2 Subjects

Twenty-seven students from the University of Biskra (Algeria), Department of Architecture, participated in the comparative study aimed at evaluating the perception of the three lighting environments. Thirteen subjects were female with ages ranging from 20 to 28 (M=24), and fourteen males ranging from 20 to 28 (M=23) years old. Thus, 23,5 represents the mean age of the design-classroom users (i.e. students). None of the participants had any visual correction.

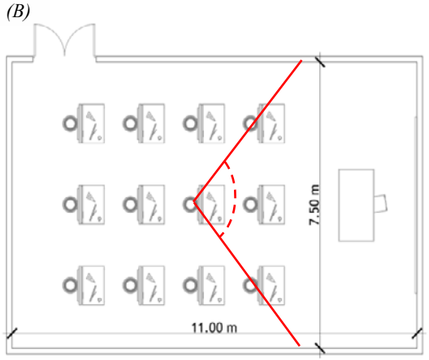
2.3 Experimental procedure

A sample of twenty-seven participants was divided into three groups; each group comprised nine students, five female and four males, or reverse. The first group evaluated the three scenes in the following order: overhead lighting, peripheral lighting, and mixed lighting. The second group evaluated the three lightings scenes in a different order; peripheral lighting, overhead lighting and mixed lighting, using a video projector. The last group evaluated the same scenes in a third order, mixed lighting, , peripheral lighting and overhead lighting using a VR headset (Fig 02). Afterward, each group switched the other visualization settings (screen, projection, immersive VR) until all the twenty-seven participants were exposed to three lighting conditions of the design classroom using the three devices.

The virtual model of the university classroom was created with the LUMION software for enabling the personal and immersive exploration of the environment in VR from the same point of view. In particular, three 360° panoramic images representing three different lighting conditions were rendered for allowing the immersive visualization via a Samsung gear VR coupled with a smartphone (Samsung S8+). A Side-Sync application has been installed on both the smartphone and the computer to control the procedure in real-time. This application allowed to visualize in real-time on the PC what the user was looking at through the headset and switch between the three lighting configurations (Fig. 1). The questionnaire was administered to the participants to investigate the user perception about the three scenes; in VR, the questionnaire was incorporated directly in the 360° panoramas. To measure the subjects' perception of the virtual space, the questionnaire used a semantic differential method: 6 pairs of 19 bipolar items were (Flynn, Hendrick, Spencer, & Martyniuk, 1979; Tifler & Rea, 1992; Yacine, Noureddine, Piga, Morello, & Daich, 2017; Rea & Flynn's, 1979). The questionnaire was repeated for the three luminous configurations to all participants.

Figure 2: *A) Picture of the environment for the screen visualization; B) Screenshot of video projector visualization; C) VR Picture of the environment for the headset visualization.*

(B)



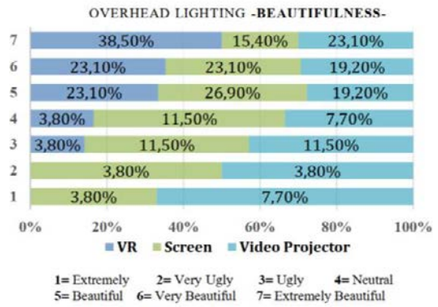
(B)

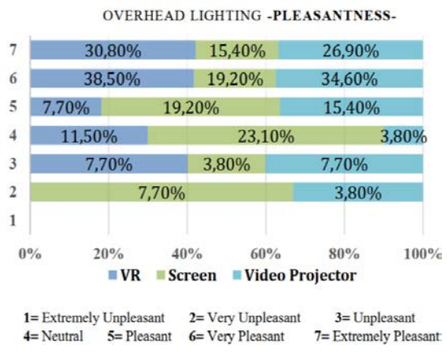
(C)

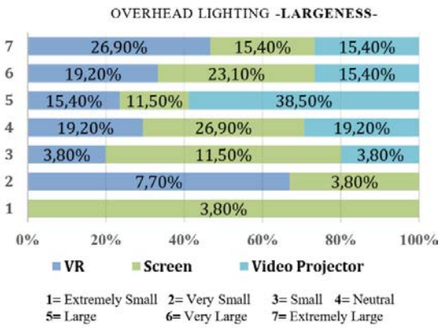
3. RESULTS

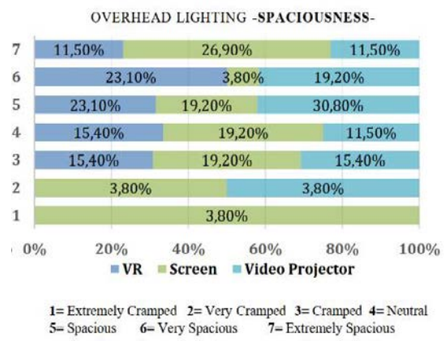
3.1 The overhead lighting condition

Figure 3: *Subjects evaluations of the peripheral lighting scene using the three devices for the variables, pleasantness, Beautifulness, Largeness, and Spaciousness.*







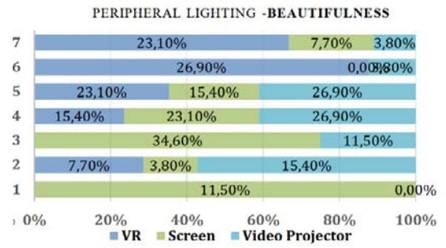


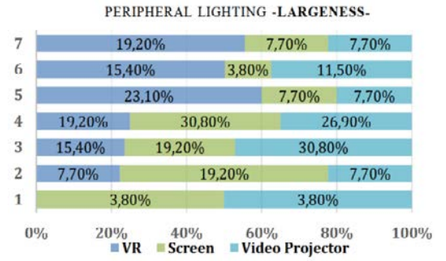
The comparison of the collected data for the overhead lighting scene using the three visualization devices is illustrated in Fig 3. Results show a similarity for the lighting assessment between video-projector and VR devices for Pleasantness, Largeness, and Beauty variables. Independently from the device used, around 60 % (cumulated three devices) of the subjects were more satisfied with the luminous quality of the overhead lighting scene than the other options with the three . Almost the opposite effect can be observed for the Spaciousness variable, where more than 55% of participants rated the classroom as more spacious using the screen for the visualization than video-projector and VR devices.

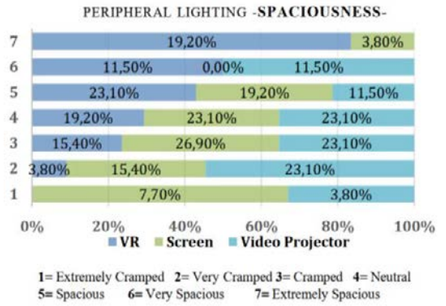
3.2 The peripheral lighting condition

The collected data for the peripheral lighting scene showed a wide divergence between the three visualization devices presented in the Fig 4. Despite this, about 62 % of the subjects were more satisfied with the VR than the two other devices. The classroom visualized via VR was perceived as more Pleasant, larger, more beautiful, and spacious. The results also show that the subjects were more satisfied with the screen than with the video projector. Then, results show a preference for the peripheral lighting scene, as positive reactions decreased from VR to the screen to the video projector.

Figure 4: *Subjects evaluations of the peripheral lighting scene using the three devices for the variables of Pleasantness, Beautifulness, Largeness and Spaciousness.*



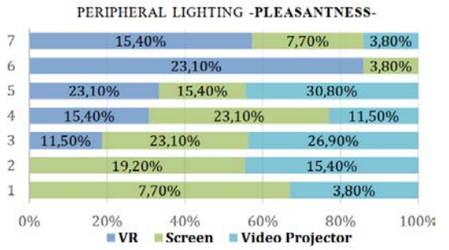


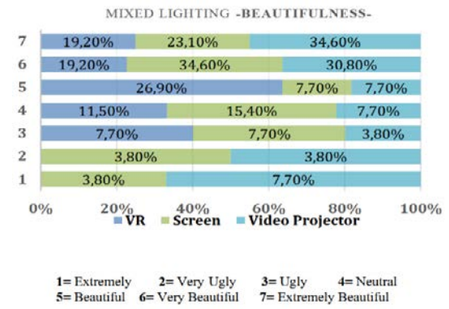


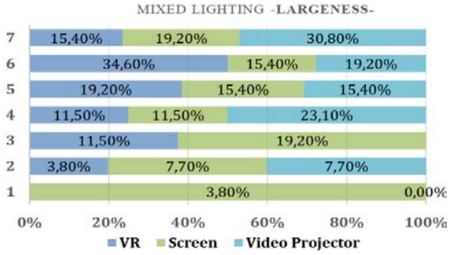
3.3 The mixed lighting configuration

The mixed lighting configuration scene using the three visualization devices, illustrated in Fig 5, showed similar outcomes to the lighting assessment using the video-projector and the screen for the four variables of Pleasantness, Largeness, and Beautiful, and Spaciousness. However, about 65% of the subjects were more satisfied with the VR than with the two other devices. Thus, the immersive VR solution for lighting visualization in an indoor space was judged with higher values for all the investigated variables (followed by the screen and video projector.

Figure 5: Subjects evaluations of the mixed lighting scene using the three devices for the variable's pleasantness, Beautifulness, Largeness, and Spaciousness.







3.4 Data analyses ANOVA test

An ANOVA for mixed-design analysis was carried out to evaluate the effects of the devices used for the

lighting scenes assessment. This analysis highlights significant differences between the three devices tested in the study (screen, video-projector, VR). To better understand the impact of the devices on the visual ratings by users, two 3×4 ANOVA were performed with Groups (Screen-Video Projector - Virtual Reality) 3-level between-subject factor and scenes evaluations as a 4-level within-subject factor (Pleasantness, Beautifulness, Spaciousness, Largerness). The Bonferroni correction was used to analyze post hoc effects. No significant difference between the groups (VR - screen) emerged (F<1). There was a main effect of global evaluations, F (3, 116) = 9.961, P-values < .001 since Spaciousness and Large showed higher ratings than all other evaluations. In addition, no significant difference emerged between the groups (video projector - Screen) (F<1). The main P-value < .001 showed higher ratings than all the other evaluations due to Spaciousness. A significant interaction between the groups (VR - video projector) factors emerged F (3, 116) = 3.189, P-values < .005, with the Spaciousness and Large showing higher ratings than all the other evaluations. The comparison of the three devices highlights that only two variables were significantly correlated for the screen (Large /Spaciousness). On the other hand, the four variables Large/Spaciousness and Pleasantness/Beautifulness of the VR and video-projector are significantly correlated per pair, with the VR P-values significantly lower than the video-projector for the Large/Spaciousness pair. A value of (M= 5.9) is obtained by comparing all tested devices using the VR tool for the lighting scenes assessment, meaning that the VR was more appreciated than the screen and video projector.

4. Conclusion

This research investigated the possibility of using VR for lighting assessment studies by comparing it with other devices (screen and video-projector) typically used by researchers in the lighting field for images visualization. The comparison of the subjective evaluations of the three lighting conditions (overhead lighting, peripheral lighting, mixed lighting condition) of a virtual design classroom using three different devices (screen, virtual reality, and the video-projector) shows that users perceive the lighting conditions in the same way with three devices. The ANOVA test analyses showed higher ratings with VR and video-projector than the screen. A higher number of significant correlations between variables, i.e. Large/Spaciousness and Pleasantness/Beautifulness, emerged with VR than the video-projector. Compared to the video-projector device, the results obtained with the VR present lower P-values than the video-projector. The significant correlation recorded between Large/Spaciousness with P-values <.003 and significant correlation between Pleasantness/Beautifulness with P-values < .001, is hypothetically explained by the significant sense of presence of the virtual environment in VR. This should be of course further investigated in future studies. In addition, the value of (M= 5.9) means that VR was more appreciated than other devices in the lightning assessment experiment. In conclusion, the findings presented are encouraging and sustain the multisensory study of lightning virtual environments with VR devices.

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Impact of brightness on glare perception when using shading fabrics

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ABSTRACT: Access to daylight and views out are usually recognized as beneficial to occupant comfort at the workplace. Simultaneously, discomfort glare due to direct sunlight is a known source of occupant dissatisfaction. Shading fabrics with low openness factor have been identified as capable of mitigating this source of discomfort. Yet, as these fabrics tend to be dense, views out and illuminance can be limited. Our objective is to evaluate the effect of shading control when it comes to the visual comfort reported by occupants interacting with such blinds. We first exposed participants to a space with the shading fabric down and, in a second session, allowed them to freely position the blind. Our usable sample included 24 participants, and the sun was visible through the blinds within their field of view. Three quarters of the participants raised the blinds in the second session primarily to increase the light levels and have better view out. Glare assessments showed that despite the opening of the blinds –and thus the significant increase in illuminance–, perceived discomfort glare did not increase. This result was in line with the Daylight Glare Probability metric, whose contrast term is able to counteract for the increase in saturation.
KEYWORDS: Discomfort glare, Shading fabrics, Occupant control, View out, Daylight, User assessment

1. INTRODUCTION

Many studies have demonstrated the critical importance of daylight and views to the outdoors for building occupants [1,2]. At the same time, spaces with abundant daylight and sunlight can be subject to glare. Discomfort glare is defined as that "condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme luminance contrasts" [3]. It is common in work spaces and represents a source of disturbance for occupants [4].

The European standard EN14501 classifies shading fabrics with low openness factor (OF) as capable of addressing discomfort glare from daylight and thus act positively on visual comfort [5]. The standard was established on the basis of annual simulations [plea-paper on fabrics] conducted with Radiance and relying on the Discomfort Glare Probability metric (DGP) [6], a glare metric that was found to be the most reliable according to the literature [7,8]. It has the advantage of having a contrast and a saturation term which makes it more robust than metrics based on saturation solely, such as the vertical illuminance at eye-level (Ev). However, deriving these two terms requires luminance mapping from HDR images, which induces some both complexity and cost in the measurement, whereas saturation-based metrics are much simpler in terms of instrumentation.

Fabrics with low OF are typically come in dark colors to increase view through the fabric to the outside, with a low openness factor to limit the amount of direct light. Yet, these characteristics will also limit the daylight penetration (e.g., illumination in the room). A low OF also reduces the visual contact with the outside, defined as "the capacity of the solar protection device to allow an exterior view when it is fully extended" [5]. Note that visual contact to the outside has sometimes been referred to as *view clarity* [9,10]. A way to overcome the reduced light and view clarity in the case of fabrics with low OF is to offer free control of the operation of the blinds to the occupants. This would align with recommendations from the previous literature, whose findings frequently highlight the importance of daylight control in buildings [11–13].

This study focuses on shading fabrics with low OF, glare and blind control. In particular, we are interested in glare from direct sunlight and the occupants' glare perception when fabrics with low OF are first fully deployed (i.e., fully down) then left to their control. This study also puts a special emphasis on the participants' motivations for controlling the blinds.

2. METHOD

2.1. Experimental protocol

We conducted human-subjects testing in a semi-controlled office-like setup with pre-defined visual scenarios, involving four types of fabrics (differing in OF and visual transmittance so as to create different glare conditions) installed on an operable roller blind system on the South opening of a rectangular test chamber (Figure 1). The OF of the fabrics was between 1 and 5% and the visual transmission between 0.015 and 0.079. The approach adopted for the study was to expose participants to a total of five exposure conditions: the first four conditions in which the fabrics were fully deployed, and the fifth condition in which participants were asked to adjust the blind to their preferred position. Fabric order was randomized but the fabric used in condition four was always kept for condition five.

The study follows a psychophysical approach with a series of physical measurements complemented by subjective assessments. In this paper, we will focus on the last two consecutive conditions of the study, namely a condition where the shading fabric is fully deployed, (i.e., down, hereafter labelled "A"), and the successive condition where the same shading fabric could be freely positioned by the participant (labelled "B").

The study was conducted under stable sunny sky conditions for critical sun positions (i.e., the sun was in the field of view and the angle between main viewing direction and sun was comprised between 13° and 47°). Daylight was the only source of light in the room. The experimental procedure was approved by the Human Research Ethics Committee at EPFL (ref. No. HREC 035-2019). The experiment was conducted in the Fall and Winter of 2020 and 2021 to match the desired sun positions.

2.2. Study sample

33 college-aged students with full or corrected vision and full color vision participated in this study. After reviewing the weather conditions and limiting our sample to participants who experienced *both* conditions under a consistently sunny sky (i.e., with a deviation in outdoor global horizontal irradiance (GHI) not greater than 25%, outside of short bursts during the typing task), we ended up with a sample of 24 participants.

2.3. Experimental facility and equipment

The experiment took place in a semi-controlled office-like experimental chamber located on the EPFL campus and equipped with a series of instruments aimed at measuring the visual conditions in the space (see Figure 1). Of particular interest were: a calibrated HDR camera (model: LMK 98-4 color High Resolution camera with a "Dörr Digital Professional DHG" fish-eye lens and a neutral density filter ND4) and two handheld illuminance sensors (model: LMT), one of which was fixed right next to the camera mentioned above.

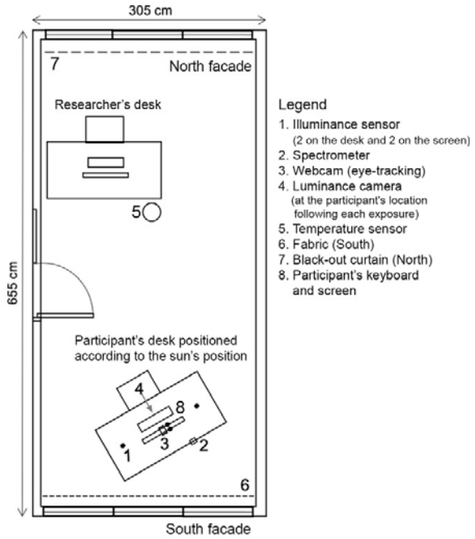

Figure 1: (top) Diagram of the test chamber, and (bottom) Example of participant exposed to condition A (blinds down, no control) and B (free control over roller blind position)

2.4 Experimental procedure

Participants gave their subjective feedback on the environmental conditions by completing web-based questionnaires. During each exposure condition, the participants were asked to perform a typing task (5') before answering a questionnaire on indoor conditions. For condition A, the fabric shading was lowered while for condition B, participants could control the height of the fabric shading at the beginning of the exposure (and only at that time). Between each condition, participants had to sit on a second chair (located at the back of the room) and were blindfolded so that the researcher could take measurements, and – when needed – adapt the conditions (e.g., rotate the desk so that the sun stays in the center of the field of view).

During the testing we tried to keep the illuminance level on the desk at 300 lux to allow acceptable daylight levels. However, for the fabrics with the lowest transmittance, the illuminance was sometimes far from this target. In such cases, we did not use artificial lighting but partially opened the blackout curtain of a Northern

window to increase daylight levels. The Northern window was neither in the field of view of the participants nor caused it reflections on the computer display. The opening of the blackout curtain for session A was then retained for session B.

2.5. Measurements

The monitored visual conditions (measured), the participants' feedback (subjective comfort ratings) as well as their motivations for controlling the shading fabric were the primary variables in this study.

Discomfort due to glare was assessed using the vertical illuminance (Ev) and the Daylight Glare Probability (DGP) [6], both measured at the eye level of the participant right after the exposure. We performed the measurements for these metrics right after each exposure by positioning the camera at the location of the participant's head. We derived DGP by running Evalglare (v 3.02) [14,15] on the calibrated HDR images captured after each condition (see examples in Figure 2). For Ev, we will refer to the value measured with the handheld illuminance sensor (fixed right next to the calibrated HDR camera). We used the second handheld illuminance sensor to measure desk level illuminance.

Table 1 provides an overview of the main subjective questions asked of participants. Subjective ratings for discomfort glare perception were collected based on two scales: the binary and the ordinal Osterhaus-Bailey scales [16]. The survey also included questions about light level sensation (7-point scale), visual comfort (4-point scale), blind preference, and motivations for changing blind position (multiple choice).

2.6. Statistical methods

Objectively measured data are displayed using box-plots, subjective responses using alluvial and bar plots. In addition, we compared conditions A and B by means of statistical significance and effect size tests. We relied on the Shapiro test to test the normality of the data. We used R (v.4.0.3) and Rstudio (v.1.3.1093) for these analyses.

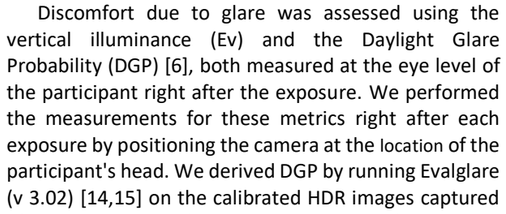

Figure 2: Fish-eye Luminance map from the participant's eye position after the testing. Condition A (left) & B (right))

Table 1: Details on the survey questions

Type	Question	Answer scale
Glare binary	"At this time, do you experience discomfort from glare?"	Binary scale: Yes/No
Glare Osterhaus	"How would you describe the level of glare in your field of view?"	4-point ordinal scale: "Imperceptible", "Noticeable", "Disturbing", "Intolerable"
Light levels sensation	"How do you feel about the light level in your desk?"	7-pt scale from "very low" to "very high" with "just right" in the center
Visual comfort	"How do you find the general visual environment in the room?"	4-pt Likert comfort scale: From "Very uncomfortable" to "Very comfortable" without central point
Motivation for change	"Why did you change the position of your shading device?"	Multiple choice (check all that apply): - I liked to have a change - More light in the room - More light on my desk - More light on my screen - A better view out - Other (free text field)
	"Why did you decide *not* to change the position of your shading device?"	Free text field

3. RESULTS

Eighteen of the 24 participants (75%) raised the shading fabric up at the beginning of condition B. The height to which the roller blind was raised was on average of 25 cm above the sill (median 21 cm, SD 22 cm), which corresponds roughly an angle of 10° vertically, seen from the users' perspective.

3.4. Participants' motivations for controlling blinds

Participants were asked to indicate their motivation for controlling or not controlling the blinds, based on suggested answers and free text fields (see Figure 3). The primary motivations for raising the blinds were "more light in the room" (15/18 participants) and "be able to see outside / better view out" (14/18). Some participants also indicated that they wanted more light on their desk (5/18) and/or wished for a change (5/18) (to be noted that the participants were exposed to a total of 5 sessions and only the two last are reported in this study). Additional answers based on free text fields showed that one participant wanted a warmer space.

Reported reasons for not raising the blinds indicate that participants found the conditions too bright (3/6) and/or that the conditions were good and did not bother them (2/6). One person stated that the view out (car passing) could bring them out of focus. Finally, one person indicated having gotten used to it and thus preferring to keep it that way.

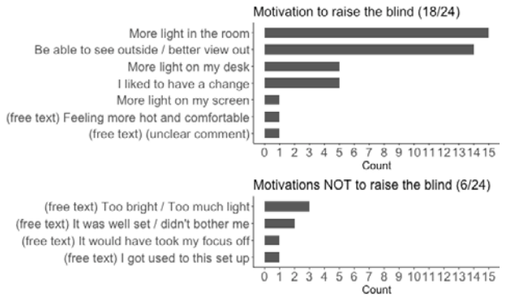

Figure 3: Motivations behind blinds actions/inactions

3.1. Glare

Figure 4 shows boxplots of DGP (top) and Ev (bottom) for each condition. We observe different trends between the metrics: while Ev significantly increased between conditions A and B (increase in mean by a factor of 1.8, p=0.0063, ρ=0.4), DGP did not show statistically significant differences between the two conditions (p=0.56). This result highlights the difference between the metrics: Ev, which is based only on saturation is not able to account for the decrease in contrast between the two conditions, differs from DGP, which involves both terms, accounts for changes in contrast.

Figure 6 show the spread and change in the participants' responses for the binary and Osterhaus glare questions for conditions A and B. We note that the number of participants having experienced glare (i.e., answering 'Yes' to the binary glare question) and finding it uncomfortable (i.e., answering 'Disturbing' or 'Intolerable' to the Osterhaus glare question) remained the same across conditions A and B, with only a few participants changing their minds. Statistical tests did not show any difference in the subjective responses across conditions.

We note that the two scales do provide different reading of the glare experience: from uncomfortable (binary) to disturbing (ordinal). The binary scale seems more sensitive and could lead to overprediction considering that positive responses often correspond to "noticeable glare" in the ordinal scale, and rarely to "disturbing glare."

3.2. Desk illuminance

Figure 5 shows boxplots of desk level illuminances for each condition. The measured levels significantly increased from conditions A to B (increase in mean by a factor of 2.5, p<0.0001, ρ=0.57). This output follows Ev, which is not surprising given that the two metrics are using the same physical quantity, just measured at different locations and in different directions).

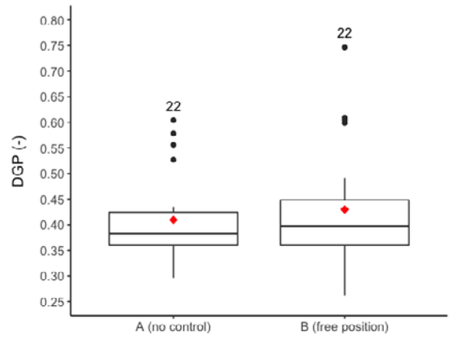

Figure 4: Boxplot of DGP (top) and Ev (bottom) for each condition. The diamond indicates the mean and the number the sample size. Ev is represented according to a logarithmic scale

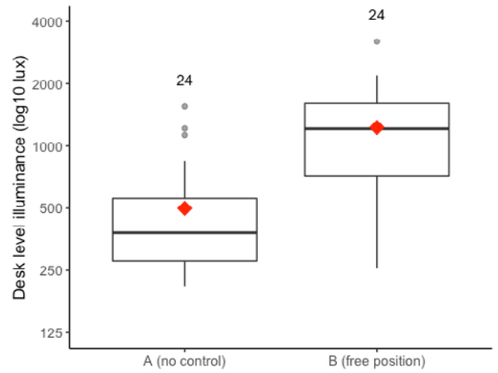

Figure 5: Boxplot of desk illuminance for each condition represented on a logarithmic scale. The diamond indicates the mean and the number the sample size.

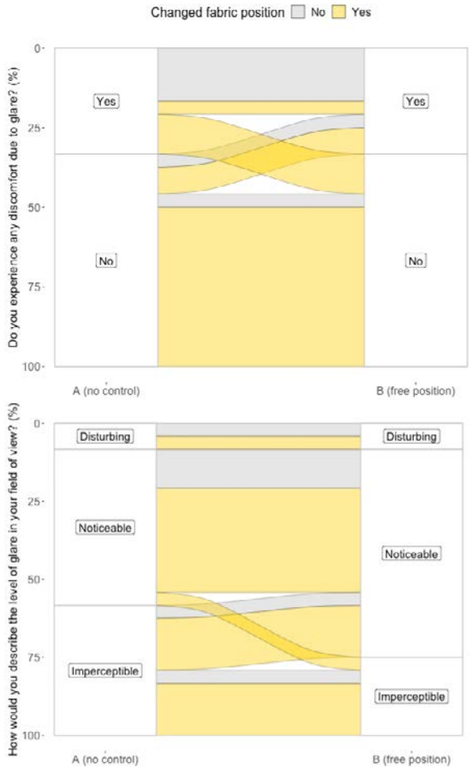

Figure 6: Alluvial plot showing the spread and change in occupants' responses for binary (top) and Osterhaus (bottom) glare question across conditions. The yellow band represents the share of participants having modified the fabric position.

Figure 7 (top) shows the spread and change in the participants' responses for the light level sensation questions for conditions A and B. While the measured values increased threefold between conditions A and B, only two participants (8%) changed their light sensation ratings. In addition, only 5 participants (20%) reported either 'slightly low' or 'low' light sensations while wanting more light was the primary reason for opening the blinds. There was no statistical significance with respect to the sensation of light level experienced by the participants between conditions A and B.

3.3. Visual comfort

Figure 7 (bottom) shows the spread and change in the participants' responses for visual comfort questions for conditions A and B. This time, 7 participants changed their rating across the two conditions: five positively (from 'uncomfortable' to 'comfortable' and from 'comfortable' to 'very comfortable') and two negatively (from 'very comfortable' to 'comfortable'). This change in visual comfort sensation suggests that participants were slightly more satisfied with condition B, but this trend was not confirmed by statistical tests (p=0.37).

We note that comfort levels were already high in condition A: it would therefore have been surprising if the extra control given to participants had reduced this trend. In fact, it increased it, but only marginally. This result shows that the fabrics with low OF were successfully capable of ensuring visual comfort under clear sky conditions and critical sun angles.

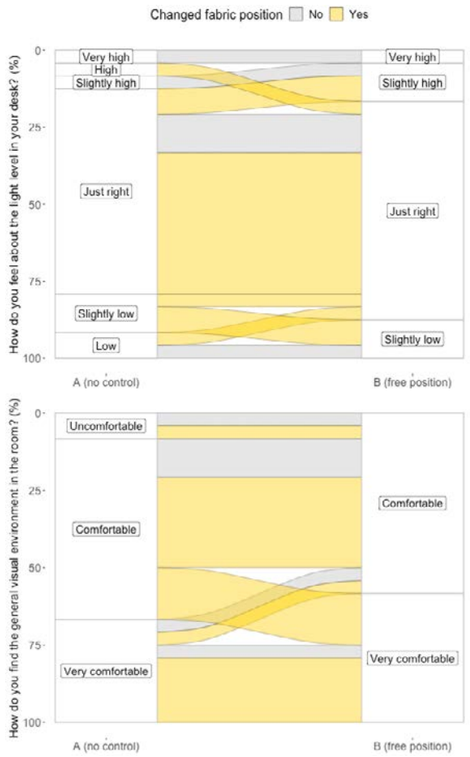

Figure 7: Alluvial plot showing the spread and change in occupants' responses for light level sensation across conditions (top), and for visual comfort (bottom) across conditions. The yellow band represents the share of participants having modified the fabric position.

4. DISCUSSION

The conditions tested caused both contrast and saturation glare. While Ev is able to capture the increase in global illuminance due to many participants raising the blinds (saturation effect), this metric was not able to capture to reduction in contrast of condition B, which plays an important role in discomfort glare perception. Yet, the conditions in this experiment remain 'transition' conditions, where both contrast and saturation play a role. Our analysis shows that metrics that take into account contrast (such as DGP) provide a much better representation of the user's perception of glare in the case of shading fabrics.

The literature had highlighted the presence of a possible 'forgiveness factor' for discomfort glare in the case where occupants are provided with a satisfactory view to the outside [17]. We could not observe this forgiveness effect that would potentially have resulted in a lower glare perception in condition B, considering the DGP value was rather constant between A and B. Yet, our experiment was not designed to emphasize the forgiveness effect. Indeed, conditions A and B were not randomized and the fabric remained the same, hereby providing the opportunity for participants to remain on the same subjective assessment of glare. Possible forgiveness mechanisms, by definition unconscious, therefore could not take place. Conversely, the fact that neither the subjective responses nor the DGP increased does not necessarily imply the absence of forgiveness.

Despite the partial opening of the blackout curtain of the Northern side during some sessions, the illuminance levels on the desk remained oftentimes below 300 lux. Although this study did not focus on illuminance per se, it is important to note that fabrics with low OF and Tv were not able to provide the desired illuminance levels when fully down despite the clear sky conditions. As such, the fabrics cannot provide adequate daylighting if fully lowered. In order not to fall into the paradox of using artificial light when it is very bright outside, the use of such fabrics should be accompanied by the adoption of control strategies that allow for partial opening and closing. As observed with the glare assessments, such as strategy would not necessarily result in increased glare.

Participants raised the roller blind to an average height of 25 cm above the sill, which represents roughly 10° of view angle to the outside. Although this represents a relatively low angle, for most participants it allowed them to see some of the ground and landscape layers. None of the participants raised the blinds in a way that direct sun would be in their field of view. Considering the clear sky conditions necessary for this experience, participants had to find a balance between view-out, illumination and glare.

5. CONCLUSION

This study focused on visual comfort and blind control for shading fabrics with low OF. It involved two conditions, namely condition A, where the roller blind was set down, and condition B, where participants could control the height of the fabric shading at the beginning of the exposure. Three quarters of the participants decided to partially raise the blinds in the second condition primarily to increase the brightness in the space / their desk and to have a view to the outside. Discomfort glare assessments showed that participants did not substantially change their perception between conditions. This result was in line with glare predictions according to the DGP, where the increase in the saturation was counteracted by the decrease in contrast, but not according to Ev, which only relies on saturation.

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Comparative overview of lighting credits from WELL environmental assessment method

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ABSTRACT: Beyond an energy-centric perspective, Building Environmental Assessment Methods (BEAM) may contribute to the achievement of healthier indoor built environments, allowing building sustainability to reach its full potential as a public health transformation tool. The objective of this paper is to characterize WELL V2 by means of two-stage heuristic analysis method (i.e. based on expert criteria): (i) a qualitative screening based on seven dimensions of analysis and (ii) a 0-100 quantitative assessment of nine dimensions of analysis. Our first stage results showed that WELL fulfilled all of the proposed criteria for other more established BEAM. Stage two results showed an overall score of 68, below LEED and BREEAM scores from the literature, and above CASBEE, HK-BEAM, and GREENSTAR. In terms of applicability, WELL lacks of lifecycle related criteria. WELL V2 showed a good comparative performance among BEAMs, placing it as a seminal method for the creation of new and more suitable wellbeing and health labelling systems, mimicking the role BREEAM played at the end of the 20th century.

KEYWORDS: Integrative Lighting, Environmental Assessment Method, Overview

1. INTRODUCTION

Some of the greatest challenges that humanity is facing today are environmental degradation, overuse of limited resources, and climate change [1].

Potential consequences for life on our planet are driving a paradigm shift regarding how we live, work, and consume, demanding actions to prevent and mitigate damage and promoting sustainable development. The response to this challenge from a built environment perspective was green building design. In the 1990s, the Building Research Establishment Environmental Assessment Method (BREEAM) from England was the first initiative to establish an objective and comprehensive method to simultaneously evaluate a wide range of environmental considerations in relation to explicit criteria and summarize them in a label as a global measurement of environmental performance. The objective of Building Environmental Assessment Methods (BEAM) was to promote a change in the construction industry, encouraging the development of sustainable constructions and to transform the market, which would see an increase in the real value of buildings with certified better environmental attributes [2].

Initially, these methods were conceived as voluntary in their application. With several countries selecting or developing their own BEAM, the authority is gradually adopting these tools to establish minimum legal requirements for environmental performance. Beyond a reduction in energy use and a higher market value, BEAM´s main strength may be the achievement of healthier indoor built environments, allowing building sustainability reach its full potential as a tool for transformation of public health [3].

Within the BEAM Building Environmental Assessment Methods, a new tool called WELL was created in 2014. It aims to asses interior spaces from a more comprehensive view, taking into account well-being and health of the occupants.

There are ten concepts (i.e. dimensions of analysis) in WELL v2: air, water, food, light, movement, thermal comfort, sound, materials, mind, and community. Each one of them intends to address specific aspects concerning health and well-being of community members. Its latest version added a new concept, called Innovation, so that projects can earn additional points for this item. Each WELL concept consists of features with distinct health intents (i.e. goal). Features are either preconditions or optimizations. All preconditions – including all parts within them – are mandatory for certification, while Optimizations are optional pathways for projects to meet certification requirements. Project teams may select which optimizations to pursue and which parts to focus on within each optimization.

WELL v2 operates on a points-based system. In the WELL universe, each concept has a different incidence in the total. Each of the concepts is given a particular valuation. All optimizations are weighted with varying point values. The maximum point value of a feature is determined by the sum of its parts. A part is weighted by its potential for impact, defined as the extent to which a feature addresses a specific health and well-being concern or opportunity for health promotion, and the potential impact of the intervention (table 1).

Table 1:
WELL v2 concepts, preconditions, optimizations and score.

Concepts	Preconditions	Optimizations	Score
AIR	4	10	18
WATER	3	6	14
NOURISHMENT	2	12	16
LIGHT	2	7	18
MOVEMENT	2	9	21
THERMAL CONFORT	1	8	16
SOUND	1	8	18
MATERIALS	3	9	18
MIND	2	9	19
COMMUNITY	4	14	39
INNOVATION	0	6	28

Projects must achieve all preconditions, as well as a certain number of points towards different levels of WELL Certification. Table 2 shows thresholds to achieve Bronze, Silver, Gold, and Platinum categories. The difference in score between one category and another is 10 points, except for Platinum, which requires 20 points.

Table 2:
WELL v2 scores and categories.

Total points achieved	Minimum points per concept	Level of certification
40 pts	0 pts	WELL Bronze
50 pts	1 pts	WELL Silver
60 pts	2 pts	WELL Gold
80 pts	3 pts	WELL Platinum

This article will analyze the WELL methodology to determine if it can be considered as other widely known and installed systems such as LEED, BREEAM, CASBEE.

2. METHOD

We carried out a two-stage overall assessment: First, a qualitative screening based on Fowler & Rauch exclusion criteria [4] that organizes, concentrates and sequentially filters the existing information on classification systems in seven dimensions: Applicability, Development, Usability, System Maturity, Technical Content, Measurability & Verification, and Communicability. Secondly, a quantitative assessment based on [5], where a 0 to 100 score is obtained from the following dimensions: Popularity and Influence, Availability, Methodology, Applicability, Data Collecting Process, Accuracy and Verification, User-friendliness, Development, and Results Presentation. The core of both stages is heuristics, an assessment approach widely used in the field of human factors and ergonomics. A heuristic evaluation verifies whether a set of desirable principles (i.e. heuristics) are met according to the expert criteria of the evaluator.

Heuristic evaluation is the most commonly used usability inspection method. It became popular in the early 1990s because of its speed, cheapness, and ease of implementation. It could be performed by only 4–5 evaluators who, managing a limited set of principles to detect a high proportion of usability problems. In other words, each evaluator inspects the designed system or artefact alone and judges its compliance according to a set of usability principles. Heuristic evaluations can be implemented quickly and conveniently through a competent pool of evaluators and the most well-known heuristic principles are the 10 ones developed by Nielsen (1992) [6].

In this paper, our sources were WELL experts and the official WELL technical documentation.

3. RESULTS

Table 3 shows stage one results of the following dimensions of analysis:

Applicability. This criterion encompasses two aspects: (i) Type of Projects, e.g. New Construction, Major Renovations, Tenant Build-Out (leases), and Operations & Maintenance; (ii) Type of Buildings, e.g. Office Buildings, Courthouses, and Border Stations. WELL complies with this dimension.

Development, including: (i) System Management, which identifies the involvement level in the development, funding, and management of the rating system by Government, Private Industry, Non-Governmental Organizations, and others; (ii) Development Approach, which Identifies if the system was developed using a consensus-based approach, life cycle analysis, expert opinion approach, or other.

Table 3:
Stage one qualitative screening.

Dimension	Criteria met	Assessment
Applicability	(2/2)	Designed for indoor spaces, it adapts to different kind of projects.
Development	(4/6)	Development included different actors and scientific and technical knowledge
Usability	(3/3)	Cost, ease of use, and online assistance are identified
System Maturity	(3/3)	Available information on system age, number of buildings, and stability is enough
Technical Content	(3/3)	Its ten modules are relevant and comprehensive
Measurability & Verification	(5/5)	System based on performance. Each project is assessed in field.
Communicability	(3/3)	Results are measurable, comparable, and identifiable in ten offline modules.

In WELL, the participants are private, scientific, and others, without government intervention. It is based on expert consensus. As a drawback, it lacks of life cycle analysis.

Usability. This dimension summarizes data related to: (i) Cost of using a system, including cost for use or rating system materials, cost of project registration, fees associated with certification, and time typically needed to complete an application. (ii) Ease of Use: Complexity of the tools and technical knowledge needed to complete rating system process, especially for the optimization of energy use, environmentally preferable products use, and indoor environmental quality enhancement. (iii) Product support: Availability and responsiveness of direct requests for assistance, availability of training, and usability of information available on the website, through case studies, documented inquiries, and frequently asked questions.

WELL has product support: availability and responsiveness of direct requests for assistance, availability of training and usability of the information available on the website, through case studies, documented queries and FAQs.

System Maturity: It is analyzed from three points of view: (i) System Age: Identify when the rating system was developed, first used, first available for public use, and when the most recent revision was completed. (ii) Number of Buildings: Identify the number of buildings participating in the rating system and the number of buildings that have completed the process for denotation as a green building. (iii) Stability of system: Identify the processes that allow for full implementation of a rating system, including development, testing, and review process, systems for upgrades, process for modifications, and the expected frequency of modifications.

WELL could be evaluated in all of these terms, giving results like the other certification systems evaluated by Fowler & Rauch. Updated information on this is available on the official WELL website. Such as age of the system, square meters and certified buildings among various inputs regarding this topic.

Technical Content: Where a sustainable building design guide is identified. Having a detailed review of how the rating system addresses the key features of sustainable design, optimization of energy use, use of environmentally preferable products, and improvement of indoor environmental quality (IEQ). There are ten concepts in WELL v2, these lead to a study of the points mentioned in technical content, such as efficient use of water, indoor air quality, measurement and review.

Measurability & Verification: This section discusses about standardization, quantification, verification process, and documentation.

WELL is a performance based system and each project is verified by on-site testing of the building which makes the system measurable and verifiable. Within all categories, there are items and each one has a number of points to achieve. Projects seeking WELL certification can earn points based on performance results for various policies, design and operational strategies and can achieve one of four levels of certification: Bronze, Silver, Gold or Platinum.

Communicability: Clarity, versatility, comparability, and results usability are evaluated in this area.

WELL presents its well-defined results in ten measurable concepts, which allows them to be perfectly identifiable, measurable, and comparable with others. They are not available online, they must be requested. They are clear to be integrated, and they are susceptible to normalization in order to make comparisons between different types of buildings, stay, years, or different characteristics of sustainable design. The results allow the usability of the rating system documentation to communicate the achievements of the construction project.

Our results show that WELL fulfilled all of the proposed criteria as well as other more established BEAM [3]. Having successfully pass this screening stage, we proceeded to stage two. To perform a quantitative evaluation based on the criteria proposed by Nguyen & Altman (2011), where nine aspects are evaluated, and each one has an assigned score, adding up to 100 points. Table 4 shows stage two quantitative results based on [5] assessment method.

Popularity and influence, we rated WELL 8 out of 10. This aspect includes parameters such as being well known, importance, number of cities or countries where it is applied and its versatility. WELL gives a similar evaluation to older systems.

Availability, obtaining a score of 7 out of 10, WELL obtained the same results as more established systems, evaluating aspects such as costs, ease of access to information, availability of information.

Methodology, reached 9 points of 15, based on *how* are the methodological aspects to apply the scores, quantitative and qualitative evaluations, efficiency of the methods used, scoring levels, life cycle analysis. Here there are points such as life cycle that are not evaluated in WELL, which determined a lower score.

Applicability, we assigned 7 points on this dimension, resulting in a poor performance on this specific item because we identified two issues. On the one hand, the lack of life cycle analysis, and on the other hand, aspects that have to do with the economic part, social aspects, quality of life, the latter being addressed by WELL.

Data Collecting Process scored 9 out of 10. In relation to data collection, including data gatherers, formatting, and information presentation, among others, WELL has clearly defined and organized these procedures. Therefore, it achieves a good performance.

Accuracy and Verification, scored 8 out of 10 considering data collection and evaluation, and the training of WELL experts. WELL trains professionals for these tasks and once they submit their assessments, audits are carried out. This contributes to reliable assessments.

User-friendliness, WELL got the highest score in terms of availability and responsiveness of direct request for assistance, questions, registration of queries, available courses, training sessions, clarity of instructions. Being at the level of more established BEAMs such as LEED.

Development, scored 7 out of 10, taking into account the maturity of the system and its upgrades. The relative youth of WELL and the lack of a future life cycle assessment perspective, led to a lower performance in this item.

Results Presentation, scored 3 out of 5. This item takes into account the system´s reachable levels, the clarity of their descriptive information and whether it can be compared with other systems or not. Since WELL is targeted to occupant´s well-being, it cannot be compared to other BEAMs, which are aimed to energy performance assessment.

Table 4:
Stage 2 WELL quantitative results

Categories	LEED	CASBEE	WELL
Popularity and Influence (10 p)	10	6	8
Availability (10 p)	7	7	7
Methodology (15 p)	10	13	9
Applicability (20 p)	13	11.5	7
Data Collecting Process (10 p)	7	6	9
Accuracy and Verification (10 p)	7	9	8
User-friendliness (10 p)	10	6	10
Development (10 p)	8	7	7
Results Presentation (5 p)	3	4	3
Final Score (100)	75	58	68

Table 4 also shows, for the sake of comparison, LEED and CASBEE results from [5]. The former presented the highest (75 points) scores while the latter showed the lowest (58 points) scores. Our results place WELL between CASBEE and LEED, and according to [5], below BREEAM (75 points), and above HK-BEAM (66 points), and GREEN STAR (60 points). The worst WELL performing dimension in relation to other BEAM was Applicability, probably because WELL does not consider the whole lifecycle of the building.

4. CONCLUSION

We carried out a two stage comprehensive characterization of WELL V2 rating system based on two previously published papers [4,5]. Our results showed that a non-energy based BEAM such as WELL can be assessed using the same criteria of other well established BEAM. It met Fowler & Rauch inclusion criteria and hence it was eligible for a quantitative assessment [5], where it achieved a score of 68 points.

Its performance was among other more consolidated and updated BEAMs, such as LEED, CASBEE, or GREEN STAR. This not only positions WELL as a proper BEAM but also it can be

considered a seminal method for the creation of new and more suitable wellbeing and health labelling systems, correlating the role BREEAM played at the end of the XX century. As a drawback, both [4] and [5], and ourselves in this exploratory analysis, performed a sole-expert heuristic assessment. It is recommended to perform such methodology in groups of experts, to reach a consensual homogeneous result.

CONFLICT OF INTEREST STATEMENT

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Will Cities Survive?

The changing needs in residential design post-pandemic

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ABSTRACT: As people's needs from their homes have changed due to COVID-19 pandemic, the design of homes will also have to change for the future. Flexible and adaptable spaces have become more important. There has also been a shift from apartments to houses as people sought to move away from constrained dwellings to larger (and sometimes cheaper) homes out in the suburbs. The importance of mental health and general well-being also emerged as the effects of isolation were experienced. This study seeks to explore how people's lifestyles and needs may have changed after the pandemic and how this change could bear impact on future design and master planning of residential buildings and new developments. The research adopts a mixed method design, based on a questionnaire survey, to gain more insight into occupants' experiences with their homes, behaviours and needs post pandemic. The case study is the first phase of a new residential development in Kent, UK. Survey results show that 77% of respondents started working from home due to lockdown, with 37% of them making changes to their internal home layouts. Changes made were mainly for work/study space, and/or exercising space/ gym equipment. Further results and analysis are hereby discussed.
KEYWORDS: Residential design, Post-pandemic, Wellbeing, Outdoor spaces, Lifestyle

1. INTRODUCTION

In 2019-2020, the world was hit by the global pandemic of COVID-19 disease, which has had detrimental health, social and economic impacts on all nations. In mitigating the spread and impacts of the pandemic, new norms and lifestyles evolved; such as social distancing, and self-isolation which led to minimal human physical interaction. With people confined in their homes, and new lifestyles developing, their spatial needs changed where, flexible and adaptable spaces have become more necessary [1, 2]. The need for more space also became more essential, where a notable shift from apartments to houses became more evident as people sought to move to larger homes, with more private outdoor space in the suburban areas. Houses also offered more privacy and health risk control, compared to apartment blocks [3].

As people have become more confined to their homes, going outside became more important to their mental health. The use of open spaces and affiliation with nature helped people maintain their health and wellbeing and proved to be especially beneficial in mental and cognitive development of children during lockdown [4]. A survey in several countries indicated that frequent park visits improve the quality of life and helps reduce health-related issues [6]. Views of greenery and the clear sky are also very effective in restoring the sense of self-esteem, as shown in a recent study [7]. Ensuring open spaces are large enough and varied to accommodate social distancing measures as well as users' needs when designed in the future will be vital [5]. This study seeks to explore how people's lifestyles, needs and preferences may have changed as a result of COVID-19 pandemic and how this change could bear impact on future design of residential buildings and master planning of new developments. The paper starts with the research context and background, followed by the research methodology, results and discussion, and ends with some reflections for future research.

2. LITERATURE REVIEW

The COVID-19 pandemic led to the generation of the social distancing measures, or the 'new normal'. This meant physical isolation, and minimal social interaction, leading to almost full reliance on virtual communication methods [8], including virtual meetings and social media platforms. People of all ages felt mandated to get more used to living in virtual worlds, within the confined spaces of their homes. Furthermore, adaptability and flexibility within domestic spaces to allow for the abrupt changes in daily routines and lifestyles; including working and studying from home became key for the then unprecedented times. More focus shifted towards maintaining one self's health (physical and mental) and wellbeing by spending more time in outdoor spaces, gardens and parks, often referred to as restorative environmental design [3]. There has also been evidence of shifts towards sustainable lifestyles and pro-environmental behaviour [9].

2.1 Post-pandemic changes to homes

As people became more confined to their homes for long durations; many opted to (re)create spaces to

suit their new lifestyles. People reinvented the spaces that they could no longer go to within their own homes. Spare rooms were transformed into office / study space or spaces for leisure / exercise [10], whilst balconies and front doors became socially distanced socialising spaces [11]. A home was no longer a 'centre for departure and return' but had to become a 'mini city' [1].

For working families, work and/or study spaces were the primary areas created during lock down periods. Depending on the number of people residing in the dwelling, it was found that either more enclosed spaces were created or spaces were opened to create larger, more open plans/rooms. For families, setting up separate spaces for each individual was a priority, ideally with good acoustic control so as not to be disturbed with background noise whilst at meetings or in lessons [1, 2]. Privacy was an amenity sorely needed as one could not retreat elsewhere as most spaces within a home became more intensely used and shared. As a result, some furniture was discarded or stowed away to make more internal space, in many homes (1).

As many people became less physical, a need for exercising was identified as vital to help reduce potential health risks such as obesity, depression, insomnia, and dementia [6]. Whilst most of this was achieved outdoors through walking and cycling, indoor spaces were also created for home workouts, and simple gym equipment [1, 2]. The kitchen was another space where more time was being spent as people had to cook more due to restaurant and fast-food outlets closure. A study involving a survey found that a lot of kitchen surfaces, such as countertops, were replaced during the pandemic, due to more intense usage. There was also more evidence of do it yourself (DIY) interventions within homes to accommodate the changes needed. Some concerns were raised by respondents concerning sink sizes and general kitchen area as it was realised to be limited for everyday and all-day comfortable use [12].

2.2 Value of outdoor space

It has been asserted that the extended durations of lockdown led to more people developing symptoms of psychological disorders at various levels such as anxiety, stress, emotional fatigue and depression [3]. Moreover, the pandemic exacerbated the issue of health inequalities, where research identified particular groups most at risk from mental health conditions during and post pandemic, including young adults, women, those with pre-existing mental health conditions, those from minority ethnic backgrounds, and people experiencing socio-economic adversity [13, 14].

Balconies, private gardens, and doorways became central threshold spaces transformed into gathering points, activating private and semi-public spaces to communicate with neighbours and engage with nature [3]. As loneliness and stress levels increased during the pandemic due to isolation, it was proven important to connect with nature in some ways [7]. People could no longer meet indoors, hence the only way to socialise was in public spaces, whilst maintaining social distancing measures. Green spaces have been proven to help improve mental health, reduce anxiety, encourages physical activity, and distanced social interaction [6].

2.3 Sustainable Behaviour and Lifestyle

Undoubtedly, the pandemic led to significant changes in social behavioural patterns catalyzed by fear, panic stress and anxiety [15]. This included more reliance on private vehicles for commuting, over-consumption of water and exploitation of single-use plastics for sanitary purposes, besides production of large volumes of health-care waste (including disposable face masks, gloves, antiviral wipes, etc.) [9].

However, other studies also suggest that the pandemic acted as a turning point concerning the public considerations for environmental protection [15]. It has been asserted in various studies that the pandemic outbreak has led to higher awareness and knowledge about environmental problems, thus activating people's consciousness and attitudes towards environmental protection and the development of more pro-environmental behaviors [15–17). Those pro-environmental behaviors included reducing waste, recycling, composting, and actions contributing to reducing energy consumption. Notably, some of those behaviors may be attributed to socio-economic factors, such as loss of jobs or income, and not necessarily to environmental concern [17].

3. RESEARCH DESIGN

The study is novel in that, to date, few studies exist which focus on people's shifting needs post COVID-19 [1, 2]. The research adopts a mixed method design, based on a questionnaire survey, that aims to gain insight into occupants' experiences with their homes, behaviours and needs post COVID-19. The case study is the first phase of a new residential development in Kent, UK; designed by BPTW Architects, and comprises of around 1,400 homes (a mix of 1, 2 and 3 bedrooms) built across seven development phases.

Fig 1: One of the Riverside elevations which comprises pitches that rise towards the River Medway (BPTW).

Open spaces have been embedded in the plan to provide a series of spaces along the riverfront that may be used for various purposes. The masterplan of the development includes substantial recreational outdoor spaces, waterfront settings, landmark buildings and quieter residential areas (Figs 1 and 2). The existing Riverwalk is enhanced to improve the public realm and landscaping and provides a more welcoming experience for visitors and occupants within the development.

Fig 2: The development master plan (BPTW)

The development has been designed to be flexible where there are designated areas designed to accommodate a higher density of housing of up to 22%. "*By carefully considering and designing in the flexibility to both increase and decrease heights and density at certain points, and designing the parameter plans to reflect this, it creates a scheme that is responsive to the local needs and pressures of Rochester as and when they change during the lifetime of the project*." (BPTW Rochester Riverside - Design + Access Statement)

The buildings are designed with a energy efficient measures that reduce energy demands and associated carbon dioxide emissions. Measures include well insulated fabric elements, high efficiency glazing, high levels of air tightness and energy efficient lights and appliances.

3.1 Survey Design

The questionnaire was developed through a series of consultations among the researchers, Countryside Properties, and BPTW Architects prior to it being piloted with a few participants. Their suggestions and feedback helped improve and finalise the questionnaire form. For example, a few questions were simplified, and the follow-on questions were further structured to provide meaningful data. The questionnaire was designed into five sections: Lifestyle and wellbeing, Experience of home in the summer, Experience of home in the winter, How people use their homes and open spaces, and Basic information (Table 1).

Before the launch of the survey; leaflets describing information about the research project and the potential benefits participants could get were distributed to all homes in order to inform residents about this initiative. The questionnaire was then distributed via a link sent to residents' emails from the property developer. Residents were also sent reminders to encourage them to complete the survey. Quantitative and qualitative data were obtained from the questionnaires for analysis.

Table 1: Summary table of the questionnaire

Section	Questions Overview
1. Lifestyle and wellbeing	Levels of activeness
	Ownership of vehicle(s) and type
	Sustainable lifestyle
2. Experience in Summer	Levels of comfort (air temp. and ventilation)
	Air flow control
	Need/usage of cooling systems
3. Experience in Winter	Levels of comfort (air temp. and ventilation)
	Air flow control
	Need/usage of secondary heating systems
4. Your home	Satisfaction with home layout pre-COVID
	Non-COVID related changes to internal layout
	COVID19 related changes to internal layout
5. Open spaces and facilities	Satisfaction with gardens/balconies
	Use of shared open spaces
	Quality and quantity of open spaces
6. Additional information	Type and size of home and duration of residence
	Gender, number of members & age group
	Economic status & income

3.2 Survey Response and Analysis

The survey link was shared with 150 residents of the first phase within the development between 1-31 August 2021. A total of 35 responses were received, which comprises a 25% response rate. As for the statistical analysis, IBM SPSS (Statistical Product and Service Solutions) Statistics Version 27 (IBM Corp., Armonk, NY, USA) is used to perform descriptive analyses. Chi-square statistical analyses is applied to further investigate associations and correlation between variables.

4. RESULTS AND DISCUSSION

Almost half the respondents have lived in their homes for 12-18 months while the other half have lived for less than 12 months, hence all respondents have lived in their homes during the COVID-19 lockdown(s). The results hereby discussed focus on the analyses of sections 1, 4 and 5 of the questionnaire as per the focus of the paper (as in Table 1).

4.1 Changes due to COVID-19

Initial results indicated that 77% of households started working from home due to COVID with a total number of 42 people working from home in 27 households. By applying Chi-Square test, a significant association (p-value 0.04 < 0.05) appears between those who started working from home and making changes as a result. 37% of those who started working from home have made changes to their internal home layouts to accommodate their new routine. Only 5 households reported children studying from home, which relates to the demographic profile of respondents as couples or young families where the age range of more than half the residents within the survey is 25-44 yrs.

Changes done to accommodate working/studying from home depended on the number of occupants, and type and size of home. For example, several respondents dedicated a bedroom / spare room as a study / office room, while a few others converted their garage to office space, and a few adjusted their bedrooms to accommodate workspace. Three respondents indicated they converted garages or lofts, and/or garden room(s)to create more room space. Several respondents realised they needed more storage space and decided to invest in more shelving, cupboards, fitted wardrobes and storage units. Notably, respondents who reported they made changes within their homes due to COVID would still purchase their homes now. This indicates that internal changes to layouts or usage of spaces during lock down, would not be considered major changes that would require a completely different home. Moreover, only 17% of respondents indicated they intended to make changes to their homes, non-related to the pandemic. Examples of those changes are; new kitchen sink, converting large cupboards to wardrobes, and garage and loft conversions.

The importance of daylight has been highlighted particularly during lockdown. Only 9% of respondents indicated they were unsatisfied with window sizes in their homes; whereas 91% indicated they were very satisfied or satisfied with their window sizes. Those satisfied, mentioned their window sizes allowed ample natural daylight into their habitable spaces which had a positive impact on their mental health and a feeling of spaciousness. 16% of respondents indicated the window sizes allowed for good views across the development and beyond. Those unsatisfied with their home window sizes, indicated the issue of maintenance and cleaning as well as large unopenable panels were limitations.

As only 28% of respondents indicated they plan to live within the development for more than 15 years, whereas all 72% planned to reside for less than 15 years, with 31% planning to stay between 5-10 years, this may need consideration as to providing more flexible and adaptable homes. Several respondents suggested for future design, more 'age-friendly' design would be preferred, which may explain the results above.

4.2 Open spaces

Concerning open spaces, 46% of respondents have private gardens, 44% of whom are satisfied or very satisfied with the size of their gardens. 86% of those who are satisfied or very satisfied with their gardens use them once a week. 65% of respondents have balconies, of which 61% are satisfied or very satisfied with the size of their balcony. Around half respondents who have balconies use them regularly (once a week), while a quarter use them occasionally.

Concerning activity levels, 20% of respondents reported they would normally exercise at home, while 45% reported they would normally exercise in the outdoor spaces within the development. One third of those who reported they normally exercise at home suggested the open plan layout enables them to exercise at home, and they would not consider internal layout change. 83% of respondents indicated they would use the Riverwalk, once open, fairly regularly or regularly. 85% of respondents indicated they felt the proximity to the waterfront positively affects their health and wellbeing. This indicates the importance of outdoor spaces during and following the pandemic in people's activity levels and sense of wellbeing.

Around 63% indicated they were comfortable in using shared open spaces (surfaces, footpaths, green areas) within the development for exercise. Notably, 69% of those who responded they were uncomfortable to use shared spaces for exercise, indicated they will be encouraged to be more active if there is a designated indoor space for exercise within the development. A few respondents suggested that some outdoor gym equipment would help residents become more active. A few other respondents mentioned having designated cycle lanes would encourage safe walking, and further maintenance to the softscape would improve the quality of open spaces. Only 29% of respondents indicated they were satisfied with the quantity of open spaces, whereas 56% indicated they were satisfied with the quality of open spaces. This indicates people value the sizes of open spaces, as a means to accommodate their needs and activities. People are also aware that visiting greenspaces helps their sense of life satisfaction, self-esteem, and happiness [7].

4.3 Sustainable lifestyle

The survey focused on further understanding people's possible changes to lifestyle related to sustainability that may be associated to the pandemic. Notably, only 26% would consider cycling instead of using their vehicles to commute, although 54% indicated they own a bicycle but only half of them felt comfortable to store it in the shared cycle storage due to concerns about security, and potential impact on longevity of the bicycle. Only 14% would consider car sharing, while 69% would occasional and regularly use public transport (28% use it almost at a daily basis). However, only 14% would consider selling their car to use more public transport post-COVID, which may indicate that the majority would still prefer owning a private vehicle. Two respondents reported they purchased a private vehicle due to concerns over virus transmission. 87% of respondents owned a conventional petrol/diesel vehicle whereas only 13% owned a full electric. Notably, 77% would consider owning a full electric/hybrid vehicle in the near future, near half of them would do so due to environmental concerns, while nearly a quarter would consider this for financial savings in the long run.

Moreover, 91% of respondents would walk instead of use their vehicles. This may indicate people prefer walking to cycling, due to practicalities and less hassle compared to cycling. Notably, 86% of respondents would frequently recycle waste, while only 31% would compost their food waste. Concerning using less electricity, 88% of respondents usually try to reduce the use of electricity, while 80% usually try to use less water. Studies assert that the public's emergency cognition of the pandemic, corroborated with scientific research showing its important relationship with 'nature' may have stimulated various pro-environmental actions; particularly in the household-sphere and workplace [15, 17].

5. CONCLUSION

It may be inevitable that with people's changing needs within their homes due to the pandemic, the design of homes will have to adjust to the changes. With more time spent at home, the need for more open, well-lit and well-ventilated spaces has become priority. Quality of internal spaces need to be enhanced by designing for daylight, natural ventilation and thermal comfort. Flexible and adaptable internal layouts and space saving furniture has become popular during and after the pandemic. Many respondents indicated they would prefer more storage space and larger sized wardrobes.

The importance of mental health and general well-being rose as the effects of COVID-19 isolation were experienced. As people were confined to their homes for lengthy durations of time, it has become evident that more attention to individuals' health and wellbeing is to be prioritised in future design. During lockdowns, people rearranged their homes according to their changing lifestyles, creating spaces they would not normally require, such as office space or space for leisure or exercise. People have also been innovative and found new uses for existing spaces such as social spaces that may have been lost. Balconies, front doors and streets have been activated and transformed into multipurpose and communal spaces.

Exercise was also one of the few reasons to go outside during lockdowns. Space was created in homes to accommodate daily routines on days when exercising outdoors was not feasible. Because of this, the outdoor spaces near homes need to be designed as flexible and adaptable to accommodate various outdoor activities in all weather conditions. The survey results indicate that designing outdoor space for safe exercising was considered a priority for residents' satisfaction.

As for the shift towards sustainable lifestyles, and behaviours, there have been a few significant changes noted post-pandemic. People indicated their preference towards walking instead of using vehicles or public transport. Many residents commented that a top priority for purchasing their homes was due to the location, close to train and bus stations, as well as to all essential amenities, where everything is within walking distance. The majority of respondents also indicated they would consider electric vehicles for environmental and financial implications. There is significant potential in capitalising on this surge in pro-environmental behaviour to accelerate people's effective contribution to achieving global carbon emissions reduction targets. As social distancing appears to possibly continue to be the 'new normal' for a while and may probably be applicable again in any such future circumstances, it is important to move away from 'business as usual' models and take into account the above-mentioned aspects when designing new homes and new developments. Existing homes will need to be more resilient and sustainable in adjusting to any similar future situations.

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ANALYSIS AND METHODS

DAY 01
15:00 — 16:30

CHAIR
FRANCOIS SIMON

PAPERS
1229 / 1594 / 1424 / 1264 / 1492 /
1402

20TH PARALLEL SESSION / ONLINE

The concept of a data-driven platform for mitigating heat stress at the neighbourhood scale

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ABSTRACT: Cities are experience increasing urban heat stress while the number of new construction and renovation of neighbourhood is growing. The integration of heat stress mitigation into urban planning at neighbourhood scale is a critical topic with seriously challenges due to the poor and uneconomical collaboration among involved stakeholders (governors, professionals & investors, civil society and researchers), which leads to a shortage of relevant data for deep understanding of built environment and stakeholders' demands. This inevitably affects the decision making and eventually results in inefficient measures. This study focuses on a digital platform named "E-tool" that is expected to bring about a digital transformation onto the interaction prototype among stakeholders and thus enables a stronger capacity of data collection in order to provide all participants with comprehensive information of urban built environment. The goal of the study is to lay a foundation of the E-tool concept for future studies to facilitate the real digital transformation of participatory approach to city and neighbourhood plan for mitigating heat stress. The results of the study identifies the next steps for the development of evaluation indicators and algorithms for heat-mitigating neighbourhood plans.
KEYWORDS: Urban heat stress, data-driven platform, neighbourhood development, multi-stakeholder approach

1. INTRODUCTION

The environmental conditions over cities worldwide are expected to deteriorate due to increasing climate change and extreme weather patterns. Urban heat stress is one among important issues and causes a rise in diseases and mortality [1], [2]. At the same time, many cities worldwide are in the evolution of urbanization most of which leads to increased energy consumption as well as significant shortcomings related to carbon capture and sequestration. The cities are responsible for roughly 70% of the carbon emissions [3], they have been a point-of-interest in several platforms, networks and international policy organisations such as ICLEI [4], C40 cities [5]. The relation between higher urbanization rate and more severe urban heat stress were found in [6]. This issue is in the focus of stakeholders from various sectors of governance, academia, developers, industry and civil society, and requires their collaboration for solutions.

Due to the complexity of an urban setting, a whole range of inter-related natural and anthropogenic impacts are responsible for the mentioned problems. Even if a number of analytic research and digital tools are either available or ongoing for comprehending the current status of the urban built environment and related urban heat stress namely CoolTowns [7], ENVI-Met [8], UWG [9], Cove.Tool [10], still additional efforts is needed. On the other hand, local urban actors, developers and researchers are on parallel tracks that hardly come to one common end for a successful integrated and optimized plan.

The above-mentioned facts raised an idea for a platform that facilitates the collection and analysis of immense dataset from environmental IoT networks and matrices of responses from stakeholders. Belgium and Vietnam, who also experience urban heat stress, join efforts from multiple perspectives into mitigating the impacts and providing better built environment of cities. We realize the necessity of environment-based consideration for the development of neighbourhoods and making our actions onto the neighbourhood level.

The Flemish-granted Global Minds (GM) Multi-Stakeholders research projects is a demonstration of technical support to the neighbourhood development. The study aim to lay a foundation to the transformation of neighbourhood plan prototype in Vietnam from single-stakeholder and experience-based scheme into multi-stakeholder and data-driven approach. One of the highlighted outcomes is the proposed digital platform called "E-tool" that provides stakeholders with the open access to collected data, facilitating better decision making based on deep understanding on the neighbourhood through data. This paper introduces the concept and workflow of "E-tool" for data management and design support for mitigating urban heat stress in neighbourhood planning.

2. LITERATURE REVIEW

There are distinct efforts in the literature to cope with and improve the understanding the urban environment and human behaviour through available data in an urban scale. Two existing approaches that relate to the research goal are given below in detail.

District Logbook and District Information Model (DIM) [11]**.** The District logbook is developed for information management at the city and district level. The tool allows the simultaneous participation of governors and investors as main stakeholders involved in the management of the city environment context. The application of the tool can be flexibly decided according to the life cycle phase and to the specific case. During the period of management, information can be collected gradually, beginning with compulsory documentation regarding the city environment and its components. In addition, this tool provides digitized forms that can be filled out during different phases and by different participants from community with computers or mobile devices. For the city, data can be helpful to control and monitor different neighbourhoods and environmental services provided, which optimizes the planning practice.

E-Footprints Energy Game [12] The main goal of the application is to investigate the possibilities of improving home environments through game-based simulation and data collection from participants. The E-footprints creates simulation of built environments that enables players to make decisions in order to feel comfortable in the simulated home. The Energy Game can be considered the first contribution to the online collecting data method about human reaction. The tool has high potential to collect a large volume of data about human behavior in a built environment, facilitating the analysis of big data on human comfort.

The above novel tools are evidences for a major transformation from physical to virtual prototype of data collection from the environment and stakeholders. The recent technological trend is struggling to complement structured databases with real-time data streams [13], and present a great potential to "democratization of data-dependent processes" [13]. This would allow for the smart collection of data from diverse urban source, forming a concrete basis for urban development and decision making.

Although a variety of pathways to deeper understanding from urban data were introduced, there is no single one that covers all geographical contexts, and thus there should be a specific initiatives that are sensitive to local conditions. This refers to the necessity of a context-specific tool for deeper insights of Vietnamese neighbourhoods and cities through more comprehensive mining of urban data.

3. MATERIAL & METHODS

This section describes methods used during the course of E-tool development. As of a pilot study, an urban district in the city centre of Ha Tinh (Vietnam) was chosen for thermal comfort monitoring. In this project, urban heat stress is more of concern among aspects of built environment; hence, all the input focus around the actual thermal condition and people's perception to the local thermal environment through various surveys. During the conceptualization and development, consultations with stakeholders by using quadruple helix approach were performed. Finally, the scheme for interactions between participants through the platform was defined.

3.1 Data collection

In this pilot project, data of physical thermal environment at selected neighbourhoods was acquired from several sensors located at representative locations over the sites of interest. Therefore, several weather stations were located across the selected neighbourhoods during typical hot periods of summer 2020 and 2021. The points of measurement are pinned on an satellite-mode map (Figure 1).

Due to the fact that the local community is major beneficiaries of the development, their responses should be necessarily considered in addition to the monitoring of physical environment. To this particular case, local people were asked to participate a survey by responding to a number of questions related to their thermal perception and expectation at the study site. A survey on people's thermal perception took place at the same time with measurement campaign during August 2021. A number of respondent sheets were collected before they were processed for the design of the E-tool.

Figure 1. Locations of measurement and survey points

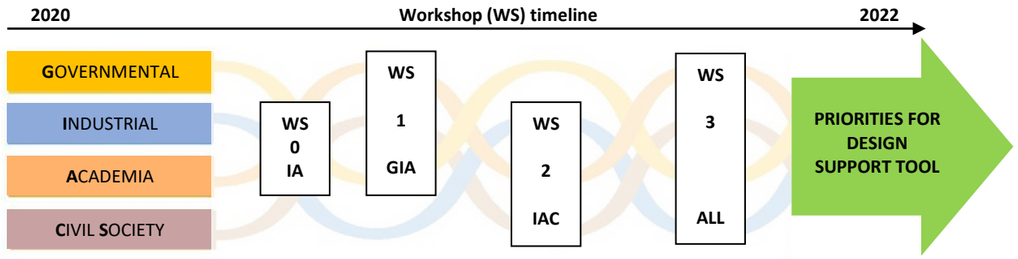

Figure 2. Workshop timeline (adapted from In For Care, Interreg Project, 2018)

3.2 The consultation with multi-stakeholders

In order to support the data collection with measurement and surveys, a series of local (Belgium and Vietnam) and international workshops were performed. The aim of the workshops was to receive feedbacks for the E-tool framework from experts in different sectors who are identified as possible end-users of the developed system.

For collecting qualitative data in a semi-structured manner, a quadruple helix approach was utilized [14]. Quadruple helix is an innovation and collaboration model with a citizen/end-user perspective. It is useful in an innovation process where the user needs are central, in this case in urban context. In many cases where an innovation is targeted, it is often observed that there is a lack of involvement of the citizens and end-users (see Fig 2). For example in the use of Triple helix approaches, the users are considered as 'recipients' rather than contributors for a solution [15].

The workshops were designed as a semi-structured discussion with provision of a guiding theme and four questions to record the responses. The theme was given as 'urban heat stress' and challenges were identified as 'data complexity and limited stakeholder cooperation'. Then four focal points that are similar to a SWOT analysis were provided as:

- urban development challenges
- strengths against heat stress
- target / people and environment
- proposals / opportunities

As seen in Figure 2 [16], a preliminary workshop was conducted with core project group to validate the workshop framework. Then the first workshop was conducted locally in Vietnam and second workshop followed in Belgium, both in a hybrid (online and in-person) format. In the workshops, the participants were requested to provide their comments for each stakeholder group (including their own group). The duration of the workshops were two hours.

The results were collected in a brief matrix that displays the questions in the X-axis and stakeholder groups (governmental, industrial, academia and civil society) in the Y-axis. The matrix then filled with commonly repeated keywords during the workshops. It was also possible to follow the focus of each stakeholder group by use of a colour code.

In the third workshop, the theme was changed to 'E-tool case study'. A similar workshop format was designed by revising the focal points to:

- parameters for evaluating urban plans
- expected unit for E-tool output
- evaluation of E-tool

3.3 The workflow

A close and active interaction among stakeholders and app-developers should be maintained to ensure the relevance and accessibility of the E-tool to all expected users. The web-based and mobile versions of the platform were designed for the relevant stakeholders who are expected to make a shift in their interaction from physical to digital world. Requirement and suggestions as input from policy makers, community and researchers were collected and delivered to the developers and their consultants. An automated analysis with machine learning algorithm, thanks to big input dataset, was performed by the E-tool for the recommendation onto the plan scenarios to the developers and contractors. These two stakeholders make their decision on the generation of the plan before consulting the other participants for comments and revision. All the iterations were enclosed by the E-tool and significantly reduce physical contacts and administrative interaction. Visual description of the interaction can be found in Figure 3.

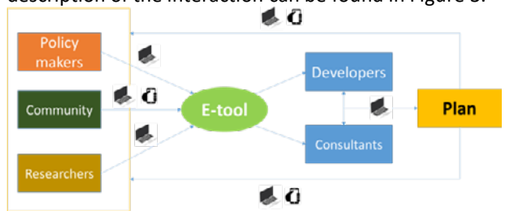

Figure 3. Interaction scheme among stakeholders through the E-tool

4. RESULTS

4.1 Multi-stakeholder workshop results

In this section, the results of workshops are provided in a combined manner with an exemplary display of the second workshop (see Table 1). In the end of the section, some of the take-aways for E-tool development are underlined.

The responses are analysed in two fronts: SWOT analysis (X-axis) and per stakeholder group (Y-axis). In order to differentiate comments considering the citizens, an additional stakeholder category (not represented in workshops) were added as 'users'.

It was seen that the participants had sufficient amount of information about challenges and strengths when compared to target groups and proposals / opportunities.

Challenges were identified as a problem of optimization between expectations and available sources (Precision vs required data, demand for maximum area vs expectations on green networks)

It was seen that there is a lack of comprehensive tools that includes several layers of data from adequate number of sources (thermal, geographical, infrastructure, vs) to support the urban design processes. Moreover, the date of the multi-layered data sources are varying which results in an integration of data from different time frames. This was significantly important for the identifying the priorities for the E-tool development.

Several parties referred to the citizen science method as a high potential for data collection in collaboration with the end-users. This insight was quite important for the E-tool to facilitate a similar data collection perspective. It was also seen that the target group is quite various in two fronts (i) groups that are affected by heat stress (ii) groups that are potential end-users.

Depending on the variation in end-users of the tool, multiple interfaces for each end-user group such as governance and industrial practitioners were proposed. This issue was coupled with the previous challenge on how precise should the E-tool be. For the first stage of the E-tool development, it was decided to keep a medium level of detail for practical reasons.

4.2. The organization of E-tool

This part describes the workflow of the novel E-tool, how it incorporate the collected data and complicated input from involved stakeholders, i.e. governors, civil society, researchers and professionals, as well as visually and literally translate these into a common decision/ solution.

The E-tool is a useful application that provides supports to the governments when it comes into collecting, visualizing and managing environmental data. In addition, the tool enhances the capacity of monitoring, operation and analysis of built environment at the neighbourhood scale by automatically and continuously visually integrate the observational and computational analysis of heat stress into urban development and management plans.

After successfully logging in, the user will create a

Table 1. Results of the second workshop, Belgium, Technology Campus Gent on 25th November 2021

	Challenges	Strengths	Target	Proposals
Civil Society	Public awareness Lack of public space Independent civil society	Green networks Structured system for social organizations	Youth Workers / children Local authorities	Inclusion of media for public awareness Inspiring communities via co-design and tools
Academia	Qualitative & quantitative Accuracy vs practicality Transparency Training programmes take time Resistance to share data	Bio-based solutions Citizen science	Citizen science projects Projects accessible to users	Different interface for e-tool Inclusion of urban renewal research projects
Industry	Many layers of data Static tool No comprehensive framework Short-term benefits Not easy to reflect data on design CO2 taxing in design tools	Main principles for urban planning are the same in different countries Increasing interest in social and environmental aspects Financial incentives	Convincing users and authorities via reflecting scientific data in urban design	Inclusion of urban renewal initiatives Comprehensive dynamic e-tool
Governance	Green network hard to convince Demand for maximum area of built environment Could data provide design goals?	Continuous development in urban planning regulations	Alternative scenarios to convince policy makers	Different interface for e-tool
User	Citizen science may not yield neutral results Comparison between social and spatial mapping	Citizen science Low-key questions High awareness in educated people	Vulnerable groups Immigrants Air quality	Dynamic use of citizen science for data and awareness rising

new or ready-made planning plan that has been assigned. To create a new plan, the user clicks on the map icon in the corner of the screen and enters all the information of the new plan. Once there is a plan, the user chooses the plan to work on to start the process of collecting survey questionnaires.

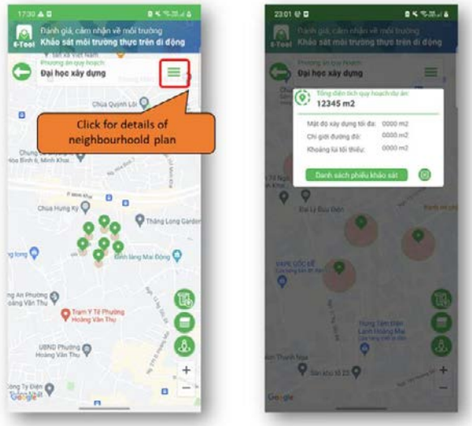

Figure 4. A snapshot of E-tool application installed on a smartphone for use by civil society (local community)

All considered parameters regarding the neighbourhood development can be automatically retrieved from CAD-based drawings and displayed to the users (Figure 4). For the interaction on the outdoor thermal comfort, the users are able to fill in the e-survey with their actual perception given that their location is confirmed. The comprehensive environmental map is organized with various layers and thus E-tool and thus be able to be separately visualized.

Apart from the mobile app, a web-based tool is also developed and expected to provide extra access to governors and professionals who need visualization and management of data on higher resolution or in more detail.

4.3. The preliminary discussion/ evaluation

Outcome of the proposed platform could potentially have multiple effects, including:

– speeding up the process of collecting responses from community by transforming survey prototype from physical to digital interact

– the professional and investor could verify the presence of comfortable and uncomfortable areas in relation with business trade-offs, and therefore decides their investments more efficiently;

– linking the thematic map of the outdoor thermal comfort with the real estate values of the different municipal areas, it is possible to verify the influence that energy certification can have on the trend of the real estate values themselves;

– the local authorities can gain insights into the territory by estimating which and how many places are exposed to the low outdoor comfort, and will navigate the local development in a more sustainable way;

– the community may be able to estimate the "influence" of development projects on the surrounding area and more actively participate into the development with stronger voices.

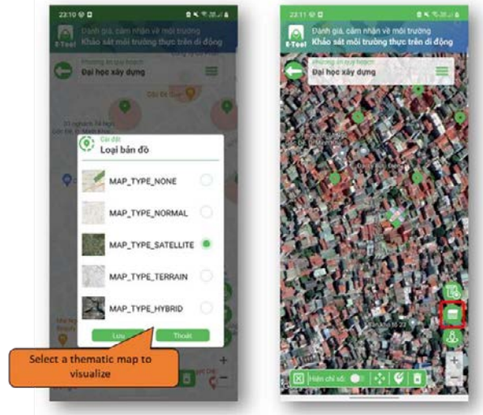

Figure 5. Visualized layers of collected data

Figure 6. A screen of web-based E-tool visualizing different points of survey or monitoring in Ha Tinh (as once shown in Figure 1) – interface designed for the consultants and governors

5. CONCLUSION AND FUTURE WORKS

The E-tool can be considered as a "support tool" to prevent disputes among stakeholders, caused by a potentially scarce knowledge and/or availability of the district's status. Employing the application on the environmental analysis may mark a transition point that turns conventional stakeholders' cooperation into IT-based prototype and therefore lays a comprehensive digital transformation of urban planning.

Recognizing the importance and complexity of urban environmental data, the E-tool will be further improved for data-driven design approach that makes better use of big data and machine learning. In the next development of the E-tool, typical features of an urban project will be considered as rating parameters for the evaluation of the plan performance. Moreover, successful practical lessons are used to develop further the algorithm and thus able to "train" the E-tool to provide reliable suggestion for decision makers. This will enhance our understanding of relation between physical urban environment and stakeholders' responses, which then accordingly leads to smarter development, i.e. improving the urban quality while satisfying participants' demands. The application of E-tool is a reasonable answer to the quest of technique for participatory approach that is long required for the work of urban planning.

In general, the collection, analytics and visualization of environmental data is a growing sub-domain of built environment. It shows a great potential for further study, development, and implementation. It may bring together experts from different areas varying from urban planning, urban informatics, computer & data science, and machine learning. A successful smart E-tool requires an interdisciplinary effort, where urban scientists take a navigating role in determining the evaluation indicators of a development plan, while contribution to the realization of smart algorithms from IT is an indispensable part. In the next steps, the E-tool is expected to assist stakeholders during generating and evaluating scenario plans with machine learning-based algorithms, based on determined assessment indicators on neighbourhood performance and collected data.

ACKNOWLEDGEMENTS

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Innovative design solutions for the school of the future

The case Study of the secondary school Cino da Pistoia in Italy

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ABSTRACT: The EU recognizes the need for near-complete decarbonization of the building sector, defining energy performance requirements to encounter longer-term climate neutrality goals by 2050. To facilitate this transition, it is necessary to identify suitable passive strategies, innovative design solutions, and building integrated renewable energy systems specifically studied concerning climate conditions. The paper presents a simulation-based optimization process to evaluate design solutions' effectiveness on energy performances and indoor comfort for building the new school building "Cino da Pistoia" in Italy. The applied methodology helps enhance nZEBs design and facilitate decision-making in early building design phases. In addition, a comprehensive study on occupants' indoor comfort is presented with specific reference to thermo-hygrometric comfort and lighting comfort. The results have demonstrated that it is possible to reduce the global energy demand of the building and to improve the level of perceived comfort through the adoption of high efficiency building envelope technological systems and passive strategies.
KEYWORDS: Net zero energy building, Simulation-based optimization, Indoor Comfort, Daylighting analysis, School building.

1. INTRODUCTION

The sustainable design of public buildings through innovative technological solutions and the integration of renewable energies is one of the priority objectives of European policies (2010/31 / EU) and the new Next Generation Europe Economic Development Plan. Furthermore, the 2030 Climate Target Plan proposed by European Commission sets an intermediate target for reducing GHG to at least 55% below 1990 levels.

In Italy, these objectives were implemented by the D.M. 11/10/2017 on Minimum Environmental Criteria (CAM). Moreover, they have become the subject of numerous funding policies of the PNRR [1], which plan to improve, by 2026, the energy performance of public buildings through deep renovation or demolition interventions and reconstruction.

Moreover, in Europe, educational buildings are a significant part of public property and represent a critical issue because of their age and maintenance needs. Therefore, many schools need sustainable retrofitting interventions to improve buildings' performance in terms of energy consumption and deliver economic, environmental, and social benefits to the whole community [2].

The sustainable targets set by international regulations and the transition to Positive Energy Buildings (PEB) led in recent years to develop numerous research aimed at creating sustainable, efficient, and safe school buildings and even more at developing strategies intervention based on the use of BIM and BEM tools, which allow managing the design process by predicting the impact of integrated technological and functional solutions [3-4].

This paper shows the design proposal for the new secondary school "Cino da Pistoia" developed by the Municipality of Pistoia with the contribution of ABITA Interuniversity Research at the University of Florence. In particular, the analysis and dynamic simulations will be shown to study the building envelope solutions and the indoor comfort inside the classrooms.

The main aim of the research work was to demonstrate how to achieve the nZEB targets and the improvement of energy building performances, as well as aesthetic, architectural, and functional quality objectives to set the characteristics of future schools. Furthermore, the analysis procedures and verification methodology developed for verifying the sustainability of the design process could be replicated for other types of buildings.

2. THE CASE STUDY

The school building Cino da Pistoia is located in Pistoia, a city in the Tuscany region in Italy. It is part of an existing school complex including the primary school "G. Galilei", a gymnasium and a school canteen. The regeneration interventions consist of building demolition and reconstruction of a new school made up of two-story buildings (buildings 1 and 2) connected by a solar greenhouse (building 3).

Buildings 1 and 2 host classrooms and laboratories, while building three has the function of the entrance to the common areas and to the vertical connections that allow access to the different floors.

The new school was designed according to the CAMs Italian law [5], implementing design solutions for the building envelope and plant systems that meet the minimum requirements for building energy efficiency. Therefore, attention was paid to the environmental impact generated by the building throughout its life cycle and to the indoor environmental quality (IEQ), health, and global comfort of occupants.

Figure 1: Render of the new secondary school "Cino da Pistoia", south façade.

Figure 2: Plant of the ground floor: A) classrooms; B) toilets; D) Corridors; I) Green house; T) Technical room

As a result, the new building was realized with a light steel frame structure to reduce its environmental impact and guarantee reversibility at the end-of-life cycle. Furthermore, according to the national legislation and EU directives, the school "Cino da Pistoia" was designed to achieve high sustainability and energy efficiency standards, reaching nZEB targets. For this reason, the classrooms and laboratories were exposed to the southeast to take advantage of solar gains in winter during the teaching activity's hours.

Similar passive strategies were applied to the bioclimatic greenhouse, which shows the same classrooms' exposure to solar radiation during the morning, to reduce the building energy needed for heating during winter. The shading devices outside the glass façade and the operable windows integrated into this transparent volume guaranteed to decrease the overheating phenomena in the summer months.

Moreover, the high thermal performance of the transparent and opaque envelope of the other two buildings and floor thermal mass allowed to reduce energy consumption, related costs, and greenhouse gas emissions.

In detail, the opaque building envelope was made using a lightweight aluminium ventilated facade insulated with mineral wood panels (U value = 0.17 W/m2K), while the windows were designed with thermal break frames and low-emissivity double glazing and fitted with external shading (U value=1.20 W/m2K). The ground floor was built with sub ventilation system (U value=0.12 W/m2K), and the rooftop was constructed using a corrugated slab system insulated with EPS panels (U value=0.23 W/m2K).

The heating and cooling were provided from a radiant floor integrated with a mechanical air exchange system and heat exchanger. In addition, a PV plant of 25 watt-peak was integrated on the roof to produce renewable energy that will be possible to use for the electricity need of the school building.

Table 1: Thermal performances of building envelope components.

Building Envelope	Thermal Transmittance [W/m²K]	Indoor Thermal capacity [kJ/m²K]	Periodic Thermal Transmittance [W/m²K]
Wall	0.17	49.57	0.02
Windows	1.20	-	-
Floor	0.12	63.64	0.00
Rooftop	0.23	65.83	0.01

3. RESEARCH METHODOLOGY

The present study defines and analyzes the main sustainable design strategies adopted for the new construction intervention to assess the energy performance of the new school building through Building Energy Modelling (BEM) and dynamic simulation analysis.

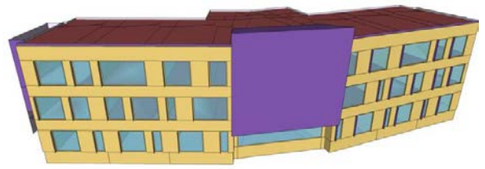


Figure 3: Building simulation model

Two relevant aspects were investigated using simulation tools to support the designer's decision-making in comparing the performance of different design scenarios. First, a thermal performance

assessment of the building envelope was carried out to choose the better façade solutions that meet the current national standards and improve indoor thermal comfort. Furthermore, a daylighting analysis focused on design optimization of the classrooms to improve their indoor daylighting quality.

3.1 Building dynamic simulation

The Italian legislation (Italian Ministerial Decree 26/06/2015) specifies a series of mandatory energy requirements for public buildings to reach nearly zero-energy buildings targets, concerning the minimum performance that the building must guarantee considering both energy performances of envelope solutions and energy needs related to technological plants such as heating, cooling, hot water, ventilation, and lighting, integrated with renewable energy sources.

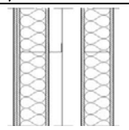
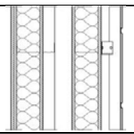
Accordingly, in the first phase of the design process the simulation methods was finalized to compare the results between the real building and the reference building (defined as a target building), which has the same location, function, size, and minimum values for thermal performances and technical systems efficiencies. This comparison between the two building models allowed to define the degree of sustainability of the design options (Tab. 2).

Table 2: Energy performances parameters for heating and cooling, hot water, mechanical ventilation and lighting.

Real building	Reference building	Verification
H'_T 0.37 W/m²K	$H'_{T,lim}$ 0.80 W/m²K	verified
$A_{sol,est}/A_{sup,utile}$: 0.03	$(A_{sol,est}/A_{sup,utile})_{lim}$: 0.04	verified
$EP_{H,nd}$: 50.69 kWh/m²	$EP_{H,nd,lim}$: 57.50 kWh/m²	verified
$EP_{C,nd}$: 15.20 kWh/m²	$EP_{C,nd,lim}$: 17.77 kWh/m²	verified
$EP_{gl,tot}$: 65.05 kWh/m²	$EP_{gl,tot,lim}$: 161.69 kWh/m²	verified
η_H: 2.22	$\eta_{H,lim}$: 1.34	verified
η_W: 0.63	$\eta_{W,lim}$: 0.53	verified
η_C: 1.64	$\eta_{C,lim}$: 1.26	verified

At the same time, a building simulation energy model for dynamic analysis was developed using the Energy Plus software to study the energy performances of two opaque envelope solutions (Tab.3): 1) a traditional pre-assembled dry facade with thermal cladding and outdoor plaster (P1: plaster); 2) a ventilated façade with an external aluminium surface (P2 ventilated facade). The objective was to compare their energy performance to choose the one that performs most efficiently throughout the year.

Table 3: Characteristics of the two opaque envelope solutions analysed with the dynamic simulation in the design phase

	
P1: Traditional pre-assembled dry facade with thermal cladding and outdoor plaster.	P2: Ventilated façade with an external aluminium surface
Thickness: 32.5 cm	Thickness: 38.5
U value: 0.20 W/mqK	U value: 0.17 W/mqK

In particular, the environmental conditions considered acceptable for indoor thermal comfort and those representing local discomfort were investigated, analysing the internal heat gains related to the occupancy profile of indoor spaces and users' activities.

The study was carried out according to ISO 7730:2005 methods for predicting the general thermal sensation and degree of discomfort of people exposed to moderate thermal environments through PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indexes. Therefore, the Clothing Insulation Index (Clo) and the heat loss of the Metabolic Flow (Met) were defined considering different year periods. For better accuracy, the Met threshold for sedentary behaviour in children has been increased from 1.5 to 2.0 Mets depending on age-specific definition of sedentary behaviour in children aged 11 - 14 years (in fact people of this age group have a higher metabolic rate than adults).

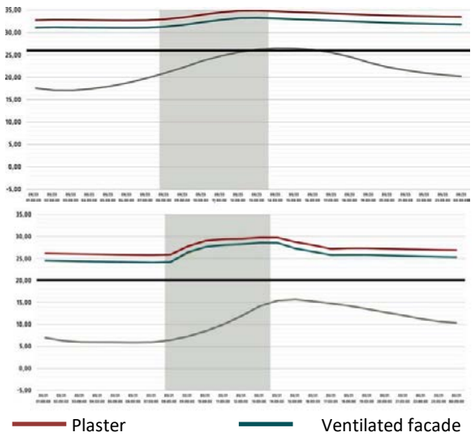


Figure 4: Comparison pre-assembled dry facade (plaster) and aluminium ventilated façade (ventilated facade): a) Indoor air mean temperature profile 21st March (upper); 23rd September (lower).

For sedentary such as school activities, the UNI EN ISO 7730 standard suggests a value equal to 1.2 meths, while the experimental data collected showed average values for subjects of that age group equal to about 2.2 Met [6].

The simulation was carried out without cooling, and the mechanical ventilation system made it possible to highlight an improvement in the perceived comfort values, limiting internal overheating in the final part of the heating period and, in general, in the spring and autumn season.

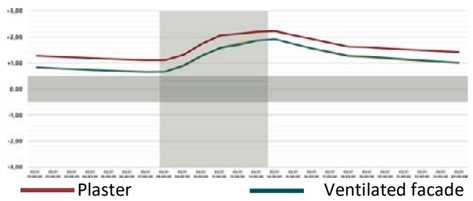


Figure 5: Comparison between outdoor plaster and ventilated facade (21st March): b) PMV index.

The average values recorded on the simulated dates of March 21 and September 23 allow us to observe a positive variation of the average internal temperatures between 1°C and 2 °C (Fig. 4), and a PMV index closer to the condition of thermal neutrality with a reduction of 0,5 compared to plaster solution. Regarding the PMV index, on the 21 March, the value related to the ventilated solution is closer to the condition of thermal neutrality with a reduction of 0,5 compared to plaster solution (Fig. 5).

3.2 Daylighting analysis

The daylighting of a school building must provide adequate light levels in the classrooms and on their work plane during the daytime, mainly from natural light. In detail, for the classrooms of a school building, depending on their exposure and building orientation, the following parameters influencing daylighting performance were analysed:

- Daylight Factor (DF) [%]
- Illuminance [lux]
- Luminance [cd/m2]

Accordingly, the daylighting analysis was conducted to evaluate the impact of passive design strategies for the classrooms of the new school "Cino da Pistoia" to achieve adequate daylight conditions and daylighting requirements in line with Italian and international regulations.

Concerning the mean value of Daylight Factor (mDF), which is expressed as a percentage of the amount of daylight available inside a room (on a work plane) compared to the amount of unobstructed daylight available outside under overcast sky conditions, the minimum threshold value set by the Italian regulations is DF≥3%.

Furthermore, for the Illuminance parameter, which refers to the amount of light received on the classrooms interior surfaces, typically expressed in lux (lm/m2), daylighting simulations were performed throughout the year with different sky conditions, comparing results with the minimum requirements for school spaces provided by EN 12464-1:2011, to estimate the energy needs from the artificial lighting system.

The daylighting parameters were predicted through a simulation tool for a qualitative evaluation of visual comfort and glare in the interior of each classroom. Finally, the total amount of daylight entering a classroom was linked to the total glazing area of windows.

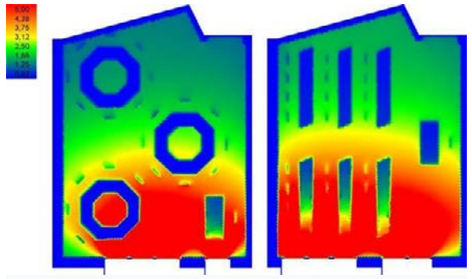


Figure 6: Mean Daylight factor (mDF) calculation for a classroom of the ground floor (left) and of the first floor (right).

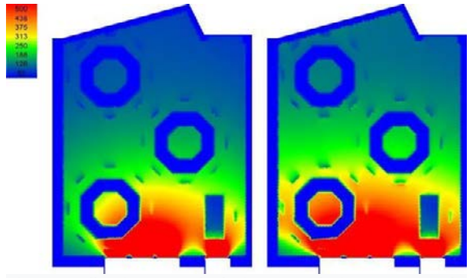


Figure 7: Illuminance calculation considering overcast sky (left) and clear sky condition (right) for a classroom of the ground floor.

Figure 8: Luminance calculation of a selected classroom of the ground floor.

The simulation results showed a difference in daylighting performances between the classrooms on the ground floor and those on the first floor. In

detail, the classroom on the ground floor had a mean Daylight Factor of less than 3% (mDF = 2,8%), for the smaller glazing to floor area ratio than the other classrooms.

Furthermore, even in some classrooms on the first floor, the calculated mean Daylight Factor (DF) was very close to this minimum requirement but not sufficient to reach a good daylighting indoor quality. The DF was highly non-uniform and not well distributed over the work plane area (Fig. 6 and Fig. 7), with very high values near the window and low values at the back, a typical condition that can cause visual discomfort and luminous glare. Also, results from the Luminance calculation (Fig. 8) give further evidence of the poor daylighting quality of indoor spaces.

As shown in Table 4, the illuminance calculations were performed with different sky conditions, and the results show a mean value of 180 lux for the classroom on the ground floor and 240 lux for that on the first floor, both below the minimum target of 300 lux.

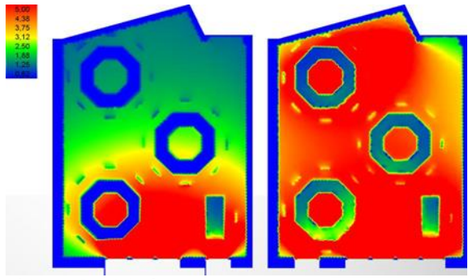
The glazing to floor area ratio was increased to provide useful DF levels over the entire work plane and to improve the indoor daylighting quality in the classrooms on the ground floor. Also, the design solution of the solar shading device was optimized based on data derived from the sun path analysis throughout the year. It adopted a horizontal reflective screen that prevents excessive light from direct sun radiation and, at the same time, allows a homogeneous distribution of natural light within the interior space.

Table 4: Simulation results comparison of daylight parameters before and after intervention.

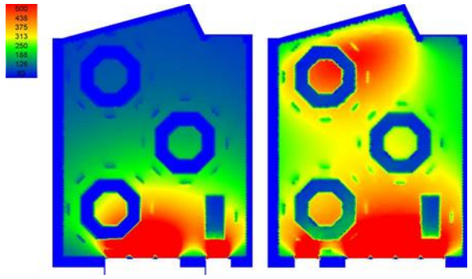
	Before	After
mean Daylight factor (mDF)		
Ground floor	2,8%	5,0%
First floor	3,7%	5,0%
mean Illuminance (I)		
Overcast sky		
Ground floor	180 lux	320 lux
First floor	240 lux	450 lux
Clear sky		
Ground floor	310 lux	450 lux
First floor	400 lux	450 lux

In addition, to ensure the light source from multiple directions and to mitigate the daylight glare effect, a different glazing surface was opened facing the hallway to obtain a better uniformity of light in the classrooms. As a result of these interventions, simulations of daylight parameters report an improvement in daylight parameters (Tab. 4).

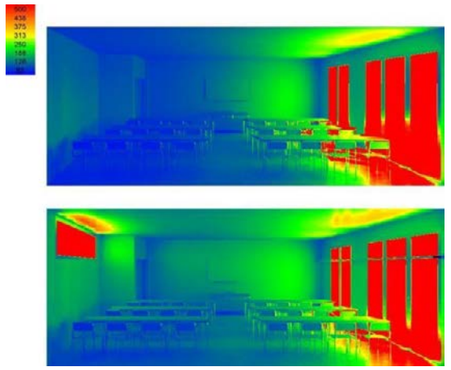
Furthermore, even in overcast conditions, the average Illumination values were significantly increased above 300 lux in all the simulated scenarios, reducing the energy needed for the artificial lighting of the school.



a) Mean Daylight factor



b) Illuminance



c) Luminance

Figure 9: Comparison of daylighting simulations results before and after the changing of the widows' size for a classroom of the ground floor: Daylighting simulations results

The simulation-based optimization process for daylighting analysis of the new building made it possible to obtain an important improvement both in the lighting comfort of users and in reducing glare effects.

Figure 9 illustrates the effect of design solutions compared after and before the intervention for a classroom of the ground floor: the results show a better uniformity of daylight in the classrooms and greater daylight levels in the interior spaces, achieving the minimum requirements for all the parameters.

4. CONCLUSION

This paper presents the new design project of a school building in Pistoia, developed using a simulation-based optimization method to evaluate the design solution's effectiveness on energy performance and the indoor comfort of users throughout the design process.

The analysis and dynamic simulations to study the highly insulated building envelope show the benefits of integrating a ventilated façade compared with a multilayer dry facade. About energy efficiency, the energy performance index for cooling the school building is equal to 15.20 kWh/m2, achieving the target nZEB.

With regards to thermal comfort, the ventilated façade can reduce the average indoor temperatures between 1°C and 2°C, depending on the season, improving the PMV index (closer to the condition of thermal neutrality) with a reduction of 0,5°C compared to plaster solution.

Furthermore, the in-depth daylighting quality of interior spaces in selected classrooms confirmed the effectiveness of all the design strategies concerning increasing the glazing to floor area ratio and integrating a new horizontal reflective screen for windows to prevent excessive light from direct sun radiation.

Finally, this study shows how simulation tools allow the designers to simultaneously assess the geometric-formal characteristics of a new building and its energy-environmental performances from the implementation phase to the use phase.

Besides, it is evident how, alongside the rapid evolution of indicators and legislation on the building's energy efficiency, new computer models for evaluating the design can assess the behaviors of the built environment and of the indoor comfort from the static to the dynamic situation [7].

In the future, the work will deepen the topic related to environmental assessment - in terms of LCA and LCC - of the implemented design solutions, with a particular focus on the façade technologies to analyze more in detail the vantage of using the ventilated envelope in cold climate area, as southern Europe. Moreover, after the realization, the building will be monitored to compare the simulated data of indoor comfort performances with the real data to improve the design simulation process with BEM tools.

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Energy modeling of the residential building stock

Climate change impact and adaptability of the existing housing stock in Santiago de Chile

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ABSTRACT: Energy modeling of the existing building stock as a decision-making tool for governments is necessary for drafting national roadmaps to the carbon neutrality of the built heritage. A set of 297 building energy models is stochastically generated using architectural archetypes and national information. The energy models are created and simulated in batch mode using R and EnergyPlus, and tested using the weather files of the Metropolitan region of Chile under seven scenarios; the historical climate and six climatology modeling scenarios by 2050. After predicting the thermal behaviour of the simulated models, hours of discomfort and space heating energy use are analyzed, comparing the results under the historical climate against the six projected climates. Results show that the hours of discomfort are strongly impacted by the number of building floors and moderately by the window-to-wall glazing ratio. Considering that the residential air conditioning in Chile is a new and fast-growing market, retrofit strategies in the Metropolitan region should consider the risk of overheating in dwellings under different climate change scenarios.
KEYWORDS: Thermal comfort, Representative concentration pathways, Energy performance,

1. INTRODUCTION

Almost all countries reaffirmed their commitment at COP21 to reduce greenhouse gas (GHG) emissions to keep global warming below 2 degrees Celsius by 2050 compared to pre-industrial times (1850-1900). According to the International Energy Agency (IAE), the building sector accounts for 8% of the global greenhouse gas emissions in 2020 (2,9 of 33,9 $GteCO_2$) (International Energy Agency, 2021). To achieve a carbon-neutral economy by 2050, the target is to reduce 1.2 Gt by 2030 and 0.3 Gt by 2050. In addition, countries must implement new energy efficiency measures in buildings that lower their energy needs and ensure acceptable comfort inside by using renewable sources.

Although several countries have introduced thermal standards to increase their energy performance (Laustsen, 2008), numerous studies have highlighted the disparity between calculated and measured performance (Burman et al., 2014; Kelly et al., 2012). Furthermore, governments require decision-making tools to detect current energy consumption aspects and unintended consequences of new codes and policies on future energy use, GHG emissions, and population well-being.

Building energy modeling (BEM) is a valuable tool to estimate buildings' current and future energy use. Moazami et al. (Moazami et al., 2019) used 16 ASHRAE commercial building prototypes to study the energy use variation compared to historical data, considering typical and more extreme climate change scenarios in Geneva. The authors highlight the relevance of studies on the impacts of climate change on the built environment at national scales to involve architects and building engineers. Ultimately, various researchers are publishing their work at city scale, such as Nik and Sasic in Stockholm (Nik & Sasic Kalagasidis, 2013), or at national scale, like Olonsheck et al. in Germany (Olonscheck et al., 2011) and Gürsel and Meral in Turkey (Dino & Meral Akgül, 2019).

Regarding Chile, Rubio-Bellido et al. optimized office buildings' form factor and window-to-wall ratio for nine different Chilean climate zones (Rubio-Bellido et al., 2016). Verichev et al. simulated a house prototype in the southern macro zone of Chile (Verichev et al., 2020). The authors highlight the high variability of spaced heating shifts due to climate diversity. Finally, Rouault et al. (Rouault et al., 2019) studied the impact of climate change on space heating and cooling needs of houses in Chile using the simplified hourly calculation method from the international standard ISO 13790. The authors emphasize the critical situation of the Metropolitan Region (RM), the most populated area of Chile, about the potential increase of space cooling needs. However, the study only focuses on a unique archetypal house in each city, and so limiting the conclusion.

To account for the variability of input parameters in the housing stock, this study proposes an estimation of the impact of climate change on the energy use and thermal behavior of the residential building stock of Chile's most heavily populated region on a horizon to 2050. For that purpose, the current building stock is modeled in EnergyPlus, based on the previously defined geometric Chilean archetypes (Molina et al., 2020) and under six different climate change scenarios.

2. METHODOLOGICAL APPROACH

This work's methodological approach consists of generating a set of building energy models (BEM) that can be considered representative of the RM housing building stock. The input data are randomly generated using the Latin hypercube sampling (LHS), which ensure a multidimensional distribution, and uses national surveys (In-Data, 2019; Ministerio de Vivienda y Urbanismo, n.d.), datasets currently available, and the literature (Molina et al., 2020, 2021). The generated BEM models are then simulated in Energy Plus using different weather files of historical climate and projected climates of Santiago de Chile.

2.1 Inputs data

Molina et al. (Molina et al., 2020) defined 496 archetypes representing the Chilean residential stock and four thresholds of 2, 8, 29 90 archetypes, representing 13%, 35%, 70%, and 90%, respectively. These archetypes are based on the available data of the housing stock, and are defined by housing type (detached, mid-terrace, terrace), the construction period (before or after the current thermal regulation), the number of stories, the floor area, rooms, and the number of occupants. The set of 29 archetypes is selected for this study.

Table 1:
Input data of the energy model

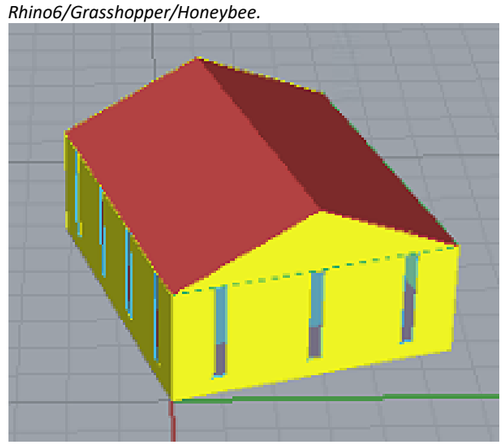
Input	Unit	Range
Permeability	ach	[0,001; 7]
Heating setpoint	°C	[18; 22]
Month of heating	-	[0; 12]
ΔU_{Wall}	W/m^2K	[-0,15; 0,43]
ΔU_{Roof}	W/m^2K	[-0,15; 0,27]
$U_{windows}$	W/m^2K	[2,8; 5,8]
$\Delta U_{windows}$	W/m^2K	[0,03; 0,08]
Lighting loads	kWh/m^2year	[0,15; 38]
Appliance loads	W/m^2	[1,2; 185]
DHW	W/m^2	[1,3; 194]
Kitchen	W/m^2	[0,39; 69]
Form factor	-	[1; 2]
Orientation	°	[0; 179]
Glazing ratio	%	[5; 32]
Thermal mass	kg/m^2	[10; 100]

297 sets of input data, including the archetypes' ID, are stochastically generated, including other design parameters (see Table 1) and using the Latin hypercube sampling method to respect input data distribution.

2.2 Building Energy Modeling (BEM)

The Software Rhino6 (*Rhino - Rhinoceros 3D*, n.d.) with the plugins Grasshopper and Honeybee (*Ladybug Tools | Honeybee*, n.d.) are used to generate the BEM models (see Figure 1) and export in .idf file format compatible with the simulation software EnergyPlus (US Department of Energy, n.d.). The batch simulations are carried out using the statistical software *R-cran* and the *eplusr* package (Jia & Chong, 2021). The number of simulations is increased until a stopping criterion is met (here, the difference in the mean energy use is less than 0.5% between one sample and the previous).

Figure 1:
3D representation of the building energy model using Rhino6/Grasshopper/Honeybee.



2.3 Climatic data

The current climatic are export form Meteonorm v7.2(METEOTEST, n.d.) at .epw format. The temperature and precipitation estimations for 2045–2054 were possible using three climatology modeling scenarios: MIROC-ESM, IPSL-CM5A, and CCSM4 considering two different representative concentration pathways: 4,5 (RCP4,5) and 8,5 (RCP8,5) W/m^2.

2.4. Data analyses

The results of the BEMs thermal behavior using the historical climate are visually compared to monitoring data from the national housing monitoring network (RENAM in Spanish); see Section 3.1. The Chilean Ministry of Housing program, RENAM, collects and anonymously broadcasts hourly indoor environment quality indicators from 294 houses in five cities (Antofagasta, Valparaiso, Santiago, Temuco, and Coyhaique).

To evaluate the summer comfort, the adaptive thermal comfort is defined by the European standard EN 16798-1 (European Committee for Standardization, 2019). The following equation defines the comfort zone of temperature for existing buildings (category B):

$$T_{conf} = (0{,}33\ T_{rm} + 18{,}8) \pm 3°C \quad (1)$$

With

$$T_{rm} = \begin{pmatrix} T_{ed-1} + 0.8\ T_{ed-2} + 0.6 T_{ed-3} \\ +0.5\ T_{ed-4} + 0.4 T_{ed-5} \\ +0.3 T_{ed-6} + 0.2 T_{ed-7} \end{pmatrix} / 3.8 \quad (2)$$

Where T_{rm} is the running mean outdoor temperature and T_{ed-i} (i vary from 1 to 7), T_{ed-i} are the daily mean of outdoor temperature from the previous seven days.

Hours of discomfort (HoD) are calculated as the sum of hours exceeding the upper limit of comfort in occupied hours (this is, 24 h/day and 8766 h/year); see section 3.2. For two-story houses with two thermal zones, the highest indoor temperature of the two zones is considered for the comfort calculation.

Finally, the evolution of space heating in kWh/m^2 and hours of discomfort in six projected climates are compared to the historical climate, and the relationship between these two indicators and the inputs are analysed using the Pearson's correlation coefficients.

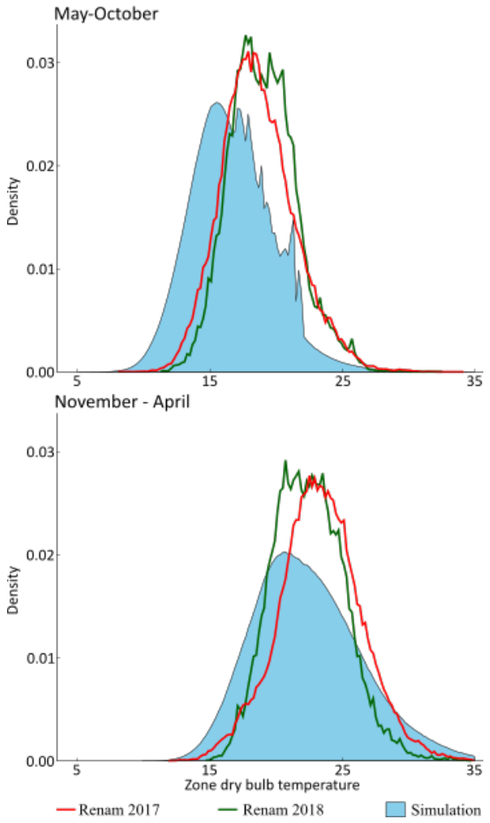
3. RESULT AND DISCUSSION

3.1 Thermal behaviour in historical climate

Figure 2 compares the air temperature between the simulation in the historical climate and the temperature inside 142 dwellings in the RM from the national monitoring network (RENAM) during 2017 and 2018.

Although some discrepancies can be identified, the simulation can be considered consistent with the measured data. For example, the distribution of simulated temperature shows a slight offset compared to measured temperature, probably due to an underestimation of the heating hours by the survey respondents.

Figure 2:
Comparison of indoor air temperature between simulation results (in light blue) and measured temperature by RENAM in 2017 (in red) and 2018 (in green). The top and bottom graphs show the heating and cooling season, respectively.



3.2 Projected summer comfort

Table 2 shows that at least 25 % (Q1) houses have no HoD in all scenarios. On the other hand, HoD exceeds 5% of occupied hours (438 hours) in more than 75 % (Q3) of houses HoD in all CC scenarios except IPSL 8.5; considering that the EN 15251 standard establishes the 5 % deviation as an acceptable limit (McNeil et al., 2008).

Figure 4 presents the Pearson correlation coefficients for space heating EUI and the HoD, and some of the input parameters. The results show a *strong* and *moderate* correlation between the HoD and the number of stories and glazing ratio, respectively. On the other hand, the space heating EUI and internal mass have a moderate correlation.

Figure 4 depicts the HoD according to energy use intensity (EUI) of space heating from each BEM model in historical climate and future scenarios. Each climate scenario result is linked to each to the historical climate result. Regarding historical results, two-story houses (triangle markers) generally have higher discomfort hours than one-story houses (circle markers).

Furthermore, space heating in *CC* case scenarios decreases and HoD increases except for IPSL 8.5, in which HoD decreases in some cases. Figure 4 presents the Pearson correlation coefficients for space heating EUI and the HoD, and some of the input parameters. The results show a *strong* and *moderate* correlation between the HoD and the number of stories and glazing ratio, respectively. On the other hand, the space heating EUI and internal mass have a moderate correlation.

Figure 4 shows that many houses without HoD in historical climate stay with no HoD for the *CC* scenarios. Furthermore, the HoD in two-story houses are >500 h; the historical scenario appears to be more sensitive in terms of HoD increase.

Table 2:
Summary statistisc of the total HoD [h] per house for the different simulation scenarios.

Scenario	Min	Q1	Med	Q3	Max
Current	0	0	23	434	2247
ccsm45	0	0	17	509	2342
ccsm85	0	0	19	520	2432
ipsl45	0	0	18	517	2422
ipsl85	0	0	13	454	2250
miroc45	0	0	17	519	2398
miroc85	0	0	17	520	2425

Figure 3:
Hours of discomfort vs. heating EUI of each model in historical and future climates

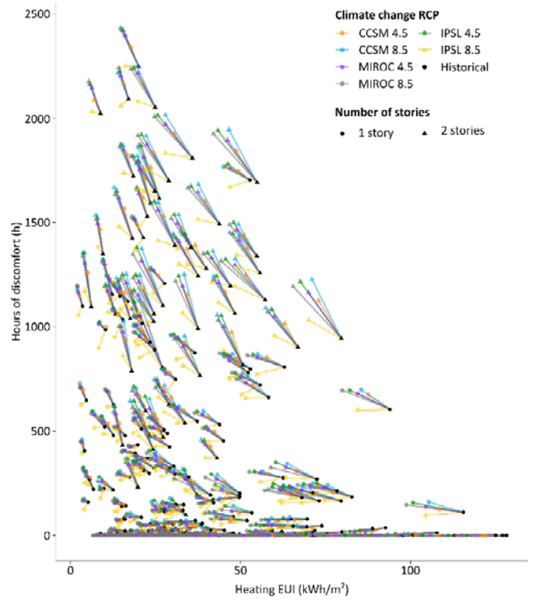


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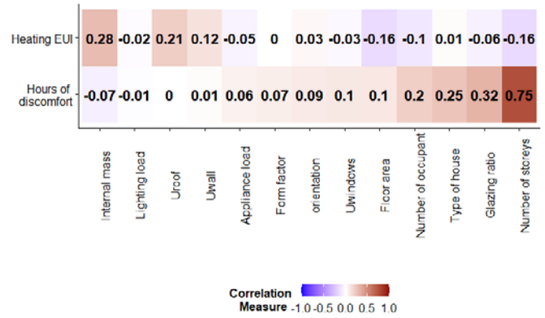
Figure 4:
Pearson correlation coefficients of Heating EUI and hours of discomfort according to some of the input data.



4. DISCUSSION

As presented in Figure 4 presents the Pearson correlation coefficients for space heating EUI and the HoD, and some of the input parameters. The results show a *strong* and *moderate* correlation between the HoD and the number of stories and glazing ratio,

respectively. On the other hand, the space heating EUI and internal mass have a moderate correlation.

Figure 4, HoD is strongly impacted by the number of floors, mainly because the reference indoor temperature is higher in two-story houses. The second floor generally has the highest temperature because it does not benefit from the thermal inertia of an uninsulated ground contact floor, contrary to the first floor. Window-to-wall glazing ratio is the second significant input affecting the HoD, showing the importance of controlling solar heat gains to reduce the HoD. Surprisingly, the orientation has a low significance, probably due to the architectural symmetry of BEM models.

Regarding space heating, the significance of internal mass might be explained by the intermittency of space heating reported in the 2018 national energy survey. An 80% of the respondents living in the Metropolitan region declared using space heating for 6 hours a day or less. For the same reason, the impact of some parameters might be underestimated, such as the heat transfer coefficients of the roof and walls.

The residential air conditioning in Chile is a new and growing market. Indeed, the national energy surveys (Corporation de Desarrollo Tecnológico, 2010; In-Data, 2019) indicate that air cooling in RM increased from 1% in 2009 to 4.5% in 2018. Furthermore, according to the bottom-up model by (McNeil et al., 2008), the market saturation in Chile is estimated to be 35% of the stock - considering a GDP per Capita (PPP) of US$ 24,750 (The World Data Bank, n.d.), a household size of 3.1 members (Instituto Nacional de Estadísticas de Chile (INE)., 2018) and 319°C.days of cooling degree days, with a base of 18°C (CDD_{18}) in historical climate. Furthermore, the market saturation might increase to 60 % approximately by 2050 considering a prospect of GDP per capita at 31,500 USD (OECD, n.d.), a household size of 2.85 members (estimated through a linear regression between the household size and the logarithmic base 10 of GDP per capita) and CDD_{18} between 480 and 550°C.days.

Given that projection and the simulation results, the existing residential building stock needs to be adapted to prevent RM households from aquiring air conditioners. Although air conditioning devices might help reduce the carbon footprint of space heating due to better energy efficiency, they would add an extra energy consumption for space cooling, with the associated impact on the electrical grid and the carbon footprint associated with the operational and fugitive emissions. Considering that the glazing ratio is the second most influential parameter of HoD, the control of solar heat gains through exterior solar protection like overhangs, external shadings, and vegetation should be encouraged.

Current national energy policies are focused on increasing the energy performance of new buildings and subsidizing the retrofit of low-income dwellings such as wall and roof insulation, replacement of windows or renewables installation. Although these subsidies aim to eradicate energy poverty, an estimated 15.5% of the Chilean population (Villalobos et al., 2021), the national retrofit strategy should also consider the risk of overheating under future climates. Therefore, subsidies must include technical support for the benefiting families to ensure that the retrofit solution is tailored to their energy performance and comfort requirements.

5. CONCLUSION

A BEM method based on archetypes and stochastic input parameters is proposed to simulate the thermal behavior of a housing stock in the Metropolitan region of Chile under historical and projected climates. Preliminary results show a similar indoor temperature distribution as measured temperature by the RENAM program. The building stock is then simulated under different projected climates using six climate change scenarios based on three climates models with two representative concentration pathways. The main findings of the present study are the following:

- It is possible to generate a set of BEM models which improves the representation of the heterogeneity of a building stock using archetypes, and national datasets and surveys
- As expected, hours of discomfort will increase by 2050 and more especially in two-story houses with low energy use intensity of space heating
- Window-to-wall glazing ratio appears as the second more influent parameter in the hours of discomfort, highlighting the need for solar gain control through solar protection in retrofit strategies

Future work should deepen the presented analysis, including multifamily buildings and the operational carbon footprint of space heating and cooling systems. Finally, different scenarios of the existing building-stock adaptation to climate change should be studied.

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Designing thermal factors

Modelling heat balance variables for thermal adaptive environments

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ABSTRACT: Thermal sensations and associated thermal comfort is based on six primary factors. These factors are used to determine if the human physiology is in heat balance. While the six factors principally are dynamic values, they are commonly used as static factors assuming an isothermal and generic indoor environment. A dataset on how people spend their lives, across 23 nations around the globe suggest that human activity is largely similar, but also that activities across the day vary greatly. This study examines the relations between actual activities of humans and thermal comfort by modelling three cases of thermal sensations by designing the thermal input factors of Fanger's heat balance model. The study demonstrates that thermal factors can be modified to greatly reduce the heated/cooled air temperature, which directly impact the significant energy and economy spend on air conditioning in buildings. The study also suggests that the thermal factors in a much higher degree can be designed to accommodate individual thermal sensations, related more specifically to the activities of the person.
KEYWORDS: Thermal Sensation Factors, Thermal Comfort, Specific Daily Activities, Simulation

1. INTRODUCTION

It is commonly stated in architectural discussion that humans spend 90% of their time inside buildings. Despite the importance of the specific number, and the background for such a statement, it is often used without further elaboration. From medical science, more specifically epidemiology [1], a study related to environmental pollution presents evidence that 87% of the American population on average spend their time indoor. This number comes with some variance, and yet, it is argued that Canadians present a similar occupancy pattern, just as other Western countries are assessed to have a similar daily condition. The study also includes a detailed account of activities for one Hispanic American individual, providing some, albeit limited as statistical evidence, understanding of daily activities over time. Another more recent study [2] provides a highly detailed dataset and understanding, across 23 nations, with nine activity categories. The dataset is based on surveys of diaries, person aged 15-64, collected between 2009-2016. The nations include North America, South America, Asia and Europe regions.

Through this dataset, we get the insight of what a population is spending the time on. This enables the deduction of possible thermal conditions in which we may understand and model thermal conditions and thermal adaptive potentials through behavioural actions. The dataset reveals what people are doing and for how long, such as time watching TV, sleeping or eating and drinking. This opens the possibility for relating activity over time with thermal sensation modelling to identify, understand and explore thermal conditions based on dynamic thermal factors.

Behavioural actions, such as adjusting clothing intensity, physical activity and positioning the body in radiant heat, are central in regulating thermal sensation, and thermal comfort. Conditions that are fundamental for life quality [3], work productivity [4] and energy use in the built environment. Today, we heat and cool our buildings against a general setpoint temperature, commonly around 22 Celsius, based on generalised thermal comfort standards. Considering that heating/cooling accounts for 50% of the CO_2 production in the built environment, with the sector producing a 40% of the total global CO_2e emission [5], [6], an actual change in thermal design and adaptation in indoor environments advocate significant environmental advancements through a focus on specific thermal conditions of the individual. One study shows how heating and cooling can be significantly reduced in dwellings by individualised devices [7] and another study [8] concludes that an average saving of 10% energy can be achieved by moving the setpoint 1 degree Celsius above or below the temperature setpoint in offices.

The idea and approach to temperature sensations and thermal comfort in buildings aligns with the established *Thermal Adaptive Comfort* (TAC) [9]–[11]. However, with TAC defined by outdoor temperature alone, relying on non-defined human activity and associated adaptive behaviours, it does not provide insight or instrumentality for design decisions.

This study combines the dataset of detailed daily activities with human thermal sensation simulation by the use of Fanger's six factor *Heat Balance Model,* based on the *Predicted Mean Vote* (PMV) method [12].

The study contributes with concepts and knowledge about thermal design, based on heat balance conditions under a standardised temperature setpoint for the specified activities. This is followed by expanding the study through simulating thermal comfort if the setpoint is lowered to 16 degrees Celsius, as stated to be the lower thermal adaptive limit [3], [9]. A third study is then conducted by variables (clothing, metabolic rate, air and mean radiant temperatures) with the aim to decrease heated air by mechanical means, while searching and analysing suitable clothing and radiant temperatures to create sub 10% *Predicted Percentage Dissatisfied* (PPD), which defines a comfort condition [12].

2. METHODS

2.1 Archival Dataset Studies

The research uses archival data from an OECD survey based on personal diaries, collected between 2009-2016 (Fig, 1). The data covers all regions of the world, people aged 15-64, with a time resolution in minutes, divided in 9 categories, from left to right, paid work, unpaid work, sleeping, housework/shopping, personal care, eating/drinking, tv/radio, seeing friends and other leisure. The time-use presented in the survey is averaged from each nation and may include nation-based variance not shown in the dataset.

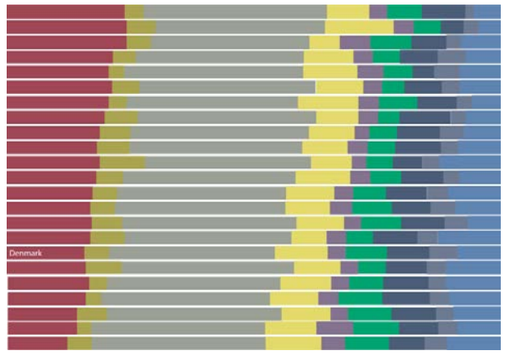


Figure 1: *Graph of how people spend their time across 23 nations in 9 activity categories. Redrawn from source.*

2.2 Simulation Studies

Human thermal sensation and comfort modelling have largely been defined by Ove Fanger's heat balance framework developed since the 1970s [3], [13], [14]. The six primary heat balance factors: Air Temperature (Ta, C), Mean Radiant Temperature (Tr, C), Relative Humidity (RH, %), Air Velocity (Vel, m/s), clothing insulation (Icl) and metabolic rate (MET) determine the physiological heat balance state (Fig. 2). While studies suggest that the framework is most accurate close to thermal neutrality and estimated thermal comfort, it is also widely accepted that the method and model is applicable at conditions far from neutrality, to calculate a thermal sensation by a *Predicted Mean Vote*, with the vote ranging from neutral thermal sensation to different levels of cold or warm sensation plotted on a 7-point scale. Hence, the thermal sensation simulation method is evaluated appliable in HVAC conditioned and free-running buildings, albeit used in practice to set HVAC system settings to maintain a prescribed and assumed thermal condition of the occupants [3], [12].

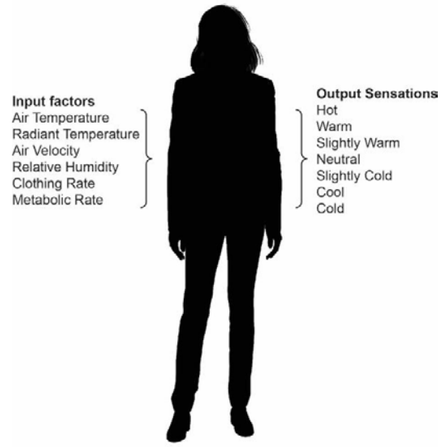


Figure 2: *Schematic of the six primary factors influencing the physiological heat balance of humans, based on Fanger's PMV method and model.*

Readily accessible calculators of Fanger's PMV method, and model, can be used online [15]. For this study, we used the software framework, Rhinoceros+Ladybug Tools [16], as it allows an open software structure with possibility to integrate the OECD dataset and generate graphical output of the simulation results through programming in the software (Fig.3). The latter is central as part of the experimental studies, where we use the graphical output as a way to inform manual versioning of the six heat balance input factors. By this method, we are able to explore and understand the impact on the input factors in relation to the understanding of the activities in the activity dataset.

Activity	Paid work	Unpaid work	Sleep	Housework	Personal care	Eat/Drink	TV/Radio	Friends	Other leisure
Hours	3,4	1,25	8,3	2,5	0,9	2,1	2,15	1,3	2,1
A									
Ta (Cel)	22	22	22	22	22	22	22	22	22
Tr (Cel)	22	22	22	22	22	22	22	22	22
RH (%)	50	50	50	50	50	50	50	50	50
Vel (m/s)	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
Icl	1	1	4	1,2	1	1	1	1	1,1
MET	1,2	1,2	0,7	3	1,5	1,3	1	1,5	1,5
PMV (Cel)	-0,71	-0,07	0,58	1,75	0,34	0,08	-0,5	0,34	0,44
PPD (%)	5,1	5,1	12,1	64,8	7,4	5,1	10,3	7,4	9,1
B									
Ta (Cel)	16	16	16	16	16	16	16	16	16
Tr (Cel)	16	16	16	16	16	16	16	16	16
RH (%)	50	50	50	50	50	50	50	50	50
Vel (m/s)	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
Icl	1	1	4	1,2	1	1	1	1	1,1
MET	1,2	1,2	0,7	3	1,5	1,3	1	1,5	1,5
PMV (Cel)	-1,36	-1,36	-0,41	0,91	-0,66	-1,08	-2,14	-0,66	-0,51
PPD (%)	43,8	43,8	8,6	22,5	14,3	29,8	83	14,3	10,52
C									
Ta (Cel)	15	15	12	10	12	16	16	16	16
Tr (Cel)	19	19	12	10	22	23	24	20	16
RH (%)	50	50	50	50	50	50	50	50	50
Vel (m/s)	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
Icl	1,5	1,5	4	1	1,2	1,1	1,5	1	1,1
MET	1,2	1,2	0,7	3	1,5	1,3	1	1,5	1,5
PMV (Cel)	-0,45	-0,45	-0,51	0,15	-0,45	-0,42	-0,44	-0,42	-0,51
PPD (%)	9,3	9,3	10,4	5,4	9,3	8,77	9,1	8,78	10,5

Table 1: *Table with OECD dataset values for Denmark, simulation input variables for the six factors, and the simulated output PMV and PPD values.*

2.3 Exploration Studies

As can be seen in figure 1, the activity variance between the nations is relatively small. For this study the variance is insignificant. Hence, we have focused and explored the dataset from one country, which is suggestive and generalisable given the low variance. The dataset used includes the daily activities from Denmark.

Three simulation studies are then conducted with integrated data from the OECD survey. The first study, A, maintains the air temperature and radiant temperature equal and at 22 degrees Celsius. Equalling the radiant temperature with air temperature is common practice, with the combination of the two temperature factors described as the operative temperature [3]. Through all three studies relative humidity is set to 50% and air velocity to 0.2 m/s. In the A study, Clothing insulation and metabolic intensity is set from best-practice and tabular values [17]. The model then computes the PMV and PPD for assessment, where the sensation is mapped for each minute of the activity over the day. All input data for the three studies is seen in (Table 1).

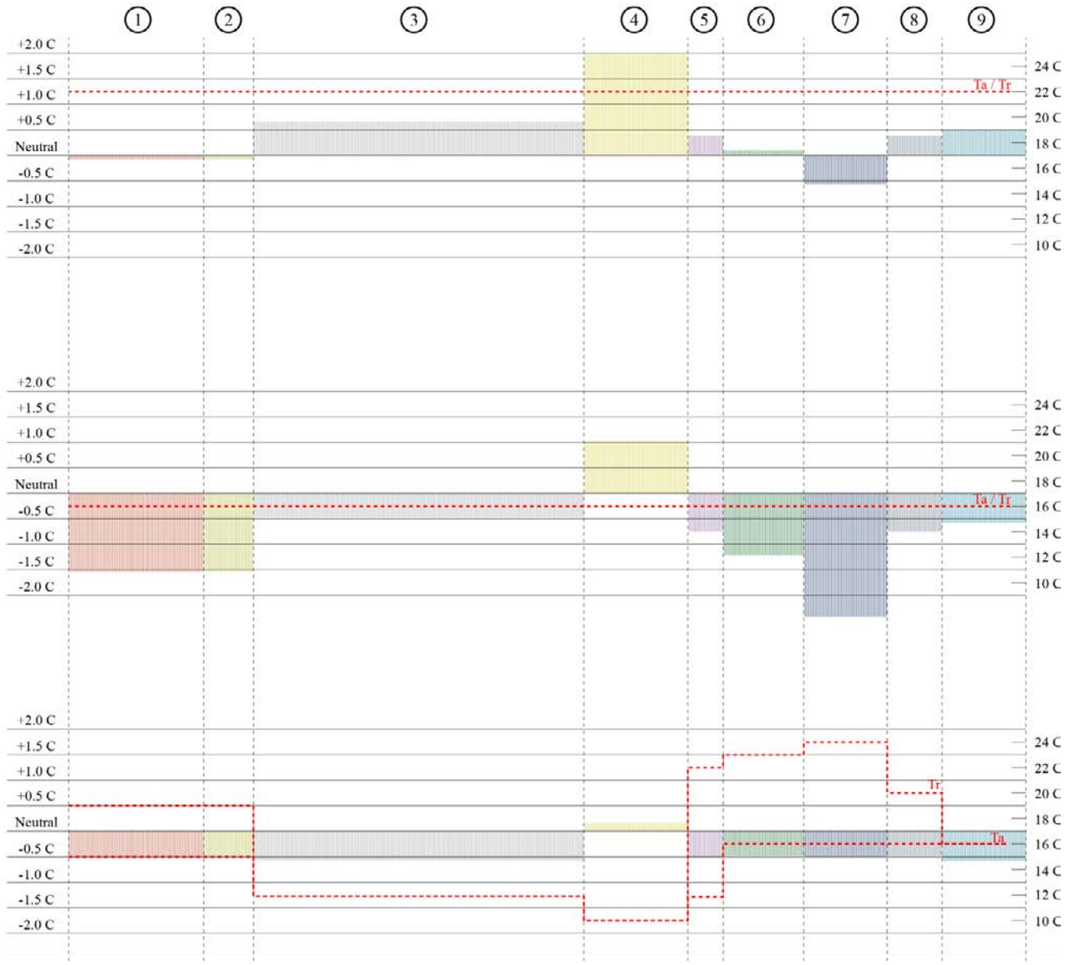
The resulting graphical output of the studies can be seen in (Fig. 3).

The second study, B, simulates through the activities, with the air temperature and radiant temperature lowered to 16 degrees Celsius as is suggested to be the lower thermal adaptive limit for indoor environments [10], [18]. The other factors are kept the same as study A. Simulation data in (Table 1) and graphical output in (Fig. 3).

The third study, C, simulates through the activities by an iterative process of manually altering the six factors with the primary objective to reduce the air temperature and secondary objective to reduce the radiant temperature, while maintaining PMV score close to +/- 0.5 degree Celsius, resulting in a PPD score below 10%. The manual input variation process is also possible to conduct as an automated exploration using search and optimisation procedures, if a fitness function is described by a search through objectively defined criteria, such as Linear Approximation, Simulated Annealing, Genetic Algorithms or other deterministic and stochastic methods [19]. Besides the objectives to manipulate the temperature factors, as described above, is the clothing rate, Icl, the primary variable modified, given that the metabolic rate is tied largely to activity, such as sleeping, desk work and eating/drinking presented in the OECD dataset.

The tabular structure of (Table 1) is maintained below, with time along the x-axis. 1: Paid work period (200 mins), 2: Unpaid work (73 mins), 3: Sleeping (489 mins), 4: Housework (154 mins), 5: Personal care (52 mins), 6: Eat/drink (119 mins), 7: TV/Radio (123 mins), 8: Friends (81 mins), 9: Other leisure (124 mins). On the left y-axis is the deviation from an estimated thermal neutral condition, understood as thermal comfort sensation, PMV, ranging from +2 to -2 degrees Celsius. Beyond +/- 2 degrees Celsius from neutrality is PPD considered higher than 90%. Hence, from a thermal comfort objective the sensation should be below +/- 0.5 Celsius. On the right y-axis are temperature factors mapped, Ta = air temperature and Tr = radiant temperature. By graphical mapping of the activity dataset with calculated thermal sensation it is possible to investigate and understand the relationships between thermal factors, thermal states based on activities and how thermal factors can be modified in relation to the specific activity. In a housework activity condition, #4, it is fair to assume that a free dressing conduct is possible, enabling the clothing parameter to be the principal factor to be modified. The same is considered true for the control of air and radiant temperature in a home environment, asregulation thereof do not interfere with co-workers' personal preference of thermal comfort.

Figure 3: Calculations and graphs of activity dataset with the PMV method for case A, B, C. The six primary thermal factors are modified in relation to specific daily activities.



3. RESULTS

By focusing on what people actually do, combining a detailed dataset with thermal simulation and experimental modelling of thermal factor variables, the study explores the possibility to significantly reduce mechanical heating for the increase of air temperatures in indoor environments.

From this basic study, we identify and demonstrate how thermal factor variables can be designed to meet current standards, by focusing on modifying the individual and activity related radiant temperature, metabolic rate and clothing rate factors.

As the metabolic rate is directly related to activity, such as deskwork, construction work, cleaning work etc, this factor should potentially always be described in relation to the subject, rather than the space condition. The same applies to clothing rate, albeit social conventions prevent free dressing styles particularly during deskwork, such as in offices and education. Focusing on operative temperature, as a combination of air temperature and radiant temperature, reduces the potentials of agile thermal constructions and conditions. If considering the two temperature parameters individually, omnipresent air temperature can be significantly reduced while radiant temperature is strategical employed in dedicated space regions and directed towards the individual by control of the view factor. The impact of this separation is clear in the C case, (Fig. 3), where radiant temperature and air temperature is unequal in 6 of 9 activities where the activity is close to stationary, allowing radiant surfaces to be activated as a predominant heat source. These results align with studies on thermal-active surface research, and how such systems may be implemented in architecture [20], [21].

The resulting variation in temperatures during daily activities, as opposed to a static isothermal temperature condition, as seen in case A and B, is also that the human thermal sensation is triggered by transient thermal registrations. This causes a potential stronger relation between the occupant, the environment, and the acting architecture, such as induced from thermal-active chairs to thermal-active building surface structures, described as and for thermal pleasure sensations [22], [23].

4. DISCUSSION

It is argued that humans already perform the adaptive behaviour described in the design of the thermal factors shown in this study. The Adaptive Thermal Comfort model relies principally on such adaptation. However, this study shows how much and what thermal adaptation that is needed to stay within a comfort temperature as defined by the PMV/PPD framework, and which is implemented into the rulesets that guide thermal comfort control and management in buildings. The activity dataset used for thermal sensation modelling presents variance, albeit minor, between the nations included in the survey. Hence, further studies can be conducted to extend the reach of this study, which will allow a nation-based mapping of how much the temperature setpoint can be moved from a generalised number. Given that up to 10% energy can be saved by moving the setpoint up or down by just 1 degree Celsius, many nations stand to make significant energy savings if following the methodology of thermal sensation modelling presented in this study.

5. CONCLUSION

The study finds and suggests that significant changes can be made to heating and cooling of indoor air temperatures if other principal thermal sensitivity factors can be designed against the specific activities that people do in their lives. The great similarity between nations indicates that the method shown here, to find and design thermal factor setpoints, can have great impact on energy use in the built environment, and come closer to designing thermal conditions related to the specific individual sensations during the daily activities.

ACKNOELEDGEMENTS

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Effect of window opening schedule on indoor thermal environment

An investigation into the effect of natural ventilation in low-rise apartments in warm and humid climate of India

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ABSTRACT: In India, the gross electricity consumption of residential buildings has been increasing at a fast pace. This is mainly due to the increasing use of air-conditioning units in homes to achieve a thermally comfortable environment. Thermal comfort in a warm and humid climate is mainly associated with increased air velocity through natural ventilation. Natural ventilation can be implemented to reduce discomfort hours, which leads to less energy consumption. The objective of this study is to investigate the potential for natural ventilation on different floors, months, and times of the day. To this end, a low-rise residential building constructed in India's 'warm and humid climate has been selected for the investigation. Indoor thermal parameters of two living spaces were logged from July 2019 to June 2020 to evaluate the comfort hours on different floors. Further, an energy simulation model was developed and validated by monitored data, and a thermal simulation was done to evaluate the effect of different window opening scenarios. The effect of different scenarios was evaluated based on the Indian adaptive thermal comfort model. Results showed the potential of ~19.2% increase in comfort hours on top floors and ~32.4% on ground floors during the summer month by natural ventilation.
KEYWORDS: Energy Simulation, Natural Ventilation, Field monitoring, Comfort Hours

1. INTRODUCTION

In India, the gross electricity consumption of residential buildings has been increasing at a fast pace. It is expected to reach around 2383 TWh by 2047, which is a significant increase from the consumption of about 342 TWh in 2017 [1]. This is mainly due to the increasing use of air-conditioning units in homes to achieve a thermally comfortable environment [2].

Most people spend 65 percent of their time at home, though this percentage can vary greatly based on various factors [3]. As a result, it is important to ensure thermal comfort in residential buildings to enhance the health and well-being of its residents [4]. Thermal comfort in a warm and humid climate is mainly associated with increased air velocity through natural ventilation or mechanical fans. [5]

The living room can be considered as the most occupied space in a house where most of the activity like family get together, discussion on family matters and multiple activities take place [6].

Since the living room combined with dining is being used most of the time in a house, improving the indoor thermal environment of the living room by using solar passive strategies suitable to warm humid conditions can significantly reduce the requirement of new AC as well as AC use hours. Solar passive strategies like cool roofs, insulation material, night ventilation can significantly improve the indoor thermal environment at low cost and reduce energy consumption [7-13].

As part of a larger project, this investigation involved long-term monitoring and simulation of the thermal environment of a few low-height apartment buildings. The objective of this paper is to apply and analyse the monitored data of living rooms located in different floors to assess the effect of natural ventilation in extending comfort hours.

2. METHODOLOGY

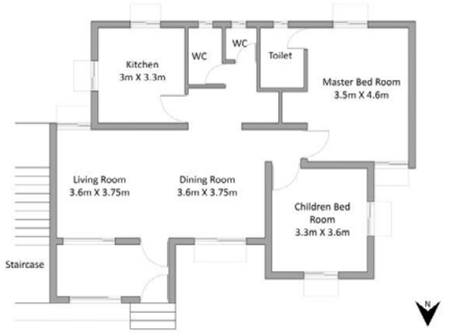
2.1 Building description

A residential building at the National Institute of Technology, Tiruchirappalli, India, was selected for the investigation. This building consists of 6 residential units distributed on three floors. The research was carried out in two living and dining rooms, one on the ground floor and the other on the second floor, each measuring 7.2 X 3.75m size, with three windows (one 1.2 X 1.3m, and two 1.8 X 1.35m each) (refer Fig.1). Floor to floor height of the residential unit was 3.04m.

2.2 Data monitoring and Energy Simulation

Hobo datalogger was used for indoor monitoring, and A HOBO U30 USB outdoor weather station was used for the outdoor monitoring of air temperature and relative humidity. Indoor Air temperature, Globe temperature, and Relative humidity were monitored with HOBO U12-013 Data Logger on a 15 min interval from July 2019 to June 2020.

Figure 1:
Ground Floor plan of a residential unit considered for this research



Thermal simulations were done on Open studio using Honeybee tool, which is a plugin of grasshopper and gives the flexibility to change the inputs parametrically. The studied building was modeled in Honeybee tool, and thermal properties of building envelope (Table 1) were specified in the simulation model.

Table 1:
Thermal properties of the building envelope

Building envelope construction specifications	Overall U Value (W/m^2K)	SHGC
External Wall	2.14	-
Internal Wall	3.06	-
Roof	2.7	-
Internal Floor	2.5	-
Window	5.8	0.8
Door	1.18	

Table 2:
Statistical criteria threshold limits

Statistical indices	ASHRAE Guideline 14 (Hourly Calibration)	Achieved in the Simulation Model for Current Study
CVRMSE	30%	5.6%
MBE	± 10%	-2.1%

Weather data from the Indian Society of Heating Refrigeration and Air-conditioning Engineers (ISHRAE) were modified using the outdoor monitored data and used for simulation purposes. The simulation model was validated by comparing monitored and simulated data, using two statistical indicators, namely MBE (mean bias error %) and CVRMSE (Coefficient of Variance of root mean square error %) as per the ASHRAE (American Society for Heating Refrigerating and Air Conditioning Engineers) Std 14 guideline [14]. Error in the simulation model was found within the prescribed limits (Table 2).

The calibrated model was used to analyze the potential for natural ventilation. Three different scenarios were considered in this research:

Case 1: Windows closed all the time (WS1)

Case 2: Windows open all the time (WS2)

Case 3: Window open only during the night-time (8 pm to 8 am) (WS3)

2.2 Data Analysis

A custom script was used to compute the difference between indoor operative temperature and comfort temperature as described by the Indian Model of Adaptive Comfort (IMAC) Standard for Naturally ventilated buildings.

Comfort temperature was calculated by using the following Equation (1):

$$T_N = 0.54\, T_{rmt} + 12.83 \quad (1)$$

Where:

T_{rmt} - 30-day outdoor running mean temp. (◦C);

T_N - Neutral temperature (◦C);

Based on the difference in temperature, data were further processed to calculate the percentage of comfort hours and discomfort degree hours. Cooling or heating discomfort degree hours are calculated by adding the difference in temperatures below or above the minimum comfort temperature or maximum comfort temperature limits, respectively, whereas comfort hours were calculated from the data which falls under IMAC comfort range.

3. RESULTS AND DISCUSSION

3.1 Outdoor Weather Conditions

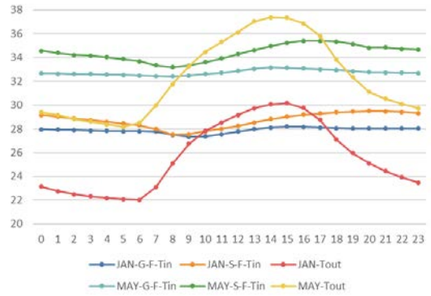
Hourly averaged outdoor temperature (Tout) and relative humidity (RHout) during peak winter month was found between 22-30.2°C and 59–94 respectively, while during peak summer Tout and RHout was between 28.1-37.4°C and 43-79 respectively (refer Fig.2).

3.2 Indoor Thermal Conditions

Monitored data showed that the hourly average Tin and RH for the ground floor room during peak winter months was between 27.3-28.2°C and 67.1–75.4 respectively, while second-floor room Tin and RH was between 27.5-29.5°C and 63.4-72.8 respectively.

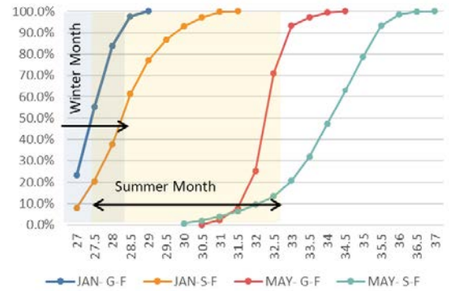
Figure 2:

Average Indoor and outdoor temperature during peak summer and winter month



During peak summer months, ground floor Tin and RH varied from 32.4- 33.2°C and 57-64.6, respectively, while second-floor room Tin and RH was varied between 33.2-35.4°C and 49-62 respectively, which is around 2°C difference in temperature. Because the rooms have the same amount of exposed wall area, the roof makes the most significant contribution to the temperature difference.

Figure 3:
Cumulative frequency curve of indoor temperature during different months in different floors



3.3 Comfort hours (monitored data)

Based on the IMAC model (in Jan 24.3 to 29.0°C, and May 27.6 to 32.4°C), comfort hours in both the living rooms have been calculated for peak summer and peak winter months (Table 3). A cumulative frequency chart with IMAC comfort band was also plotted to evaluate the percentage of comfort hours (refer Fig.3). The second floor living room is not performing well during the summer months and has very less comfortable hours. A huge scope of improvement in the thermal environment can be seen from the results. Calculation of comfort hours has been done for a whole year to better understand the indoor thermal environment and scope for improvement.

Table 3:

Percentage of comfort hours in different floors

Month	Ground Floor	Second Floor
JAN	100%	76.9%
MAY	71.2%	6.4%

3.4 Natural Ventilation Potential (monitored data)

The percentages of time for which climatic conditions allow NV for cooling to occur is identified based on thresholds of indoor and outdoor air temperature. Firstly, hours for which the inside temperature was higher than outside temperature were selected. Secondly, hours for which the inside temperature was outside the comfort band suggested by IMAC were selected, indicating that NV for cooling is beneficial. The remaining hours of the year were considered feasible to apply NV for cooling.

Figure 4:
Percentage of time when natural ventilation is useful during May month in different floors

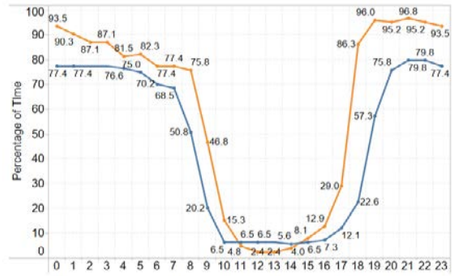
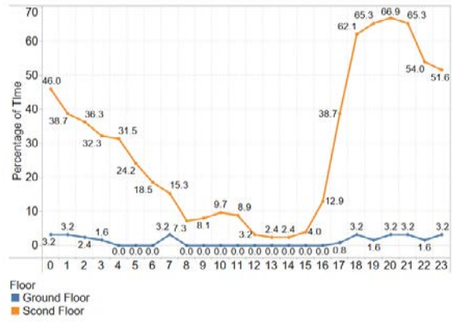


Figure 5:
Percentage of time when natural ventilation is useful during January month in different floors

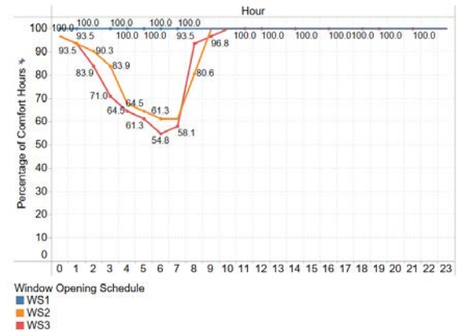


It can be seen from the figure (refer Fig.4 and Fig.5) that natural ventilation can be useful to reduce the indoor temperature during night-time mainly in May month. During January month, night ventilation during night-time for second floor can be an effective solution to increase the comfort hours.

3.5 Comfort hours in different window opening scenarios at a different time of the day

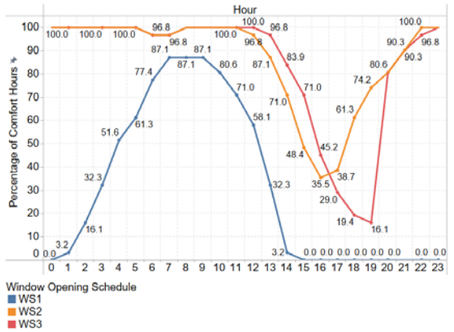
Percentage of comfort hours in the living room located on the ground floor was found 100% throughout the day when the windows are closed (WS1), whereas when the windows are open (WS2 and WS3), comfort hours in the living room located on the first floor were found 54.8% at 6:00 am (refer Fig.6). This is primarily due to an increase in the discomfort associated with cooling.

Figure 6:
Percentage of Comfort Hours at the ground floor during January



In January month, as shown in Fig.7, one can clearly see that in the case of closed windows, the top floor is almost 87% of the time falls under comfortable zone in the morning hours and start decreasing after 9:00 am. whereas in the afternoon and evening hours there is extremely less or no comfort hours.

Figure 7:
Percentage of Comfort Hours at the top floor during January



After 3 pm, there are no comfort hours in the case of WS1, and occupants living on the top floor need to use a mechanical cooling system to be comfortable in May month. These discomfort hours can be reduced by opening the windows and using natural ventilation. Whereas in between 3 to 5 pm discomfort hours are more than 50% in all the cases. One interesting fact is, in the afternoon hours from noon 12:00 to 4:00 pm, WS3 can provide more comfort hours compare to WS2, mainly by reducing the heat gain through convection. However, during evening hours after 5:00 pm, the curve of comfort hours from WS3 decreases, whereas the curve from WS2 starts increasing.

In May, the ground floor falls under the comfort zone 100% of the time during morning hours from 5:00 am to 9:00 am in all three scenarios (refer Fig.8). In the case of WS1 and WS2, the percentage of comfort hours starts decreasing after 9:00 am, whereas it remains 100% till 3:00 pm in WS3. The comfort hours decrease to 9.7% at 2:00 pm in WS2, which is lower than WS1 (48.4%). These results suggest that closing the window during the daytime helps reduce the discomfort hours on ground floors, mainly during the summer season.

Figure 8:
Percentage of Comfort Hours at the ground floor during the month of May

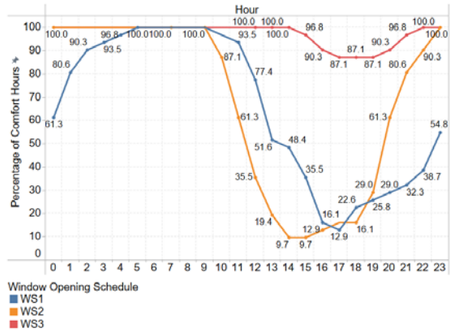
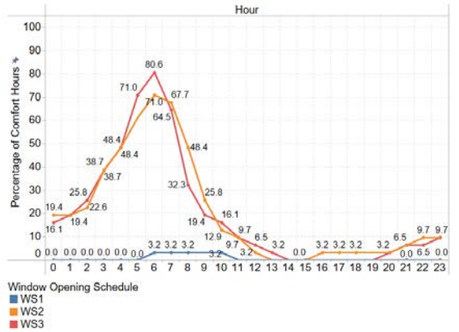


Figure 9:
Percentage of Comfort Hours at the top floor during the month of May



The pattern of comfort hours on the top floor during May is presented in Fig.9. WS1 can provide a maximum of 3.2% comfort hours, whereas, Using WS2 and WS3, comfort hours can be increased by 80.6 percent during the morning hours at 6:00 am. In contrast, in the afternoon and evening hours, even with the windows open, comfort hours can

only be extended by 3 percent, indicating that cooling from any other source is required during summers in top floors, and ventilation alone cannot bring the temperature within comfort limits.

To see how well each of the three types of window schedules worked over the whole year, the percentage of comfort hours data for the whole year was plotted in Fig.10 and Fig.11.

WS3 performs better in the case of providing comfort on the ground floor. Although WS2 and WS3 could not perform well during the morning hours at 5:00 am compared to WS1. Whereas in the afternoon and evening hours, WS3 performs better than the other two.

Figure 10:
Percentage of Comfort Hours at the ground floor considering whole year

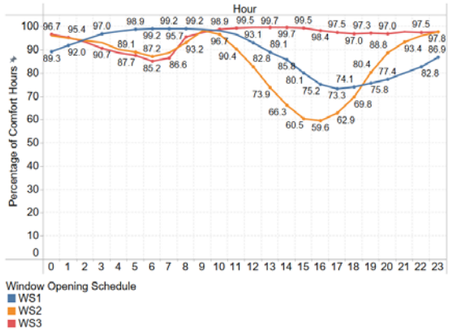
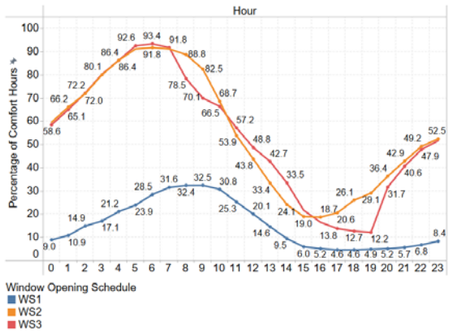


Figure 11:
Percentage of Comfort Hours at the top floor considering whole year



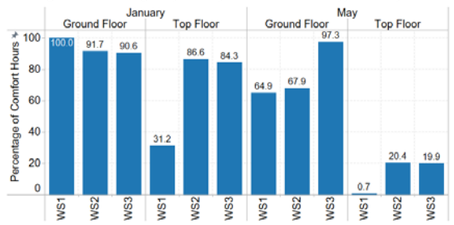
Conversely, WS1 performs worst on the top floor in all the hours throughout the day while comparing the yearly data. WS2 and WS3 perform almost in a similar way. WS2 and WS3 can provide comfort hours up to 93.4% during morning hours, whereas can only provide up to 26.1% comfort hours at 06:00 pm. Although after 7:00 pm, comfort hours started increasing in both WS2 and WS3 and reached up to 52.5% at midnight.

3.6 Average percentage of comfort hours and degree discomfort hours

Figure (refer Fig.12) explains the average comfort hours achieved by different windows schedule in peak winter and summer months. During the winter months, WS1 can provide 100% comfort hours on the ground floor. At the same time, the use of WS2 and WS3 reduces comfort hours up to 9.4% on the ground floors. During May month WS1 can provide up to 64.9% of the comfort hours on ground floors. WS3 is very effective for the ground floors during May month, and it increases the comfort hours by almost 30% compared to WS1 and WS2.

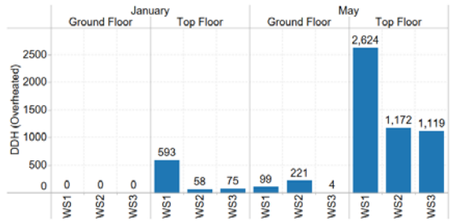
WS1 can provide only 31.2% on top floors during January, which can be increased by using WS2 and WS3. Comfort hours in January can be increased by 55.4% on the top floors by Using WS2. Whereas using WS1 during May month only provide 0.7% comfort hours on the top floors. This data explains that discomfort due to heat gain from the roof is considerable even in winters.

Figure 12:
Average Percentage of Comfort Hours at different floors



During May month even after using WS2 and WS3, comfort hours can be increased by only 19.7% and 19.2%, respectively, from 0.7% with WS1. This data confirms that the summer months for top floors are very critical, and comfort cannot be achieved by only natural ventilation.

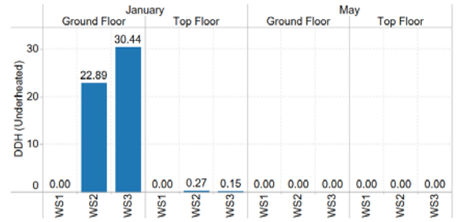
Figure 13:
Overheated Discomfort Degree Hours at different floors



Overheated discomfort degree hours at different floors are plotted in (refer Fig.13). During January months, there are no discomfort degree hours in all the three-window schedules. On the top floor, there are 593 Overheated DDH in the case of WS1, which is reduced to 58 by WS2 and 75 by WS3.

In May, when the weather outside is harsh, there are 99 Overheated DDH on the ground floor in the case of WS1, which increased to 221 in the case of WS2 and reduced to 4 in case of WS3. WS3 is performing well During May month on the ground floor compared to WS1 and WS2. Similarly, on the top floor also, WS3 performs better compared to the other two and was able to decrease the DDH to 1119. From this data, it can infer that the top floor required multiple solar passive strategies besides natural ventilation during May.

Figure 14:
Underheated Discomfort Degree Hours at different floors



Underheated Discomfort degree hours were calculated and plotted in a bar graph (refer Fig.14). In the case of WS1 there is no underheated DDH in any month, which explains that discomfort occurs mainly due to overheating in the Tiruchirappalli climate. Whereas in January month on ground floors, using WS2 and WS3 increases the underheated DDH mainly during the early morning hours. Closing the window during summers on ground floors can be an effective solution to provide thermal comfort in the living rooms.

4. CONCLUSION

It was found that a dwelling unit with a roof exposed to the sun had a high indoor temperature and very few comfort hours compared to the one on the ground floor. Opening the windows can significantly reduce the amount of discomfort and bring down the temperature. Natural ventilation can increase the comfort hours by almost 19% on top floors during the summer month. In May month on ground floors, closing the windows during daytime and left open during the night can increase the percentage of comfort hours by almost 30%, compared to when windows are open all the time. Since most of the literature focuses only on simulation-based results, this research includes real-time data monitoring and simulation, which can provide a better understanding of the performance of building envelopes and the effect of passive solar technique to achieve thermal comfort in Indoors. However, further investigation is required to explore the effect of outdoor air speed on indoor-outdoor temperature differences.

5. ACKNOWLEDGEMENTS

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Comparative Evaluation of Thermal Performance and Energy Conservation of Residential Buildings in Cold Climate of India

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ABSTRACT: This paper focuses on studying the thermal performance of residential buildings through field measurements in cold climate of India. The objective is to evaluate and compare the thermal performance of naturally ventilated residential buildings on seasonal and locational aspects. Real-time thermal performance monitoring of buildings is carried out for one year in Mussoorie. The three residential buildings are distinct in terms of location, spatial arrangement, and income category. The models of the buildings are simulated in TRNSYS and validated using real time field data. This paper compares the maximum and minimum indoor temperature, time lag, decrement factor and heating degree discomfort hours. The effect of prospective energy conservation measures is compared for each house w.r.t the reduction in heating degree discomfort hours. It is observed that not all energy saving strategies result in the same reduction in heating degree discomfort hours. Incorporating the energy conservation methods like reducing wall and roof U-value, infiltration and changing glazing type results in HDD reduction of 46%, 38% and 43% in in House A, House B and House C respectively.
KEYWORDS: Thermal Performance, TRNSYS, Energy Conservation Measures, Heating Degree Discomfort Hours, Residential buildings.

1. INTRODUCTION

The residential buildings in the Himalayan region require strategic intervention considering the increasing energy demand and climate change impacts. The design and construction must minimize heat loss and promote heat gain to enhance indoor thermal comfort while optimizing energy use. As per the Uttarakhand state government statistics [1] the residential sector accounts for 24% of the total electricity consumption in the state.

This paper focuses on the thermal performance of residential buildings through field measurements in the cold climate of India. The objectives of the study are (a) to evaluate and compare the thermal performance of naturally ventilated residential buildings through field measurements and (b) to analyse the effect of energy conservation measures on different building types. The study is limited to cold climate of India and the study focuses on low-rise detached residential units. To evaluate the thermal performance of the buildings, various thermal performance indexes like time lag, damping, decrement factor and degree discomfort hours have been used. To improve thermal performance, energy conservation measures were analysed through simulations performed using TRNSYS.

2. LOCATION AND CLIMATE

The study pertains to Mussoorie city (30.45°N; 78.06°E) located in Uttarakhand state in India, which represents a cold climate zone (Cwb). The dry bulb temperature ranges from -4°C to 18.5°C in winter (January) and 9.8°C to 33°C in summer (May). The diurnal temperature range during winter is around 15°C, and that during summer is about 17°C. The mean monthly Relative Humidity (RH) ranges from 29% to 100% in winter (January) and 36% to 78% in summer (May). The mean monthly solar radiation is 784 Wh/m^2 in winter (January) and 1124 Wh/m^2 in summer (May).

3. THERMAL PERFORMANCE OF RESIDENTIAL BUILDINGS

Three distinct naturally ventilated residential buildings are chosen to study the thermal performance through real-time field measurements. The indoor and outdoor temperature and relative humidity are recorded at ten minutes interval from January 2021 to December 2021.

3.1 Characterisation of Residences

House A is a three-story detached house that belongs to a higher-income family. House B is a single storey detached building belonging to lower income group. House C is a duplex belonging to middle income group. The photographs of the three selected residences are shown in Fig. 1. The floor plans with the sensor locations are shown in Fig. 2.

Figure 1: *House A, B, and C in Mussoorie*

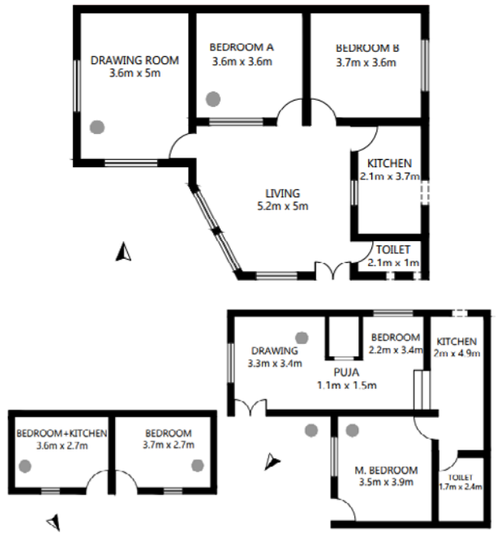

Figure 2: *Floor plan and sensor locations in House A, B, and C in Mussoorie*

Table 1 presents comparative details of House A, B, and C, describing the dimensions, area, volume, and building envelope details.

Table 1: *Comparative description of House A, B and C*

	HOUSE A	HOUSE B	HOUSE C
Perimeter	41.17 m	22.57 m	35.57 m
Floor Area	84 m^2	20.7 m^2	53.6 m^2
Volume	235.2 m^3	47.6 m^3	171.5 m^3
Floor-to-Floor height	2.8 m	2.3 m	3.2 m
Orientation	South	North-East	North-West
Wall type	230 mm Brick Masonry	230 mm Brick Masonry	230 mm Brick Masonry
Wall U-value	2.08 W/m^{2}K	2.08 W/m^{2}K	2.08 W/m^{2}K
Roof type	RCC slab	GI sheet	RCC slab
Roof shape	Flat	Sloping	Flat
Roof U-value	3.75 W/m^{2}K	5.82 W/m^{2}K	3.75 W/m^{2}K
Window type	Wooden frame with 3 mm single glass	Wooden frame with wooden panels	Wooden frame with 3 mm single glass
Sill height	0.8 m	0.9 m	0.9 m
Lintel height	2 m	1.8 m	2.1 m
WWR	15%	5%	8%
Overhang depth	0.6 m	0.75 m	1 m

3.2 Evaluation of thermal performance

Fig. 3 shows the real-time indoor environment conditions in the bedrooms and living rooms for three consecutive days in the winter month of January, the summer month of May, and a transition month of March. The readings are obtained using a temperature and humidity data logger with the precision of ±0.5^{0}C & ±3% RH and resolution of 0.1^{0}C & 0.1% RH.

The outdoor temperature ranges from -0.7^{0}C to 31^{0}C and relative humidity ranges between 15% to 96% during the recorded period. The indoor temperature ranges from 3.3^{0}C to 33.2^{0}C and relative humidity ranges between 20% to 95% for House A. The indoor temperature ranges from 0.6^{0}C to 36.6^{0}C and relative humidity ranges between 24% to 98% for House B. The indoor temperature ranges from 2.4^{0}C to 29.7^{0}C and relative humidity ranges between 26% to 98% for House C.

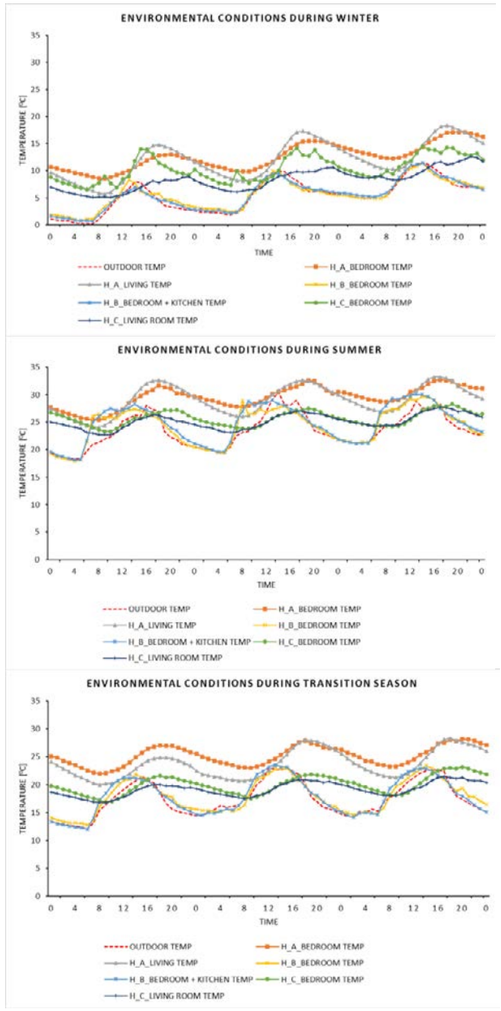

***Figure 3**: Indoor temperature variation measured in House A, B, and C for three consecutive days in January, May and March in 2021*

The solar exposure of building envelopes and the resultant variation in heat exchanges impact indoor thermal comfort. A comparative assessment of thermal conditions between a south-west (living room) and north (bedroom) exposed residential space in House A indicates that orientation leads to around 1.8^{0}C difference in spatial average indoor air temperatures of these spaces. It is seen that the pattern of variation in indoor thermal characteristics due to orientation changes are similar irrespective of the materials used for construction.

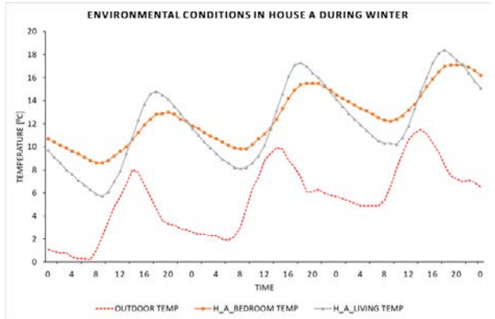

***Figure 4:** Indoor temperature variation measured in bedroom and living room of House A to study the impact of orientation.*

The thermal performance is evaluated by heating and cooling discomfort degree hours which measures how far the indoor temperature is below or above the neutral temperature [2]. The smaller the DDH, the better the thermal performance. The comfortable temperature is calculated using the Indian Model for Adaptive Comfort (IMAC) model given by [3]. Thermal performance parameters like minimum and maximum temperature, HDD (Heating degree discomfort hours), CDD (Cooling degree discomfort hours), time lag [4] and decrement factor have been discussed in the context of building performance.

Given the occupancy pattern in a residential building, thermal discomfort at specific time periods is more critical for certain zones than the others. For instance, the night-time DDH is crucial to a bedroom, while daytime DDH is crucial for a living room. Hence, DDH is calculated separately for daytime (7:00–20:00 h) and night-time (21:00–6:00 h) durations.

Table 1 presents a seasonal comparative thermal performance of three houses. The living rooms and the bedrooms are compared among each other.

***Table 2:** Comparative thermal conditions prevailing in the living rooms and Bedrooms of House A, B, and C from measured data.*

	HOUSE A	HOUSE B	HOUSE C
PEAK WINTER DAY – 10th Jan	**LIVING**	**BED + KIT**	**LIVING**
T_min	5.2 ^{0}C	0.6 ^{0}C	4.7 ^{0}C
T_max	13.3 ^{0}C	7.2 ^{0}C	8 ^{0}C
HDD_day	51.4 deg hrs	118 deg hrs	90 deg hrs
HDD_night	40.2 deg hrs	107 deg hrs	54 deg hrs
CDD_day	0	0	0
CDD_night	0	0	0
Time lag	5	1	6
Decrement factor	0.60	0.74	0.37
PEAK SUMMER DAY – 6th June			
T_min	26 ^{0}C	21.1 ^{0}C	24.8 ^{0}C
T_max	33.2 ^{0}C	35.6 ^{0}C	28.5 ^{0}C
HDD_day	0	0	0
HDD_night	0	0	0
CDD_day	48 deg hrs	26.2 deg hrs	4.5 deg hrs
CDD_night	28 deg hrs	0	0.8 deg hrs
Time lag	4	2	3
Decrement factor	0.64	0.85	0.44
TRANSITION DAY – 29th March			
T_min	20.7 ^{0}C	14.5 ^{0}C	17.5 ^{0}C
T_max	28 ^{0}C	23.6 ^{0}C	20.9 ^{0}C
HDD_day	0	1.5 deg hrs	0
HDD_night	0	11.5 deg hrs	0
CDD_day	20 deg hrs	0.3 deg hrs	0
CDD_night	14 deg hrs	0	0
Time lag	3	1	5
Decrement factor	0.54	0.98	0.39
PEAK WINTER DAY – 10th Jan	**BEDROOM**	**BEDROOM**	**BEDROOM**
T_min	8.3 ^{0}C	0.6 ^{0}C	7.1 ^{0}C
T_max	12.1 ^{0}C	7.4 ^{0}C	12.4 ^{0}C
HDD_day	35.8 deg hrs	109 deg hrs	40 deg hrs
HDD_night	23 deg hrs	102 deg hrs	36 deg hrs
CDD_day	0	0	0
CDD_night	0	0	0
Time lag	5	1	2
Decrement factor	0.43	0.76	0.6
PEAK SUMMER DAY – 6th June			
T_min	28 ^{0}C	21.2 ^{0}C	24.2 ^{0}C
T_max	32.7 ^{0}C	29.7 ^{0}C	28.3 ^{0}C
HDD_day	0	0	0
HDD_night	0	0	0
CDD_day	55.7 deg hrs	17 deg hrs	6.7 deg hrs
CDD_night	39.2 deg hrs	0	2 deg hrs
Time lag	5	1	6
Decrement factor	0.52	0.86	0.53
TRANSITION DAY – 29th March			
T_min	23 ^{0}C	15.2 ^{0}C	17.6 ^{0}C
T_max	28 ^{0}C	22.9 ^{0}C	21.9 ^{0}C
HDD_day	0	2.6 deg hrs	0
HDD_night	0	8.6 deg hrs	0
CDD_day	24.4deg hrs	0	0
CDD_night	21.3 deg	0	0
		hrs	
Time lag	9	2	7
Decrement factor	0.56	0.89	0.49

The three residences exhibit significant differences in thermal performance. In House A, the bedroom has the lowest HDD, i.e., 58 deg hrs during peak winter. House B is not thermally comfortable throughout the year, according to thermal performance metrics such as HDD, time lag, and decrement factor. House C's bedroom performs moderately in comparison to House A. Due to the higher floor-to-floor height of House C, the CDD in summer is comparatively less. House C performs best during summer due to its orientation and ceiling height. The HDD_day is more than HDD_night for all three Houses, which means residents feel discomfort during the day than at night.

4. VALIDATION OF SIMULATION MODEL USING FIELD MEASUREMENT

The three houses are modelled in TRNSYS, and the simulation results are validated with the actual field measurements under similar conditions comparing the indoor air temperature for a week. The results of a survey on the average and maximum errors recorded in simulation validation studies are presented, whereby the typical max error is below 7^{0}C, and the average error is 4.3^{0}C. The CVRMSE [5] value between modelled and measured indoor temperature is 9.4%. According to the ASHRAE Guide, the models are validated when the CVRMSE values fall within 30% [5]. CVRMSE (Coefficient of variation of the root mean square error) is given by Equation (1):

$$\text{CVRMSE} = \frac{\sqrt{\sum_{i=1}^{Ni} \frac{(Mi - Si)^2}{Ni}}}{\frac{1}{Ni}\sum_{i=1}^{Ni} Mi} \qquad (1)$$

where M_i – Measured data;
S_i – simulated data;
N_i – count of the number of the data used in the validation.

Fig 5. shows the simulated and measured indoor temperature data.

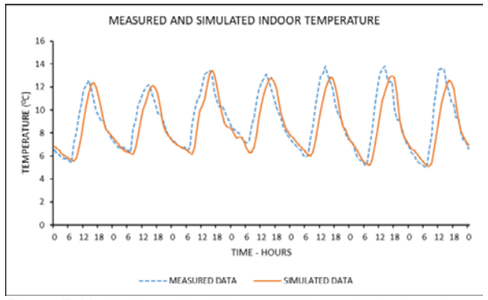

Figure 5: *Validation of building model for a typical week.*

5. ENERGY CONSERVATION MEASURES

This section compares the effect of prospective energy conservation measures implemented in each house, such as lowering the U-value by adding insulation to the walls and roof, altering the glazing type, and reducing the infiltration.

Six commonly used wall combinations were first analysed in terms of thermal performance. The following walls are:

- 200mm Aerated Concrete + 10 mm XPS – 0.62 W/m^{2}K
- 200mm Aerated Concrete – 0.77 W/m^{2}K
- 222mm Brick + 10 mm XPS – 1.36 W/m^{2}K
- 450 mm Random Rubble masonry – 2.04 W/m^{2}Ks
- 222mm Brick – 2.08 W/m^{2}K
- 200 mm Fly-ash Bricks – 2.27 W/m^{2}K

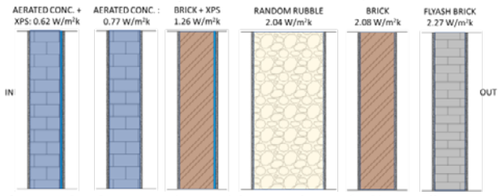

Figure 6*: Cross-section with U-value of Six wall types commonly used for construction.*

The Aerated Concrete wall with XPS insulation outside reduces DDH the most of the six wall types studied.

The brick walls with U-value 2.08 W/m^{2}K of the three houses are replaced with Aerated Concrete walls with 10 mm XPS insulation in the exterior side with the U-value of 0.62 W/m^{2}K. The roofs of the Houses are upgraded to RCC roof with 10 mm XPS insulation with U-value as 1.6 W/m^{2}K. The glazing is changed from a single 3mm glass with a U-value of 5.8 W/m^{2}K to a double 6 mm glass with air between the panes with a U-value of 2.67 W/m^{2}K. The infiltration is reduced to 0.5 ach. The WWR is already as per standard [6] for all three buildings, so it is not considered a solution to decrease HDD.

Energy conservation measures are implemented incrementally in stages. Table 3 presents the reduction in heating discomfort hours for the houses and the energy conservation measure applied.

Table 3: *Reduction in annual HDD for each energy conservation measure applied step-wise.*

ECM	HOUSE A	HOUSE B	HOUSE C
HDD	3,528 deg hrs	32,067 deg hrs	16,040 deg hrs
Reducing U-value of Wall	2,929 deg hrs	28,882 deg hrs	12,832 deg hrs
Reducing U-value of Roof	2,158 deg hrs	21,912 deg hrs	10,523 deg hrs
Double Glazing with Air	1,938 deg hrs	20,614 deg hrs	10,313 deg hrs
Reducing infiltration	1,870 deg hrs	19,885 deg hrs	9,076 deg hrs

6. CONCLUSION

This paper presents a comparative assessment of the building envelop thermal performance with respect to naturally ventilated buildings in a cold climate. Thermal performance of building envelops has been demonstrated through real-time field studies in three residential buildings distinct in terms of location, spatial arrangement, and income category. The indoor-outdoor temperature and humidity are measured for a year to capture the seasonal and diurnal behaviour of the residential buildings. The real-time measurement indicates the distinct indoor conditions for the three houses. The thermal performance is evaluated by heating and cooling discomfort degree hours, indoor minimum and maximum temperature, time lag and decrement factor.

The architectural features like building orientation, building height, WWR, roof properties (U-value), and floor plan determines the difference in thermal behaviour of the three residences. 15% WWR in a south oriented floor plan leads to higher indoor temperature in House A during peak winter. The time lag in House A, B and C are 5 hours, 1 hour and 6 hours. House A and C are thermally comfortable in peak summer; however, House B is uncomfortable throughout the day, night, and year. The decrement factor is highest for House C among all the three houses which suggests that its envelope doesn't dampen the outdoor conditions effectively.

The HDD for House A is 3528 deg hrs, House B is 32,067, and House C is 16,040 deg hrs. To further reduce the HDD, buildings are modelled and validated using real-time data. The energy conservation techniques are applied to the validated building models. We deduce that not all energy saving strategies result in the same reduction in heating degree discomfort hours. For Houses A and B, installing 10 mm XPS insulation to the roof is the most beneficial upgrade. However, adding 10 mm XPS wall insulation from the outside is more useful for House C. Incorporating energy conservation techniques such as lowering wall and roof U-values, minimising infiltration, and altering glass type results in HDD reductions of 46%, 38%, and 43% in Houses A, B, and C, respectively.

The study implies that not all buildings perform similarly in the same climate zone due to the distinct building type, location, and architectural layout. The energy conservation measures result in different reductions for heating degree discomfort hours which is beneficial to know as choosing the measure will be appropriate and cost-effective.

ACKNOWLEDGEMENTS

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Comparative approach of the environmental impact induced by different architectural visions of a new periurban neighbourhood

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ABSTRACT: The objective of this research work is to compare the environmental impact, expressed in terms of non-renewable cumulative energy demand (CEDnr) and greenhouse gas (GHG) emissions, of nine architectural visions for a new neighbourhood located in the periurban area of Lausanne in Switzerland. The visions have different morphologies and their buildings are furthermore declined in a series of constructive scenarios generated by varying parameters such as the type of insulating material or the heating system. In order to compare and analyse the results of this multi-variant evaluation, the target values established by the SIA 2040 and resulting from the 2'000-Watt society concept are used as a reference framework. The present study offers a double perspective allowing both a comparison of the environmental impact of the different visions between them, but also an exploration of the results of a parametric analysis carried out for each of them. This double approach allows to highlight on the one hand the influence of the urban morphology proposed by each vision, and on the other hand the room for manoeuvre at the level of materialisation that each vision presents intrinsically.
KEYWORDS: Environmental impact, sustainable neighbourhood, periurban, multi-criteria assessment, sustainable architectural design

1. INTRODUCTION

The objective of this research work is to compare the environmental impact, expressed in terms of non-renewable cumulative energy demand (CEDnr) and greenhouse gas (GHG) emissions, of nine architectural visions. The latter results from the work of an architectural design studio at EPFL [1] for a new neighbourhood located next to a train station in Bercher, a periurban area of the Lausanne conurbation in Switzerland. The visions provide different urban morphologies and their buildings are furthermore declined in a series of constructive scenarios generated by varying parameters such as the type of insulating material or the heating system. In order to compare and analyse the results of this multi-variant evaluation, the target values established by the SIA 2040:2017 [2] and resulting from the 2'000-Watt society concept are used as a reference framework (Table 1). The present study offers a double perspective allowing both a comparison of the environmental impact of the different visions between them, but also an exploration of the results of a parametric analysis carried out for each of them.

This double approach allows to highlight on the one hand the influence of the urban morphology proposed by each vision, and on the other hand the room for manoeuvre at the level of materialisation that each vision presents intrinsically.

Table 1:
Target values according to SIA 2040:2017 for the residential building sector (new constructions).

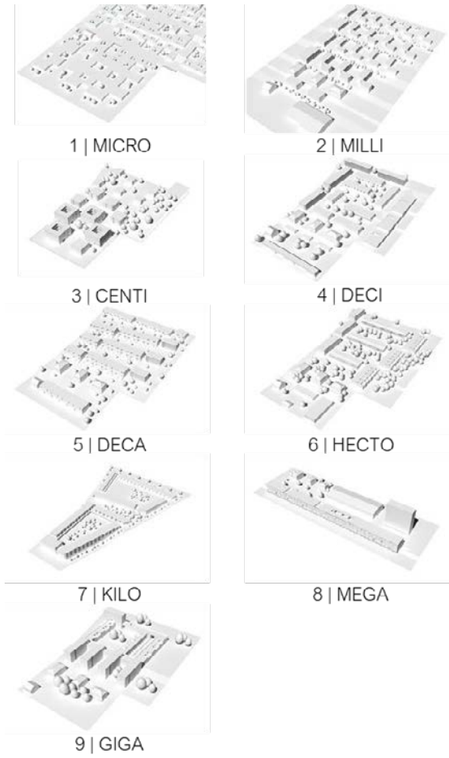
Criteria	CEDnr [kWh/m².year]	GHG [kgCO_2/m².year]
Construction	30	9
Operations	60	3
Induced mobility	30	4
Total target value	120	16

The evaluation method, which focuses on primary energy and carbon footprint by taking into account the entire life cycle related to construction **materials**, the induced **mobility** of the inhabitants and the energy consumed by the building during its **operation** phase, is innovative and allows to move towards the digitalization of the construction sector thanks to the integration of BIM approaches from the first design phases. The results of this multi-criteria evaluation are presented using web-based visualization tools that allow a quick interpretation and dynamic exploration of the proposed visions and scenarios, each defined by a unique combination of various parameters.

2. METHODOLOGY

The approach uses as input data the 3D digital models of the nine visions (Figure 1) in Rhinoceros 3D format, in order to automatically obtain the surfaces and material quantities of the different constructional components (e.g. glazed surface or opaque façade). At the same time, the available roof and facade surfaces are automatically detected to evaluate the solar and electricity production potential on site.

Figure 1:
Presentation of the 9 visions of the neighbourhood.



Then, using the visual programming language Grasshopper [3], the reference environmental impact values of the KBOB 2009/1:2016 building material database [4] and the guidelines of the SIA 2032:2010 standard [5] are applied to calculate the complete environmental impact of each vision and scenario. The resulting environmental impact for each scenario is expressed in terms of non-renewable primary energy (CEDnr [kWh/m² of building element]) and greenhouse gas (GHG, [kgCO_2/m² of building element]) emissions.

The set of design and materiality variants over the nine visions is generated from six different criteria which concern 1) the performance of the building envelope, 2) the type of construction, 3) the insulation material used, 4) the heating and domestic hot water (DHW) system, 5) the solar electricity production using the roof and 6) the solar electricity production using the facades.
For each of the criteria, we have proposed a series of parameters that can be varied (Table 2).

Table 2:
Presentation of the criteria and parameters to be combined, leading to a total of 576 scenarios per vision.

Criteria	Parameters	
1 - Building envelope | Opaque part	0.17 | 0.14 | 0.10 W/m²·K	
2 - Construction type	**Heavy**	**Light**
Horizontal components	Concrete	Wood
Vertical components	Brick	Timber frame
Façade cladding	Plaster	Wooden slats
Window frame	PVC	Wood
Ventilation system	Simple flow	Double flow
Glazing | U-value	Triple | 0.6 W/m²·K	
3 - Insulation type	- Fiberglass - Expanded Polystyrene - Rock wool	
4 – Heating and DHW system	- Heat pump - Biomass boiler (pellets) - District heating (<= 50% non-renewable) - Natural gas boiler	
5 – BIPV | Roof	0% | 30% | 60% | 90%	
6 – BIPV | Facade	0% | 80%	

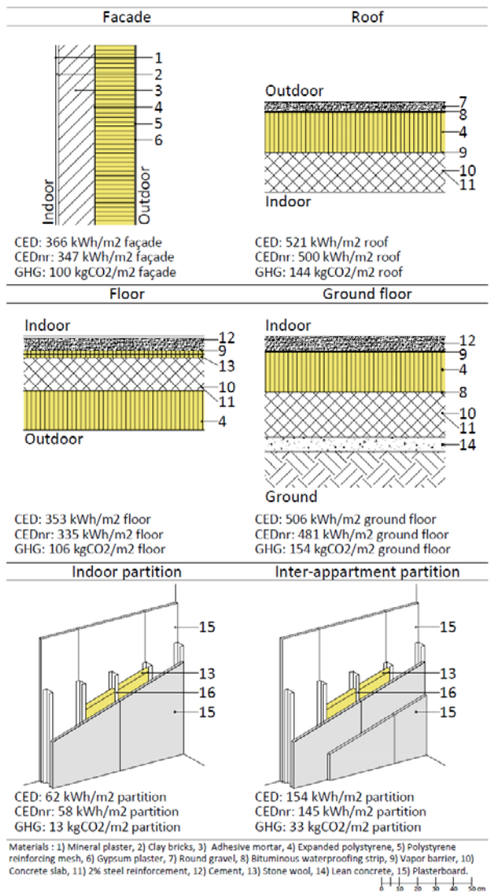
By applying each possible combination to each of the visions (Figure 1), we obtain a total of 5'184 scenarios, or 576 scenarios per vision. For criterion 1) performance of the building envelope, the variation of the insulation thickness together with the different layers that make up the envelope allows us to determine the three global transmittance values proposed for the facades, the walls against the ground, the slabs, the floors and the roof.

In connection with this first criterion, we proposed for criterion 2) type of construction two well-differentiated construction typologies: heavy and light construction, characterized respectively by a concrete/brick and wood structure, as well as a plasterboard versus wood particleboards partitions and PVC versus wood window frames.

The composition of the layers for the two thermal envelope options is detailed in Figure 2 (heavy) and Figure 3 (light).

In order to estimate the overall energy balance as well as the environmental impact of the operation phase for each vision and scenario, a dual approach was used. On the one hand, electricity consumption values for standard building use were defined on the basis of SIA 2024:2015 [6] (hot water requirements: 19.8 kWh/m2.yr, lighting consumption: 4 kWh/m2.yr and appliances: 14 kWh/m2.yr). On the other hand, the effective energy requirements for heating (Qh, eff) were obtained from the form factor of each vision following the calculation method of SIA 380/1:2016 [7].

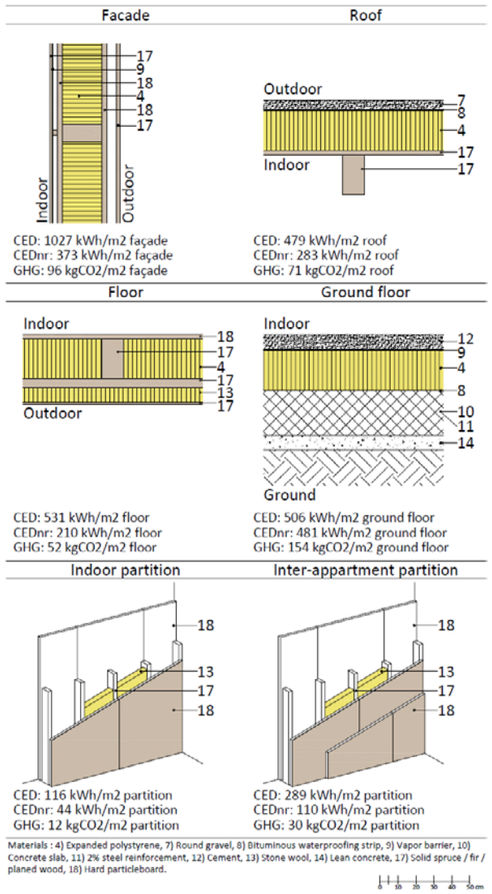
Figure 2:
Construction type heavy and the environmental impact in terms of CED, CEDnr and GHG using KBOB database.



Then, reduction coefficients, determined using partial dynamic thermal simulations on a representative part of the neighbourhood, were applied on the limit energy requirements for heating (Qh,li) according to the performance of the thermal envelope defined by the thermal transmittance (U) of opaque parts. For the three simulated options (U-value: 0.17, 0.14, 0.10 W/m2-K), the coefficients used to reduce the heating energy requirements are 20%, 34% and 63% respectively.

For the impact due to the mobility induced by the inhabitants of the neighbourhood, the calculations were carried out using SIA 2039:2016 [8] taking into account the fleet of vehicles expected for 2050.

Figure 3:
Construction type light and his environmental impact in terms of CED, CEDnr and GHG using KBOB database.

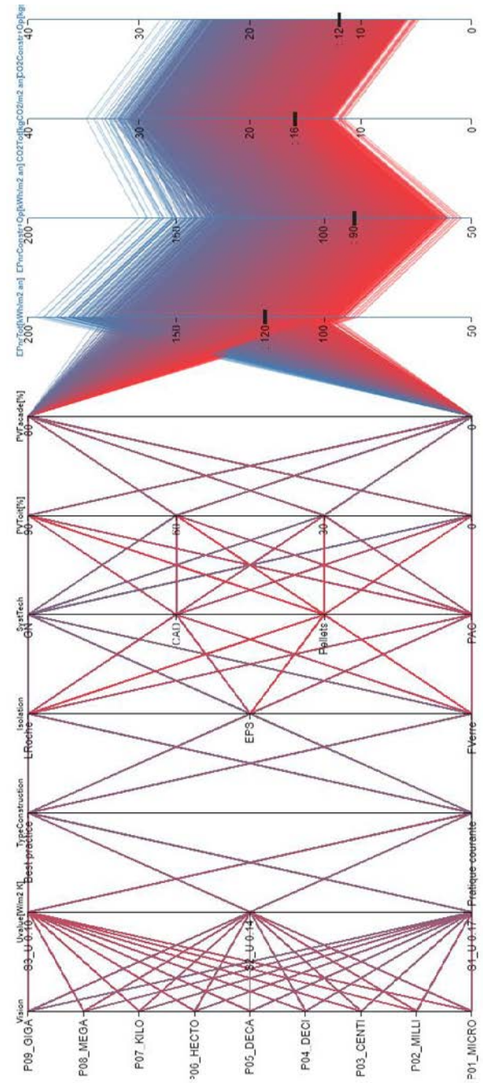


3. RESULTS

This study links the scale of the neighbourhood to that of the building component, through a bottom-up approach to assessing the environmental impact on the life cycle of buildings.

The results of the evaluation of the scenarios generated by the combination of the different parameters on the basis of each vision will be presented graphically using a parallel coordinate diagram (Figure 5) and online exploration tools such as DesignExplorer [9] or using boxplots (Figure 6), providing an overview of all scenarios and visions.

Figure 5:
Parallel coordinate diagram showing the distribution of environmental impact values..

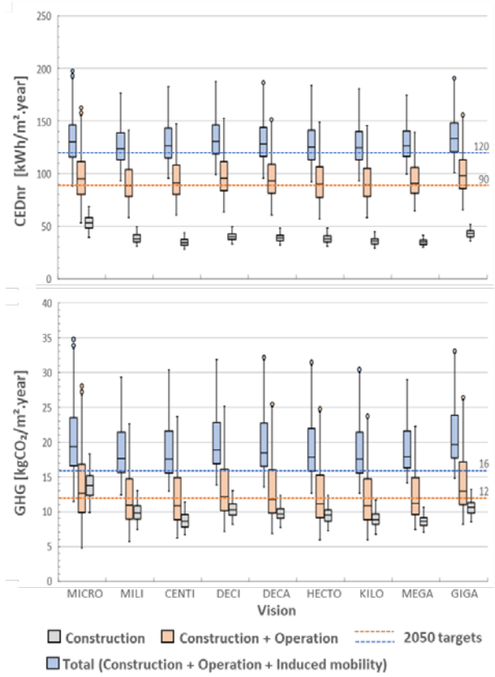


Note: The 2050 targets (Table 1) are identified in bold on the CEDnr and GHG axes.

With respect to the 2050 targets stated at the beginning (Table 1), the diagram (Figure 5) shows that all visions have the potential to achieve the targets in terms of non-renewable primary energy requirement and greenhouse gas emissions. By applying filters on the different axes of the parameters via the web application [9], it can be observed that the "ease" of reaching these targets will depend on the performance values of the thermal envelope, to be set at the design stage, the technical choices for the heat supply and the environmental quality of the materials used during the construction.

In order to explore the feasibility of the different visions according to the 2050 targets, the results are analysed using standardized boxplots showing the distribution of the data (Figure 6). In general, the wider the interquartile box, the larger the distribution of results, which could therefore be interpreted as greater variability in results.

Figure 6:
Boxplot illustrating the distribution of results for CEDnr and GHG emissions for the construction and operational phases.



Note: The 2050 targets (table 1) are identified with dotted lines: orange for construction + operational phase) and blue for total construction + operational + induced mobility.

Essentially, we observe that all visions can potentially meet the targets for 2050, however the possible choices are more or less limited depending on the vision. The most constraining criterion to reach is that of greenhouse gas emissions (GHG), in this sense, figure 6 shows that the visions farthest from these objectives are mainly 4 (DECI), 5 (DECA), 8 (MEGA) and 9 (GIGA).

For these four visions, no scenario with natural gas or district heating allows to reach the objectives. Visions 4 (DECI), 5 (DECA), 8 (MEGA) offer some leeway in terms of the type of construction (heavy or light) and the choice of whether or not to use the facades to produce electricity on site. On the other hand, contrary to the other three visions, vision 9 (GIGA) is constrained to a wood construction (light) and must integrate a photovoltaic production on the facade in order to compensate the small amount of well-exposed roof available.

4. CONCLUSION

This study linked the neighbourhood scale to the building component scale through a bottom-up approach to assessing the life cycle environmental impact of buildings.

The analysis shows that, from the point of view of meeting the 2050 objectives, the choice of vision for the development of a periurban neighbourhood can either 'facilitate' or 'complicate' the task of the developers of the individual plots and/or buildings, in the sense that the freedom of choice with regard to the type of construction, materiality, on-site power generation and type of technical system is more or less restricted.

In this context, the use of dynamic exploration tools on urban scale projects can help to make the link between land use and energy planning. For example, if at the district energy planning level, the installation of a "classic" district heating network with a renewable energy rate of about 50% is planned, it must be anticipated already at the urban planning level that some visions will have difficulties to concretely reach the 2050 objectives.

In these cases, very restrictive choices will have to be imposed on building designers, limiting their creativity in terms of architectural design and their freedom in terms of construction choices. Furthermore, the results also highlight that if the authorities decide to impose the use of a natural gas network for district heating, the 2050 targets would not be met, regardless of the construction choices and other parameters, and of the performance of the vision considered.

In sum, out of the nine visions and 5'184 simulated scenarios, 764 meet the target values for 2050, that represent only 14.7% of the total number of scenarios considered. This relatively low percentage highlights both the ambition of Switzerland's 2050 targets and the real possibility of achieving them.

Focusing only on these scenarios, we can see that the average distribution of GHG emissions due to construction is 44% (6.20 $kgCO_2/m^2$.year), that due to operating energy is 8% (1.18 $kgCO_2/m^2$.year), and that due to induced mobility of the inhabitants is 48% (6.70 $kgCO_2/m^2$.year). This distribution highlights the high-energy efficiency that can be achieved for the operation of buildings - even positive energy buildings - with well-known and accessible technologies. On the other hand, even with the projected mobility fleet for 2050, which should be half as "polluting" as the current reference fleet in 2015, the mobility induced by the inhabitants represents about half of the total impact.

Therefore, an effort to reduce the impact of induced mobility must be made to achieve the objectives and thus minimize the effects of the built environment on climate change.

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PLEA SANTIAGO 2022
Will Cities Survive?

Study of land use/cover change impacts on thermal microclimate using QGIS in urban agglomeration

Case study: city of Biskra, Algeria

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ABSTRACT: Thermal comfort and air quality are major concerns for people living in urban areas. In the last decades, cities are growing quickly and the increased urbanization is leading to the expansion of cities, which changes the properties and composition of the landscape. However, the surface temperatures are increasing, globally, because of anthropogenic climate change. Land use and land cover change have been shown to have a significant effect on climate through various pathways that modulate land surface temperature and rainfall. The objective of this study is to understand how the land use and land cover change affects the thermal microclimate in the city of Biskra (Algeria) using QGIS for the period between 2010 and 2020. The analysis results reveal that the mean temperature of the city has increased by ~4 °C during the past decade with the most accelerated warming (~7 °C) occurring during the recent decade (2010 to 2020). Our study shows also that 32% to 56% of this observed overall warming is associated with land use/cover and the largest changes are related to changing vegetation cover as evidenced by changes to both land use and land covers classes and normalized difference vegetation index (NDVI).
KEYWORDS: Thermal microclimate, Land use/land cover, QGIS analysis, LST, NDVI, Statistical correlation

1. INTRODUCTION

Nowadays urban design requires comprehensive and vast knowledge in different fields. Many problems related to urban climate, air pollution, ecosystems, energy consumption, traffic and health are caused by the highly densified development despite of the benefits brought by the urbanization process [1]. From the literature review for background studies, the local climate of an urban area can be affected by several features that should be properly cared for a sustainable urban environment such as: the urban thermo-physical and geometrical characteristics, anthropogenic activities and heat sources present in the area.

There is a strong relation between the urban morphology and the urban microclimate [2]. In other words, urban morphology parameters have an obvious impact on microclimate. Designers are obliged to consider many issues for the effective urban design such as the local climate, which has become a crucial task to consider for high-density cities [3].

Stromann Andersen and Sattrup in their research [4], stated that the geometry of urban canyons may affect the total energy consumption of low-energy buildings. In the other hand, Wong in his research [5] proved that increasing the height and density of the surroundings (greenery and buildings) lowers the temperature of the external microclimate and reduces the cooling load of the building by around 5%. A simplified spatial model developed by Adolphe [6], based on a set of morphological indicators in terms of various parameters, such as density, rugosity, sinuosity, contiguity and solar admittance in order to simplify the analysis of outdoor microclimate tendencies and the energy balance of urban patterns.

Based on previous studies and research show that human outdoor comfort is influenced by multiple factors depending on air temperature, wind speed, relative humidity and solar radiation [7]. It was found, that peoples feel comfortable in the temperature range of 21 °C to 27.5°C, and relative humidity included between 30% to 65% with wind speed values greater than 5 m/s [7]. In hot and arid region, which is the case in our study, factors such as strong solar radiation, high temperature, low humidity, dazzling light and dust storms can reduce thermal comfort, which has higher health risks for city dwellers [8]. Therefore, researchers are paying more attention to outdoor thermal comfort in urban settings as part of urban design. Land surface temperature (LST) and normalized difference vegetation index (NDVI) are very important factors mainly used in surface urban heat island (SUHI) analysis [9].

The objective of this research is to analyse the effect of land use and land cover change on the urban microclimate of the city of Biskra (South-East of the capital Algiers) by analysing Land surface

temperature (LST) and Normalized Difference Vegetation Index (NDVI) data for a period of 10 years using QGIS.

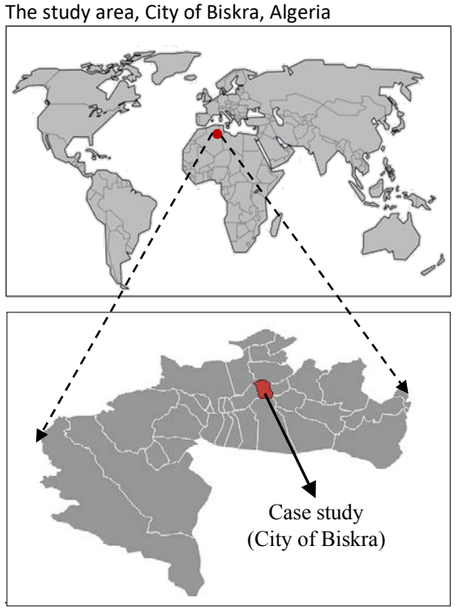
2. MATERIALS AND METHOD

Through a combination of ground, satellite remote sensing and reanalysis products using QGIS, we investigate the recent changes of land surface temperature in the urban agglomeration of the city of Biskra (Algeria) between 2010 and 2020 and assess its relation to land use/cover. However, we analyse whether the surface temperature and the vegetation would increase and, if so, whether these are in response to changes in land cover and/or changes in climate.

2.1 Case of study

Biskra is a main town in Algeria, situated in the south east (Latitude: 34° 52' North, Longitude: 5° 45' East) on the border of the Sahara Desert with a surface of 127,55 km2 (Fig. 1). The city has a large amount of solar potential (5-6 kWh/m²/day) and (2190 kWh/m²/year). In addition, the microclimate of Biskra city is characterized by sunny sky, little rainfall and high air temperatures exceeding 30°C during nearly half of the year (from April to November), an average annual humidity of 46%. Research given by Daich et al (2017) has shown that Biskra has an intermediate sky with an average annual cloud cover of around 40% [10].

Figure 1:
The study area, City of Biskra, Algeria



2.2 Data collection

In this study, MOD11_A2, Terra MODIS LST eight-day data, the Landsat 7 and the Landsat-8 Operational Land Imager (OLI), the Landsat-8 (ETM+) and TIRS (Thermal Infrared Sensor) have been used to collect data about Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI). The data can be obtained and retrieved based on spatial and temporal criteria.

LST was retrieved by applying the split-window algorithm from Landsat 8 TIRS data. The image code, date, cloud cover and scene searched are presented in Table 1. TIRS data were then converted to TOA spectral radiance using the radiance rescaling factors provided in the metadata file. The conversion of thermal bands of Landsat 8 satellite data into luminance values is necessary; the luminance values obtained are then used to transform the luminosity into temperatures.

Table 1:
Landsat 7 and Landsat 8 (OLI, TIRS and ETM+) images selected in the study.

Image Code	Acquisition Date	Cloud cover	Zone /Path
LE07_L1TP_194036_20100427_20161214_01_T1	24-04-2010 10 :05 :53	4	194
LC08_L1TP_194036_20200430_20200509_01_T1	30-04-2020 10 :13 :07	4	194

In addition, it is known that Land Surface Temperature was based on fractional vegetation cover (FVC) and was calculated using NDVI images. The NDVI was calculated using Landsat 8's bands 4 and 5 images as inputs with NDVI-min from the dry soil and NDVI-max from dense vegetation. This index was calculated using Equation (1):

$$NDVI=(\rho NIR-\rho RED)/(\rho NIR+\rho RED) \quad (1)$$

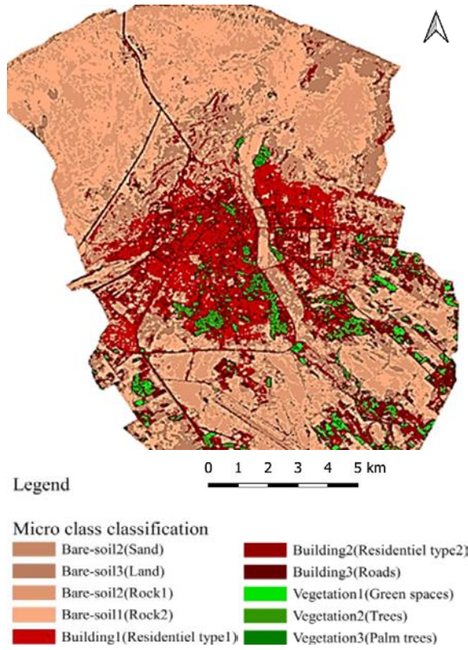
Where NDVI - Normalized Difference Vegetation Index;

ρNIR - near-infrared light;
ρRED - visible red light;

At the end, the LST derived from Landsat data sets are analyzed and compared with NDVI calculated values.

Figure 2 shows Land cover types, which were categorized using the maximum likelihood classifier, into building (type 1, type 2 and roads), vegetation (green spaces, trees and palm trees) and soil (sand, land, rock 1 and rock 2).

Figure 2:
Surface biophysical properties: Micro class classification of the case study



3. VALIDATION OF THE RESULTS

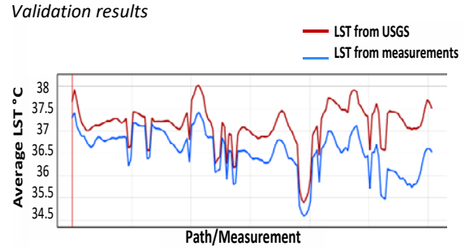
Mobile measurement was frequently used in micro-scale urban investigations [11]. ,In order to validate the Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) results obtained by QGIS 3.22.4 and analyse the relationship between these two indices, we have used a mobile meteorological station equipped with multifunction thermometer, infrared thermal camera and GPS (Fig. 3). The observation campaign was executed in April, 20, 21, 22, 23, 24, 25, 26 and 27, 2020. For this, seventy-four stations were defined to cover the micro-scale urban features for representative areas of the Biskra city center in a path of 3700m (Fig. 4). The distance between two stations is fifty meters. The measurement height was about 1.1 m above the ground surface level. The observed data represents the exposed micro-climate conditions of each station (measurement point). Thus, normalization on the measured air temperature in eight days of investigation is demanded before doing the comparative analysis.

The Results presented in Figure 5 showed that the measured mean temperature in the path is with a range of ±7% which indicates a significant positive correlation between LST obtained from USGS and LST measured with the mobile meteorological station. In the next section, the presented data have been obtained only from QGIS.

Figure 3:
Mobile meteorological station

Figure 4:
Selected Path for the validation

Figure 5:
Validation results



4. RESULTS AND DISCUSSION

4.1. Land Surface Temperature (LST) Analysis

Figure 6 and Figure 7 show the LSTs and the spatial dynamics of changes over time in LST in the study area for the analysed years (2010-2020). The results show that the mean LST (°C) increased from 29°C in 2010 to 33°C in 2020. The greatest transformation in Land Surface Temperature was in the West, South and top South-Western parts of the city, while the lowest LST was observed at the top of the Northern. The high LST zones represent bare earth surface (sand, land, rock 1 and rock 2) surrounding the city, whereas the low LST zones are developed mainly by the concentration of dense vegetal cover especially trees and built-up especially residence type 1 and 2. The data shows also that in 2020, the city center of Biskra faced a range of 35.98°C and 41.18 °C, some 3°C–7 °C higher than that of the suburban/rural area (range of 33.68°C and 35.98°C) which causes the urban heat island phenomenon. The study shows also that

32% to 56% of this observed overall warming is associated with climate change and land use/cover.

Figure 6:
LST results (2010)

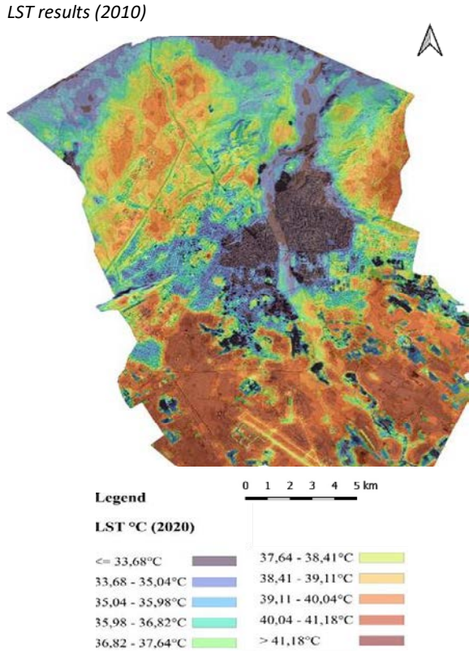
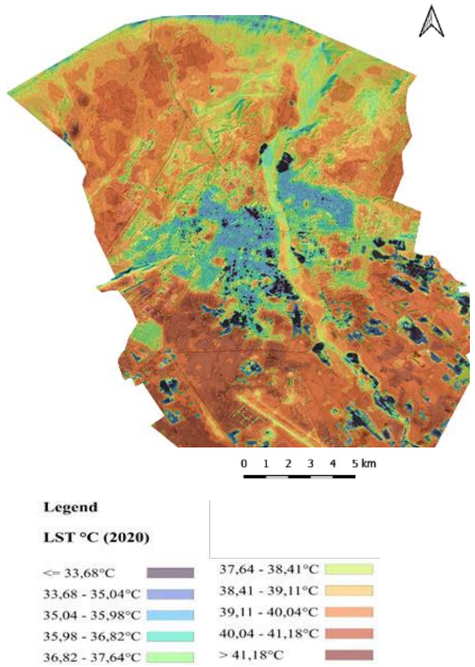


Figure 7:
LST results (2010)



4.2 Normalized Difference Vegetation Index (NDVI) analysis

Figure 8:
NDVI results (2010)

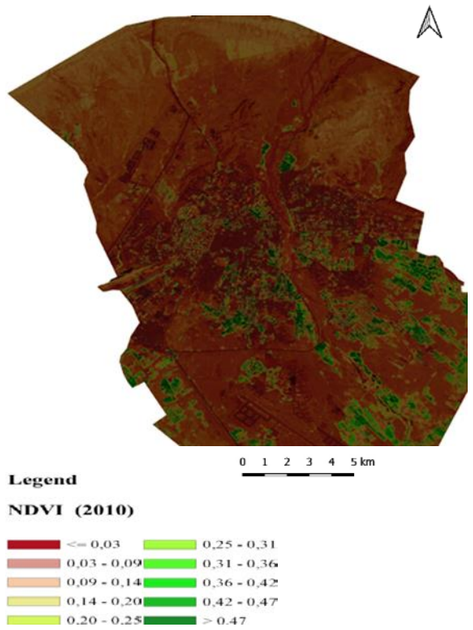
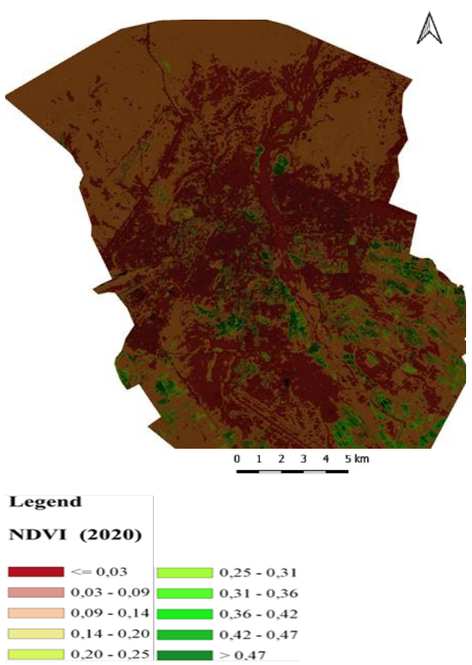


Figure 9:
NDVI results (2020)



5. CONCLUSION

This investigation aims to study the effect of land use and land cover change on the urban microclimate by assessing the trend of spatiotemporal relationship between Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) for Biskra city (Algeria) using QGIS from 2010 to 2020. The results show that mean LST of the study area has been increased with a very significant rate (~4 °C). Generally, the average land surface temperature (LST) increased by nearly 5 °C in the city and nearly 3 °C at the city boundary situated at 10km from the city center. LST level increased due to increased greater population pressure resulting in rapid expansion of built-up areas with detriment of green space area, which cause the urban heat island phenomenon.

Moreover, the data indicates that there was a negative relationship between Land Surface Temperature and Normal Difference Vegetation Index for the whole of the study area. The relationship is quite insignificant for low LST zones (north and north-eastern areas). These areas have relatively high NDVI values.

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Urban agriculture
For the people, by the people

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ABSTRACT: The population of cities in India continues to expand exponentially. It is predicted that by 2050, 55% of Indians will be living in urban areas. The combined issues of population explosion, rapid urbanization, and climate change are posing a great threat to the food supply. The pandemic disrupted food supply chains which showed their massive dependence on fossil fuels and supporting infrastructure to transport agricultural food over thousands of kilometers. On the other hand, the potential of local food systems was brought to the forefront and growing food in the urban areas started gaining momentum. Urban agriculture has been a well-integrated part of many Indian cities for many years. It provides cities and urban communities an opportunity to counter food scarcity, while also strengthening their resilience. In recent months, people are becoming more aware of the urgent need to support and participate part in local, sustainable food systems. To sustain these practices at the neighborhood level, people need to build critical consciousness and awareness of the food system. The purpose of the research was to study the feasibility of incorporating urban agricultural practices considering the existing architectural typologies at a neighborhood level in a compact city like Mumbai.
KEYWORDS: Urban Agriculture, Sustainable Development, Feasibility, Mumbai City, Urban Growth

1. INTRODUCTION

India, being an agriculture-based country, ranks 2nd worldwide in farm outputs (Wikipedia, 2022). Since the economic reforms of 1991, there has been a sharp decline in the productivity of the agricultural sector and growing pressure on the fast-developing tertiary sector. This has led to a decrease in the food output and rising unemployment rates. Along with this, there is the problem of India's increasing population. Hence, the limited resources, and growing population, have resulted in the shortage of even the most basic resources such as food and food security are a concern in all the major cities. (Madaswamy Moni,2009)

The way in which the city is developing, requirements of the city are increasing and in upcoming built forms, there are very few reserved open and vacant spaces available. Repairs of existing buildings, protecting natural spaces, etc. have become extremely crucial and require a thoughtful process of assessment and manifestation. Undoubtedly, while coping with the existing space crunch, it's difficult to find as well as allot areas for urban agriculture. (Hariprasad Agarwal & Radha Sinha, 2017)

Urban agriculture is defined as an activity that produces, processes, and markets food and other products, on land and water in urban and peri-urban areas, applying intensive production methods, and using natural resources and urban wastes" (U.S Department of Agriculture, 2022).

With 55% of the Indian population projected to live in cities by 2050, when climate change is a concern and mental illness due to overcrowding, pollution, etc. would be at a peak. Reliance on conventional farming would not be possible then urban agriculture would be a lucrative option (Farhat Ali, Chitra Srivastava, 2017).

The rapid growth of the city population in the developing world is placing enormous demands on urban food supply systems leading to food shortages during the time of crisis (Chaitra Bhat and Amit Paschapur,2020). The knowledge of how food grows, what grows regionally and seasonally, how it is treated after harvest, and how it moves from one place to another in a food route before final consumption is an all-important lesson of urban agriculture. Urban agriculture also provides fresh food, generates employment, recycles urban wastes, creates greenbelts, and strengthens cities' resilience to climate change (Chaitra Bhat and Amit Paschapur,2020).

Urban agriculture and peri-urban agriculture will help to meet the supply of vegetables within the urban centers and ease the pressure on imports to the government. It has now become essential for the government and the people to start considering options to meet their individual needs by ways engaging themselves in agricultural farm work. The integration of urban and peri-urban agricultural strategies and policies would undoubtedly create a sustainable and resilient future city, not only in the terms of livelihood and the environment but also in the economy of the country as a whole (Dhanapati Sharma, Nima Wangchuk, Amrit Sharma and Phub Dorji,2022).

As per Copenhagen's case study for urban agriculture, the positive and negative impacts of urban agriculture are categorized as Environmental, economic, social, civic, and public health.
In positive impacts, it is stated as:

- Environmental - reduces freight transportation, regulates urban temperature, and mitigates stormwater runoff.
- Economic - raise property values, and create competition to lower overall food prices.
- Social – Promotes cultural and cross-generational integration, increases community engagement, aids lower-income populations, and provides health and environmental education opportunities.
- Civic – Reduce dumpling and cost of upkeep on vacant lots, decreasing the burden on the department of public works and waste management agencies.
- Public Health – Provides healthier food options and improves air quality.

In negative impacts, it is stated as:

- Environmental – causes potential chemical pollution from inorganic fertilizers and needs a large amount of water.
- Social – creates unpleasant noises and smells
- Public Health – soil contamination can potentially contaminate produce.

Mumbai is a metropolis with a limited amount of open area suitable for urban agriculture. However, it is also a city where there has been a surge in interest in urban agriculture. Growing our own food is a simple way that can address this concern. Urban agriculture can be practiced at various levels ranging from balcony gardens to an entire commercial farm. The basic thought of calling urban agriculture sustainable is that the food is grown and consumed in the very same place which saves on the transportation cost. Also, the nutritional value of the food is maintained as the owner himself maintains the farm. Thus, healthy food is consumed. The understanding of urban farming is better and more relevant by interviewing users who practice the same.

This research aims to study how urban agriculture can be integrated into compact cities or in building planning. The research tried to understand how people practice agriculture in a city where there is hardly any space to live comfortably. The objective of the study was to analyze the different architectural typologies and the feasibility to grow food considering the same. The paper also studied the issues in the current urban agriculture scenario from a user's perspective. The scope of research is to identify the areas that can be utilized for agricultural practices and food production within a neighborhood. Through building-integrated agriculture including concepts such as aquaponics, indoor agriculture, vertical farming, rooftop production, edible walls, as well as through urban farms, edible landscapes, school gardens, community gardens, etc.

1.1 Aim

To study the feasibility of urban agriculture in various architectural typologies in a neighborhood - case of Mumbai.

1.2 Objectives

To understand the user's perspective on urban agriculture, to identify the feasibility of the existing areas for urban agriculture, to identify the challenges and benefits of urban agriculture, and identify the possible areas for urban agriculture.

2. DESCRIPTION OF STUDY AREA

Mumbai was an erstwhile set of seven islands, merged through reclamation. It has several kinds of house types developed over various stages of its history. The housing condition of today's Mumbai can be discussed through its various kinds of housing types, which form a bulk of the city's lived spaces (Crit, 2007).

Dadar was Mumbai's first planned suburb. Mumbai is a densely populated residential and commercial neighborhood. It is also a prominent railway and transit hub with local and national connectivity. Having two distinct built characters to the east and west of the railway land, where the east has an organic pattern of developments and the west has a wide mix of new and old building typologies (Nallathiga 2007).

The delineated boundary lies in the confluence of 3 wards: G-North, F-North, and F-South (refer to Figure 1: Mumbai zone map).

As per the census of India 2021, the population of this area was 1.31 lakh, People/sq.m. was 51500 and the Number of Households was 28000.

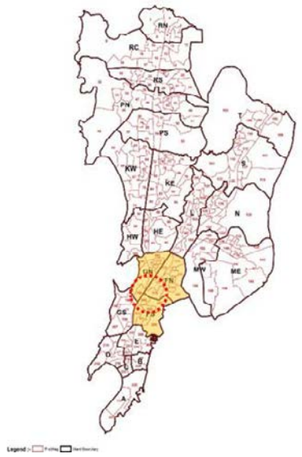

Figure 1: *Mumbai zone Map*
(Reference: BMC ward maps 2022)

3. RESEARCH METHOD AND METHODOLOGY

3.1 Research Method

The research topic from the literature and its review helped to establish the research gap. The aim and objectives were later defined and the secondary study and literature study helped to understand urban agriculture, its processes, and the benefits and problems associated with it. A neighborhood gives some details of the same was identified as the study area.

3.2 Questionnaire Development & Data Collection

This study was a mixed-mode cross-sectional study using the following tools:

- Structured questionnaire was prepared to understand the user profile, the user's awareness, and willingness to undertake urban agricultural practices.
- Un-structured and open-ended questions were also asked to understand the process better.

Data was collected with the help of a questionnaire. From the initial pilot survey, the revised questionnaires were prepared to cover the demographic, socio-economic, and agricultural characteristics, and user details. The area of study was identified considering the existing residential typologies and varying unit sizes. The respondents include people practicing urban agriculture as well as those not practicing urban agriculture. A total of 3 interviews and 34 household questionnaire surveys were conducted in a neighborhood from 15th June 2022 to 30th June 2022 using a convenience sampling method.

3.3 Research Methodology

The research was conducted qualitatively in nature dealing with a comparative analysis of different housing typologies. The various typologies included slum or informal settlement, chawl as building, chawl as baithi chawl (sitting chawl: one-story building type in western India), building, bungalow, and row House. The second phase of the study used an analytical approach to SPSS statistics to better comprehend the correlation between architectural typologies and urban agricultural practices. This survey followed a specified methodology to ensure a thorough understanding of each interviewee's perspective on the urban agricultural movement's aims, benefits, and practice type.

The respondents were asked to share their challenges in promoting urban agriculture. The scale of the area dedicated to urban agriculture and the crops produced were different in different cases. The users were interviewed, and the responses helped in knowing the practical aspects of urban agriculture from their point of view as well as their perceptions of the activity. The interviews provided a clear understanding of the respondent's urban agricultural aspirations, the degree to which the household had fulfilled their goals, and the reasons that prevent them from being met.

The observations of the existing neighborhood and unit sizes of different residential typologies were made. Data collected through the surveys and through observations were analyzed leading to the results, conclusion, and findings.

4. RESULTS AND FINDINGS

4.1 Questionnaire Survey Analysis

As per table 1, Spearman rank correlation (non-parametric test) as seen in table number 01 was used to measure the degree of association between two variables. Through the correlation, testing the strength and direction (positive and negative) of the correlation between two variables was done.

Table 1: *Spearman correlation result (SPSS Statistics)*

Spearman's rho	What is the total area of your home in m2? (Approximately in sq.ft)	Correlation Coefficient	.379*	Are you willing to grow food at home?
		Sig. (2-tailed)	.042	
		N	29	
	What is the Balcony/ garden area of your home in m2? (Approximately in sq.ft)	Correlation Coefficient	.603**	How much space out of balcony/garden area you have dedicated to Urban Agriculture in m2? (Approximately in sq.ft.)
		Sig. (2-tailed)	.004	
		N	21	
	Do you feel It is necessary to grow food at home?	Correlation Coefficient	.444*	Are you willing to grow food at home?
		Sig. (2-tailed)	.016	
		N	29	
		Correlation Coefficient	.467*	Which space of house/open area you have dedicated to Urban Agriculture?
		Sig. (2-tailed)	.038	
		N	20	
	Do you have space to perfom Urban Agriculture activities?	Correlation Coefficient	-.548*	How much space out of balcony/garden area you have dedicated to Urban Agriculture in m2? (Approximately in sq.ft.)
		Sig. (2-tailed)	.015	
		N	19	

The number of rooms and total area of the home is positively correlated with the willingness to grow food at home as well as provides food security as a benefit. Participants are majorly willing to allot their balcony/garden area to urban agriculture.

4.2 Comparative Analysis

The results of the comparative analysis of urban agriculture practice for both urban farmers and who do not practice urban farming indicated that the availability of space was a major challenge followed by maintenance and soil availability (refer to Fig. 2).

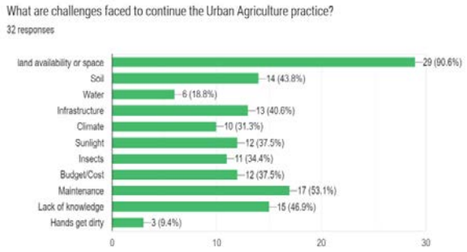

Figure 2: *Challenges of urban agriculture*
(Reference: Survey study, author)

As seen in figure number 3, From the list of dedicated spaces for urban agriculture, a window grill was the most popular option amongst all as there was a space crunch. In actuality, balconies are the next option if it has it in architectural planning (refer to Fig. 3).

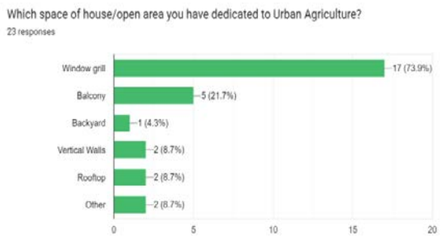

Figure 3: *Dedicated area of urban agriculture*
(Reference: Survey study, author)

As per the survey, those respondents who have space available were willing to dedicate 1-2 m2 of the area from that space (refer to Fig. 4).

Figure 4: *Balcony/garden area of the house*
(Reference: Survey study, author)

As per the survey, 42.9% have less than 1 sq.m. of space available followed by 47.6% having less than 2 sq.m of space. Thus, nearly 90% of the surveyed respondents had no space available for this activity. 10% of the respondents who had the space available between 2-5 sq.m were willing to dedicate 1-2 sq.m for the same (refer to Fig. 5).

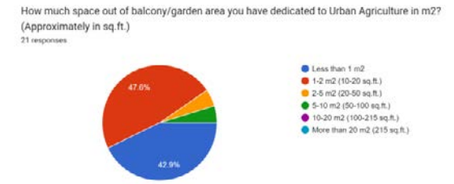

Figure 5: *Space dedicated from balcony/garden*
(Reference: Survey study, author)

4.3 Typology Analysis (Reference: Google image)

Figure 6: *Type 1*
2BHK rooms + balcony

Figure 7: *Type 2*
1RK rooms

Figure 8: *Neighborhood study area boundary in Mumbai*

Figure 9: *Type 3*
3BHK + balcony

Figure 10*: Type 4*
Chawl (Building)

The selected architectural typologies are the major and representative housing types from the selected neighborhood (Fig. 8). The analysis from the study calculation was as follow:

Type 1: 2BHK Rooms with balcony (Fig. 6)

- A dedicated balcony area in the building planning can generate a considerable amount of homegrown farm products which was sufficient for all households in a building. Scope to perform urban agriculture through outdoor agriculture & compost etc. on the terrace.

Type 2: 1RK Rooms with no balcony (Fig. 7)

- No dedicated balcony area in the building planning. Apart from potted plants, very less scope for practicing urban agriculture which was only through the window grill. The farm products grown on the terrace are sufficient for residents for 15 days a month.

Type 3: 3BHK Rooms with balcony (Fig. 9)

- Bigger unit sizes can generate more farm products as per the study. Balcony space can be used for urban agriculture by doing indoor agriculture, vertical farming & compost, etc., and sufficient for the entire month. The cost of land is high to perform urban agriculture.

Type 4: 1RK Rooms with no balcony (Fig. 10)

- Terrace-tops can be used to perform urban agriculture as a part of community farming since the building planning has space constraints. Space between two buildings also can be used to perform urban agriculture. Participants are not willing to dedicate more space to urban agriculture.

4.4 Neighborhood Analysis

To calculate the potential food production through urban agriculture the following steps are taken. Firstly, the types of produce were defined by different architectural typologies in the neighborhood. For urban agriculture, the yields of suitable produce were selected. For the production of food, it was assumed that mainly fed to each building.

In order to define the space defined for urban agriculture that was available in an urban area, the following data were collected: the number of houses, and the total surfaces of private balconies/gardens, flat roofs, and public green space. The surface of unbuilt land that could be used for agriculture, an urban farm was measured too. (refer to Fig. 11).

Figure 11: *Neighborhood community garden analysis in Mumbai, (Reference: Author)*

4.5 Study Limitations

Since the study was conducted in a selected urban neighborhood of the urban population of a specific neighborhood of Mumbai city, the result may vary in the other urban areas of Mumbai (Fig. 8).

5. CONCLUSION

According to the study, for most low-income households in cities, urban agriculture is an important source of food security and a source of income. A detailed investigation of the study revealed and validated the assumptions that urban agriculture was primarily of interest to and profitable for the high-income background. Balcony and window grills are quite popular among urban middle- and lower-class families**.** The most impressive benefits of urban agriculture are its proximity, accessibility, and adaptability.

From the study, it was seen that kitchen waste is the added element that had been used along with the soil. Due to the space constraint, potted plants or some basic plants can grow in an area of 2 sq.m. and the average space available was 5 sq.m to perform urban agriculture activities. The bigger areas, like balconies or terraces, allow for growing more food through urban agriculture. This helps the user to consume farm products for their daily requirements. From the observation, the various food crops that could be grown in this space are as follows:

- Produce (2-5 sq.m): Aloe vera, Hibiscus, Tulsi, Rose, Carom (Ajwain), Coleus, Money plant, Snake plant, Jasmine, Chandani, Herbs, Lucky bamboo, Spider plant, Mint, Brahmakamal (Saussurea obvallata), Marigold, Periwinkle, etc.
- Produce and Consume (5-10 sq.m): Chilli, Wheatgrass, Beans, Brinjal, Leafy vegetables like spinach, Amaranthus, fenugreek, Palak, Methi, Coriander, Mint, etc., Spring onion, Capsicum, Bell pepper, Garlic, Tomato, Ladyfinger, Cluster beans, Lemongrass, Bitter Guard, Carrot, Cucumber, Curry leaves, turmeric, lemons, etc.

The study concludes that in a compact city like Mumbai, it was not a feasible option to perform urban agriculture in the residential spaces as 'space' was a major constraint as seen from the results of the survey and actual mapping. Therefore, carving out spaces for this is the biggest challenge, as per the study. The identified community spaces aim to systematize the available area for urban agriculture more significantly.

As seen from the study (refer to Fig. 11)., 25% of the footprint area of existing building terraces was considered for services like water tanks, staircases, lift rooms, etc. The remaining area of 75% could be utilized for community agriculture purposes, which is only sufficient to provide 50% for the individual building's need for food. Hence for the remaining 50% of produce, the urban community spaces were identified that were capable to be the source of food security were catering to neighborhood buildings. Measuring community urban farms becomes more important for understanding the spatial urban structure to intervene accordingly for sustainable urban development.

6. FUTURE STUDY AND RECOMMENDATIONS

If most of Mumbai city's population started implementing urban agriculture activities, large growth in the development of the city would be seen in terms of having access to food for all. The urban farms can be green spaces in the city and could serve as city lungs to produce a sustainable urban environment. The future study could look at understanding feasibility in other areas of the city to get a better understanding of its feasibility on a larger scale. Also, policy level implications could be studied further. The rural farmers would not be at risk as their farm produce would still be in the markets. The urban production would just help reduce the demand-supply gap in the growing cities. The future study could also explore the possibility of urban agriculture as a sustainable model for upcoming developing cities in India.

An experimental study is needed to improve the productivity, efficiency, and sustainability of these systems, as well as outreach, to inform urban producers about the findings.

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Methodology for scenario-based analysis of future energy performance of Swiss settlements at urban, sub-urban, and rural scale

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To design decentralized and renewable-based energy supply systems, future energy demand scenarios that factor in urban development trends are essential but rarely considered. The current work aims to develop a methodology to assess the impact of urban development on future energy demand through scenario construction in the Swiss context. We construct three urban development scenarios based on trend extrapolation, creative-narrative, and trend impact analysis. The three resulting scenarios are business-as-usual, polycentric urban network, and digitalization. We then apply these overarching scenarios to three district archetypes (urban, sub-urban, rural) through modeling population, occupancy density, and building use types in the future. The results from urban building energy simulations show significant differences between energy demand in the sub-urban archetype, when comparing business-as-usual and polycentric urban network scenario. The corresponding differences amount to 40% in final energy consumption. We conclude that considering urban development trends has a non-negligible impact on energy consumption and thus the design of energy supply systems. This aspect should be taken into account along with building retrofit strategies and climate change scenarios, which further highlights the indispensable interdisciplinary collaboration between urban planners and energy system designers when designing sustainable energy supply systems.
KEYWORDS: future energy demand, urban development, scenario construction, urban building energy modeling, urban energy systems

1. INTRODUCTION

1.1. Projecting future energy demand

As energy infrastructures are planned for long-term usage, it is important to consider energy demand scenarios over the lifetime of the installed technologies (20-50 years). In line with the transition towards decentralized energy supply, more supply systems will be implemented at the building and district levels. Thus energy demand scenarios at the district level are expected to play a key role in future supply system planning processes. The Urban Building Energy Models (UBEMs) should reflect the evolution of future climate, building densities, building use types, building properties, and building energy systems. In these aspects, bottom-up engineering UBEMs are more versatile than statistical models and allow stakeholders to quantitatively assess development strategies and energy supply options (Sokol et al., 2017).

In Switzerland, the foreseeable long-term changes in building energy demand are due to climate change and socio-technical transitions. Many studies have worked on projecting the future building energy demand considering either climate change, retrofit rates, or the combined scenarios (Frank, 2005; Murray et al., 2020; Schneider et al., 2017; Wang et al., 2018). The latest study developed optimal retrofitting and district energy system solutions for various district archetypes (Murray et al., 2020).

Considering the necessity of energy demand assessment at the district scale, future energy demand scenarios that incorporate urban development trends become essential. The current work aims to develop a methodology to incorporate the impact of urban development on future energy demand through scenario construction in the Swiss context.

1.2. Urban Development Trends in Switzerland

The Swiss Federal Office for Spatial Development (ARE) constantly reviews recent urban development trends and updates strategies for future development. In the next paragraphs, the main trends in Swtizerland are summarized from reviewing relevant reports published by ARE (Bundesamt für Raumentwicklung, 2005; Rat für Raumordnung (ROR), 2019).

The urban and sub-urban areas host almost 90% of Swiss population as well as more than 80% of work places. These areas include metropolitan regions of Zurich, Basel, Geneva-Lausanne and their corresponding agglomerations. They have the highest built density and mix of building uses. The recent trends in these areas comprise population and economic growth, as well as the urban sprawl.

Three urban development trends are being observed or implemented in urban or sub-urban areas. First, the inward development and densification strategies of the core cities are used to combat urban sprawl. Second, future population growth in the urban areas may decrease due to heat waves, density stress and traffic congestion. This promotes residency outside of the cities. Third, as a result of digitalization trend, flexible work conditions would decrease demand for offices and drive their conversion into the mixed-use or residential spaces.

The rural areas comprise 50% of total land area, but host only 12% of Swiss population. The trends of economic decline, emigration, brain drain and population ageing are observed. Regional development programs aim to strengthen these areas by providing jobs, necessary services and attractive living conditions to the residents. If the living conditions become as attractive as in the metropolitan regions, the rural areas could still experience population inflow.

1.3 Scenario approach

The scenario approach uses a systematic process of creating alternative pictures of the future as opposed to projecting the future based on the extrapolation from the past. This method has been used to gain a deeper understanding of existing trends and their impacts in relation to sustainable development (Schemel et al., 2019), to engage citizens to understand the topics that are relevant to a desirable future to the public (Geneva Council of State, 2020), and to help decision-makers to prioritize climate adaptation measures (Economics of Climate Adaptation Working Group, 2009).

As the future of urban development also entails complex and uncertain interactions of various factors, it has not been fully incorporated in the context of projecting future building energy performance to the author's knowledge. Past studies have acknowledged the evolution of total Swiss residential building areas due to changes in population and GDP (Streicher et al., 2021). This work aims to extend the scope of building stock projection to building uses beyond residential buildings to provide a complete picture of entire districts.

2. METHODOLOGY

2.1 District archetypes

Based on the spatial division method of the Swiss Federal Statistical Office, Swiss municipalities can be divided into three main groups (urban, sub-urban, rural) and further into 25 spatial typologies depending on the municipality size, population density, accessibility, and various socio-economic parameters (Bundesamt für Statistik, 2012). Following this division method, the current work focuses on one case study per urban, sub-urban, and rural group:

- Urban archetype: Core city of a large agglomeration (Altstetten district, city of Zurich, 3100 buildings);
- Sub-urban archetype: High-density sub-urban commercial municipality (Echallens, canton Vaud, 1050 buildings);
- Rural archetype: Mixed rural peripheral municipality (Airolo, canton Ticino, 1400 buildings).

2.2 Method of scenario construction

To construct the urban development scenarios, three methods of foresight and scenario analysis were used: trend extrapolation, creative-narrative technique, and trend impact analysis (Kosow Hannah & Gassner, 2007).

Firstly, through trend exploration, we collect multiple existing trends and their future projections. They are collected from federal spatial planning and statistical offices as described in Section 1.2.

Secondly, through the creative-narrative technique, we form distinct scenarios by grouping relevant trends together to shape their narratives. The creative-narrative technique is characterized by the implementation of intuition and background knowledge of experts. Several e-mail and phone interviews with the experts from municipal planning offices were conducted to gain feedback.

Lastly, with distinct narratives supported by various trends in each scenario, we develop coherent assumptions across scenarios through trend impact analysis. It is done by examining the alternative courses of events that may take during a trend, which leads to multiple future projections of trend development. For example, following projections from statistical offices, population growth was assumed to be low, moderate or high depending on prevalence of a certain trend.

As a result, three contrasting urban development scenarios that overarch through all three district archetypes were worked out. The resulting scenarios are presented in Section 3.1.

2.3 Quantifying the urban development scenarios

For the purpose of urban building energy modelling, we reflect future urban development trends through parameters that affect the future building stocks. These parameters are population, total built area, building use ratio and occupancy density. The future required built

areas for each building use were calculated using these parameters. An automated area assignment algorithm then allocated these areas to existing building footprints under local urban planning constraints, including building heights, permitted building uses and planned development (Hsieh et al., 2021). Finally, personal interviews with planning authorities are conducted to discuss the plausibility of the constructed scenarios.

To collect information on the relevant parameters, various data sources are explored. These sources included surveys, statistical reports and regulations from cantonal offices, and literature regarding housing development trends. The future parameter states in 2040 and 2060 were examined and compared with the current states, represented by the year 2020. When values were unavailable at the year of projections, we assumed a linear trend and extrapolated the unknown values. To increase the data resolution from cantonal reports to the municipal levels, we conducted surveys with municipal planning offices. We contacted planning offices of 15 urban, sub-urban and rural municipalities in different regions of Switzerland. The survey inquires the following information:

- Statistics on the population and building use development, as well as projected built area.
- Strategies to accommodate the increasing built area requirements. E.g., by increasing maximum allowed building height, constructing new buildings on green parcels or assuming higher occupant density?
- Master plan for years between 2040 to 2060.

From the 7 replies received from municipalities, population development data are available, while future building use and built area projections are mostly unavailable. For status quo data, most municipalities referred to the GWR building database (Bundesamt für Statistik, 2022). The most detailed information was provided by sub-urban municipality of Echallens, more specifically by the head of the local planning office. This allowed to use direct municipal data for modelling of sub-urban archetype of Echallens, while parameters for urban and rural archetypes were future projections stated in the cantonal reports.

The future building stock of different urban development scenarios is not only influenced by the population and density projection but also by their spatial typologies. The characteristics of different spatial typologies are quantified with building use ratios, which describe the composition of a district in terms of building use. It is calculated with the ratio of the floor areas of each building use type to the total floor area of a district.

2.4 Future climate and building retrofit

In this work, the future climatic scenarios chosen were set for the years 2040 and 2060 since the energy systems designed today will likely be used in the next 20-50 years. The selected weather scenario represents a business-as-usual projection (NCCS, 2018). Local weather data for each case study district is available via the Meteonorm software (METEOTEST, 2018). In terms of heating degree days, a general downward trend is observed between the years 2020 and 2060, while the cooling degree days show opposite trends. Another important factor to building energy performance is building envelope and system retrofit. In line with the strategies proposed in the Swiss Energy Perspectives 2050+ (Prognos AG et al., 2020), this paper assumed annual rates of 1% for envelope retrofit, 3% for heating system retrofit, and 1% for cooling system up-take. The properties of retrofitted building envelopes follow the Swiss standards (*Heizwärmebedarf SIA 380/1:2016*, 2016).

2.5 Urban building energy modeling

The analysis of future energy demand is conducted using the City Energy Analyst (CEA) tool (J. Fonseca et al., 2021). The CEA is an open-source tool for analyzing and optimizing urban energy systems. Inside CEA, dynamic and multi-physics models are used to forecast the load profile of heating, cooling, and electricity of single and multiple buildings up to entire districts. The energy demand model in the CEA includes a comprehensive database of building archetypes and energy technologies in the Swiss context (J. A. Fonseca & Schlueter, 2015).

3. RESULTS AND DISCUSSION

3.1 Urban development scenarios

Through the scenario construction exercise described in section 2.2, three overarching urban development scenarios were constructed:

Scenario 1: "Business-as-usual (BAU)". Urban areas experience high growth of population and economic activity. Urban sprawl takes place around metropolitan core cities, while densification strategies are used within urban area. Rural areas experience further economic decline and population decrease.

Scenario 2: "Polycentric urban network (PUN)". Sub-urban and rural areas follow own spatial development concepts and transform into well-connected hubs with attractive living conditions to satisfy need of residents for working, educational and shopping opportunities.

Table 1:
Parameters used to reflect the three urban development scenarios for the three district archetypes. MFH: Multi-family house.

	URBAN	SUB-URBAN	RURAL
Business as usual			
Population growth	↑↑↑	↑↑	↓↓
MFH Occupant density	40 m2/person	50 m2/person	60 m2/person
Building use ratio	Unchanged	Unchanged	Unchanged
Polycentric urban networks			
Population growth	↑↑	↑	↓
MFH Occupant density	-13 %	-20 %	+0 %
Building use ratio	Unchanged	Urban core	Rural service center
Digitalization			
Population growth	↑	↑↑↑	↑
MFH Occupant density	+13 %	+20 %	+33 %
Building use ratio	Only add residential GFA	Urban residential	Rural tourist center

Scenario 3: "Digitalization (DGT)". Digitalization promotes flexible work conditions. Sub-urban and rural areas become more attractive to live in due to remote working possibilities and higher environmental quality.

These three scenarios of future urban development trends are then applied to all three district archetypes through parameters that affect the future building stocks. These parameters are presented in Table 1.

Three plausible population growth projections (high, middle, low) are assumed for each district archetype. These projections are then matched to each urban development scenario. Under the BAU scenario, as urban sprawl is the dominating phenomenon, the urban area is expecting the most vigorous push in population growth, while the rural area is expecting the strongest decline in population. Under the DGT scenario, the urban area is no longer the most favourable option for many residents. Population in the urban district starts declining between 2040 and 2060, while the sub-urban and rural areas are facing the highest growth. As for the PUN scenario, the population growth is more evenly distributed to all three districts as the result of well-connected networks and increasing services in sub-urban and rural areas. Rural residents are more likely to remain where they currently reside compared to the BAU scenario.

Residential occupancy density (i.e. living space per occupant) influences the total required residential building areas. It is assumed that the BAU scenario follows the future targets from the municipalities when available. The general tendencies in DGT and PUN are the same for all district archetypes. Under the DGT scenario, it is assumed that the required living space increases due to the need for home office spaces. Under the PUN scenarios, it is assumed that the required living space decreases due to the incentive to contain building areas and increase public services.

Finally, the characteristics of different spatial typologies are quantified with building use ratios, which also influence the growth in the total built area, or Gross Floor Area (GFA). Under the BAU scenario, all districts remain their original spatial typologies. As for the PUN and DGT scenarios, it is assumed that the urban districts remain the same typology, while the sub-urban and rural districts are converted into new typologies. Under the PUN scenario, both sub-urban and rural districts are assumed to increase the portion of offices and other commercial buildings. A sub-urban district is likely to take up characters of a middle-size urban agglomeration, while a rural district is likely to take up characters of a rural central service municipality. Under the DGT scenario, it is assumed that sub-urban districts become more attractive to live in, while the rural districts also increase in commercial and institutional buildings. A sub-urban district resembles a middle-size urban residential municipality, and a rural district resembles a rural tourism municipality.

Figure 1:
Projected growth in Gross Floor Area (GFA) and population in year 2060 compared to year 2020 under the three urban development scenarios in the three case study districts.

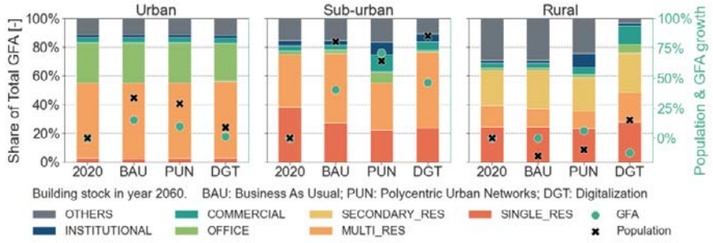
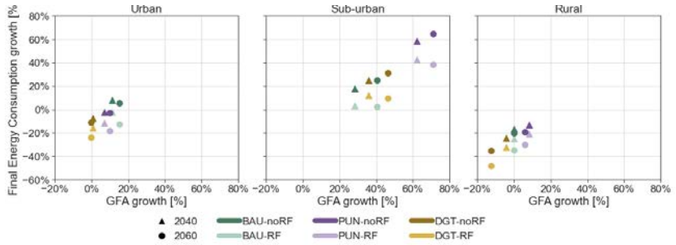


Figure 2:
Projected growth in final energy consumption compared to year 2020 of all district archetypes uder the three urban development scenarios.



The resulting building stocks of all three urban development scenarios in the three districts are shown in Figure 1. Population and GFA growths are observed in most scenarios in urban and sub-urban districts. Sub-urban districts are projected to face the biggest growths. The BAU scenario is projected with the highest growth in population, and the PUN scenario is projected with the highest growth in GFA. In contrast, limited growth is projected in the rural district. Only the DGT scenario boosts the population, but the total GFA decreases due to the reduction in industrial areas.

Part of the results from this section is publicly available in this repository (Hsieh et al., 2021). It contains an automated script to transform building stock models, in the City Energy Analyst model format, from the state in 2020 to the future years.

3.2 Quantifying the impact of Urban Development Scenarios

Figure 2 shows the simulated final energy consumption with and without retrofit measures in year 2040 and 2060 compared to year 2020. The total GFAs are proportional to final energy consumption and are influenced by different urban development scenarios. Both sub-urban and rural archetypes have the highest consumption under the PUN scenario due to the increase in office and commercial buildings.

In contrast to the upward pushes in energy consumption from the increase in GFA and cooling energy requirement, the downward pushes are contributed by the decrease in heating energy consumption due to climate change and building retrofit measures. These downward pushes are the most prominent in urban and rural archetypes, in which the final energy consumptions decrease from 2040 to 2060. Building retrofit measures further intensify this downward trend and bring the final energy consumptions to below 2020 values.

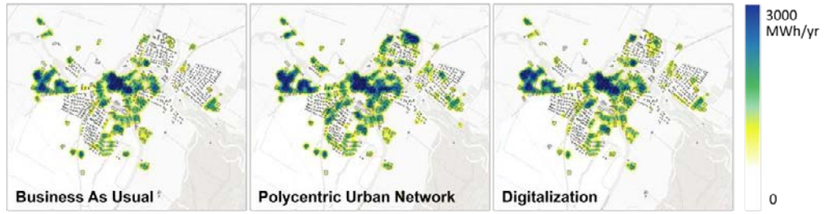
Converse to urban and rural archetypes, the sub-urban archetype, final energy consumptions increase from 2040 to 2060 due to the large amount of additional GFA in all three urban development scenarios. Although building retrofit measures could bring down the energy consumption in 2060 compared to 2040, the total consumption is still increased by up to 40% compared to the year 2020.

It can be concluded that the sub-urban district archetype is facing the strongest increase in future energy consumption. With the strongest and most diverse growth trajectories, the sub-urban archetype is the most sensitive to the future urban development trends, and thus in-depth analysis should be carried out for sub-urban districts when setting energy performance goals.

3.3 Spatial Consequences for infrastructure development

The results from this study also provide insights to electrical and thermal network planning with the spatially resolved energy demand data. This information is crucial for planning efficient operations of energy networks. Figure 3 shows the spatial allocation of annual space cooling demand in the sub-urban district. It can be seen that urban development

Figure 3:
Spatial distribution of annual space cooling demand in the year 2060 of the sub-urban district archetype.



scenarios vary the allocation of energy demand hotspots in the same district. The main factor is the placement of office and commercial building uses. Utility suppliers should not neglect the uncertainties posed by urban development trajectories, especially in the sub-urban districts.

4. CONCLUSION

We have presented a methodology to analyze future energy performance that incorporates urban development trajectories through scenario-based analysis. The results conclude that urban development trends have a significant impact on energy consumption and thus the design of energy supply systems. This aspect should be taken into account along with building retrofit strategies and climate change scenarios. The need for considering the urban development aspect in designing future energy systems further highlights the indispensable interdisciplinary collaboration between urban planners and energy system designers in the governmental planning offices.

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From repetition to diversity:
A workflow for energy-driven optimization of heterogeneous urban blocks in hot climates

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ABSTRACT: Despite the global trend toward mixed-use developments as a key strategy toward urban sustainability and compactness, quantitative research on the energy performance impacts of heterogeneous urban environments of different building typologies and uses is currently lacking. This study bridges this gap by offering an analytical method to explore and optimize the energy load and generation performance of an urban block in a diverse building-use and layout configuration. The methodology includes a two-phase analytical approach in Grasshopper – first, a multi-objective optimization (MOO) study using the block's energy load cover factor and the context solar exposure as its objectives; and second - a visual selection of the non-dominated results from the optimization based on several environmental performance indicators. The combination of these two analytical modules offers a novel analytical framework for designers and policymakers, through which they can reach an optimized starting point of building-use and mass distribution on the site, based on several quantitative environmental performance indicators.
KEYWORDS: Energy balance, Mixed-use design, Urban design, Zero energy, Optimization

1. INTRODUCTION

The fast pace of a changing climate, rapid global urbanization (of up to 70% in 2050 [1]), as well as the increasing impacts of urban areas on both energy performance and greenhouse gas emissions (of 75% and 70%, respectively [2]) – are shifting the performative focus from the individual building to the urban landscape. Under the debate on urban compactness, which pros and cons should be closely considered [3], urban design theories have been promoting a conceptual shift from 'high density' to 'better density' [4]. In contrast to the modernists' repetition and zoning schemes, these approaches promote diversity (of uses, building types, and public spaces) as a key principle, which also works well with other contemporary urban sustainability values (walkability, infrastructure reduction, etc.). These approaches are gaining popularity nowadays as part of the 'new urbanism', and mixed-use buildings and districts in various configurations are becoming the new norm in many new urban developments.

Correspondingly, the pursuit to explore the impacts of diverse urban morphology on energy and other environmental metrics served as the basis of a few studies. Notable among them include Cheng et al. [5], whose results supported the morphological diversity both horizontally (in plan) and vertically (in section) for improved solar potential; Zhang et al. [6] who performed an energy performance parametric study and highlighted the self-shading trade-off as one of the main energy performance issues in diversifying urban blocks in hot climates; Hachem et al. who employed multi-objective optimization methods to explore the preferable combination of different building uses, typologies and density scenarios in a mixed-use neighborhood in Canada [7], and later used optimization to explore the optimal mix of energy sources in a mixed-use building cluster archetypes [8]; and Fonseca et al. [9], who developed an interface for spatiotemporal energy mapping which can explore the energy performance impact of several building use scenarios.

However, despite the growing body of knowledge in the field, each of these studies encompasses a limited number of factors, and holistic morphological research on the impacts of mixed-use blocks on environmental performance, solar potential, and energy balance - is currently lacking. This gap is even more pronounced in areas that are undergoing a significant change in their climate and are exposed to a massive construction boom. This is the case in countries such as Israel - where designers and planners urgently need useful indications of the energy performance implications of their designs.

The work presented in this paper is a part of ongoing research aiming to bridge this gap by establishing a comprehensive computational workflow to evaluate the energy and environmental trade-offs of diverse urban district designs. The hypothesis is that such quantitative workflow, driven by a wider performative perspective, will inform the designers on preferable building use and massing design configurations on a given site. Under this aim, this paper establishes a seamless two-phase analytical workflow for responsive mixed-use urban block designs. The following sections describe the novel analytical sequence and discuss the set of results, mimicking the same analytical process a designer using this workflow could conduct - from running the optimization analysis, to exploring the best-found results using performance indicators, and to concluding with some architectural observations by studying the most viable design options. Finally, the paths for future research and design applications are drafted.

2. METHODOLOGY

The methodology encompasses the development and application of digital workflows tested for the design of a mix-use block in Tel Aviv (Figures 1 and 2). It includes an automated workflow, set in Grasshopper (a parametric interface for Rhino), in which two dynamic design inputs - namely building height and building use - trigger a multi-objective optimization analysis based on the energy load and generation balance and the context solar exposure as the optimization objectives. As a second analytical phase, a wider environmental performance evaluation is then conducted for the best performing solutions from the optimization and used for a visual interactive design exploration by the user.

2.1 The analyzed block

The workflow was tested on an existing urban block in Holon (32.0158° N latitude). The site is categorized as a Hot-summer Mediterranean climate, in which solar radiation plays a pivotal role in energy demand, energy generation potential as well as indoor and outdoor environmental quality. The climatic data for Bet Dagan (the closest weather station) indicates high annual solar radiation values, which require outdoor space shading across most daytime hours of the year.

This site, like many others which are candidates for urban regeneration (i.e., demolition and re-construction in higher densities), reflects the huge challenge many Israeli municipalities face – the need to double the built area in the next 30 years while addressing a growing number of urban quality and environmental performance considerations. The enclosed urban block (or courtyard) was selected as a starting point for the analysis, representing an alternative to the prevailing high-

Figure 1:
The geometry iterator generates a wide design space for the optimization study based on three main variables (wing height, building use, and glazing ratio).

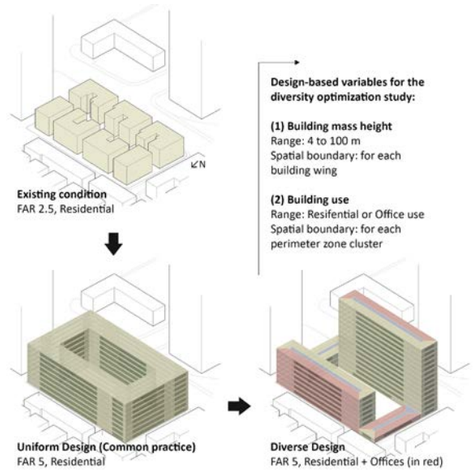
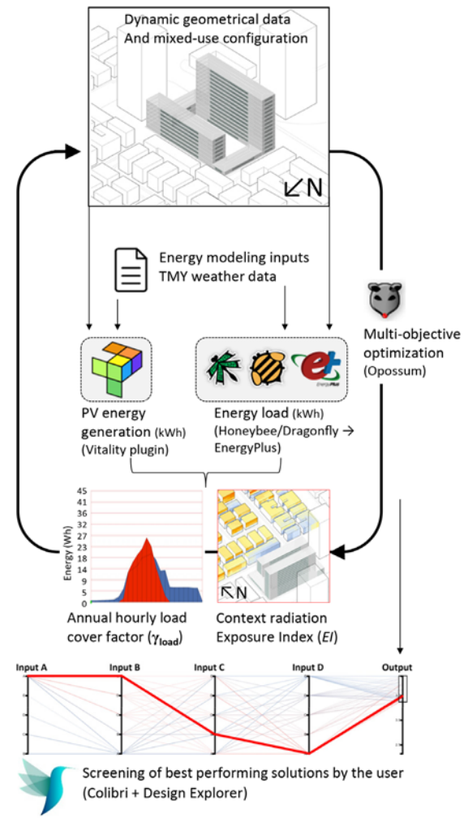


Figure 2:
The Analytical workflow showing the iterative energy load cover and solar context exposure optimization sequence.



rise typology. The division of the block into four wings (Figure 1), allows reaching spatial diversity which works well with the aim of this study to explore the impacts of diverse design configurations on energy and solar performance.

2.2 Geometry iterator

The analytical sequence starts with the geometrical iterator which generates a verity of spatial configurations for the urban block by altering each wing's height within a predefined range (Figure 1). The height of each wing, which is controlled by the optimization module (see section 2.5), is then factored to fit the desirable Floor Area Ration (FAR) for the urban block which was set to FAR 5 - twice the density of the existing buildings on site to be demolished.

2.3 Energy load calculations

The geometrical data of both the urban block as well its surrounding buildings are then streamed to a set of *Honeybee* and *Dragonfly* components (version 1.4) [10] which are used to assign the required inputs for the energy simulation via *EnergyPlus* according to the following steps (Figure 2): (1) the building mass is divided to floors which are then divided to core and perimeter thermal zones using an offset of 6m; (2) window sizes are assigned (50% window to wall ratios, corresponding to the Israeli code for energy rating in buildings specifications SI 5282 [11]); (3) office or residential building uses are assigned to each orientation in each of the four wings. This is factored in a way that an even distribution between the uses is obtained throughout the block; (4) construction materials, heating and cooling setpoint temperatures, and other simulation inputs are automatically streamed according to each building use (office or residential) based on the same energy code SI 5282 [11], similar to the input parameters used by Natanian et al. [12]). Bet-Dagan historic climatic data was extracted from *Meteonorm* (Version 8.0) and was used as the weather file input for both the solar radiation studies and energy simulations.

2.4 Energy generation calculations

Energy supply relied on hourly Photovoltaic (PV) potential calculated for each iteration. External vertical (walls) and horizontal (rooftops) surfaces from the energy model are streamed to a preliminary annual radiation analysis conducted for each surface across the model – then roofs and façade surfaces which receive annual radiation values of above 1000 kWh/m^2 and 800 kWh/m^2, respectively are selected and streamed to the *Vitality component* for annual hourly PV calculation [13]. *Vitality* is a Grasshopper component performing PV energy yield calculations based on hourly solar irradiation values for each surface, user-defined inputs, and the shading urban geometry. Polycrystalline solar panels with 18% efficiency in a non-ventilated installation were defined for the selected facade and rooftop surfaces.

2.5 Energy load cover factor

The different combinations of the block's form and building uses distribution are expected to influence the hourly energy curves of both load and generation. For that reason, the load match metric - which stands for the share of local energy load which is covered by on-site energy generation [14] – was chosen to indicate the best energy balance starting point 'by design'. As recommended in [14], the load match indicator used in this study is the *load cover factor* (γ_{load}) which is described by the following equation (Equation 1):

$$\gamma_{load} = \frac{\int_{\tau_1}^{\tau_2} min[(g(t), l(t))]dt}{\int_{\tau_1}^{\tau_2} l(t)dt} \quad (1)$$

where – γ_{load} the *load cover factor*;
g - on-site energy generation (kWh);
l – energy load (kWh);
t – time interval (hours of the year);
τ_1 – start of the evaluation period;
τ_2 – end of the evaluation period;

2.6 Context solar exposure index

To balance the solar exposure of the evaluated building with the reduced solar exposure of its urban context, the context *exposure index* (*EI*) [15] was set as the second objective. The *EI* stands for the ratio between obstructed and unobstructed diurnal cumulative insolation values for the 21st of December which falls on the rooftops and southern facades of the surrounding buildings, as described by the following equations (Equations 2 and 3):

$$EI_p = \frac{insolation_p}{Insolation_r} \quad (2)$$

$$EI = \frac{\sum_{i=1}^{n_p} EI_p}{n_p} \quad (3)$$

where – EI_p the *exposure index for a given point p;*
$Insolation_p$ - cumulative diurnal insolation for the 21st of December for a given point *p*
$Insolation_r$ - cumulative diurnal insolation for the 21st of December for a given point *p* for an unobstructed environment (i.e., without the new building)
EI - average of EI_p values for *n* number of evaluated points across the rooftops and southern facades of an urban section.

2.4 Optimization settings

When evaluating the impact of several design variables on energy performance and solar exposure as done here, the wide design space (i.e., number of possible solutions) hinders the possibility to conduct an effective parametric study due to the high computational cost, thus making the use of an optimization module unavoidable. Following a previous study by the first author who explored the energy balance of an urban block using an optimization module [16,], this study uses *Opossum* – a plugin for Grasshopper which utilizes python implementations of several single (RBFOpt, CMA-ES) and multi-optimization (RBFMOpt, MACO, NSGA-II) algorithms. Among these algorithms, this study uses RBFMOpt (Radial Basic Function Optimization), which allows for a more effective optimization by leveraging the learning process of a surrogate model [16]. Furthermore, RBFMOpt showed the highest performance among the other widely used algorithms in smaller function evaluation budgets [17]. Based on those capabilities a multi-objective optimization (MOO) analysis was set using the load cover factor and the context exposure index as objectives with a function evaluation budget of maximum of 500 iterations.

2.5 Visualization and screening of the results

Parallel to the optimization run, a set of dedicated components under the *Colibri* plugin were used to automatically record the inputs and outputs for each of the 500 iterations. In addition to the annual hourly energy load and generation values, the energy load cover, the average monthly load match, and the context exposure index - two more values were recorded for each iteration - the inner courtyard exposure index for both winter (21.12) and summer (21.6) days. Then, the *DesignExplorer* online platform was used to interactively explore the non-dominated results highlighted by *Opossum*, by plotting the entire range of outputs (recoded by Colibri) and their corresponding 3D images.

3. RESULTS AND DISCUSSION

The results showed in figures 3 and 4 describe a two-phase analytical process in which first - an automated multi-objective optimization sequence is performed, and second - the best performing solutions from the optimization are then visually screened by the user using an additional set of performance data for each of these solutions.

3.1 Multi-objective optimization

Figure 3 describes the results obtained from running the MOO. The graph shows the entire range of results and the 27 highlighted non-dominated results among them on the Pareto front. The distribution of the points indicates the contrasting nature of the two metrics selected for the MOO. As previous studies showed [6, 12], the energy load match (load cover in our case) is mostly affected by energy generation. As such, the solar exposure of the buildings' roof and southern facades becomes a driving factor for the energy balance calculation and competes with the solar exposure of the surrounding context. The left part of Figure 3 describes the three extreme results on the graph – maximal Y_{load} (A), maximal EI (B), and the front's "knee" (C) – representing the best-found trade-off between them. Observing the energy load and generation plots of these three results as well as their volumes and building-use distributions – some interesting insights are revealed: *The results for option A* show the positive impact of unobstructed southern façade on the energy balance (due to higher energy yield and lower heating and cooling demands), which also works with the optimized building-use distribution – residential uses with higher heating demand are directed towards the south while the offices with higher cooling demand and lower heating demand is directed towards the north; In *option B*, the pursuit to balance the building's energy performance and the context solar potential resulted in a higher volume oriented east and west. The position and proportions of the tower allow for a vast unobstructed west façade for energy harvesting, and at the same time a shaded east façade by a neighboring high-rise. Again, the diverse distribution of uses is supporting the massing optimization – higher cooling demand office uses are directed towards the shaded section towards the east. When emphasizing the context's solar availability -*in option C* - the form of the building is following the logic of the 'solar envelope' with a gradual reduction of height towards the north wing of the courtyard to allow solar exposure of the southern facades of the surrounding buildings to the north.

3.2 Performance data exploration

Figure 4 shows a plot of the full range of output metrics recorded for the 27 non-dominated results from the optimization. The recordings of the several performance metrics can help the designers gather a wider performative perspective by allowing them to interactively browse through the non-dominated results and test the trade-offs between several performance metrics. In this case, beyond the two objectives used for the optimization (i.e., energy load balance and context solar exposure), the user can explore the monthly energy balance, the energy demand and supply separately.

Figure 3:
Non-dominated results from the optimization study (left) and 3D volumes, building use distributions and energy curves of three representative samples (right).

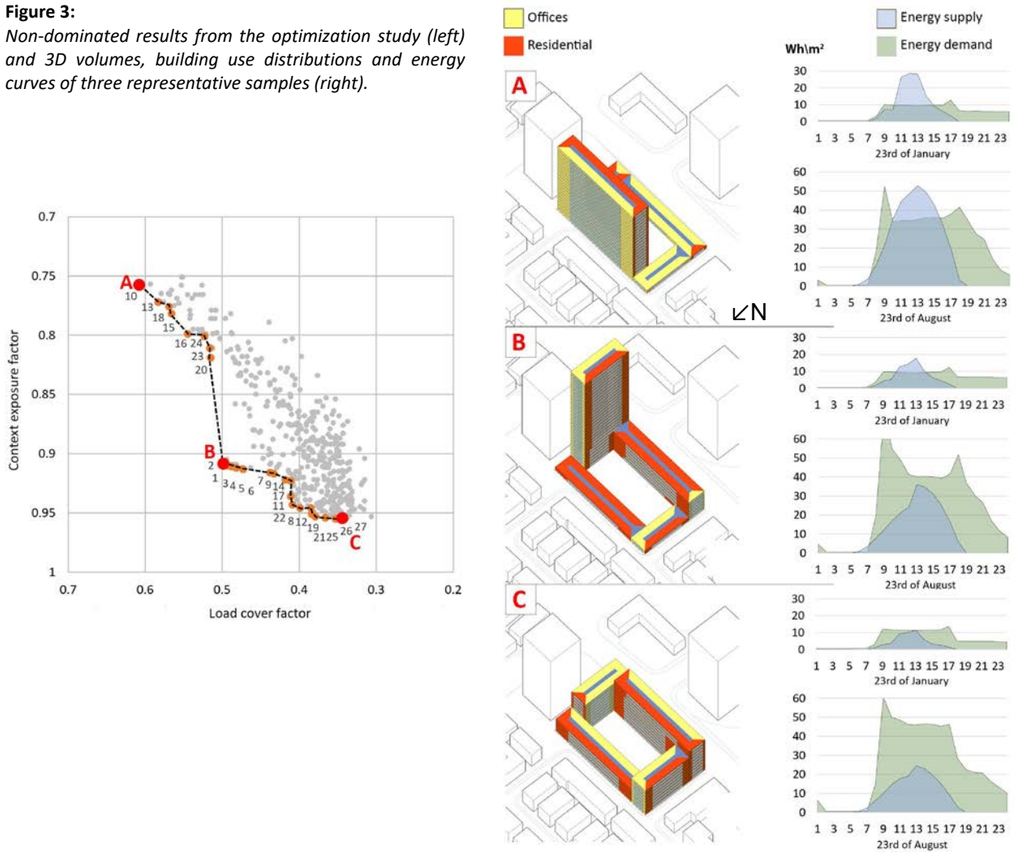
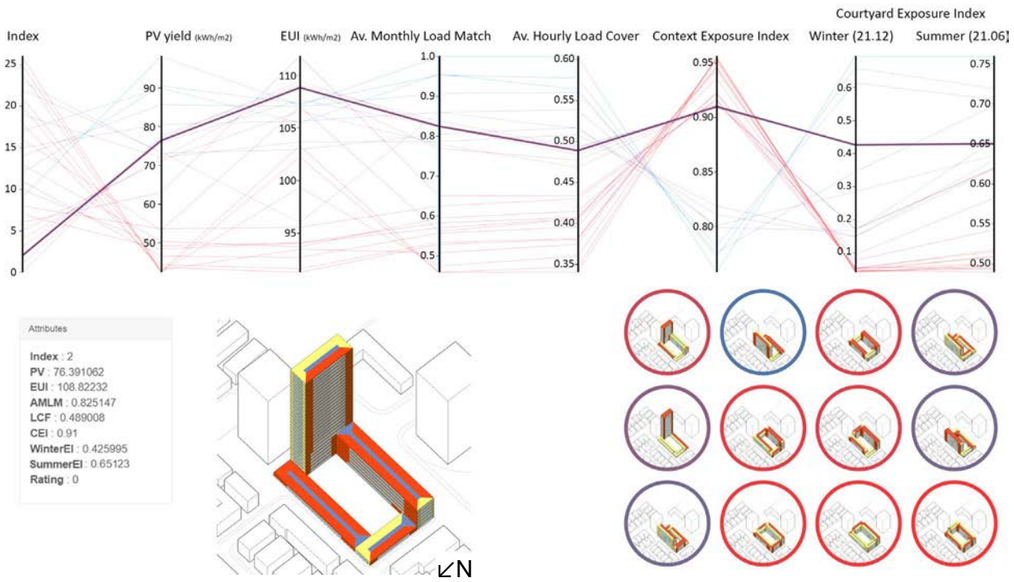


Figure 4:
Performance data exploration of the non-dominated results using the DesignExplorer online platform.



The exploration of the seasonal outdoor thermal comfort trade-offs using the inner courtyard's summer and winter exposure indices highlights the value of a two-phase process - these additional quantitative indications for each of the non-dominated results allow the designer to reach an informed decision among them based on performance data.

4. CONCLUSION

This study presents a computational workflow to explore and optimize massing layouts and uses allocation of an urban block, based on the energy load cover performance and the context solar exposure. The Grasshopper-based analytical approach includes an optimization sequence, followed by a visual selection of the non-dominated results from the optimization using different environmental indicators. This two-phase analysis demonstrated the wide amplitude of design solutions which can be highlighted by the optimization algorithm and thus the benefit of a complimenting performance-driven visual screening of the optimization results by the designer.

The integration of several environmental performance indicators works well with the complexity of urban performance evaluation in which many considerations interact beyond the energy balance. Thus, future research will capitalize on the adaptive nature of Grasshopper to include several other performance indicators such as views, daylight, and carbon emissions, and will test combinations of energy and environmental quality-driven optimization workflows. Additionally, our next studies will explore this workflow in different typological configurations, urban settings, and climatic conditions (including future climate). The focus of this study on energy performance as the driver for the optimization will be expanded to other environmental performance indicators.

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Carbon neutral music venue
A sustainable urban development

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ABSTRACT: The viability of cities in the future will depend on whether they can offer facilities and opportunities for residents whilst maintaining a sufficiently low environmental impact. Cities encompass more than just buildings; they are complex organisms comprised of layers of social, economic, political, environmental and cultural systems. Taking this complexity into account will benefit attempts to implement reductions of CO2 emissions. An approach to this challenge is explored through a case study of a music venue with an integral community centre. A short review is provided defining carbon neutrality and examining current work towards reducing emissions in the music industry. The development of a methodology is described and results of modelling the venue's total CO2 emissions from Scope 1, 2 and 3 activities are given. Options for refurbishment and renewable energy systems are compared with emissions from the wider organisational activities of staff and audience travel, and proposals for emissions reductions are discussed. This work is being used to formulate a roadmap for the organisation to reach its goal of carbon neutrality. The approach described aims to provide a model for organisations seeking to reduce emissions, thereby allowing them to contribute more positively to the future of their cities.
KEYWORDS: Carbon emissions, energy use, refurbishment, sustainability

1. INTRODUCTION

Globally, business sectors are moving towards sustainability initiatives to help achieve the goals laid out in the Paris Climate Agreement, which are to keep the global temperature rise this century well below 2◦C above pre-industrial levels, with a further aim of reducing the temperature increase even further to 1.5◦C (United Nations, 2015). The arts and culture sector are recognising their own role and have begun addressing the need to develop more sustainable festivals and events, and for artists to make touring decisions based on emission reduction obligations (Cummings, 2014).

Traditionally, 'sustainability' has been described as balancing three pillars of longevity: financial, environmental and social (Brennan et al. 2019). Hawkes (2002) meanwhile cited culture as the 'Fourth Pillar of Sustainability', arguing that 'a society's values are the basis upon which all else is built. These values and the ways they are expressed are a society's culture.' Or, to put it another way: without integrating certain cultural norms into sustainability practice, the other three pillars of sustainability will fall. The founding constitution for UNESCO (UNESCO, 1945) explicitly mentions culture as one of the areas which has the potential to transform societies. This paper will start to explore the relationship between the music industry, communities, and the minimisation of carbon emissions.

2. BACKGROUND AND LITERATURE REVIEW

This section reviews literature and previous research concerning carbon emissions from the music industry overall, discusses carbon neutrality, and gives an overview on the methodology for calculating a baseline carbon footprint**.**

2.1 Carbon Emissions in the music industry

Increasingly, the arts and culture sector are recognising their own sizeable contribution to greenhouse gas (GHG) emissions and are addressing the need to develop more sustainable festivals and events (Cummings, 2014). Despite more recent awareness, Brennan et al. (2019) notes that an advertised interest in sustainability has been present in music festival culture since at least the 1960s, but actions typically do not reflect the rhetoric. For example, music festivals where rural land areas are transformed into music villages or cities have been found to be particularly damaging (Mair and Laing, 2012). Julie's Bicycle, a foremost environmental consultancy for the British music sector, estimated in 2007 that the UK music market resulted in emissions of 540,000 t CO2e (Bottrill et al. 2007).

Despite growing recognition of the need to minimise carbon emissions within the music and culture industries, serious attempts to calculate and control emissions are rare. Brennan et al. (2019) and Upham et al. (2009), provide bases for calculating the carbon footprint of either a single music event/festival or a tour. Although these examples are both for a one-off event, they can serve as a blueprint to defining the calculation for a permanent venue. As Brennan et al. (2019) notes, many calculations only take into account onsite emissions and do not consider indirect emissions, such as audience travel. This is a critical exclusion and could result in an underestimation of up to 75% of overall emissions (Bottrill et al. 2007). Another study by Bottrill et al. (2010) found that audience travel resulted in 43% of the overall emissions from the UK music market.

2.2. Carbon Neutrality: Description and problems

'Carbon neutrality' implies that all outgoing carbon emissions are balanced or neutralised by some method of carbon sequestration. Most often, organisations achieve this by purchasing external carbon offsets through carbon sequestration projects, such as reforestation schemes. These offset schemes often are misguided or fail (Strand 2011). For example, the band Coldplay claimed that production of a 2006 album achieved carbon neutrality by supporting a reforestation project, but it was found that only a fraction of the planted trees survived for even one year (Dhillon and Harnden 2006).

Although carbon offsets can be less expensive upfront than other solutions, there is a considerable risk that relying on carbon offsets 'justifies continued inaction and shifts the burden of emission reductions to other sectors and future generations' (Scott et al. 2016). Worse, offsets could even have an increasing effect whereby they lull buyers into a false sense that their carbon emissions are removed from the atmosphere, and they can therefore make no efforts to reduce emissions (Peeters et al. 2016).

A better path is thus to first aim for ultra-low emissions to reduce the reliance on carbon offsets, and then seek to fund local projects with high potential impact or internal emissions reduction schemes as an alternative to offsetting.

2.3 Calculating a baseline carbon footprint

Achieving reduced emissions or working towards zero emissions requires quantification of a baseline carbon footprint. Various guidelines, such as the GHG Protocol (2013) and WBCSD and WRI (2012), describe a methodology where emissions are typically categorised as Scope 1, Scope 2 and Scope 3, defined as;

- Scope 1: direct emissions that the venue is in control of such as those resulting from fuel burned on site (e.g., the units of gas used annually for heating and cooking).
- Scope 2: indirect emissions such as the electricity purchased to power the site;
- Scope 3: all other indirect emissions, which can cover all aspects related to the activities of the organisation or within the company's value chain.

Scope 3 emissions are often neglected or considered not within the company's direct operations (see for example Hertwich and Wood (2018); Patchell (2018); Thomas et al. (2020)). Increasingly however, the sizeable contribution of Scope 3 to the overall emissions is being recognised, and it is therefore considered essential to both estimate and reduce them as much as possible.

3. METHODOLOGY

The methodology described here is based on guidelines from GHG Protocol (2013), WBCSD and WRI (2012) and suggestions by Bottrill (2010) and will attempt to encompass the building operations (i.e., Scope 1 and 2) as well as explore the Scope 3 impact of transportation of building users. Guidelines and carbon conversion factors are available from Defra (2019), and are used to convert usage values to tonnes of emitted CO2 (t CO2e) using the following formula:

$$GHGe = \text{activity data} \times ECF \quad \ldots\ldots(1)$$

where GHGe = GHG emissions
ECF = emission conversion factor

3.1 Quantifying Scope 1 and 2 emissions

For Scopes 1 and 2 (in this case, gas and electricity) the methodology may be used both for scenarios where primary energy data is available and also where it is unavailable. For the former scenario, bills or meter values can be obtained to directly quantify electricity and gas usage. For the latter scenario, Building Performance Simulation (BPS) or a simplified method capable of calculating heat flows may be used. Ideally both BPS and primary energy data are available, with BPS used to explore potential refurbishment scenarios and metered data used to calibrate the simulation results.

BPS is used to determine heating and cooling loads of the building. There are also benchmarks for energy use (electricity and thermal) that can be used (e.g., CIBSE, 2008) but these will not allow retrofit options to be explored in any detail. However, they can enable quick estimations of emissions for comparison with emissions from other aspects of the building operation.

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3.2 Quantifying Scope 3 emissions due to transportation

Although publications such as GHG Protocol (2013) provides some instruction to quantify Scope 3, there are 15 categories covering all upstream and downstream operations and it can be difficult or impossible to obtain accurate or acceptable data for each category. Navigating issues with data quality and inconsistencies are given by PCAF (2020), who assigned the following reliability scores for different types of data:

- Score 1 (highest): Audited emissions data or actual primary energy data.
- Score 2: Non-audited emissions data, or other primary data.
- Score 3: Averaged data that is peer/sub-sector specific.
- Score 4: Proxy data based on region of country.

Whilst a comprehensive analysis of Scope 3 should attempt to include data across all categories outlined by the GHG Protocol (2013), the present research will seek to focus only on the highest emitting activity, as described by Bottrill (2010): audience transport. Carbon emissions from materials used in the refurbishment could be relatively easily quantified as sufficient databases exist (e.g. Hammond and Jones, 2008), but are not addressed in this paper as low quantities of materials are being used in the refurbishment. Considering the reliability scores outlined by PCAF (2020), it is suggested that the following three methods could be used to obtain audience travel data:

1. Model audience transport habits based on estimated number of audience members and previous data collected on typical transportation methods used (Score 3/4);
2. Conduct surveys of audience members where survey responders are asked how far they travelled to the venue and by what means of transport (Score 2);
3. Utilise mobile phone data using transport apps to track exact travel distances and method of transport used for all consenting audience members (Score 1).

From the data of distance travelled and transport method used, the overall carbon emissions output can be calculated using equation 1. The same methodology is used to predict transport emissions of regular commuting staff as well as artists and performers traveling to an event.

4. FUTURE YARD CASE STUDY

Future Yard, an event and recording venue in the Wirral, United Kingdom, is an organisation with strong links to the cultural life of the city and surrounding areas. The following section illustrates the range of factors involved in the quantification of emissions for the Future Yard live music venue. The initial aim of the organisation was to explore aspects of how it could approach and integrate sustainability into its operations, and as a first step the goal of 'net-zero' emissions was considered (Future Yard, 2022).

4.1 Building and operation

Future Yard is housed in a Victorian brick building with a single storey extension. The building contains a concert hall, café and bar, offices and workspaces, and changing rooms. A basement will be converted to small practice studios, as will the large space above the concert hall. The walls of the main building are solid brick, and all roofs are currently uninsulated.

The organisation requested information on exactly how carbon emissions were generated from day to day in order to understand how to reduce emissions through the refurbishment, and to explore how changes to the buildings operation and its fabric could alter emissions levels under Scopes 1 and 2. Information was also required to facilitate decisions on which parts of the building to renovate first, and which could be left until a later date.

The building occupation varies greatly from day to day, for example on some evenings there are large audiences while on others there are small teaching classes. The café is open all day and evening as are some of the music practice rooms. There are greatly increased heat gains and ventilation rates when a concert is held in the main hall. The design of the services will therefore have a large influence on emissions and at this stage these were only considered in outline, for example use of existing gas boiler for heating and Mechanical Ventilation and Heat Recovery (MVHR).

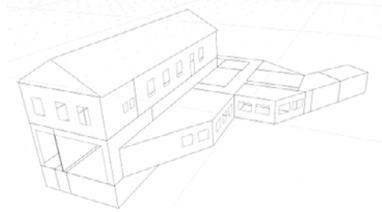
4.2 Scope 1 emissions: Refurbishment and building operations

Low carbon in-use strategies (e.g. GBC, 2019) often include the following stages or similar;

1. Reduce heating and cooling and other loads as far as practicable
2. Design efficient systems that provide optimum carbon performance
3. Supply the energy that is required in a form that minimises carbon emissions.

To date the work has focussed on Stage 1: reducing heating and cooling loads. If these loads are minimised the heating and cooling systems that are designed in Stage 2 will be smaller and more economical to install and run. Stage 3 involves a combination of choosing how heat will be generated (gas, electricity and/or environmental heat) as well as assessing whether electricity can be generated onsite using renewable energy technologies.

Figure 1:
Main building with single storey extension



As the building had been in partial and intermittent operation for only a few months utility bills were of limited use, so a BPS model was made using a comprehensive whole-building simulation tool (IES, 2022). Detailed occupancy profiles were used to assign plant operation, heat gains, and ventilation rates to each space. Other data, such as heating set points, were set using industry recommendations. Refurbishment options were considered, and after consideration of budgets and timescales for opening the venue, a number of these were modelled (table 1).

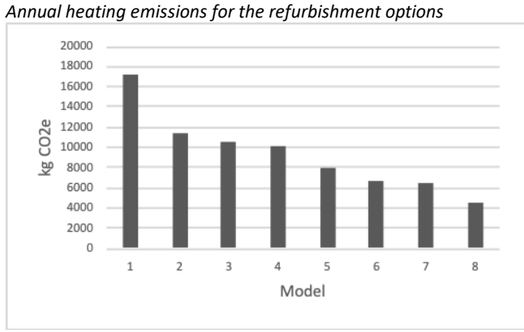
Table 1:
Renovation measures modelled

Model	Heating	Insulation (mm)		MVHR
		Roof	Wall	
1	All year	0	0	No
2	HSO	0	0	No
3	HSO	100	0	No
4	HSO	200	0	No
5	All year	0	0	Yes
6	HSO	200	0	Yes
7	HSO	200	50 (studios) [1]	Yes
8	HSO	200	100 (ext wall) [2]	Yes

HSO: Heating season only
[1] 50mm EPS to studio internal walls only
[2] 100mm EPS to external wall in heated area only

These scenarios test only the most basic strategies, in order to produce figures for comparing with other, non-building related, emissions. In the UK the roofs of the original uninsulated building would need to be insulated to satisfy building regulations, but it was thought useful to consider strategies separately (e.g. use of MVHR without insulating the building, and insulation of the building without MVHR) to enable the organisation to understand all the contributory factors of organisational emissions. A main aim of the modelling was therefore to provide the organisation with an understanding of context, with which to inform later decisions. Simulation results are presented in Figure 2.

Figure 2:
Annual heating emissions for the refurbishment options



For model descriptions, refer to Table 1

Models 1 and 2 show the emissions due to all year heating operation, and heating season only. Comparison of Model 2 with 3 and 4 shows the effect of 100mm and 200mm insulation respectively in the roof. The rather small improvements are due to the insulative value of thick plaster ceilings in the existing building.

Comparison of Models 2 and 6 show the effect of MVHR only (no insulation) which is large when compared to adding the insulation. Given that Building Regulations will require insulation to be added anyway, this result highlights to the client the potential significance of using heat recovery. Model 7 demonstrated that although sound insulation was needed in the practice studios it will have little effect on energy use as only one wall of each studio is an external wall, and half of the studios are in the basement where heat losses through the thick walls to the surrounding earth are relatively low. By contrast, Model 8 added 100mm insulation to the inner face of the external wall in all heated spaces, resulting in appreciable savings.

4.3 Scope 2 emissions: Electricity imported

Electricity consumption was estimated using benchmark figures, applying the relevent benchmark to the area of the building occupied by a particular use (CIBSE, 2008) and are shown in section 4.5 below. The benchmarks are pesimistic and actual electricity emissions would be lower as the hours of use of the concert hall are far less than the benchmark assumption, but the methodology will not permit an adjustment (ibid). A more accurate calculation of electricity consumption can be made when the plant is being designed and specified.

4.4 Scope 3 emissions: Travel

The planned number of concerts, educational classes, use of studios etc., and the anticipated staff, artist and audience numbers were used to calculate travel related emissions (table 2). The distances travelled are based on a knowledge of the audience and previous experience. The modes of transport were estimated based on data collected from a Liverpool Live Music Census (Padilla, 2018). Other indirect emissions are beyond the scope of the current paper but will be quantified in future work.

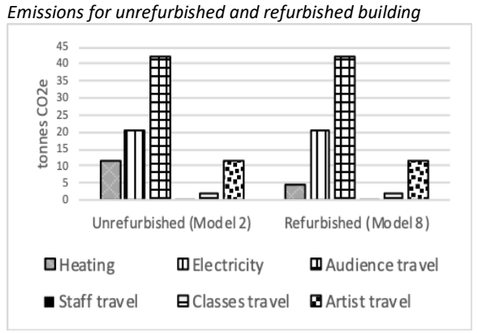
Table 2:
Scope 3 emissions from travel

Group	Annual emissions (kg CO2e)
Audience	42438
Staff	425
Classes	2121
Artist	11290

4.5 Comparison of scope 1, 2 and 3 emissions:

It is immediately clear that audience travel is the main emitter (figure 3). This result indicated clearly to the organisation that initiatives related to travel should be considered.

Figure 3:
Emissions for unrefurbished and refurbished building



4.5 Renewable energy options

The main building has a large south facing unobstructed pitched roof area and a flat roofed extension, both suitable for photovoltaic panels. The site is also suitable for air source heat pumps.

Table 3:
Emission savings from use of photovoltaics

Element	Area (m^2)	Power (Wp/m^2)	Energy (kWh.a)	Annual saving (kg CO2e)
Pitched roof (S)	140	180	25200	6441
Flat roof	280	126	35300	9018

A PV calculator indicates that the two roofs would generate 76% of the electricity requirements of the building and reduce emissions by 15459kg CO2e, further accentuating the dominance of travel related emissions (table 3). There is sufficient additional space above the yard at the rear of the building such that all the electricity required by the building could be generated. The use of some of this electricity to run air source heat pumps would lead to further reductions of gas heating related emissions. Although there is not a large requirement for hot water in the building, Solar Hot Water generation is also an option for this site and could be used to meet a significant proportion of the heating demand.

5. DISCUSSION

The results confirm earlier work that shows audience travel to be a major contributor of emissions for music and cultural venues. Future Yard are keen to consider how these emissions could be reduced, and as a socially active and creative organisation they also appreciate their relationship with their audience and musicians and are interested in whether this relationship can increase the effectiveness of any sustainability initiatives. Initial ideas related to transport include;

- Organise concerts to end earlier to allow audience to catch last bus or train
- Discuss with transport providers the provision of a late services
- Initiatives to reward people who do not drive, such as reduced cost tickets.

Schwanen et al. (2012) discuss the importance of habit change in impacting lower carbon transport and discusses the concept of embodied intelligence to affect the 'gradual change of actions from within'. It is here that the cultural sector and venues such as Future Yard could be an especially compelling messenger.

The building related emissions are less than Scope 3 emissions, and can be addressed through retrofit of building fabric, provision of efficient services, and energy generation using renewable energy technologies. If this work is done in a way that can be communicated, it could provide educational value and possibly influence the behaviour of the audience. Visible metering of energy generation and consumption is one such communication technique and could be effective in this case. Other initiatives can be envisaged such as allocating a percentage of the ticket price to pay for PV panels, or mounting air source heat pumps and PV panels where they are visible to visitors.

The results also raise the question of whether and how far an organisation should take responsibility for emissions related to their operations.

6. CONCLUSION

The methodology described is largely conventional in its modelling of emissions, but the inclusion of Scope 3 emissions prompts an initial exploration of relationships between the building, the organisation and the city and hence can focus attention on emissions reduction opportunities that might otherwise be missed. It is important to engage with the complexity of the interrelated technical, social, cultural and economic systems as these are the systems that make up the city and if dealt with separately will leave 'gaps' between them.

The case study illustrates that emissions calculations can be made using approximate and detailed calculation methods as are appropriate for the project under consideration.

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November 22 - 25, 2022

SUSTAINABLE BUILDING AND TECHNOLOGY

DAY 01
16:45 — 18:15

CHAIR
CECILIA JIMÉNEZ

PAPERS
1117 / 1205 / 1217 / 1431 / 1472 /
1475 / 1510

22TH PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Climate change, energy performance and carbon emission in a prefabricated timber house in northern China

A dynamic analysis

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ABSTRACT: Climate change can bring a big challenge to energy efficiency and carbon emission in cities. Timber houses have been recognized as an effective solution to mitigate climate change. This paper presents a dynamic simulation analysis of the energy performance and operational carbon emission in a prefabricated timber house in northern China (cold climate), considering climate change scenarios for 2020, 2050, and 2080, and various architectural characteristics. Several key findings were achieved as follows: 1) Climate change would deliver significant negative effects on cooling demand and relevant carbon emissions for this timber house, but would benefit the heating energy performance. 2) House layout and shape factor could affect energy demand and carbon emissions for this house. A terrace house may yield around 83% carbon emissions of a similar detached house base model, while a 12% reduction in shape factor can lead to an 18% reduction in carbon emissions. 3) In addition, energy demand and carbon emissions of the house could receive substantial effect from the correct choice of orientation and window-to-wall ratio WWR. A south-facing solution can deliver a reduction in carbon emissions of up to 18%, while a reduction of 0.2 in WWR would lead to a reduction of 12% in carbon emissions.
KEYWORDS: Climate Change, Prefabricated Timber House, Primary Energy Performance, Operational Carbon Emission, Dynamic Simulation

1. INTRODUCTION

Increased human activities have been recognized as the main cause of climate change [1]. Combined with the rapidly growing urbanization, climate change will deliver a significant negative impact on the building energy consumption in cities [1]. In China currently, around 45% of primary energy consumption is found in commercial and residential buildings and this number might rise with the increasing risk of global warming [2]. In addition, studies show that the construction industry is responsible, predominately through the construction and operation of buildings, for around 51.3 % of national greenhouse gas emissions in China [2]. Consequently, the Chinese government has produced numerous strategies to strongly promote low-carbon solutions to improve energy efficiency in residential buildings and achieve climate targets of carbon peak emissions [2, 3, 4].

In recent decades, the potential of timber material to mitigate climate change by reducing greenhouse gas emissions has been widely recognized in building construction [5]. Important investigations into energy and environmental performance in timber houses were mainly based in Europe. One Slovenian study first developed a simple algorithm for architects to estimate energy demand in a prefabricated timber-frame building [6]. In Sweden, a multi-story apartment building of timber construction was analysed using simulation [7]. Results indicated that there was a strong possibility to achieve a low energy target in such a timber house in a cold climate. Another Swedish study [8] compared lifecycle carbon emissions between two multi-storey timber buildings, with conventional and innovative constructions, and identified the key passive solution to reduce carbon emission in a timber structure. Moreover, under various European climates, the links between passive solutions (e.g. shape factor, window-wall ratio) and energy performance in timber-frame houses were comprehensively tested [9, 10]. In addition, a British investigation [11] found evidence to mitigate overheating in a well-insulated timber house using thermal mass. It can be found that prefabricated timber houses have been widely studied in Europe over the past 10 years.

Currently, China has embarked on the promotion of prefabricated building construction as an ambitious governmental initiative [3], because it can significantly contribute to climate change mitigation, and help to reduce carbon emissions and energy and material use [12]. In line with this purpose, there is an increasing trend to encourage the prefabricated timber buildings, especially for the dwelling [13]. However, in Chinese building industry, there is a clear lack of knowledge in terms of prefabricated timber house design and construction, particularly for energy and carbon performances under various Chinese climates.

This study presents a dynamic thermal simulation analysis of primary energy performance and operational carbon emissions in a prefabricated timber house in northern China, considering climate change and key architectural characteristics. These results can be further developed into guidelines to support the design of low carbon timber houses under current and future climate scenarios in China.

2. METHODS

2.1 Location and climate

The house studied is located in Tianjin city in northern China (Latitude: 39.12° N, Longitude: 117.19° E). Tianjin has a humid continental climate. July has the highest average temperature of 26°C, while the coldest month is found in January with an average temperature of -3.3°C [4].

2.2 Timber house models

As shown in Fig.1, the timber house studied has two floors and an attic space, with a total area of 143.56 m^2. The Base Model in this study was a detached house - it has a rectangle plan, with one living room (ground floor) and two bedrooms (first floor) – see Fig. 2. This house was built using a prefabricated timber-frame structure system. Its key components (including walls, floors, roof) were composed of a wood structure and cladding panels. The structure included a top beam, top plate, sill beam and sill plate (horizontal), and studs (vertical). Arranged with a specific spacing, the studs were connected to the beam and plate using nails. The cladding panel was mainly composed of drywall (internal) and sheathing wall (external). The cladding sheets of timber structure wall were available in a standard size with nominal dimensions (1220×2440mm) and thickness (12mm). The cavity between the studs was filled with insulation materials (Rockwool) [13].

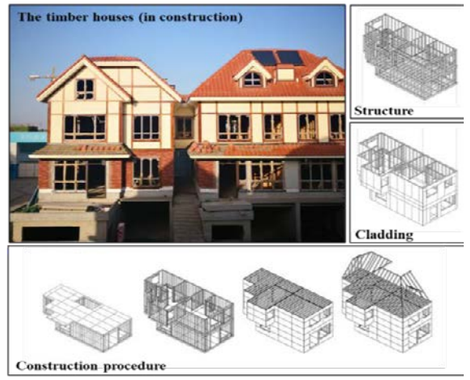

Figure 1: *The timber house and its construction procedure.*

All components of this house were assembled in a factory. In addition, doors and windows were fitted and even electrics and plumbing were installed within the wall sections. These prefabricated components were installed into rooms on site in line with the defined house plan. Finally, all connections of components were fixed by metal fastener. In this study, several key architectural parameters were studied: 1) Three layouts - the Base Model (single unit), semi-detached houses (two units), and terrace houses (four units). The Base Model was the basic house unit used to make up the other two layouts. 2) House size: three sizes of the Base Model were studied in terms of width (W) and length (L) (see Fig. 2), including M1, M2, and M3 (Table. 1). These dimensions were defined in accordance with the prefabricated requirement, i.e. to fit the standard cladding dimensions (1220×2440mm) to reduce material waste [13]. Given a fixed volume of this house model (451m^3), thus, M1, M2 and M3 have various values of Shape Factor (SF) (M1>M2>M3). 3) Orientation: three orientations were studied - South (S), Southeast (SE), Southwest (SW) [14]. 4) WWR (window-to-wall ratio): three ratios were used - 0.45 (large), 0.35 (medium), and 0.25 (small). In addition, the window positions were set according to the requirement of energy efficiency and daylighting in a regulation [4].

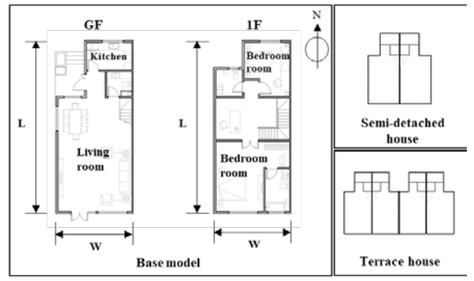

Figure 2: *Plans of base model and various layouts studied.*

Table 1: *Various dimensions of Base Model.*

Model	M1	M2	M3
W (m)	6.10	7.32	8.54
L (m)	13.42	10.98	8.54
Shape Factor	0.57	0.53	0.50

A total of 81 model combinations were finally analysed in terms of the four aspects of architectural characteristics mentioned (Fig.3).

2.3 Future climate change

The impact of climate change was tested through the comparison between three scenarios:

current year (2020), future year (2050), and future year (2080). The future weather data was achieved through the MORPHING method and the weather data generator software Meteonorm [15].

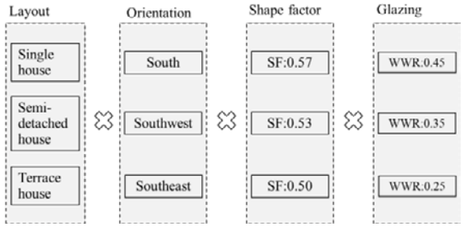

Figure 3: *Building parameters studied.*

According to Fig.4, the annual average temperature will increase by 2.25 °C over the period from 2020 to 2080 due to the increasing trend of global warming. The average winter temperature will grow from -2.65°C in 2020 to 0.36 °C in 2080, whilst a rise can be found in average summer temperature from 26.81°C to 28.87°C during the same period.

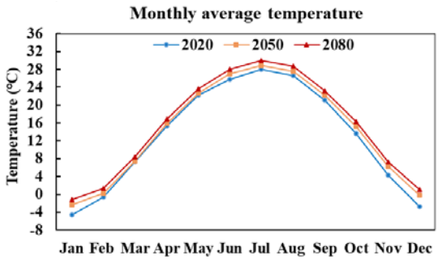

Figure 4: *Variation of monthly average temperature in current and future climate scenarios (2020, 2050, 2080).*

2.4 Dynamic energy performance simulation

DesignBuilder(+EnergyPlus) software was adopted to conduct a dynamic simulation of annual primary energy demands (heating and cooling) in all timber house models (https://designbuilder.co.uk), taking into account three climate scenarios.

In this study, the thermal transmittances (U-value) of the external wall, roof and floor of each house were set as: U(wall)=0.37 W/m^{2}K, U(roof)=0.3W/m^{2}K and U (ground floor) =0.25W/m^{2}K. A constant construction infiltration rate of 0.5 ac/h was used. A low emissivity LoE double glazing system (Clear, 3mm/6mm air) was applied for all windows, with a solar gain g-value of 0.6 and U-value of 2.4 W/m^{2}K. The U-value of the window frame (painted wooden frame) was 3.6 W/m^{2}K. All settings were defined based on the constructions of the real timber house (Fig.1).

In addition, the setpoints of heating and cooling were 18°C and 26°C, respectively [4]. Each house was assumed to be occupied by a family of two adults and one pre-school age child [4, 9, 10]. In these models, natural gas was used for providing heating while the electricity was used for cooling and lighting systems. In China, the CO_2 emission factors of natural gas and electricity are 0.202kg /kWh and 0.878 kg /kWh respectively [16], which were applied in the analysis of carbon emission in this study.

3. RESULTS

3.1 Effects of climate change and house layout

Fig. 5 indicates the impact of the climate change and house layout on primary energy demand and operational carbon emission in the house models (south-facing, M1 and WWR=0.45).

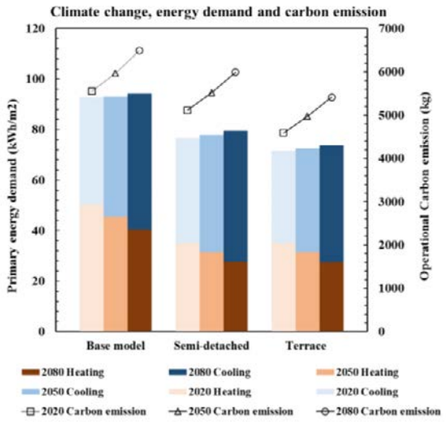

Figure 5 : *Energy demand and operational carbon emission with various house layouts and climate scenarios (South-facing, M1, WWR: 0.45).*

Generally, there was an increase in primary energy demand over the period from 2020 to 2080. For the cooling demand, a significant increase can be found during this period in each model. The base model had the largest growth: from 42.42 kWh/m^2 in 2020 to 53.76 kWh/m^2 in 2080. For the heating demand, however, there was a clear drop in heating demand in this period. The largest decrease was found in the terrace house, where the heating demand dropped from 34.97 kWh/m^2 to 27.42 kWh/m^2. In addition, there were big differences in primary energy demand in the various house models. The terrace house achieved the lowest energy demand with any climate scenario, while the highest demand was found in the base model. In 2080, the terrace house and semi-detached house energy demands were around 78% and 84% respectively of the value in the base model.

Similarly, the operational carbon emissions in all models increased from 2020 to 2080 (Fig.5). Taking the current year (2020) as reference, three models showed an increase in carbon emissions as: 7.3% (2050, base model), 7.8% (2050, semi-detached model), 8.3% (2050, terrace), 16.7% (2080, base model), 17.1% (2080, semi-detached model), 18% (2080, terrace).

In Table 2, from 2020 to 2080, there was an increase in peak cooling demand while the peak heating demand decreased in all models. The largest peak energy demand can be found in the base model. Compared with the base model, the terrace house produced lower peak energy demand, especially in cooling (40% reduction).

Table 2: *Peak energy demand (hourly) varying in house layout and climate scenario.*

		Peak energy demand (kW)		
		Base model	Semi-detached	Terrace
Heating	2020	6.02	5.08	4.68
	2050	5.94	4.95	4.50
	2080	5.28	4.87	4.49
Cooling	2020	7.47	6.74	5.37
	2050	8.16	7.41	5.68
	2080	8.17	7.67	5.87

3.2 Effects of climate change and shape factor

Fig.6 shows the impact of the climate change and house shape factor (SF) on primary energy demand and operational carbon emissions in the house models (south-facing, terrace house, and WWR=0.45).

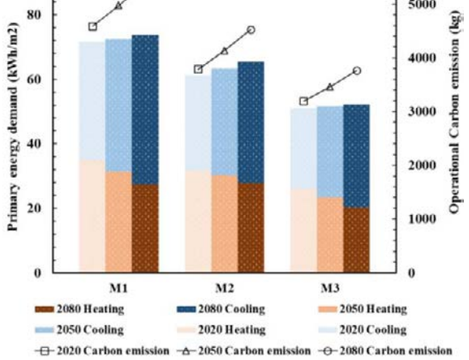

Figure 6: *Energy demand and operational carbon emission with various house shape factors (South-facing, Terrace house, WWR: 0.45).*

For each SF, both primary energy demand and cooling demand increased from 2020 to 2080, while there was a decrease in heating demand. For the three models, M1 (SF=0.57) showed the largest increase in cooling demand from 2020 to 2080 (31%). The highest reduction of heating demand over this period was found in M3 (SF=0.50) at 26%. In addition, decreasing the SF significantly reduced all energy demands. Compared with M1, average energy demands (three years) of the other models had reductions of 11% (M2) and 28% (M3). Fig.6 also shows that the operational carbon emissions of the three models increased from 2020 to 2080. Taking the current year (2020) as reference, three models showed increased carbon emission of: 8% (2050, M1), 9% (2050, M2), 9% (2050, M3), 18% (2080, M1), 19% (2080, M2), 18% (2080, M3).

Table 3: *Peak energy demand (hourly) varying in shape factor and climate scenario.*

		Peak energy demand (kW)		
		M1	M2	M3
Heating	2020	4.68	3.92	3.26
	2050	4.50	3.81	3.15
	2080	4.49	3.77	3.06
Cooling	2020	5.37	4.82	4.06
	2050	5.68	4.91	4.51
	2080	5.87	4.98	4.60

For Table 3, similarly, an increasing peak cooling demand and a decreasing peak heating demand was found from 2020 to 2080. M1 showed the largest peak energy demand, while the lowest peak energy demand was for M3.

3.3 Effects of climate change and orientation

Fig.7 shows the impact of the climate change and orientation on primary energy demand and operational carbon emission in the house models (M1, terrace house, and WWR=0.45).

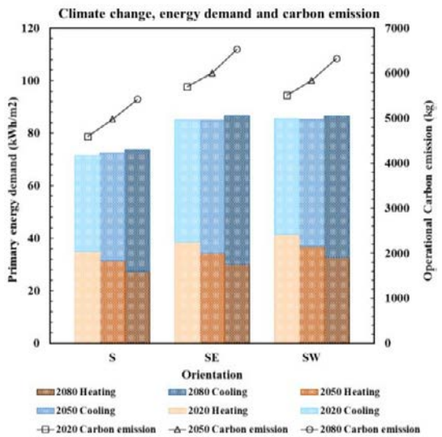

Figure 7: *Energy demand and operational carbon emission with various orientations (M1, Terrace house, WWR: 0.45).*

With each orientation, similarly, the cooling demand significantly increased from 2020 to 2080, while the heating demand tended to decrease.

However, there was a slight increase in the total energy demand for each orientation. Orientations SE and SW created similar energy demands under current and future climate scenarios, while a lower energy demand was found for the south orientation S. Energy demands with orientation S were 71.53 kWh/m^2 (2020), 72.51 kWh/m^2 (2050), 73.76 kWh/m^2 (2080). The three orientations showed an increase in cooling demand from 2020 to 2080 as 26% (S), 22% (SE), 21% (SW), while there were no big differences found between the decreases in their heating demands.

Fig.7 also shows that there was an increase in operational carbon emission from 2020 to 2080 with each orientation. Taking the current year (2020) as reference, the three orientations saw increases of carbon emissions as: 8% (2050, S), 5% (2050, SE), 6% (2050, SW), 18% (2080, S), 14% (2080, SE), 14% (2080, SW).

Table 4: *Peak energy demand varying in orientation and climate scenario*

		Peak energy demand (kW)		
		S	SE	SW
Heating	2020	4.68	5.24	5.34
	2050	4.5	4.83	5.01
	2080	4.49	4.80	4.94
Cooling	2020	5.37	6.55	7.60
	2050	5.68	7.50	8.13
	2080	5.87	7.85	8.29

In Table 4, from 2020 to 2080, there was an increase in peak cooling demand while the peak heating demand decreased for all orientations. The orientation SW led to the highest peak heating demand (5.34kW) in 2020 and the largest cooling demand (8.29kW) in 2080.

3.4 Effects of Climate change and WWR

Fig. 8 indicates the impact of the climate change and WWR on primary energy demand and operational carbon emission in the house models (south-facing, terrace house and M1).

In general, there was an increase in primary energy demand and cooling demand from 2020 to 2080 for each WWR. Similar to the results in section 3.1, 3.2 and 3.3, the heating demand tended to decrease in this period. In addition, there were big differences of primary energy demand found in various WWRs. Compared with the largest WWR (0.45), the other two WWR values delivered a reduction in primary energy demand of 7% (WWR=0.35) and 10% (WWR=0.25).

A similar trend in operational carbon variation was found in Fig.8: there was a significant rise from 2020 to 2080. Taking the current year (2020) as reference, three WWR values produced increases of carbon emissions as: 8% (2050, WWR=0.45), 8% (2050, WWR=0.35), 8% (2050, WWR=0.25), 18% (2080, WWR=0.45), 18% (2080, WWR=0.35), 18% (2080, WWR=0.25).

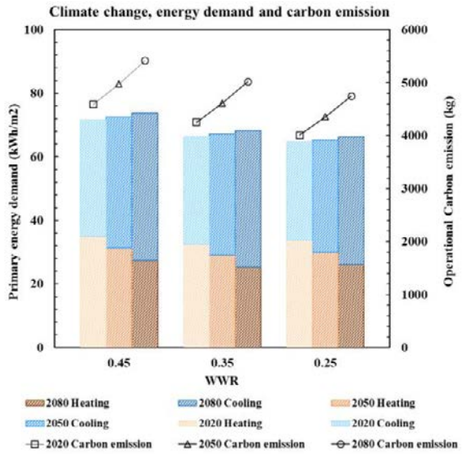

Figure 8 : *Energy demand and operational carbon emission with various WWR values (South-facing, M1, Terrace house).*

From 2020 to 2080 (Table 5), models with various WWR showed a clear increase in peak cooling demand, but a reduction in peak heating demand. The decrease of WWR reduced both peak heating and cooling demands. For example, a WWR reduction of 0.2 led to reductions in peak heating and cooling demands of 6% and 20%, respectively.

Table 5: *Peak energy demand varying in WWR and climate scenario.*

		Peak energy demand (kW)		
		WWR 0.45	WWR 0.35	WWR 0.25
Heating	2020	5.01	4.68	4.60
	2050	4.81	4.44	4.38
	2080	4.39	4.42	4.34
Cooling	2020	5.96	5.14	4.93
	2050	6.49	5.44	5.23
	2080	6.95	5.62	5.37

4. CONCLUSIONS

This study has presented a simulation analysis in terms of climate change, building layout, shape factor, orientation and WWR in a prefabricated timber house in Northern China (cold climate). Some findings that can be drawn from this study include:

1). In general, the climate change (period: 2020 to 2080) delivered significant negative effects on the primary energy demand and operational carbon emission in the timber houses, especially for the energy and carbon performances relevant to the cooling systems. However, the heating energy performance and relevant carbon emission received a positive impact from the global warming.

2). There is a clear effect of house layout on the primary energy demand and operational carbon emission in this prefabricated timber house under current and future climate scenarios. Compared with other layouts, the terrace house has been proved with the lowest primary energy demand and the smallest operational carbon emission.

3). Reducing the shape factor of the house can significantly reduce the primary energy demand and operational carbon emissions. A 12% reduction in shape factor could reduce primary energy demand by 30% and carbon emissions by 18%.

4). For this prefabricated timber house, the building orientation played a significant role in energy demand and carbon emissions under current and future climate scenarios. In comparison to south-east and south-west, the south-facing orientation reduced energy demand and operational carbon emission by around 17% and 18%, respectively.

5). Lowering the WWR could give rise to lower primary energy demand and operational carbon emissions in this timber house under current and future climate scenarios. A reduction of 0.2 in WWR led to reductions of energy demand and carbon emission of 10% and 12%, respectively. However, it could be necessary to balance the daylighting requirement and energy saving with the application of such solutions.

Limitations and future work: These conclusions are obviously limited to a simple house model. More architectural characteristics will be considered in future research. In addition, other issues relating to timber structure lifecycle assessment would be included in the calculation of carbon emission (e.g., construction, de-construction and disposal). These aspects will be studied in the future work.

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Embodied carbon in domestic timber, concrete and steel structures

A study of tools, material substitutions and socio-cultural factors based on a UK Passivhaus home

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ABSTRACT: The building structure is the largest contributor to embodied carbon in the building itself, and improving the structure can provide considerable benefits in terms of reducing the embodied carbon overall. The aim of this study is therefore to investigate and advise future architects on how to balance embodied carbon in Passivhaus homes comparing the structural performance of three key structural materials - timber, steel and concrete - in a broader socio-technical context in the UK. Six different structural material substitutions scenarios were designed for this research, using a Passivhaus home as a case study. The results show that using timber or timber + steel as the building structure material minimises the embodied carbon in the case building. However, the actual use of timber structures in the UK is not high. This research therefore analyses the influences of culture, history, resources, technology and education at a macro level on timber use. At the micro level, other influences of the building surroundings, aesthetics, material availability, robustness and design on the selection of materials is confirmed based on interviews. These socio-cultural influences show that the final choice of structural materials may not always be carbon optimal for good reasons.
KEYWORDS: Embodied carbon, Structural material, Passivhaus home, material substitutions

1. INTRODUCTION

The issue of climate change is the greatest challenge of our generation. In 2019, the building sector accounted for 38% of total global CO2 emissions [1]. Despite the global slowdown in construction growth by 10 to 20 percent in 2020 compared to 2019, due to COVID19, energy consumption in the building sector remains largely stable and CO2 emissions are at an all-time high [2].

The building structure accounts for the largest proportion of carbon in a building and has the most significant impact on the environment [3]. Therefore, of all the strategies to reduce carbon emissions in construction elements, structural design improvements are the most effective [4].

A comparative analysis of building structure and embodied carbon can provide considerable benefits in terms of building carbon reduction [5]. According to a report by the IEA (2018), although the use of structural materials in buildings varies according to each region, globally the 3 structural materials that account for the largest proportion of residential building use are concrete, steel and timber [6].

There is currently no comparison of early stage design tools for calculating embodied carbon considered within a wider socio-cultural context, and no comparison of these tools in relation to calculating the difference between using timber, steel or concrete for Passivhaus domestic construction.

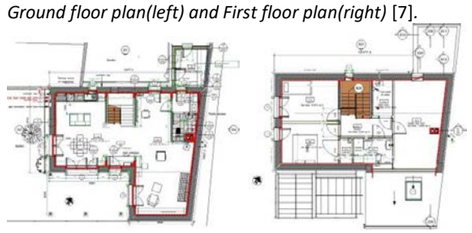
This paper therefore takes a specific UK case study as an object for comparison and calculation between materials, taking account of socio-cultural factors also. The overall aim of this comparison is to investigate and advise future designers on a balance between embodied carbon and structural performance of key materials in a Passivhaus home, within a wider socio-cultural-technical context.

2. CASE STUDY AND METHODS

The Passivhaus home in York, UK, selected as a building for this exemplar case study, is a 2-storey house with a total floor area of 138 m2 completed in 2015. Its main structure is masonry (Figure 1 &2).

Figure 1:
The outside of the house [7].

Figure 2:
Ground floor plan(left) and First floor plan(right) [7].



Four research methods are used to achieve the aim: semi-structured interviews to obtain a more realistic view of the structural materials from the architect and the client; an LCA analysis of the structural materials; an embodied carbon assessment of the existing building structure; two software tools to calculate and compare the level of embodied carbon for the different scenarios. The main construction and energy specifications of the building are shown in Table 1.

Table 1:
Original building fabric and energy specification.

Fabric and energy specification	
Roof	U-Value=0.072 W/(m2K) Plasterboard + 50mm sheep wool Thermafleece insulation + Airtightness membrane + Cellulose fibre insulation Warmcel between 406mm Ijoists + 100mm Steico Special Dry woodfibre insulation board + Tybek membrane + Sandtoftroof tile
Wall	U-Value=0.097 W/(m2K) Inside 15mm two-coat plaster +100mm concrete block （Airtec Seven）+ 300mm water repellent glass mineral wool insulation （DriTherm Cavity Slab 32 Ultimate）+ brick （York Handmade Brick）
Floor	U-Value=0.056 W/(m2K) Tile finish + 150mm concrete slab + 400mm Kingspan ThermafloorTF70 insulation
Windows	Passivhaus certified component, Progression Green Building Store, triple glazed timber & cork frame windows

Products with a shorter overall transport distance have less embodied carbon generated during the transport process. In this study, the UK transportation factor for cradle to grave is typically assumed to be 0.8% (0.6% of freight transportation + 0.2% of site waste removal) of the construction sector's carbon emissions [8].

3. MATERIAL SUBSTITUTION AND EMBODIED CARBON ANALYSIS

The case study structural materials were calculated using two UK open source H\B:ERT and FCBS embodied carbon tools [9]. Then, five structural material substitution scenarios were devised: timber, concrete, steel, a combination of timber + concrete, and a combination of timber + steel. The substitution combination of steel + concrete was not included because at the scale of the case building, this scenario is similar to the results obtained with concrete only.

The analysis focuses on the roof, walls (external and internal walls) and floor slabs (sub-floor and upper floor slabs) and foundations as key structural elements. The foundation of the building is a concrete strip foundation (750 mm wide and 275 mm thick) with RC25/30 cast in-situ reinforcement. No foundation material substitutions are made.

3.1 Scenario 1: original building structural materials

The original house structure is mainly brick, concrete and timber. The roof is framed with timber I-joists spaced at 600mm centres. The external cavity walls are 100mm thick pre-cast concrete blocks on the inner side and 65mm thick locally made handmade bricks on the outer side, with 300mm thick insulation in between. The internal load-bearing walls on the ground floor are made of concrete blocks and the internal non-load bearing walls on the first floor are stud timber frame. The sub floor slab is cast in-situ reinforced concrete and the first floor slab is an I-joist floor.

Based on the specifications and drawings provided by the architect, the house construction was modelled in Autodesk Revit using embodied carbon data from the H\B:ERT tool for the further calculations. This revealed that the original building structural materials were equivalent to 33.69 tonnes of carbon dioxide in total or 244.14 kg CO2e/m2 (see Table 2).

Table 2:
Scenario 1: Corresponding structural building materials selected in H\B:ERT tool.

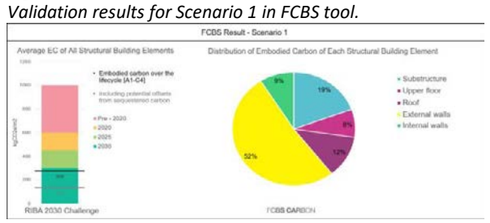
REVIT/HBERT List of Materials: Original building									
Material: Name	Material: Volume	Material: Density (ton/m3)	Material weight (ton)	Material: Waste rate (%)	Overall material weight (waste inc.) (tons)	Material: Embodied Carbon (tonCO2/ton)	Overall material EC (tonCO2e)	Material: Transport coefficient (%)	
HBA_Brick	21.57 m³	1.92	41.410465	0.2	49.692558	0.21	10.435437	0.03	
HBA_Concrete - Cast In Situ 25/30	13.15 m³	2.2	28.921814	0.05	30.367904	0.119	3.613781	0.03	
HBA_Concrete - Precast Block	27.47 m³	2.3	63.175023	0.2	75.810028	0.093	7.050333	0.03	
HBA_Wood - Laminated Veneer	6.90 m³	0.55	3.79521	0.1	4.174731	0.65	2.713575	0.03	
HBA_Wood - OSB	0.29 m³	0.32	0.094331	0.1	0.103764	0.455	0.047213	0.03	
HBA_Wood - Plywood	1.10 m³	0.54	0.593243	0.1	0.652567	0.681	0.444398	0.03	
HBA_Wood - Softwood	0.95 m³	0.55	0.522625	0.1	0.574888	0.263	0.151195	0.03	
Grand total	71.43 m³		138.512711		161.37644		24.455932		
	Overall transport EC (tonCO2e)	Material: Construction coefficient (%)	Overall Construction EC tonCO2e)	Material: End of life coefficient (%)	Overall End of life EC (tonCO2e)	Material: Replacements over 60 years	Overall EC sum (tonCO2e)		
HBA_Brick	0.313063	0.07	0.608734	0.02	0.208709	0	11.565943		
HBA_Concrete - Cast In Situ 25/30	0.108413	0.07	0.240919	0.02	0.072276	0	4.035388		
HBA_Concrete - Precast Block	0.21151	0.07	0.411269	0.02	0.141007	0	7.814119		
HBA_Wood - Laminated Veneer	0.081407	0.07	0.172682	0.02	0.054271	2	9.065807		
HBA_Wood - OSB	0.001416	0.07	0.003004	0.02	0.000944	0	0.052578		
HBA_Wood - Plywood	0.013332	0.07	0.02828	0.02	0.008888	1	0.989796		
HBA_Wood - Softwood	0.004536	0.07	0.009622	0.02	0.003024	0	0.168377		
Grand total	0.733678		1.47451		0.489119		33.692008		

The results in the final column of Table 2 shows that the three material elements that contribute the most to the overall embodied carbon are brick, laminated veneer lumber used in roof I-Joists, and precast concrete block. This means that the three structural building elements that contain the highest carbon elements in the building are the external walls, the roof and the upper floor slab.

The FCBS embodied carbon tool result (268 kg CO2e/m2) , was used to validate the H\B:ERT result, (244.14 kg CO2e/m2) which is similar . The building

external walls (yellow) are the primary carbon hotspots (Figure 3).

Figure 3:
Validation results for Scenario 1 in FCBS tool.



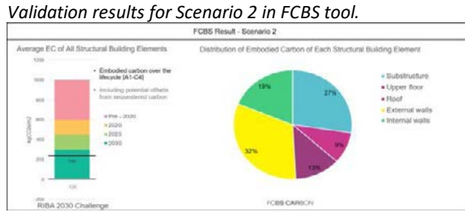
3.2 Scenario 2: substitution with timber

Timber is substituted for all structural materials in this scenario, only the original timber roof and upper floor structure is maintained. For optimum performance the JJI-450 I-joists have a spacing of 600mm for the wall studs in the external walls, with a vertical load capacity of 31kN/m and a shear stiffness of 22.18kN. JJI-220D I-joist was chosen for the wall studs in the internal load-bearing walls. The internal non-load-bearing walls maintain the original timber product. The sub floor slab substitutes JJI-450 I-joists (450mm deep, 97mm wide at 600mm centres, for the 6.7m span of the case building. Detailed parameters are shown in Table 3 and Figure 4 below.

Table 3: *Scenario 2: Corresponding structural building materials selected in H\B:ERT tool.*

REVIT/HBERT List of Materials: Substitution of structural materials with timber								
Material: Name	**Material: Volume**	**Material: Density (ton/m3)**	**Material weight (ton)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (tons)**	**Material: Embodied Carbon (tonCO2/to n)**	**Overall material EC (tonCO2e)**	**Material: Transport coefficient (%)**
HBA_Wood - CLT	5.74 m³	0.5	2.8715	0.1	3.158651	0.437	1.38033	0.03
HBA_Wood - Laminated Veneer	7.26 m³	0.55	3.991224	0.1	4.390346	0.65	2.853725	0.03
HBA_Wood - OSB	0.49 m³	0.32	0.157218	0.1	0.17294	0.455	0.078668	0.03
HBA_Wood - Plywood	2.67 m³	0.54	1.443499	0.1	1.587848	0.681	1.081325	0.03
HBA_Wood - Softwood	3.01 m³	0.55	1.655396	0.1	1.820936	0.263	0.478906	0.03
Grand total	**19.17 m³**		**10.118837**		**11.130721**		**5.872974**	
	Overall transport EC (tonCO2e)	**Material: Construction coefficient (%)**	**Overall Construction EC tonCO2e)**	**Material: End of life coefficient (%)**	**Overall End of life EC (tonCO2e)**	**Material: Replacem ents over 60 years**	**Overall EC sum (tonCO2e)**	
HBA_Wood - CLT	0.04141	0.07	0.087839	0.02	0.027607	0	1.537186	
HBA_Wood - Laminated Veneer	0.085612	0.07	0.181601	0.02	0.057074	2	9.534036	
HBA_Wood - OSB	0.002361	0.07	0.005007	0.02	0.001574	0	0.08763	
HBA_Wood - Plywood	0.03244	0.07	0.068812	0.02	0.021626	1	2.408405	
HBA_Wood - Softwood	0.014367	0.07	0.030476	0.02	0.009578	0	0.533327	
Grand total	**0.176189**		**0.373735**		**0.117459**		**14.100584**	

Figure 4:
Validation results for Scenario 2 in FCBS tool.



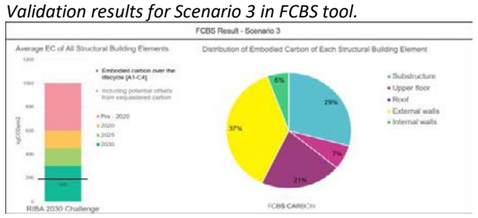
3.3 Scenario 3: substitution with concrete

Concrete is substituted for all structural materials in the original building. Cast in situ reinforced concrete is used for the roof and all floor slabs, estimated to carry the same load as the original structure (see scenario 1). The external walls retain the structure of the original building, replacing the outer layer of handmade bricks with concrete blocks estimated to carry the same load. The internal load-bearing walls retain the concrete blocks of the original building, while the non-load-bearing walls are substituted with hollow concrete blocks, which are also non-load bearing. Detailed parameters are shown in Table 4 and Figure 5 below.

Table 4:
Scenario 3: Corresponding structural building materials selected in H\B:ERT tool.

REVIT/HBERT List of Materials: Substitution of structural materials with concrete								
Material: Name	**Material: Volume**	**Material: Density (ton/m3)**	**Material weight (ton)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (tons)**	**Material: Embodied Carbon (tonCO2/to n)**	**Overall material EC (tonCO2e)**	**Material: Transport coefficient (%)**
HBA_Concrete - Cast In Situ 25/30	26.85 m³	2.2	56.87503	0.05	59.718782	0.119	7.106535	0.03
HBA_Concrete - Precast Block	48.77 m³	2.3	112.180677	0.2	134.616812	0.093	12.519364	0.03
HBA_Concrete Precast - RC 40/50	6.10 m³	2.3	14.03764	0.01	14.178016	0.178	2.523687	0.03
Grand total	**80.73 m³**		**183.093347**		**208.51361**		**22.149585**	
	Overall transport EC (tonCO2e)	**Material: Construction coefficient (%)**	**Overall Construction EC tonCO2e)**	**Material: End of life coefficient (%)**	**Overall End of life EC (tonCO2e)**	**Material: Replacem ents over 60 years**	**Overall EC sum (tonCO2e)**	
HBA_Concrete - Cast In Situ 25/30	0.213196	0.07	0.473769	0.02	0.142131	0	7.935631	
HBA_Concrete - Precast Block	0.375581	0.07	0.730296	0.02	0.250387	0	13.875828	
HBA_Concrete Precast - RC 40/50	0.075711	0.07	0.174909	0.02	0.050474	0	2.82478	
Grand total	**0.664488**		**1.378974**		**0.442992**		**24.636039**	

Figure 5:
Validation results for Scenario 3 in FCBS tool.



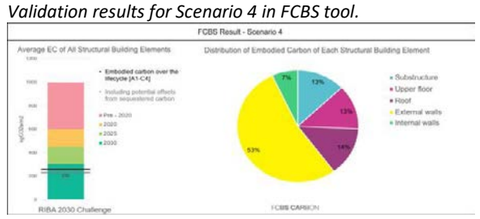
34. Scenario 4: substitution with steel

Steel is substituted for all structural materials in the original building, using the same estimated loadings from guidance. Steel I-joists of 185 mm is used for the roof. For the external walls, a stronger 235mm I-joists system is used. For the sub-floor slab and upper-floor slab 235mm and 185mm I-joists are used, respectively, with spans of approximately 2.7 to 3 metres. Detailed parameters are shown in Table 5 and Figure 6 below.

Table 5:
Scenario 4: Corresponding structural building materials selected in H\B:ERT tool.

REVIT/HBERT List of Materials: Substitution of structural materials with steel								
Material: Name	**Material: Volume**	**Material: Density (ton/m3)**	**Material weight (ton)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (tons)**	**Material: Embodied Carbon (tonCO2/to n)**	**Overall material EC (tonCO2e)**	**Material: Transport coefficient (%)**
HBA_Steel Section	2.17 m³	7.8	16.94656	0.15	19.488544	1.55	30.207244	0.03
Grand total	**2.17 m³**		**16.94656**		**19.488544**		**30.207244**	
	Overall transport EC (tonCO2e)	**Material: Construction coefficient (%)**	**Overall Construction EC tonCO2e)**	**Material: End of life coefficient (%)**	**Overall End of life EC (tonCO2e)**	**Material: Replacem ents over 60 years**	**Overall EC sum (tonCO2e)**	
HBA_Steel Section	0.906217	0.07	1.838702	0.02	0.604145	0	33.556307	
Grand total	**0.906217**		**1.838702**		**0.604145**		**33.556307**	

Figure 6:
Validation results for Scenario 4 in FCBS tool.



35. Scenario 5: substitution with timber + concrete

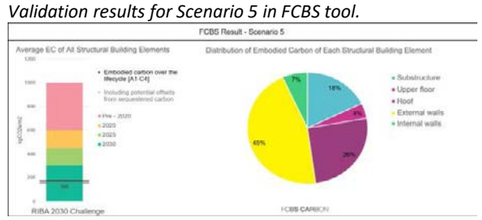
Key structural materials in the original floor slabs are replaced with timber and concrete, known as a timber-concrete composite (TCC) structure, using the same loadings. The TCC structure consists of timber elements, concrete layers and connections [10]. This structure can be used in the slab, wall and beam of a building [11]. The main technique used is timber concrete composite floors. The floor slab is the main component of the total weight of a multi-storey building, and reducing the weight of the floor slab is essential.

In Scenario 5, the slabs are substituted with timber concrete composite slabs in an all-concrete structure, using Scenario 3 as a reference. For the sub-floor, the original 150mm thick concrete floor slab is substituted with 140mm CLT joists + 100mm thick concrete panel. The original 100mm thick concrete upper floor slab is substituted with 140mm CLT joists + 50mm thick concrete panel. Detailed parameters are shown in Table 6 and Figure 7 below.

Table 6:
Scenario 5: Corresponding structural building materials selected in H\B:ERT tool.

REVIT/HBERT List of Materials: Substitution of structural materials with timber + concrete								
Material: Name	**Material: Volume**	**Material: Density (ton/m3)**	**Material weight (ton)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (tons)**	**Material: Embodied Carbon (tonCO2/to n)**	**Overall material EC (tonCO2e)**	**Material: Transport coefficient (%)**
HBA_Concrete - Cast In Situ 25/30	21.47 m³	2.2	47.234426	0.05	49.596147	0.119	5.901941	0.03
HBA_Concrete - Precast Block	48.81 m³	2.3	112.271342	0.2	134.72561	0.093	12.529482	0.03
HBA_Concrete Precast - RC 40/50	3.05 m³	2.3	7.01882	0.01	7.089008	0.178	1.261843	0.03
HBA_Wood - CLT	2.60 m³	0.5	1.300907	0.1	1.430998	0.437	0.625346	0.03
Grand total	**75.94 m³**		**167.825494**		**192.841763**		**20.318613**	
	Overall transport EC (tonCO2e)	**Material: Construction coefficient (%)**	**Overall Construction EC tonCO2e)**	**Material: End of life coefficient (%)**	**Overall End of life EC (tonCO2e)**	**Material: Replacem ents over 60 years**	**Overall EC sum (tonCO2e)**	
HBA_Concrete - Cast In Situ 25/30	0.177058	0.07	0.393463	0.02	0.118039	0	6.590501	
HBA_Concrete - Precast Block	0.375884	0.07	0.730886	0.02	0.25059	0	13.866842	
HBA_Concrete Precast - RC 40/50	0.037855	0.07	0.087454	0.02	0.025237	0	1.41239	
HBA_Wood - CLT	0.01876	0.07	0.039795	0.02	0.012507	0	0.696408	
Grand total	**0.609558**		**1.251598**		**0.406372**		**22.586142**	

Figure 7:
Validation results for Scenario 5 in FCBS tool.



36. Scenario 6: substitution with timber + steel

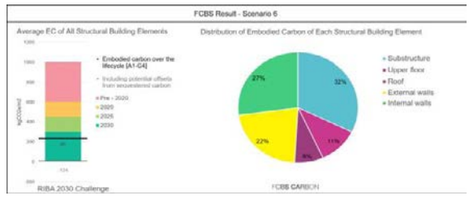
Timber and steel is substituted for all structural materials in the original building, using the same loadings and metal web joist technology (Figure 8,9 and Table 7). This technique has been widely used in recent years to replace traditional timber joists in low-rise residential buildings (medium span). It also offers more freedom of design for floor slabs and roofs. Unlike timber or metal I-joists, the metal web joist combines the lightness of timber with the strength of steel, allowing for a smaller amount of each material and a larger span to be achieved [12].

Figure 8:
Metal web joists in roof (left) and floor slab applications (right)[13].

Table 7:
Scenario 6: Corresponding structural building materials selected in H\B:ERT tool.

REVIT/HBERT List of Materials: Substitution of structural materials with timber + steel								
Material: Name	**Material: Volume**	**Material: Density (ton/m3)**	**Material weight (ton)**	**Material: Waste rate (%)**	**Overall material weight (waste inc.) (tons)**	**Material: Embodied Carbon (tonCO2/to n)**	**Overall material EC (tonCO2e)**	**Material: Transport coefficient (%)**
HBA_Steel Section	0.09 m³	7.8	0.683607	0.15	0.786147	1.55	1.218529	0.03
HBA_Wood - CLT	5.24 m³	0.5	2.622044	0.1	2.884248	0.437	1.260416	0.03
HBA_Wood - Laminated Veneer	5.89 m³	0.55	3.239269	0.1	3.563196	0.65	2.316077	0.03
HBA_Wood - OSB	0.48 m³	0.32	0.154497	0.1	0.169947	0.455	0.077326	0.03
HBA_Wood - Plywood	2.67 m³	0.54	1.443492	0.1	1.587841	0.681	1.08132	0.03
HBA_Wood - Softwood	2.60 m³	0.55	1.428831	0.1	1.571714	0.263	0.413361	0.03
Grand total	**16.98 m³**		**9.57174**		**10.563094**		**6.367029**	
	Overall transport EC (tonCO2e)	**Material: Construction coefficient (%)**	**Overall Construction EC tonCO2e)**	**Material: End of life coefficient (%)**	**Overall End of life EC (tonCO2e)**	**Material: Replaceme nts over 60 years**	**Overall EC sum (tonCO2e)**	
HBA_Steel Section	0.056556	0.07	0.074171	0.02	0.024371	0	1.353626	
HBA_Wood - CLT	0.037812	0.07	0.080206	0.02	0.025208	0	1.403646	
HBA_Wood - Laminated Veneer	0.069482	0.07	0.147387	0.02	0.046322	2	7.737804	
HBA_Wood - OSB	0.00232	0.07	0.004921	0.02	0.001547	0	0.086113	
HBA_Wood - Plywood	0.03244	0.07	0.068811	0.02	0.021626	1	2.408394	
HBA_Wood - Softwood	0.012401	0.07	0.026305	0.02	0.008267	0	0.460334	
Grand total	**0.191011**		**0.401803**		**0.127341**		**13.449917**	

Figure 9:
Validation results for Scenario 6 in FCBS tool.



4. INTERVIEW ANALYSIS

The author conducted online interviews with the client (50 minutes) and architect (31 minutes) of the case house. 12 key themes for choice of materials emerging from initial open coding and thematic analysis of the interview transcripts are shown below in Table 8, which are discussed later.

Table 8:
Scenario 6: Interview themes.

12 themes that emerged from the interviews	
1. Material Preferences	7. Exposed structure
2. Embodied carbon (EC)	8. Construction process
3. Material combinations	9. Environmental friendliness
4. Material suitability and substitution	10. End of life
5. Health	11. Reduction of EC
6. Aesthetics	12. Repair

5. DISCUSSION

5.1 Tools performance comparison

To identify the most promising scenario for total embodied carbon all six H/B:ERT scenarios are compared (Table 9). Scenario 6 (timber+steel) has the highest carbon saving potential, followed by scenario 2 (timber) and scenario 5 (timber+concrete).

Table 9:
Comparison of calculation results.

		Overall EC (tonCO2e)	Average EC (kgCO2e/m2)
Scenario1: Original	HBERT	33.69	244.14
	FCBS	36.98	268
Scenario2: Timber	HBERT	14.10	102.18
	FCBS	14.9	108
Scenario3: Concrete	HBERT	24.63	178.52
	FCBS	25.53	185
Scenario4: Steel	HBERT	33.55	243.16
	FCBS	34.5	250
Scenario5: Timber + Concrete	HBERT	22.58	163.67
	FCBS	24.15	175
Scenario6: Timber + Steel	HBERT	13.44	97.46
	FCBS	12.82	95
Scenario1, 4 > Scenario3, 5 > Scenario2 > Scenario6			

When comparing both tools, the maximum total embodied carbon deviance between them for scenarios 2 to 6 does not exceed 1.57 tonCO2e. In scenario 1, however, the total embodied carbon deviance is 3.29 tonCO2e, which equates to almost more than twice the deviance of the other scenarios. A re-examination of the calculation process for both tools revealed that the large error in Scenario 1 was due to the complexity of the materials used. The original building in Scenario 1 used 4 structural materials: wood, steel, concrete, and brick. This led to the need to enter more materials into the FCBS tool and to control their adjustment factors in order to get the volumes of the individual materials close to the true volumes. In contrast, the single material substitution scenarios produced deviance of less than 1 tonCO2e between both tools. This highlights the difficulty of gaining accurate embodied carbon results for complex buildings.

5.2 Optimising Structural Embodied Carbon

In Scenario 2, when only timber is used as the structural material, the average embodied carbon in the FCBS is 108 kgCO2e/m2. In this scenario, the main structural product is the timber I-joists. It is worth noting that carbon sequestration in timber and material replacement cycles were not taken into account in this study in order to control for experimental variables.

Surprisingly, Scenario 6 is the optimal scenario, with an average embodied carbon in FCBS of 95 kgCO2e/m2 for timber + steel as a structural building material.

Here, the webs of the traditional timber I-joists are replaced with metal. This significantly reduces the amount of timber used and requires very little steel for the webs, optimizing use of both materials

The average FCBS calculated embodied carbon for scenario 5 (timber/concrete) is 175 kgCO2e/m2, which is less than scenario 3 (concrete only) of 185 kgCO2e/m2. This is because the use of timber-concrete composite (TCC) floor slabs reduces the amount of concrete used. However, the carbon reduction achieved is relatively small, i.e. 10 kgCO2e/m2.

5.3 Cultural Factors

Both timber and steel-timber hybrids have obvious advantages over other structures in terms of embodied carbon and cost, but why is this not happening in practice? Historically, this is largely due to a combination of people's negative cultural associations with timber structures, historical perceptions and the scarcity of tree resources in the UK [14]. The current problem is also rooted in a lack of education about the use of timber and a number of misconceptions about timber, such as its 'poor' fire resistance and robustness (it can last 100 years +), the fact that it is expensive and requires high maintenance, and its susceptibility to decay [15].

5.4 Architect/Client cultural factors

The detailed analysis of client and the designer themes explained why their final material decisions and the physical results presented by this article did not match in terms of their personal perceptions (durability, robustness, maintenance-free), construction, cost constraints, etc. Examining the factors that influence the decision-making, helps to reduce this inconsistency and thus contribute to the wider reduction of embodied carbon.

They both made material decisions during the design and construction process on a much wider basis than just embodied carbon as a factor. They both considered the use of timber as a structural material at the beginning of the design. However, the client felt that even though timber was environmentally friendly, it required more maintenance and was not as robust as concrete. In addition, the client wanted to use brick on the external walls for cultural consistency with the surrounding buildings, and she did not want to use different structural and cladding materials. For all these reasons, the use of timber in the case building was only concentrated on the upper floor slab and roof structure. The architect, by contrast, was more concerned with other design issues, and highlighted that if timber is used as the sub-floor material, underfloor ventilation needs to be taken into account. The architect also believed that the use of timber as a structure did not necessarily make it cheaper, as there are many other more significant cost constraints in the design. For example, designing a Passivhaus home is often more expensive than traditional houses because of the higher quality of construction and the need to purchase better airtight windows.

6. CONCLUSION

The overall findings indicate that the steel + timber structure and the timber structure have the lowest embodied carbon as elements in a typical Passivhaus home compared to the other common material scenarios. However, in the UK timber frame buildings only represent a very small proportion of the total building stock due to macro level cultural, historical, resource, technological and educational factors. This was also borne out in the case study micro level, where material choices are also determined by factors other than embodied carbon, illustrating the need to always consider embodied carbon material choices within a broader context.

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PLEA STGO 2022 WILL CITIES SURVIVE? SUSTAINABLE BUILDINGS AND TECHNOLOGY

Impact of COVID-19 Pandemic on Building Energy Consumption and CO2 Emissions in the U.S.

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ABSTRACT: The COVID-19 has created the biggest global crisis in generations, sending shock waves through health, environmental systems, economies, and societies all around the world. According to the circumstances affected by COVID-19, global energy demand in 2020 is estimated to decline by 6% compared to 2019, a fall seven times greater than the 2009 financial crisis. It seems that during 2020, global electricity consumption is on track to fall by 2%. As a result, global CO2 emissions are expected to decline by 8%, or almost 2.6 Gt, to levels of 10 years ago. With a focus on building sector in the U.S., this article analyses energy consumption and CO2 emissions in 2020; during the outbreak of COVID-19. The finding shows that energy consumption in commercial and residential buildings decreased by 10% and 8% in 2020 compared to 2019, and CO2 emissions also dropped 6% and 16% in these sectors respectively. As conclusion, some efficient management strategies such as enhancement of digitalization, new lifestyles with lower energy usage, and opportunities for renewables and energy storage presents that may lead to optimize energy consumption in buildings and consequently to conserve usage and minimize CO2 emissions for a sustainable post-pandemic future.
KEYWORDS: COVID-19, Energy consumption, CO2 emissions, Building sector, United States.

1. INTRODUCTION

At the end of 2019, the world experienced a new health crisis caused by the SARS-CoV-2 virus that quickly spread throughout the most remote corners of each country, state and localities [1]. The coronavirus disease 2019 (COVID-19) has been swiping the world [2]. The Pandemic had many impacts on lives around the world. Beginning in mid-March of 2020, the COVID-19 pandemic caused significant disruption across the United States [3]. The COVID-19 pandemic greatly changed human lifestyles [4]. People worked from home, and students participated in distance learning. It also resulted in a series of unexpected challenges, including health, social, environmental issues which humanity continues to face as of 2021 and must overcome to ensure a sustainable and optimistic future [5]. In terms of environmental impacts, COVID-19 changed the energy consumption patterns and CO2 emissions [6]. According to the Monthly Electricity Statistics released by International Energy Agency, global electricity consumption fell by 8.6% in 2020 compared with 2019. That compares with 6.6% in the United States and 0.8% in China [7]. 8% decline in the global emissions in the first four months of 2020 is a reflection of familiar experience that is associated with the leading world carbon dioxide (CO2) emitters: the United States dec1ined by 138 million tons of CO2 (from 1753 to 1615) [8]. the reduction in energy consumption has reduced environmental impacts through lowering greenhouse gas and pollutant emissions which is considered a positive aspect of the COVID-19 pandemic [9]. The building sector is expected to consume more than one-third of the global energy consumption by 2040 [10]. In the U.S. more than 76% of all U.S. electricity use and more than 40% of all U.S. energy use and associated greenhouse gas (GHG) emissions are used to provide comfortable, well-lit, residential, and commercial buildings—and to provide space conditioning and lighting for industrial buildings [11]. Also, the buildings represent the single largest contributor to carbon output in the United States. It is clear to colleagues in our industry that buildings and their associated energy use pose a major challenge for cities and urban environments now and in the future [12]. According to the role of buildings in energy consumption, CO2 emissions, and the pandemic during almost last two years including various environmental impacts; the paper seeks to address this question: What is the impact of COVID-19 on the buildings' energy consumption and CO2 emissions in the United States?

2. RESEARCH BACKGROUND

There are a number of studies on the impact of COVID-19 pandemic on energy demand, GHG emissions, air pollutions, global warming, and climate change. With an emphasize on the sustainable development concept, some scholars investigated the environmental problem associated with the pandemic in general [13-17]. For instance, Lanshina et al. (2020), analysed over 20 policy proposals for coping with the COVID-19 crisis that have been published by influential international organizations, governments, corporations, academics and civil society groups [18]. The authors identified key areas of sustainable development that require action in the near future and which can create new opportunities for economic development: renewable energy and clean transport, cyclical economy, digitalization and environmental protection. Another study was conducted by Billon et al. (2021) on fossil fuels, climate change and the COVID-19 crisis as pathways for a just and green post-pandemic recovery. Based on their research, a combination of 'green' investments and 'just' transition reforms could help enrol fossil fuel producers into a climate-friendly post-COVID recovery [19]. Some other scholars analysed the impacts of COVID-19 on energy consumption and CO2 emission in different countries, especially during 2020 and the lockdown period [1,2,4,5,7,9,14,20,21,22]. For example, a research was carried out by Qarnain et al. (2021) to review the various actions taken by G20 member countries towards electricity consumption while in COVID-19 pandemic outbreak. As a conclusion, they provided some energy policy recommendations based on the different governments responses and actions taken that can be considered for energy consumption in buildings in future [23]. Another study was performed by Kang et al. (2021) on changes in energy consumption in different building types under COVID-19 pandemic in South Korea. Their result shows that social distancing by the COVID-19 outbreak, has changed energy consumption according to building use type that indicates the need for new energy systems to effectively manage the energy demand at the community level in the post COVID-19 era. Mantesi et al. (2022) examined the future of offices as a flexible working model, to investigate the operational energy consumption of UK office building sector in the post-pandemic era. According to their findings, by embracing emerging transitions in hybrid working model and activity-based workspace environments, the energy demand in the office buildings could fall below pre-COVID-19 levels, with significant energy savings reaching up to 50% energy reduction in comparison to the pre-pandemic situation [24]. A comprehensive literature review illustrates that there are only few researches that have specifically focused on the impacts of COVID-19 on building energy consumption in the context of the United States. While, the energy consumption and CO2 emissions changed during the pandemic, and these changes have various patterns based on the buildings' sectors [8,25-28]. For instance, Wang et al. (2021) proposed a new measurement approach based on a comparison of simulated and actual oil consumption in the U.S. Through analysing the difference between the simulated and real oil consumption in the country, they found that the impact of the epidemic on U.S. oil consumption was obvious in April-May 2020 and January-February 2021. At its worst, the oil decline in the U.S. reached 973 trillion British thermal units, compared to the state without the epidemic. During the entire survey period (January 2020-March 2021), the U.S. oil consumption under the epidemic was about 18.14% lower than that under the normal epidemic-free situation, which was 5% higher than the 13% inter-annual decline rate reported [29]. Another study was conducted by Kawaka and Cetin (2021) on the impacts of COVID-19 on residential buildings' energy use and performance. Their findings indicated increased electricity use during periods that occupants would usually be away from home. The most percent increase in non-HVAC residential loads occurred between 10 a.m. and 5 p.m.; HVAC loads increasing in total daily consumption compared to the same average daily temperatures of previous years. Additionally, dividing the data by household income, the lowest income and higher income households experienced the larger increases in consumption, while the middle-income groups experience smaller shifts [3].

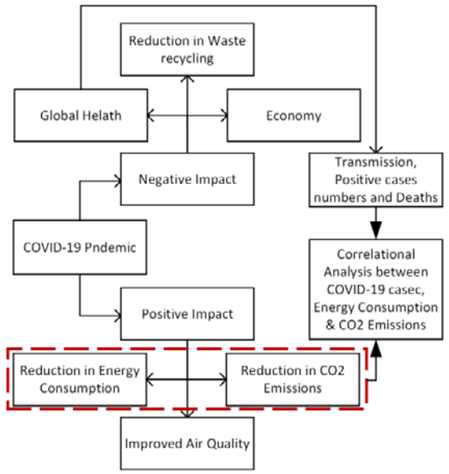
It should be noted that most of the previous research only focused on 2019 and 2020 to analyse the data in these two years. However, this article goes further to analyse energy consumption and CO2 emissions in the United States from 2019 (Pre-pandemic) to 2020 (during COVID-19), and 2021 (Post-pandemic). In the other words, this study's goal is to explore how building energy consumption and related CO2 emissions changed in the United States as a result of the COVID-19 pandemic in the residential, commercial, and industrial sectors utilizing data from 2019, 2020, and 2021.

3. RESEARCH METHODOLOGY AND DATA SOURCES

According to the impacts of COVID-19, there are changes in energy consumption and CO2 emissions worldwide, including in the United States. To study these changes, this article will investigate the impacts of the pandemic on buildings' energy consumption and CO2 emissions in the residential, commercial, and industrial sectors and demonstrate the number of fluctuations in the proposed sectors, respectively. For this aim, statistical correlational analysis of monthly and yearly levels of energy use in every three sectors and CO2 emissions compared with COVID-19 US data for infections and deaths.

The monthly period for this study includes January 2019 to October 2021 and the yearly period is based on the EIA statics regarding energy consumption and CO2 emissions, limited to 10-month data. The primary data sources were the U.S. EIA (U.S. Energy Information Administration) CDC COVID Data Tracker (Center for Diseases Control and Prevention). All sources that were used for data collection were free to use and publicly available.

Figure 1: *Research model*



4.ENERGY CONSUMPTION, CO2 EMISSIONS AND COVID-19

The declining trend of energy consumption during the pandemic is unavoidable. When running the pandemic, more attention must be paid to assessing the environment and stabilizing energy demand. Since the COVID-19 pandemic, energy consumption has declined worldwide by a projected (-)6.1% in ‘‘total energy demand,” in which only the renewables’ contribution grew by 0.8% [25]. Although the fact that overall energy demand declinesis simple and clear, the repercussions are very complicated in different energy types and consumption patterns of different regions [2].

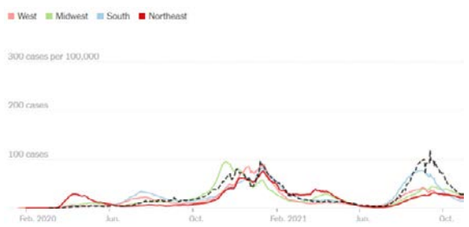
Buildings sector energy consumption profiles have changed during the COVID-19 pandemic, as restrictions on movement have prompted mass teleworking and eLearning, shifting activities and energy use to the residential subsector [30]. The quick transition between in-person and remote working is expected to demonstrate a significant shift in energy consumption [28].

In 2020, total U.S. energy consumption fell to 93 quadrillion British thermal units (quads), down 7% from 2019, according to EIA’s Monthly Energy Review. Much of the 2020 decrease in energy use is attributable to economic responses to the COVID-19 pandemic that began in the United States during the spring of 2020. In 2020, the United States produced the least CO2 emissions from energy in nearly 40 years. CO2 emissions from energy consumption in the United States fell to the lowest level since 1983. The 4.6 billion metric tons (Bmt) of CO2 emitted in 2020 was an 11% decrease from 2019 [31].

In 2020, energy consumption by the commercial sector of the U.S. economy fell by 7% to less than 17 quads. Closed offices and businesses, work-from-home orders, and relatively warmer winter weather contributed to less commercial energy consumption. Energy consumption in the U.S. industrial sector fell 5% to 31 quads. With decreased U.S. demand for many products during 2020, the energy-intensive industrial sector produced less crude oil and natural gas and, therefore, consumed less energy to produce, refine, and process those products. Residential sector energy consumption fell by only 1% to less than 21 quads. With people spending more time in their homes because of various stay-at-home orders during 2020, sales of electricity to the U.S. residential sector increased by 2% [30]. Reduction in energy consumption also led to falling in energy-related CO2 emissions. The U.S. industrial sector emitted 1.3 Bmt of CO2 in 2020, 7% fewer emissions compared to 2019. The U.S. residential and commercial sectors emitted 0.9 and 0.7 Bmt of CO2 in 2020, 6% and 12% drops from 2019 [31].

From January 20, 2020, the CDC confirmed the first U.S. case of COVID-19 in the U.S. until the end of 2021, COVID-19 was the reason for more than 55 million positive cases and 900 thousand deaths [32]. As presented in Fig 1, average daily cases per capita have a similar trend in different regions in the U.S., and after nationwide vaccination (Dec 14, 2020), the number of samples and deaths decreased significantly. However, it continues, given that more than 60% of the U.S. population has received the two COVID-19 vaccines [33].

Figure 2:
Average Daily case in the U.S. regions. [34]



Note: This chart shows how average daily cases per capita have changed in different parts of the country.

5.RESULTS AND FINDINGS

Statistics show that energy consumption and carbon dioxide production have shifted during the pandemic (Tables 1 & 2). These changes have not had the same trend in different sectors. For example, the residential buildings had minimum changes compared with others in the period of this study.

Table 1:
Total energy consumption by sectors (2019-2021). [35]

Year	Total Energy Consumption Residential (TBtu)	Total Energy Consumption Commercial (TBtu)	Total Energy Consumption Industrial (TBtu)
2019	17100	14845	27167
2020	16795	13753	25748
2021	17164	14249	26720

Note: The data collected for 10 months for each year because the last available data are for October 2021. The monthly data for study period (2019- 2021) are also available.

Table 2:
Total Co2 emissions by sectors (2019-2021). [35]

Year	Total CO2 Emissions Residential (MMT)	Total CO2 Emissions Commercial (MMT)	Total CO2 Emissions Industrial (MMT)
2019	775	642	1187
2020	722	598	1087
2021	762	642	1145

Note: The data collected for 10 months for each year because the last available data are for October 2021. The monthly data for study period (2019- 2021) are also available.

Data analysis shows that energy consumption fell in every three sectors in 2020, ranging between 1.7% to 7.35%, with the minimum in residential and the maximum in the commercial sector. It is a straightforward consequence of people spending much more time in their homes and working remotely. By 2021, energy consumption raised in 3 sectors. While more people get vaccinated during 2021, the energy consumption in commercial and industrial sectors changes by 11% and 9%, respectively. The change in the residential sector was 4%. This means that while different sectors are trying to return to pre-pandemic conditions, energy consumption in the residential sector has undergone little change, reflecting changes in people's lifestyles, such as remote work or e-learning.

For the CO2 emissions in 2020, there is a drop equal to 7%, 7%, and 8.5% in residential, commercial, and industrial sectors. In 2021, the CO2 emissions in the commercial sector raised close to 2019 by 7%, While the growth of production in the residential and industrial sectors was 5.5%.

As mentioned in the research methodology, this study aims to clarify the relationship between energy consumption, CO2 emissions, and daily COVID-19 cases. This study examined the energy consumption and CO2 emissions monthly. For this purpose, a correlational analysis was done using the number of positive COVID-19 cases for 30 months (Jan to Oct 2019-2021) (Table 3) compared with energy consumption and CO2 emissions. The correlation ratios are as below:

Table 3:
Number of COVID-19 positive cases JAN-OCT, 2019-2021

Date	2019 Cases	2020 Cases	2021 Cases
JAN	0	4	6087604
FEB	0	66	2290721
MAR	0	212593	1795524
APR	0	878240	1844341
MAY	0	743386	897609
JUN	0	860950	392071
JUL	0	1940645	1378131
AUG	0	1478419	4245521
SEP	0	1220233	4100713
OCT	0	1935558	2433669

Table 4:
Correlation between COVID-19 cases, energy consumption and CO2 emissions

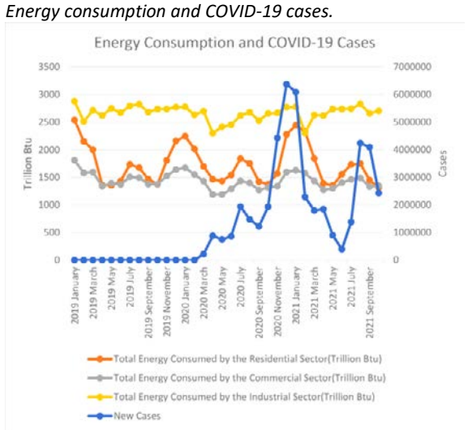
	Number of Cases	Energy Consumption Residential	Energy Consumption Commercial	Energy Consumption Industrial	Energy Consumption Residential	Energy Consumption Commercial	CO2 Emissions Industrial
R^2	0.57	0.60	0.42	0.59	0.58	0.50	

The correlation ratios show a positive relationship between energy consumption and COVID-19 cases during a 30-month study period. This correlation ratio is not the same in different sectors. While the residential and commercial sectors have a correlation ratio of almost 0.6, indicating a moderate positive relationship, the industrial sector has a less R^2 of 0.42 and 0.5 for energy consumption and CO2 emissions. This R-value indicates a correlation between the number of positive cases of COVID-19, but indicates that other factors were also involved.

During 2019- 2021, the energy consumption trend experienced different fluctuation levels. In residential and commercial sectors, fluctuations are associated with climate specifications, but it depends on other factors, such as supplies and demands in the industrial sector. In other words, energy consumption and CO2 emissions were reduced, especially in 2020, affected by the COVID-19 pandemic and the number of cases, but every sector had its scenarios. As can be seen in Fig.1, in

the 2 peaks of COVID-19 cases (Dec 2020- Jan 2021 and Aug- Sep 2021) in the U.S., the energy consumption in the residential sector increased and was significantly in line with the waveform of the number of COVID-19 patients. This trend in CO2 emissions is also similar.

Figure 3:
Energy consumption and COVID-19 cases.



6.CONCLUSION

COVID-19 has been prevalent around the world since early 2020 and has claimed many lives. In the early years of the outbreak, and especially before the vaccine was discovered in late 2020, governments adopted measures to prevent the spread of the disease, such as quarantine, social distancing, distance work, e-learning, and more. Epidemic conditions caused significant lifestyle changes, and even after a gradual decline in the incidence, these effects persisted. These changes in lifestyle, disease prevalence, different variants, and their consequences caused changes in energy consumption in different parts of the world. In the United States, energy consumption in the residential, commercial, and industrial sectors was also affected. Consumption in all three sectors will decrease in 2020 and increase in 2021, and consequently, the amount of CO2 will go through the same trend.

The outbreak of COVID-19 has led to solutions to the disease in various sectors, including buildings and their users. These strategies must be pursued in the direction of sustainability goals so that the world can deal with it in the face of another epidemic and, at the same time, reduce its negative effects because this disease threatened many goals of sustainable development. COVID-19, while having a positive environmental impact, has caused countless problems for countries, including the economic crisis. Using strategies to accelerate a green transition towards low-carbon energy systems will benefit the post-COVID era. In this regard, it seems that the following solutions will be effective as post-pandemic strategies:

- Increasing the use of renewable energy sources
- Using more smart technologies
- Attention to improving health and air quality in buildings and urban design
- Changing the daily lifestyle with lower energy use
- Flexible building design and use

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FireSURG

Fire mitigation System in Urban areas through reuse of Rainwater and Gray water

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ABSTRACT: Based on the problem of the fires in Valparaíso, Chile and in accordance with the recent declaration of a water shortage zone (MOP, 2020) in the Valparaíso region, situations that especially affect the hills during the Valparaíso fires, the need for the implementation of a fire mitigation system through the reuse of gray water, for which a treatment system is proposed through filters, with accumulation of water in underground ponds at the individual dwelling level and at the urban level, with access to firefighters and the community when the contingency requires it. The system will support domestic irrigation by promoting the cultivation and development of vegetation in neighborhoods where it is scarce. It is a very affordable system, easy to install and suitable for the steep slopes of the Valparaíso hills.
As a preliminary study, a test prototype of the gray water recycling system is built in a family home in Olmué and then a prototype is built for the post-fire reconstruction house in Valparaíso 2019, Casa FENIX 2.0, built for the Solar Decathlon competition in United States 2020 with MINVU subsidy and donations.

1. INTRODUCTION

Over the years, a large number of forest and urban fires have affected the hills of the City of Valparaíso (central Chile), which has resulted in the destruction of a high percentage of homes to date. According to the historical statistics of the Chilean National Forestry Corporation (CONAF, 2020), between 2010 and 2020, a total of 8,957 fires has been registered in the region, exceeding 90,000 burned hectares and thousands of home's lost. The recurring problem is the difficult accessibility for firefighters and water supply. Recently, in September 2020 Valparaíso was declared a water scarcity zone (mop, 2020) and there is still no an strategy to deal with this problem yet. For instance, in Israel during 2005, a reuse of 350 million m3 was recorded, of which 216 million cubic meters of water were delivered to the agricultural sector. In California, in 2009, approximately 82.5 million m^3 were reused per year, allocating 37% of this reused water to agriculture and 17% to irrigation of green areas (Innovación Chilena, 2018). In Chile, just in 2018 the first treatment plant for the agricultural area was inaugurated in Coquimbo. That same year, National Decree 21.075 on the reuse of gray water was enacted, but the possible reuse in fire mitigation is not said (MOP, 2018).

The problem of urban fires and the water shortage in Valparaíso brought the urgent need to implement a prefabricated and industrilized housing proposal that includes a primary fire mitigation system based on the reuse of the gray water and rainwater, including a water treatment process with filters and accumulation of it in ponds, which main characteristic is versatility, where the adaptation to the topography and the integration to the architecture are crucial, and at the same time it needs to be an economically feasible solution for vulnerable neighborhoods, considering that these fires affect the most this sector of society.

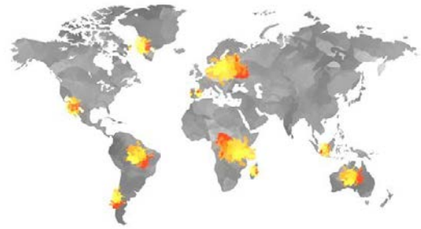
For that the proposed system has been designed and tested for a prototype reconstruction social solar home prefabricated and mechanized with parametric design. The FireSURG system relied on recycled materials, it has been implemented in one experimental home with the idea to be replicated in the devastated neighborhood in a near future. It was built in four parts counting on first, an adequate plumbing system for capturing gray water and rainwater. Second, filters and water treatment with the chemicals allowed in National Decree 21,075. Third, a buried pond for the water storage. And fourth, means of a water supply system in case of fires. All these parts of the system can be adapted to the topography of the terrain, to the great slopes of the Valparaíso lands and contribute fundamentally to the sustainability of the water scarcity, the reduction of waste, the education of water conservation and the development of green areas in neighborhoods.

2. CONTEXTUALIZATION: FIRES WORLDWIDE

The year 2019 has shown one of the most terrible edges of the climate emergency. As shown in figure 1, massive fires have devastated forests and other landscapes with very serious consequences for people, the environment and the climate global.

In 2017 Spain and Portugal suffered severe droughts. Both territories have similar ecosystems, with mild winters and hot, dry summers, as in California or Chile, and marked interface areas (WWF, 2020).

Figure 1:
Fire Lights

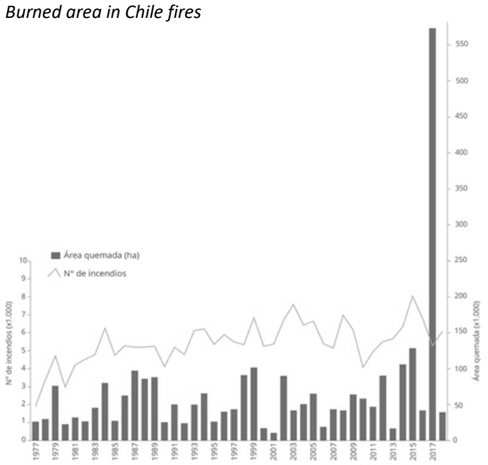


Note: Massive fires from Russia to Brazil, passing through Siberia, Indonesia, Canada, the United States, Israel, Lebanon or Congo (WWF, 2020)

2.1 Fires in Chile

In the last decade there has been a significant increase in the number of forest fires in Chile, especially in the Central-South zone, where the largest number of burned hectares is also concentrated. The largest amount of affected area was reached in the 2016-2017 season, when the mega-fire occurred in the regions of O ' Higgins and Biobío, exceeding the average of the last four decades with more than half a million hectares, reaching an increase of more than 900%.

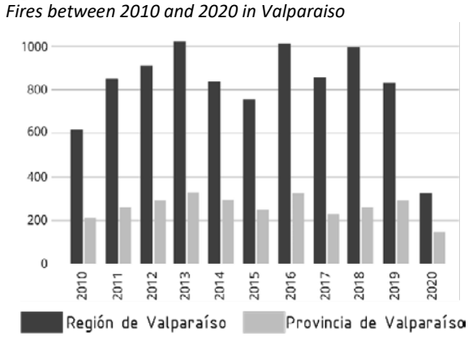
Figure 2:
Burned area in Chile fires



Note: The graph compares the number of fires and the hectares affected in the country since 1997.

In the Valparaíso region, it is possible to mention with respect to figure 3, that the seasons with the highest number of fire outbreaks occurred in 2013 and 2016, exceeding 1000 outbreaks in the region and 320 in the Province of Valparaíso (CONAF, 2020)

Figure 3:
Fires between 2010 and 2020 in Valparaiso



Note: Although the number of outbreaks has remained within a range of 800-1000 fires in the region and 200-300 in the province, the figures are still a worrying state.

2.2. Measures addressed for fires in Valparaíso

A short-term solution of 450 million pesos is the installation of 200-thousand-liter Australian water containers with modular assembly, in different high sectors of Valparaíso, as shown in figure 4.

Figure 4:
Water container in Playa Ancha, Valparaíso

Note: They have a dimension of 12 meters diameter by 2.80 meters high. Its structure is of modular assembly through prefabricated pieces of pre-formed galvanized steel.

In the article, they mention that they do not require maintenance (Min-INT, 2015). The objective is to make up for the lack of water in the hills during a fire. The work also has an eradication program for approximately 170 micro-garbage dumps. A Firefighters Emergency Water Supply Network has been considered as a project, which considers nine water supply points in 18 ponds:

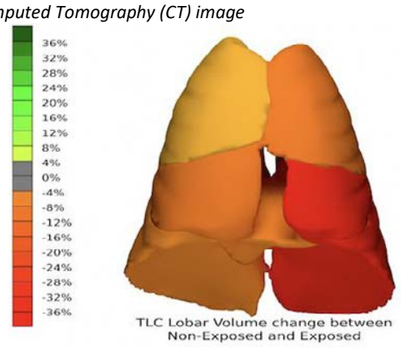
The problem that has been affected at present is its maintenance, since 6 of the 18 tanks installed are operational, which causes a setback in the techniques of protection against fires in Valparaíso.

3. HEALTH DAMAGE FROM FIRES

University of California Davis professor Lisa Miller, associate director of research at the National Primate Research Center, published a study regarding monkeys exposed to wildfire smoke in previous years. Her research indicates that adult monkeys during wildfires of 2008 did not show any long-term effects, they were only affected during the fire due to irritation, but three years later there was no difference in these animals relative to unexposed animals. However, when they evaluated monkeys that had been exposed to smoke at an early age, the differences were significant as shown in Figure 5. Those exposed to smoke also produced less than a protein related to the immune system. Monkeys that are now adults are showing evidence of lung disease much like pulmonary fibrosis. Those born to mothers exposed to smoke show a reduced immune response.

She finally mentions that everyone has an acute response to wildfire smoke, young or old, but the long-term impacts on the health of young people can be severe (Miller, L.2020).

Figure 5:
Computed Tomography (CT) image



Note: The lungs of the three-year-old monkeys exposed to smoke were smaller, stiffer, and had less capacity than monkeys born a year later that were not exposed to smoke.

4. REUSE OF WATER IN THE WORLD

There is a history of water reuse in Ancient Greece (3000 BC); in 1550, in Germany, and during the 18th century in England. Starting in the 20th century, the first antecedents are in the United States (1920) and India (1930) (Fundación Chile, 2016). In recent years, and given the need for a more efficient administration of water resources, the installation of wastewater treatment plants (WWTP) has increased worldwide, with more than 3,000 facilities of regeneration with different degrees of treatment for application in agricultural irrigation, urban, recreational and industrial use.

The distribution of these facilities varies according to the technology that the different countries have, depending on the resources that they can invest in their construction and start-up. In Asia and the United States, there is the highest concentration of these SEWPs; They are followed by Australia and the European Union, lagging behind in the Middle East, Latin America and Africa (Fundación Chile, 2016). This distribution by zone is an indicator of the potential for wastewater reuse in the world. It is estimated that currently only 4% of all the water consumed in the world is reused (Cosín, 2017).

January 2018: Wastewater treatment in Chile, Ovalle for productive use.

2015: CIMAD, Center for Research in Environment and Development; Colombia.

2012: 8% of wastewater treated, Australia.

In Israel and Peru, vertical wetlands are being applied to irrigate gardens and fruit trees in decentralized treatment systems. Israel, during 2005 registered a reuse of 350 million m3, of which 216 million cubic meters of water were delivered to the agricultural sector (Fundación Chile, 2016).

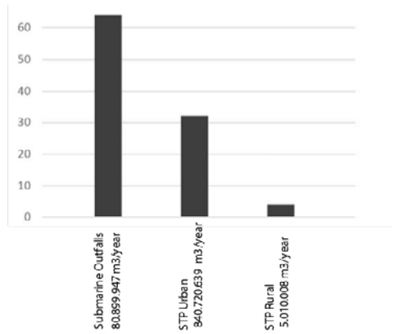
In Mexico City, approx. 2 m^3/s of water for reuse in agriculture, irrigation of green areas and recharge of recreational lakes (Fundación Chile, 2016).

In Jordan, the irrigation of forage crops predominates, with application for the irrigation of palm trees and olives (Fundación Chile, 2016).

4.1. Water reuse in Chile

At year 2016, Chile has reached levels of coverage in the treatment of wastewater close to 99% in urban sectors, with 283 sewage treatment plants (STP) authorized and monitored by the Superintendency of Sanitary Services throughout the national territory. However, the figure for the deficit of sanitary sewerage in rural sectors reaches approximately 53% (Fundación Chile, 2016).

Figure 6:
Flow of wastewater discharged per year



Note: The figure shows the breakdown of the wastewater flow discharged per year at the ocean, the urban STP and rural STP discharged into rivers or for irrigation (Fundación Chile, 2016).

Regarding figure 6, is important to observe that the discharges from submarine outfalls exceed the sum between urban and rural areas, with 64% versus 36%. There are 9 submarine emissaries in operation that discharge directly into the sea. The approximate volume of water discharged by these in 2014 exceeded 80 million m^3 (Fundación Chile, 2016). Totally alarming figures that must have a definitive solution to avoid water pollution.

5. WATER PURIFICATION LEVELS

Regarding the levels of purification depending on the size of the removed particle, the following are found (Synertech, s.f.).

Pretreatment: In it the entrained particles are eliminated. They are physical or mechanical operations. The objective is to extract or separate from the water as much as possible of the materials transported through the collectors and that can cause later problems due to clogging of pipes, wear of equipment, formation of scabs, etc.

Primary Treatment: Get the elimination of suspended particles. It is made up of fine particle removal systems, physical or specific procedures. The degree of treatment that is achieved will depend on the process used and the characteristics of the wastewater.

Secondary Treatment: Get the elimination of colloidal and sub-colloidal particles. It is made up of chemical and biological operations.

Tertiary treatment: Get the elimination of dissolved particles. Made up of fine particle removal processes.

5.1. Reed bed horizontal flow

It is one in which the effluent is applied at one end and is discharged at the other. The bed remains full of water at all times. In the underground flow type, the water level is carefully controlled so that it is always 25 to 50 mm below the surface of the gravel medium.

Figure 7:
Horizontal flow reed beds

Note: Horizontal flow reed beds are generally low in oxygen and will denitrify the effluent by converting nitrogen compounds to free nitrogen gas that escapes to the atmosphere.

They always eventually crash and fail. The life expectancy of these beds is between 5 and 15 years, depending on the strength and quality of the effluent applied to them. Those that receive strong effluents with a high level of suspended solids will be blocked more quickly. Media in blocked beds of this type must be completely replaced.

6. GREY WATER

6.1. Composition

According to the research thesis of Miguel Ángel Ruiz Castillo (UTFSM, 2019) the composition of gray waters is variable (table 1) and the concentration of contaminants that drinking water presents after being used will depend on the because they are dependent on people's customs.

Table 1:
Gray water classification

	Classification		
	Chemicals	Physical	Microbiological
Parameters	Organic material Hydrogen pH DBO Nitrogen Match Sodium	Total solids Total suspended solids Temperature Turbidity Smell	Bacteria Protozoa

Note: The main factors present in this type of water are classified into three types: chemical, physical and microbiological.

The substances present in each artifact depend on the customs of the inhabitants:

Dishwasher: Organic matter, nutrients, solids, nutrients, detergents, high levels of oils and fats.

Washing machine: High concentrations of detergents, chemical agents, fluff, solids.

Shower: Soap, Shampoo, bacteria and fats.

Sink: Soap, toothpaste, solid waste, among other hygiene products.

7. DESIGN PROPOSAL

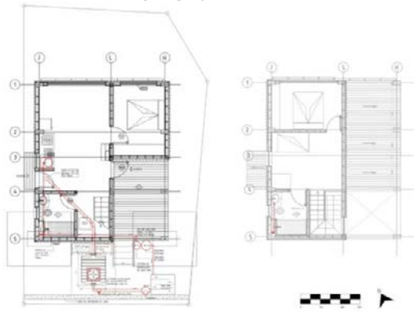
The intervention is projected in two ways: Single family Housing in Casa FENIX 2.0 and Urban Level in Reconstruction. The first responds to the need to capture gray water and rainwater for the mitigation of fires at the level of a single-family home, considering a total of 9.54m^3 per month of gray water, plus 15.6 m^3 of annual rainwater.

The second corresponds to an urban intervention future proposal, considering theleftover greywater collection of houses under reconstruction. It is proposed an accumulation of water treated through reed beds, generating humid areas to firefighters and the community in the event of a fire.

7.1 At the home level

In a single-family home, a gray water and rainwater treatment and accumulation system is built to protect the house for fires.

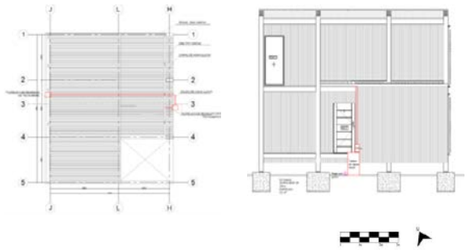
Figure 8:
Intervention in housing in grey water.



Note: Gray water is stored in a 2000 liter tank. The excess water goes directly to the urban sewage network.

The system is made up of a network of collection pipes. Then it goes to the pretreatment solids separation system, primary treatment of grease filters, secondary treatment of natural filters and tertiary treatment with chlorination.

Figure 9:
Intervention in housing in rainwater.



Note: Rainwater is designed only for a 200-liter drum due to limited space in the house, to be used for irrigation. But it is not built yet because no trees or plants have been planted in the courtyard yet.

Figure 10:
Rendering of intervention in housing

Note: The objective is the contribution to the environment and the safety of people in a green and quiet space.

Figure 11:
Actual intervention in housing

Note: The final state of the construction of the prototype and of the house without being inhabited yet.

7.2. Accumulation at the urban level

Water separation is carried out at the urban level, using modular urban ponds of 1 to 10 m^3, depending on the capacity supported by the slope and the number of homes served.

Figure 12:
Urban system design

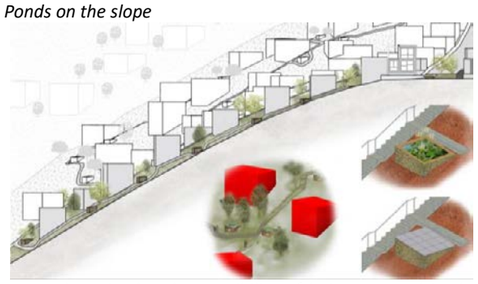
Note: The figure show the accumulated gray water networks, being connected to the urban drainage by means of a plumbing system, designed for homes affected by the forest fire of 2019 and that are not yet built.

Urban gray water networks correspond to 200 mm pipes, which collect water from four or more single-family homes. The local water networks correspond to 110 mm pipes, which transport the accumulated water of up to 4 houses. The rest of the water is transported to the other ponds under the hill ravine and finally connected to the existing urban drainage, taking advantage of gravity in favor.

The urban ponds have purification plants, which are maintained by the residents themselves and have the possibility of being covered in the future, if the residents prefer, to prevent them from filling up with garbage or producing bad odors, or for safety to avoid contact with children.

Access to urban ponds is sought through concrete platforms, sufficient to allow movement of people in the event of an emergency as shown the figure 13.

Figure 13:
Ponds on the slope



Note: There is also the possibility of being covered in the future, if the neighbors prefer it, to avoid that they are filled with garbage or bad odors, or for safety to avoid contact with children.

8. CONCLUSION

Due to variables within the problem presented, FireSURG emerges as a viable response and a sustainable architectural contribution to the current situation of fires. Complementary to the above, FireSURG stands as a means to contribute to the problem of water scarcity from the reuse of water and its use not only in the mitigation of fires, but as a safe and efficient way to satisfy the basic needs of irrigation in the houses.

The 2017 edition of the United Nations World Water Development Report, entitled 'Wastewater: The Wasted Resource', demonstrates that improved wastewater management generates essential social, environmental and economic benefits for development sustainable. According to UN-Water, in low-income nations only 8% of domestic and industrial wastewater is treated, a very small percentage compared to developed countries, where 70% of these waters are treated. Therefore, the need to create water reuse systems is of crucial importance, where an efficient use of the water resource is made, which is increasingly scarce.

Regarding the problems and demands for current solutions, this project is related to 5 of the 17 Sustainable Development Goals proposed by the UN:

Targets 3.9 and 3.d. Physical and mental health. Having a timely fire mitigation system can contribute to reducing people's exposure to smoke that directly affects the health of the population and also mental health regarding the sense of security of having access to water resources in fire case.

Target 4.7. Quality Education. FireSURG promotes learning opportunities regarding sustainable development and the reuse of water and its maintenance.

Target 10.2. Reduced Inequalities. FireSURG breaks the gap of social vulnerability, allowing a family that lives in the hills of Valparaíso, to have water for their irrigation and fires.

Target 11.1, 11.3, 11.5. Sustainable cities and communities. FireSURG proposes energy-efficient and transformable housing over time with efficient use of water resources.

Target 13.1. Climate Action. FireSURG adapts to the design of the home and incorporates preventive measures against forest fires, promoting through recycling and a more efficient use of water.

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Modelling ceiling fan flow patterns

Creating a simple tool for predicting comfort with breeze

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ABSTRACT: Ceiling fans offer the option of creating an energy efficient cooling effect for people by elevating the air velocity which increases convective and evaporative cooling from the person's skin. However, the many factors such as fan blade design, fan position, fan speed, room volume, furniture, and many more make it difficult for designers to predict the air flows and the resulting comfort. Even though benefits of elevated air speed are acknowledged, this creates as significant barrier to design with ceiling fans.
This paper presents a novel analytical model with the purpose of approximating air speeds within a space induced by various fan configurations. It is empirically derived from air speed measurements within spaces with varying fan types, fan diameters, fan amounts, speed settings, heights above floor, room volumes, distances to walls and room symmetry. The model is based on a simplified air flow pattern divided into five defined zones and predicts the air speeds within a spatial grid at four fixed heights. The results compare well with measurements and typical design values such as average air speed for a standing or seated person.
KEYWORDS: Elevated Air Speed, Thermal Comfort, Fan Design Tool

1. INTRODUCTION

In tropical and subtropical climates elevated air speed has long been used in practice as a mean to offset higher temperatures and to create thermal comfort with low energy consumption and lower reliance on mechanical systems [1]. The cooling effect provided at a low energy consumption by ceiling fans make them a cost-effective alternative to compressor based air conditioning. The cooling effect of fans depend on the local air temperature and humidity but in particular on the air movement around the person. A successful implementation of fans within a project relies on accurate predictions of these parameters and will allow to offset up to three degrees in air temperature in a space [2]. Within a larger space, the individual control of fans will allow occupants to adjust local conditions to their comfort preference.

Possibly the largest technical barrier to design with elevated air speed is the absence of simple design tools to better predict air movement by fans in rooms [3].

This paper presents a novel analytical model with the purpose of approximating air speeds within a space induced by various fan configurations. The model has been developed with the intention of providing a simplified alternative to CFD software in the early design phase, for which only limited suitable software is available for optimising fan configurations. The Centre for the Build Environment, Berkeley offers a CBE Fan Tool that allows designers to quickly select and layout ceiling fans in a given room and other constraints [4]. The tool is based on air flow patterns for single fan cells.

The Ceiling Fan Configuration Model (CFCM) in revers is intended to provide flow patterns of single and multi fan configurations for a variety of room and fan configurations and operation. CFD software is capable of simulating complex flows with a high precision, but the simulation process is too time consuming for a typical design phase and increases rapidly with the number of fans. Instead, a model that priorities simulation time above highest accuracy is more appropriate for informing which fan configuration is most efficient and creates best comfort for a given space.

2. METHOD

The development was initiated with the design process of the comfort and energy concept for the School of Design, SDE4 in Singapore [5] where the arrangement and performance of multiple ceiling fans needed to be validated. Since then, the CFC model is developed through a process of combining existing literature with measurements [6]:

1) The CFC Model definitions are based on findings of existing literature.
2) Flow patterns of 1, 2 and 4 operational fans have been measured and are used to inform the general flow pattern.
3) Additional air speed measurements within rooms of different sizes and fan locations with focus on the 'Constant Air' zone have been conducted.
4) The achieved information is dictating zone behaviours in a Rhino/Grasshopper script.
5) The model aims to predict multi fan flow patterns within any room geometry.

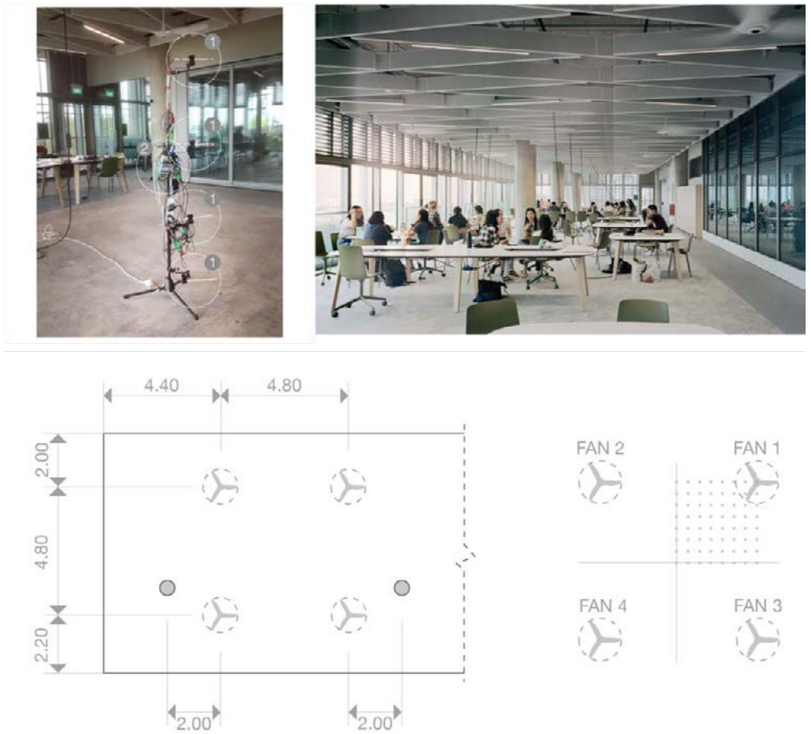

Figure 1: *Overview on experimental setup at School of Design, SDE4, Singapore [6]*

3. LITERATURE STUDY

Existing research has been utilised as corner stone for this paper. Gao et. al. [7] examined the air flow from a single ceiling fan at various speed settings within a room and divided the flow pattern into general zones. They discovered that the shape of the plume and flow along the floor appeared symmetric around the fan centre, and that it did not change significantly at different speed settings. Liu et. al. [8] investigated the interaction of two fans and measured skewness behaviour off fan jets and an occasional upward flow at various locations in between the two fans. Raftery et. al. [3] studied the effect of various fan and room parameters on the air flow of a centred ceiling fan within a squared room and derived fundamental behavioural patterns. The study developed a definition for comparing fans of various types and operation by introducing a so called 'fan air speed' (SF), defined as the airflow divided by the area swept by the blades. It found that varying SF has a linearly proportional effect on air speeds within a space, and that varying the fan diameter increases the width of the fan plume and air speeds outside of the fan plume proportionally to the diameter.

4. MEASUREMENTS

4.1. Set up

Numerous air speed measurements have laid the path to develop the model. Air speeds have been measured at 0.1, 0.6, 1.1 and 1.7 m above the floor corresponding to the relevant heights for a sitting and standing person, following the procedure described in ASHRAE 55 [2].

For the measurements the tripod seen in Figure 1 was configured to accommodate four Schmidt Technology SS20.250 air speed measurement devices with an accuracy of 5% within a measurement range of 360° radial and 45° axial.

For each measuring point air speeds were measured for 240 seconds with a sample rate of 5 seconds. For post-processing the data the first minute of measurements were removed in order to wait for the surroundings to settle down after moving the rod. An average was then calculated from the remaining values and used to represent the air speed for the specific point.

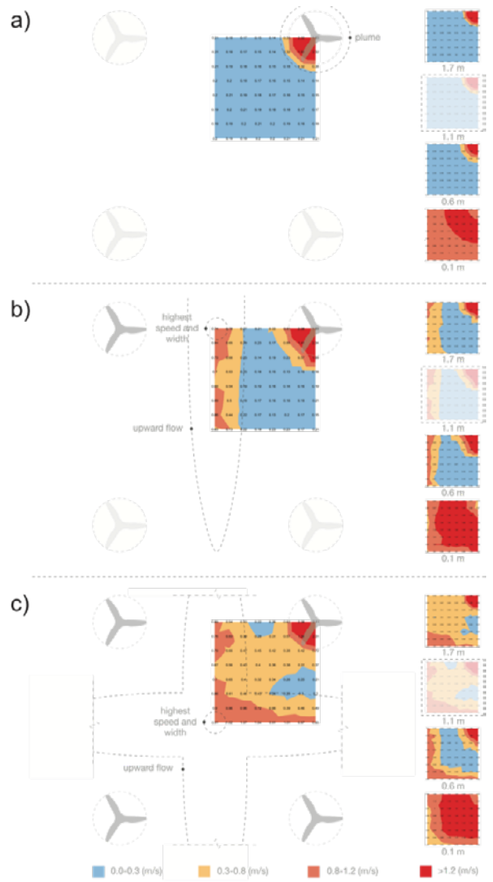

Figure 2: *Measured air speeds at four heights (1.7, 1.1, 0.6 and 0.1m) in plan view for a) single ceiling fan, b) two ceiling fans and c) four ceiling fans [6]*

4.2. Results I

The first set of measurements were conducted at SDE4, Singapore for 1.32 m diameter fans installed 2.6 m above the floor in an open studio space at three different speed settings. They identified the unobstructed shape of the fan plume as well as where the highest air speeds occurred at each of the four heights (see Figure 2 and Figure 3). They confirmed that the speed setting did not influence the shape of the plume except at 0.1 m above the floor, where the diameter increases with speed setting.

The measurements for two and four fans from the previous setup running on same speed setting revealed an explicit upward flow along a straight line in the middle of the two fans and along a cross in the middle of the four fans. Furthermore, the effect of fan numbers on the width of this flow together with the location of maximum air speeds was seen.

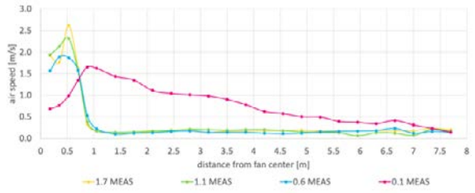

Figure 3: *Air speeds of unobstructed fan plume, single fan, medium speed settings [6]*

4.3. Results II

The second set of measurements were conducted in Germany with 1 or 2 fans of 1.32 m diameter installed 3.0 m above the floor within a semi controlled environment at two different speed settings. The fan was located asymmetric in different room volumes (86, 149 and 247 m³) and measurements were conducted perpendicular to walls with varying distances to the fan, as seen in Figure 4.

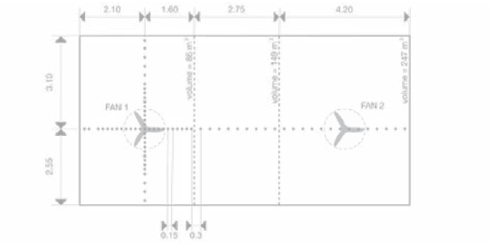

Figure 4: *Space arrangements with symmetric and asymmetric single and multiple fan locations*

The measurements confirm well the findings by Raftery et. al, that the air speeds outside of the fan plume are relative constant, but not always still, and that they scale linearly with the fan air speed. It was also seen that room volume affects the air speeds in this zone (see Figure 5), while no clear influence of distance from fan centre to wall was shown. There were indications of an impact from room asymmetry and

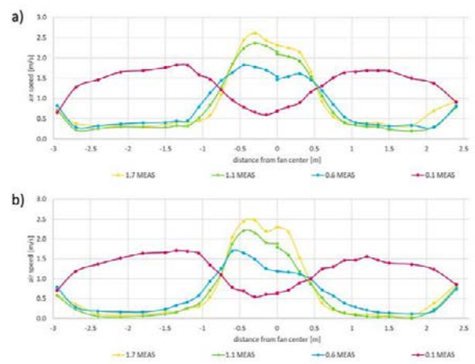

Figure 5: *Measured air velocities for short distance (-3.1 to +2.55m) a) small volume (86 m³), b) large volume (247*

fan location on the air speeds, but more data is needed for a conclusion.

Although we anticipated a distortion of the fan plume skewing towards the longer distances the data shows that this phenomenon only shifts the plume around 30 cm, thus not affecting the overall flow pattern significantly.

In general, air speeds between 0.1 and 0.4 m/s were found in this zone throughout all the measurements we carried out, which were significantly lower than what was measured by Raftery et. al.

5. MODELING

The approach for the CFC model is to define the flow pattern of a single fan, modify this flow according to relevant variables and finally to specify the interaction between this flow and other flows or walls. The following definitions have all been derived either from the literature study or from our own measurements, see Figure 6.

5.1. Fan Jet and Transition Zones

From the first set of measurements and the study by Gao et. al. [7], it was seen that the unobstructed plume of a single fan can be represented as circles in all four plans with identical air speed patterns radial to the fan center. The behaviour of the circular flow is modelled as two zones, each defined by the air speeds within and the diameter. The Fan Jet zone is defined to span from the fan centre to the maximum speed at that height, while the Transition zone ranges from the perimeter of the Fan Jet zone until the air speed becomes constant. This allows the air speed for each zone to be defined in plan by a continuous function.

Air speed functions for the Fan Jet and Transition zones are based on the unobstructed air speeds measured within these zones.

Confirming the findings by Raftery et. al. it was concluded that the air speeds within the plume at 0.6, 1.1 and 1.7 m. only depends on SF while the radius of the plume at these heights depends on fan diameter. The air speed function within the Fan Jet zone is an approximated linear function, and so is the diameter function. The air speed within the Transition zone is approximated with a polynomial function while the diameter is found with a linear function (see Figure 6).

At 0.1 m the Fan Jet zone diameter depends on fan diameter while the air speed depends both on speed setting and fan diameter. The diameter is found through linear function and air speed through polynomial function. The Transition zone air speed and diameter depends both on speed setting and fan diameter, so the air speed function is polynomial while the diameter is a linear regression of Dia and SF.

5.2. Middle Zone

Based on the two sets of measurements and the study by Liu et. al. [8] the appearance of an upward flow in between multiple running fans was determined. This zone will be referred to as the Middle zone and it is assumed to appear when opposing flows along the floor with equal air speeds collide, see Figure 7.

As for the Fan Jet and Transition zones, this zone is modelled based on a width and an air speed function. Where these variables depend on SF and Dia for the two other zones, for the Middle zone they solely depend on the air speeds for the opposing flows along the collision line.

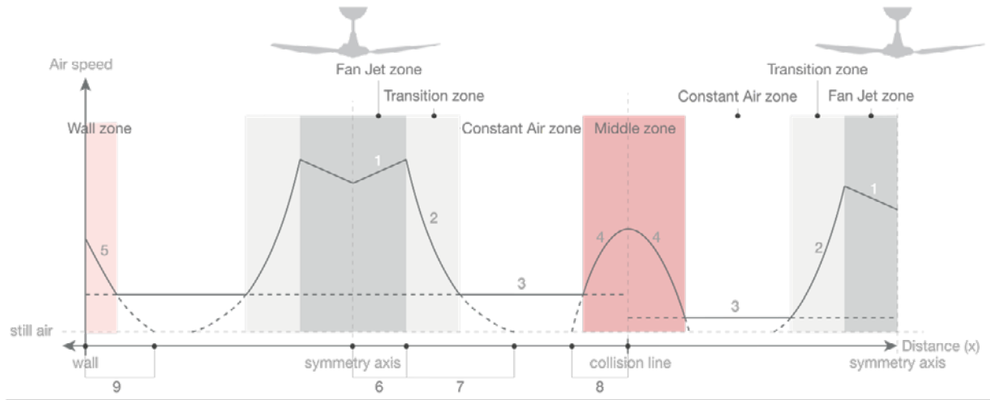

Figure 6: *Definitions of zones and mathematical functions to describe behavior of zones in CFCM model, example for 1.1 m.*

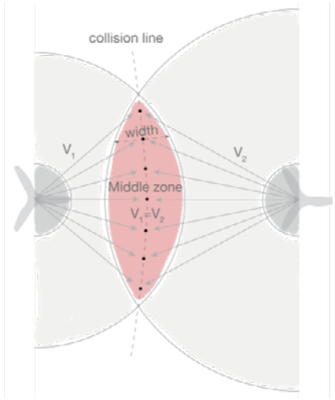

Figure 7: *Modeling of the Middle zone by identifying the intersections of Transitions zones at 0.1 m.*

The width for this zone is defined in the direction perpendicular to the collision line and the air speed function prescribes how air speeds change in this direction. The width of the Middle zone is derived from measurements with 2 fans and described with a linear function at each of the four heights while the air speeds are based on polynomial functions (see Figure 6).

5.3. Wall Zone

Based on the second set of measurements and the study by Gao et. al. [7], the final zone modelled is the Wall zone, which defines the upward flow resulting from collision between a flow along the floor and a wall.

As for the Middle zone the air speeds within this zone are based on the air speed of the flow at 0.1 m. along the collision line with the walls. The width of this zone is defined to be perpendicular to the walls and depends on the distance between the fan and the respective wall. The air speed function is polynomial while the width function is linear (see Figure 6).

5.4. Constant Air Zone

Based on the two sets of measurements and the study by Raftery et. al. [3] we found that what has been defined by others as the Still Air zone was more of a Constant Air zone with air speeds higher than 1m/s in some cases. The zone extends from the Transition zone and until the Wall or Middle zone, which makes it the largest zone by area and the most important for the thermal comfort within a space. The flow is not coming directly from the fan but rather from the ceiling as a result of air recircling the space after having been in the Wall zone. This is why air speeds in this zone are lower than in any other zone.

The behaviour of this zone depends on the three parameters SF, Dia and cell volume (Vol) and the air speed is relatively constant at each height. We use Vol (volume around a fan defined by walls and middle zone) and not room volume to describe the effect of multiple fans in a room. Once multiple fans are operated, the room volume is subdivided by the flow pattern created by the fans and their respective location, Dia and SF settings. These parameters determine the positions of the Middel zones and the air speeds in the respective Constant air zones. Air speeds will increase with the smaller Vol created by walls or Middle zones.

Both the SF and Dia have a linearly proportional effect on air speeds in this zone, and the influence of volume on the average air speed was found to be exponential (see Figure 6).

6. COMPARISON OF MEASUREMENTS AND MODELLING

Figure 8 shows an example of measured data compared to the modelled data (dashed lines) for the four considered heights for the mid volume and the longer distance (refer to Figure 4). From the data the average air speeds for a standing or seated person have been calculated and are compared to the same calculated by the CFCM modelling.

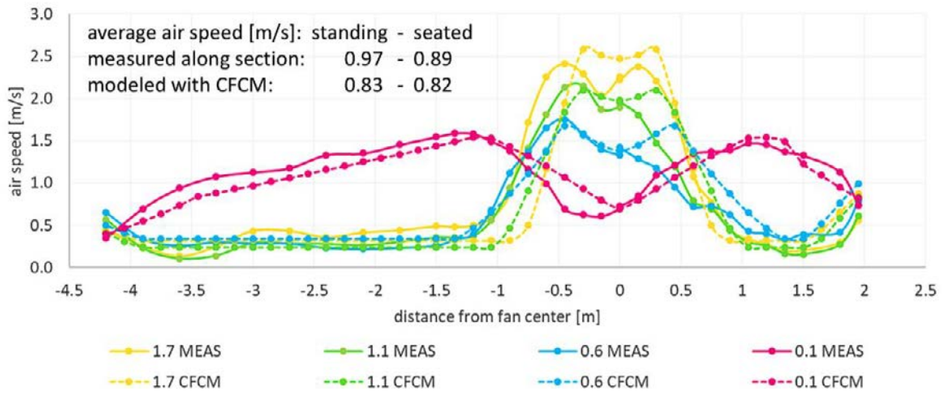

Figure 8: *Comparison of measured air speeds (solid lines, MEAS) to air speeds modelled with CFCM (dashed lines) as well as the average air speed along the section, example for mid room volume of 149 m³ and long section.*

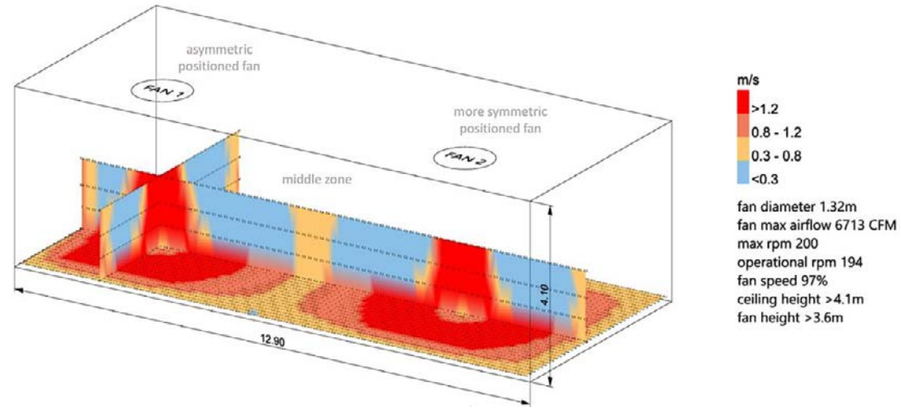

Figure 9: *Example of 3D results in a volume of two times 149 m³ with two fans. Fan 1 asymmetrically shifted to the left wall (similar to measured example in Figure 8.) Fan 2 more symmetric positioned in right halve of room volume. The colours in the section, cutting through the center of the Fan jet zones, and the plan at 0.1 m indicate the air speeds.*

For this example, the measured vs. modelled averages off air speeds in [m/s] are: standing 0.97/0.83 and seated 0.89/0.82.

In general, we found, that the modelled averages are estimating the measured values quite well, with maximum differences in a range of+/- 15 %.

7. FINDINGS

The development of this CFCM model is based on findings of full-scale laboratory measurements as well as measurements by the author verifying the published concepts respectively adding aspects and data.

With the developed CFC Model, air speeds in a space can be estimated on the relevant four heights with an acceptable accuracy and average air speeds for a standing and seated person can be evaluated with a good agreement to measured data.

The results can be simulated within a fraction of the time that CFD simulations require. This allows to test different fan configurations (fan type, Dia, fan speed, position in space) for best performance.

We found the biggest discrepancy between our own measurements and published data for the constant air zone. This has been discussed with the authors of the published data and additional equipment testing and measurements have been conducted from our side, verifying this discrepancy.

From the general results we concluded that the modelled air velocities and in particular the results for the averages are good to verify the performance of a chosen fan configuration. The existing differences will not change decisions in the design process to choose and locate ceiling fans.

Anyhow future measurements with other ceilings fans and spatial arrangements will be conducted to verify and adjust the modeling for more ceiling fan configuration conditions.

ACKNOWLEDGEMENTS

The authors want to thank Nicolas Loubser and Konstantin Bausch for conducting the many measurements as well as Fabian Jaugstetter for the continued improvement of the Grasshopper deck.

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Comparison of the embodied energy of three architectural forms in rural areas of southwest China

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ABSTRACT: This With the launch of China's Poverty Reduction policy, rural construction has become an important issue in China's social development. The environmental and energy challenges associated with turning society in a more sustainable direction are tremendous and urgent. Building and infrastructure construction, in step with developments in industry and transportation, has become an important energy consumer in China. Now more and more rural buildings have been built in recent years which are according to the urban method and construction styles. To compare with the buildings which follow the traditional culture and respect the natural environment, these kinds of buildings may cause a certain waste of resources. This has increased in environmental stress. The research team has worked in rural China for more than 10 years and built rammed-earth buildings which followed the 3L principle "Local materials, local labor, and local technology". But a complete understanding of the resource consumption, embodied energy, and environmental emissions of rural projects in China is difficult due to the lack of comprehensive statistics. How to compare the energy consumption of different types of buildings in the countryside is a very important issue.
KEYWORDS: Embodied energy,Tthree architectural forms, rural areas, Southwest China

1. INTRODUCTION

With the launch of China's Poverty Reduction policy, rural construction has become an important issue in China's social development. The environmental and energy challenges associated with turning society in a more sustainable direction are tremendous and urgent. Building and infrastructure construction, in step with developments in industry and transportation, has become an important energy consumer in China. Now more and more rural buildings have been built in recent years which are according to the urban method and construction styles. To compare with the buildings which follow the traditional culture and respect the natural environment, these kinds of buildings may cause a certain waste of resources. This has increased in environmental stress. The research team has worked in rural China for more than 10 years and built rammed-earth buildings which followed the 3L principle "Local materials, local labor, and local technology". As the project officer and on-site architect of the team, I participate in the design, coordination and construction of these prototype projects. I was mainly responsible for refining design, procuring material, organising the construction, controlling construction progress and supervising construction quality. After the construction, I also collected the temperature data and conducted the Post Occupancy Evaluation. Analysis and evaluation using rural assessment systems indicate that building strategies can be made suitable for rural areas in Southwest China. But a complete understanding of the resource consumption, embodied energy, and environmental emissions of rural projects in China is difficult due to the lack of comprehensive statistics. How to compare the energy consumption of different types of buildings in the countryside is a very important issue.

2. Methodology

Life-cycle assessment (LCA) is a methodology for evaluating the environmental load and energy consumption of processes or products (goods and services) during their life cycle from cradle to grave (ISO, 2006). For the building and infrastructure life cycle, it can be defined as a practical management approach to achieve an optimum cost and benefit solution through the process of design, building material extraction, material processing, construction, building operation, and disposal management. The approach takes into account the economic and functional considerations, as well as the environmental and safety requirements.

In the last few years, there has been an increasing interest in the energy use of buildings in a lifetime perspective. The lifetime is mostly divided into production (including all processes from the extraction of raw materials up to the time the material is ready to leave the factory and feedstock), erection, operation, maintenance, and demolition. Numerous studies show that the operation accounts for the main part of the energy use in the general run of dwellings. The energy for production accounts for only about 10–15% in most cases.

To compare with different architectural forms in rural villages, the research team take brick-concrete building(A), rammed-earth building with wall bearing structure(B) and rammed-earth building with concrete frame structure(C) in the same village. All buildings are 150m^2 with 3m floor height and the life time is 50 years.

The life cycle of rural residential buildings (from construction to final demolition) can be broken down into five processes: 1. Building materials manufacture and preparation; 2. Construction; 3. Building operation and maintenance; 4. Building demolition. Each process has corresponding energy consumption and CO_2 emissions which the key points are different. The sum of CO_2 emissions in the four stages is the total emissions during the life cycle of the building P:

P=P1+P2+P3+P4

P1= CO_2 emissions during the manufacture phase

P2= CO_2 emissions during the construction phase

P3=CO_2 emissions during the operation and maintenance phase

P4= CO_2 emissions during the demolition phase

The calculation of the energy for transport to the building site was simplified in the following way. It was assumed that 75% of all materials, except crushed rock, were, on an average, transported 200 km with a large lorry, filled to 70%, and 50 km with a lorry of medium size, filled to 50%. Crushed rock was assumed to be transported 40 km with a lorry of medium size. CO_2 emissions for transport to the recycling plants was put at 2% of the gross savings (savings if transport was not included), based on the results in a previous study. The assumed distances in are presented in Table 1.

Process	Transport distance (km)
Landfill, places for filling masses	20
Incineration plant	45
Reuse/recycling plant (stone, sand, macadam)	20
Reuse/recycling plant (other materials)	30
Mineral wool, material recycling	200
Gypsum card board, material recycling	150

Table 1 Assumed transport distances to landfills and recycling plants

2.1 CO_2 emissions during the manufacture phase

CO_2 emissions during the manufacture and preparation phase of building materials are the sum of the CO_2 emissions to the environment from the energy consumed to produce the various building materials. This is directly related to the type and amount of building materials used. The main building materials currently used in rural housing and traceable to the relevant energy consumption indicators are steel, clay bricks, cement, sand and gravel, wood, glass, stone, aluminium and paint, while other building materials are used in smaller quantities and are not included in the calculations. The relevant data are as follows.

Material	A-CO_2 emissions/t	B	C
steel	6.95	0.42	0.45
earth	0	0.2	0.2
sand	7.87	0.56	0.56
cement	34.69	3.08	3.22
wood	1.9	0.12	0.26
brick	18.59	0	0
glass	0.84	0.05	0.05
aluminum	2.05	0.26	0.26
stone	2.77	0.17	0.17
paint	4.27	0.32	0.32

Table 2 Building materials manufacture phase of CO_2 emissions

2.2 CO_2 emissions during the construction phase

CO_2 emissions during the construction phase include the amount of CO_2 emitted by the means of transport during the transportation of building materials and the amount of CO_2 generated during the construction process, while CO_2 emissions from the transportation process of building materials are related to the quality of the building materials, the means of transport chosen and the specific transport distance, as mentioned in Table 1 above. CO_2 emissions from building construction are mainly determined by the construction energy consumption, which is closely related to the construction process, and the data from Professor Shi's research is referred to in this paper as a reference.

Material	CO_2 emissions/t
steel	0.05
sand	2.62
cement	0.52
wood	0.15
brick	1.3
glass	0.01
aluminum	0
stone	0.55
paint	0.03

Table 3 Building materials during transport phase of CO_2 emissions

construction	CO_2 emissions/t
Site clean	0.13
Material storage	0.05

Site layout	0.72
foundation excavation	0.35
earthwork excavation	0.12

Table 4 Construction process of CO_2 emissions

2.3 CO_2 emissions during the operation and maintenance phase

The energy consumption in the operation and maintenance phase of the building mainly includes cooking energy consumption, household appliances and air conditioning energy consumption. The energy consumption of cooking and home appliances is mainly known from the survey of rural residents around the area, and the cooking energy consumption is mainly liquefied gas, biogas, coal, fuel wood, straw and electricity. The air conditioning load is calculated using dynamic and dynamic methods, taking into account the floor area of the rammed earth dwelling, the thermal parameters of the envelope, the local air conditioning usage habits, the heating period and meteorological data.

According to Prof. Shi's data, the annual coal consumption of a brick building is 3.99t and the monthly electricity consumption is 160 kwh, resulting in a total emission of 814.6t CO_2 over a 50-year lifetime, while the total emission of a rammed-earth building with wall bearing structure and rammed-earth building with concrete frame structure are 123.23 t over 50 years.

2.4 CO_2 emissions during the demolition phase

The demolition of buildings is essentially a manual operation with essentially no energy consumption. If no new houses are built on the same site and some building materials are removed for reuse, some transport energy is consumed, while other building materials are left in situ with essentially no other consumption. Therefore, the energy consumption in this phase is mainly the transport energy used to recycle building materials, which are still transported by tractor. Sand and gravel, clay and wood chips are considered for disposal close to the site, while steel, cement, linoleum, asphalt shingles, glass and timber are to be recycled for the vast majority, except for a small amount of waste. According to Prof. Shi's data, the demolition phase of CO_2 emission of a brick building is 6.9t, while the CO_2 emission of a rammed-earth building with wall bearing structure is 0.19t and rammed-earth building with concrete frame structure is 0.2t.

So the building full life cycle phase CO_2 emission is as follow(CO_2 emissions/t):

phase	A	B	C
manufacture	80.99	5.18	5.49
construction	5.41	1.36	1.45
Operation/ maintenance	814.6	123.23	123.23
demolition	6.9	0.19	0.2
Total	907.9	129.96	130.37

3. RESULT

According to the result of calculating we can find that the rammed-earth building with wall bearing structure has the least embodied energy, rammed-earth building with concrete frame structure has the 2nd embodied energy and brick-concrete building has the most embodied energy in life cycle. The calculations show that the whole-life CO_2 emissions of rammed earth buildings are much lower than those of brick-concrete buildings, indicating that rammed earth buildings are good at low carbon dimension. Whereas rammed-earth building with wall bearing structure and rammed-earth building with concrete frame structure have different types of structures, the difference in whole-life emissions is not significant. Secondly, the energy consumption of appliances and cooking in the operation phase of rammed earth buildings is mainly related to the residents' energy use habits and consumption levels, and the size of this part of energy consumption is basically the same as that of other types of residential buildings, while the proportion of CO_2 emissions from this part of energy consumption is as high as 73.6% of the total life-cycle emissions, indicating that the rammed earth buildings' This means that the CO_2 emissions of rammed earth buildings are much lower than those of ordinary houses in other phases and in the use of air conditioning. Thirdly, in terms of the distribution of CO_2 emissions in each phase of the life cycle of rammed earth buildings, the largest proportion is in the operational phase of the building, indicating that rammed earth buildings have good low carbon performance in terms of choice of building materials, construction methods and demolition methods, and that they are less expensive than ordinary brick houses, proving to be a suitable form of building for local construction.

4. CONCLUSION

Different economic developments and peasant income levels determine differences in construction and development strategies. They are prerequisites and constraints for any rural building development research that must be defined in advance. National architecture-related policies are the basic background for analysing rural building development. They also provide an important guarantee for the research results to be promoted. The concept of ecological sustainable development is the overall guideline that all research related to rural construction development should follow. The three aforementioned points provide an important theoretical basis for rural construction development research and practice.

Sustainable development is a major trend in global development. Sustainable development has three dimensions that are suitable for building environmental assessment: environmental, economic and social dimensions. To achieve the three dimensions of sustainable development, the passive design and active system of a building environment are significant. However, several problems exist in rural construction. Many rammed-earth buildings in Southwest China exhibit poor performance, and local governments want to rebuild villages rapidly. However, villagers need inexpensive, safe, comfortable and culture-sensitive buildings. The analysis found that rammed-earth buildings exhibit considerable advantages that satisfy the needs of rural areas in Southwest China. Improving the anti-seismic performance and durability of rammed-earth buildings has become an important issue. The mitigation of seismic risk is possible only when the villagers themselves adopt improved rammed-earth construction systems as an essential part of their own culture. The adoption of rammed-earth construction systems is important in earthquake-prone and other areas.

For some developed countries, the cost-efficiency aspect remains of paramount importance. Several authors said "earth construction is economically beneficial", nevertheless one cannot take this as a guaranteed truth because the economics of earth construction depends on several aspects such as: construction technique, labor costs, stabilization process, durability, repair needs. These authors state that production and construction costs represent the most important part because earth construction is labor intensive. However, this is not the case in less developed countries in which labor is available for a very low cost. According to our research in rural areas of China, this provides a saving CO_2 way in rural construction, at the same time it also provides a very important way to create job creation, especially for the rural construction under "Local material, local labor and local technology" strategies.

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PLEA STGO 2022
WILL CITIES SURVIVE? SUSTAINABLE BUILDINGS AND TECHNOLOGY

Integration Of An Innovative Dual Day-Night Technique For Air Conditioning Of Public Spaces

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ABSTRACT: The steady increase in population in urban centres and the evolution in our way of life need to mould a new concept of the city and the interaction of its inhabitants with urban spaces. From this idea, the Life WaterCool project. In the project, a set of actions will be developed on open public spaces to alleviate the high temperatures of the summer season in Seville and improve the thermal comfort of the attendees through passive techniques and adaptive bioclimatic solutions that mitigate the impact on the environment. The natural element of thermal dissipation is water, which will reduce the temperature in the spaces by cooling the air. One of the keys to the project is the cooling of water using the natural technique "falling film". The water is propelled from accumulation volumes by fan nozzles on the photovoltaic panels arranged on the roof of a school, forming a descending film on them. This innovative technique allows the water to be cooled through a convective-radiant effect during the night thanks to the low temperature of the sky. The system's duality enables the cooling of water at night and the production of electricity during the day.
KEYWORDS: Falling-film, energy, natural techniques, thermal dissipation.

1. INTRODUCTION

Global warming has caused the rapid growth of hot days and extreme weather, significantly increasing the demand for refrigeration [1]. This situation promotes the need to develop and use natural cooling techniques that reduce energy consumption, support the environment and the ecosystem and provide a satisfactory degree of comfort.

The Life Watercool project aims to develop and test innovative solutions to cope with high temperatures, both outdoors and indoors, and with temporary water runoff and drought situations in an urban environment subject to climate change. The urban water network will act as the basic structure for developing urban green solutions and cooling measures to adapt to the effects of climate change, maximising the sustainability of the city and the well-being of citizens.

This paper corroborates that the falling film technology developed by Servando Álvarez Domínguez et al. [2] - [4] can be adapted on photovoltaic panels through a wide-opening fan nozzle solution. It shows that the performance is identical, with the addition of solving the details of its implementation in the Life Watercool project. This natural cooling technique known as the descending sheet uses water as a heat transfer fluid. The water is propelled from accumulation volumes by fan nozzles on the photovoltaic panels arranged on the roof of a school, forming a descending sheet on them. This innovative technique allows the water to be cooled through a convective-radiant effect during the night thanks to the low temperature of the sky, obtaining promising results of thermal dissipation, whose dissipation power varies depending on the flow width and length of the sheet travel. The system's duality allows the cooling of water at night and the production of electricity during the day to guarantee a zero-energy balance.

2. METHODOLOGY

In this paper, the methodology for designing and evaluating the night-time dissipation system of the falling film on photovoltaic panels is carried out. The design and evaluation methodology is based on a simplified characterisation model of the system, which allows assessing the system's potential under different operating conditions to quickly and easily assess the use of said technique to cool the water of accumulation volumes. In the same measure, a series of nozzles are evaluated to determine the nozzle arrangement in front of the photovoltaic panel that guarantees the optimal development of the sheet, allowing the longest route of this for its correct use the photovoltaic panels placed on the school roof in the Life Watercool project.

3. EXPERIMENTAL FACILITY

3.1 Prototype

To obtain the model's parameters, an experimental prototype of the falling film system is carried out based on the work of Guerrero et al. [4]. The experimental prototype said, shown in figure 1, is described below:

1. Tank: storage tank for the volume of water to be cooled.
2. Water transport: The impulsion pipe conveys the water towards the impulsion nozzle; therefore, a circulation pump is necessary for this section. The return pipe gets the water from the collection gutter back to the storage tank. A pumping system is not required since the water circulates naturally towards the said reservoir.
3. Nozzle in charge of the impulsion: large opening fan nozzle located on the upper end of the drop panel. The large opening of the nozzle allows the water driven from the tank to bathe the panel thoroughly, forming a homogeneous water film.
4. Photovoltaic panel for lowering the water: a flat surface whose material has adequate characteristics for cooling by night radiation (low reflectivity and transmittance in the atmospheric window, which is equivalent to a high emissivity (approximately 0.90)).
5. Water collection gutter: gutter connected to the bottom of the drop panel. Said element is connected to the water return pipe to the tank.

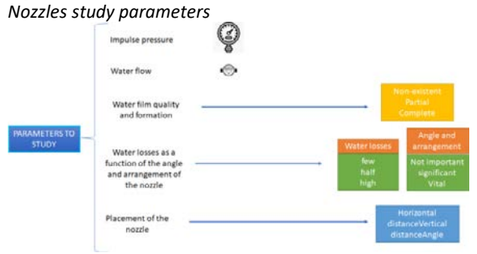
Figure 1:
Experimental prototype of the falling-film system

3.2 Study of nozzles

A set of these is evaluated to determine which nozzle is adapted to the project's needs. The ideal nozzle for applying the Life Watercool project on photovoltaic panels must meet a series of characteristics that guarantee the quality and formation of the complete falling water film. It must have low operating pressure, which translates into energy savings on the part of the pressure equipment and a flow rate that optimises the thermal dissipation of the falling film system. Another point to study, and no less important is the nozzle's arrangement for the photovoltaic panel. It must correspond to the most significant possible travel of the water film developed on the panel and low losses caused by the large opening of the nozzle or direct impact of the jet with the panel.

For this reason, for evaluating each of the nozzles, they are subjected to the following parameters to study:

Figure 2:
Nozzles study parameters



4. MODEL

The simplified model used is based on Guerrero et al. [2] - [4], which details the fundamentals of the model summarised here for calculating the water temperature in a solar collector. This simplified model performs a standard treatment of the convective-evaporative transfer, formulating the power dissipated in a falling film system according to equation 1.

$$P_d = Q_{cv\text{-}evap} + Q_{rad} \quad (1)$$

Where P_d is the total dissipation power of the falling water film system (W/m^2), $Q_{cv\text{-}evap}$ is the nocturnal cooling power referring to the heat loss due to convection and evaporation, and Q_{rad} is the nocturnal cooling power refers to the thermal losses by radiation with the sky.

The cooling power referred to the convective and evaporative thermal losses is formulated according to equation 2.

$$Q_{cv\text{-}evap} = h_{cv\text{-}evap} \cdot (T_w - T_{wb}) \quad (2)$$

Where $h_{cv\text{-}evap}$ is the convective-evaporative transfer coefficient of the water film ($W/(m^2°C)$), T_w is the water temperature (°C) and T_{wb} wet bulb temperature (°C).

The formulation associated with the radiation heat transfer between the water film, the surroundings and the sky is formulated according to equation 3. Since the form factor between the falling film system and the sky is practically unity, they are neglected radiant effects with the surroundings. Moreover, given that the temperature difference between the water and the sky is less than 100K, it

is possible to linearise the formulation developed in equation two so that the cooling power refers to the thermal losses by radiation. The sky is formulated according to equation 4.

$$Q_{rad}\ (W/m^2) = h_{rad}\cdot(T_w - T_{sky}) \quad (3)$$
$$h_{rad} = 4\cdot\sigma\cdot\varepsilon\cdot((T_w + T_{sky})/2)^3 \quad (4)$$

Where h_{rad} is the radiant transfer coefficient of the water film ($W/(m^2°C)$), T_w is the water temperature (°C), and T_{sky} is the temperature of the sky(°C).

5. RESULTS

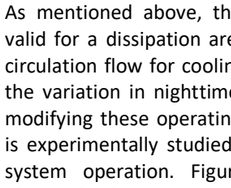
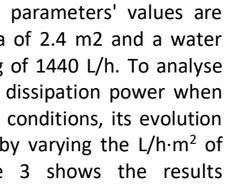
The experimental results obtained in the elaborated works [2] [3] show that the cooling of the water throughout the night presents a change of behaviour characterised by the variation of the thermal conditions of the water and the air. This evolution can be described in two sections:

- Section 1 characterises the thermal dissipation of the system when the thermal conditions of the air and water cause evaporative cooling phenomena to occur, that is when the air is not saturated.

- Section 2 characterises the dissipation of the system given the radiant exchange with the sky once the air saturation has been reached. In this section, the convective transfer of water with saturated air can even counteract heat dissipation from the sky. The slope of the water cooling in said section is more attenuated.

Therefore, given the clear distinction of water cooling trends, the simplified characterisation model parameters are obtained ($h_{cv\text{-}evap}$ and h_{rad}) in both sections. The proposed sectional model is shown below, and the results of its experimental validation (Table 1). The values of the parameters obtained are valid for a dissipation area of 2.4 m^2 and a water circulation flow for cooling it of 1440 l/h.

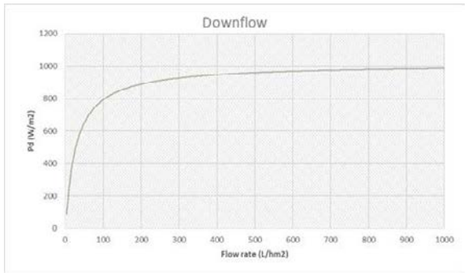
Table 1:
Proposed simplified model (reference operating conditions) [2]

Section 1: Unsaturated air (Radiation+Convection+Evaporation)	Section 2: Saturated air (Radiation+Convection)
$P_d = 33.11\cdot(T_w - T_{wb}) + 5\cdot(T_w - T_{sky})$	$P_d = 3.44\cdot(T_w - T_{wb}) + 5\cdot(T_w - T_{sky})$
	

Given the definition h_{rad} according to equation 4, said radiant transfer coefficient varies with the temperature of the water and sky. According to the experiments' results, the values of h_{rad} obtained vary between 4.8 y 5.3 $W/(m^2°C)$. The value of h_{rad} obtained from the experimental adjustment in both sections is within the expected range. In addition, the proposal made in detailed studies of the combined effect of heat and mass transfer has been revised. The proposed convective-evaporative heat transfer coefficient takes a 33.11 W/(m2°C) value. As discussed in the previous section, this value is understood as the net effect of the sum of convection and evaporation with the air. So if the approximation of the convective coefficient [7] is taken in the range of wind speeds measured between 0 and 2, we have a value that can range between 3-5 $W/(m^2°C)$. In turn, the execution of the correlations [4] returns a value of the evaporative transfer coefficient between 18 and 45 $W/(m^2°C)$. Therefore, the value of 33.11 can be considered within the expected range, and it is even proved that evaporation dominates the heat transfer with the surrounding air.

As mentioned above, the parameters' values are valid for a dissipation area of 2.4 m2 and a water circulation flow for cooling of 1440 L/h. To analyse the variation in nighttime dissipation power when modifying these operating conditions, its evolution is experimentally studied by varying the $L/h\cdot m^2$ of system operation. Figure 3 shows the results obtained where an asymptotic behaviour of the increase in night dissipation power can be observed from approximately 600 L/h·m2

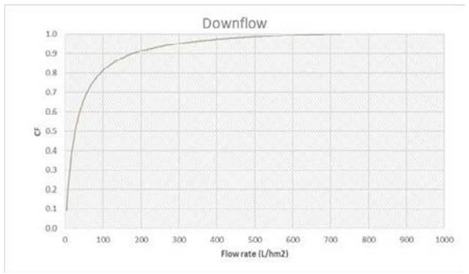
Figure 3:
Variation of dissipation power as a function of operating conditions [2]



Taking as a reference the test conditions of the experimental prototype (600 $L/h\cdot m^2$), the variation of the correction factor as a function of the operating conditions is shown in Figure 4.

Figure 4:

Correction factor for dissipation power as a function of operating conditions [4]



Therefore, the estimated nighttime dissipation power corrected for the variation of the operating conditions of the reference system is formulated according to equation 5:

$$P_{d_c} = P_d\cdot CF \quad (5)$$

Where P_d is the estimated nighttime dissipation power for the reference system operating conditions as shown in table 2 and CF is the corrective factor associated with the variation in operating conditions ($L/(h\cdot m^2)$).

The correction factor associated with the variation in operating conditions is formulated according to equation 6:

$$F = 1 - a\cdot\exp(-b\cdot \text{Flow rate } (L/(h\cdot m^2)^C) \quad (6)$$

The data graphed in figure 4 allows identifying the model presented in Eq. 6. From this identification, an almost perfect fit is obtained (correlation coefficients above 0.99, with a maximum relative error of less than 1%) with the values of the coefficients shown in Table 2.

Table 2:

Coefficients of the correction factor calculation model CF=f (L/h· m2) [4]

Correction factor coefficients CF (ver eq. 8)	Best value	95% Confidence bounds
a	**1.273**	**(1.237, 1.308)**
b	**0.1647**	**(0.1527, 0.1768)**
c	**0.5312**	**(0.5187, 0.5437)**

After multiple experimental checks, it is determined that the following configuration is optimal, minimising water losses due to side-impact and obtaining the best possible use of the panel surface:

Figure 5:
Optimal nozzle arrangement

As seen in the image, the optimal configuration places the nozzle 8 cm away from the panel (axes shown) and at the height of 5 cm up to the head of the nozzle used. Regarding the angle, an inclination of 60º for the horizontal is estimated, guaranteeing that all the water is poured onto the panel and avoiding more significant losses due to the flight of the flow directly to the outside.

From the different tests carried out, the conclusion is drawn that the optimal nozzle to perform the desired function on the photovoltaic panels placed on the roof of a house must present the following technical data and placement on the pane.

Table 3:
Technical data of the selected nozzle

Nozzle	Pressure	Flow	Water film	Loss	Optimal Layout		
CW04	0.7 bar	16 l/min	Full	Low	8 cm horizontal	5 cm height	60° angle

- This placement of the nozzle allows that for lower pressures (up to 0.5 bar), it is guaranteed that the water is deposited on the panel in the same way, only varying the beginning of a fully developed falling water film.

- The lateral leak "only" is important in the panels placed on the sides of the school roof since in consecutive panels, the water hits and jumps to the adjacent panel without generating losses. It is essential to install lateral gutters to collect this water and avoid possible leaks between panels. For safety, implement channels under the photovoltaic to redirect potential losses to the central gutter.
- Regarding the panel used, it is proposed that these do not have a frame to avoid problems in the transition of the water film between consecutive panels, guaranteeing the continuity of the film as if it were a single panel

6. CONCLUSIONS

The studies carried out at a theoretical and practical level allow natural cooling to implement a falling water film using wide-opening fan nozzles for their impulsion on the photovoltaic panels as thermal dissipation technology in the Life Watercool project. As demonstrated experimentally, the falling water film technique has a high cooling potential due to convective, radiant and evaporative transfer. Together with this, the low consumption of necessary water stands out, 7 and 8 times less than in the conventional evaporative cooling system. Therefore, the enormous interest of said technology in the project is demonstrated.

The results obtained on photovoltaic panels are similar to the enormous cooling potential of this nighttime natural dissipation technology, proposed by Guerrero et al. [5], which corroborates the integration of innovative dual technology, day-night, which combines electricity production during the day for the energy supply of the installation and the enormous thermal dissipation capacity of the falling film on the panels during the night.

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PLEA STGO 2022
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WILL CITIES SURVIVE?

Humanscapes Habitat. Integrated design for sustainable living

Design for adaptive comfort for reduced operational energy consumption

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ABSTRACT: Humanscapes is an applied research housing project in adaptive comfort for the tropical wet-dry climatic zone of coastal India. IPCC predicts a global increase in wet bulb temperature, drastically impacting the tropics, especially cities and towns along coastlines. In India, an energy deficit country, the number of hot days in the coastal zone is 100 – 125 per year and increasing. 3-pronged design intervention of (i) Site planning to reduce heat island effect with building orientation and shading (ii) Design and placement of windows in proportion to room size and activity and (iii) Use of low embodied energy building materials with low thermal conductivity and high time lag used to achieve adaptive comfort. Post occupancy, the buildings were monitored for 13 months, a cycle of 2 summers, and one monsoon season. Sensors were placed in relation to the various strategies adopted like building orientation, natural ventilation, shading, and materials. The data analysis of air and surface temperatures, relative humidity, and operational energy consumption demonstrates that the design interventions mentioned above, along with the use of ceiling fans, lead to adaptive comfort throughout the year without the use of air conditioning and reduced operational energy consumption.

KEYWORDS: Tropical coastal climates, adaptive cooling, reduced operational energy consumption, climate-responsive buildings

Figure 1. Panorama of Humanscapes habitat, building 1 and 2.

1. INTRODUCTION

With the built environment currently contributing 38% of worldwide energy-related carbon emissions-architects are on the frontline of global climate action [1]. IPCC predicts a global increase in wet bulb temperature, drastically impacting the tropics, especially cities and towns along coastlines. In India, an energy deficit country, the number of hot days on the east coast is 100 – 125 per year [2] and increasing. The electricity demand already exceeds supply, and the largest and most significant end-use of electricity in buildings is air conditioning. To achieve an energy-efficient building regime, governments, businesses, and individuals must transform the way buildings are designed, built, and operated [3].

The housing shortage in India has increased from 18.78 million to 29 million between 2012 to 2018 [4]. To fill this gap, the State has to tackle five distinct challenges – (i) provision of lands for development of housing, (ii) accesses to financing, (iii) provision of potable water and sewerage, (iv) sustainable and affordable building materials and technology and (v) energy for lighting and cooling/heating. This will be combined with increased thermal comfort aspiration, leading to a surge in demand for air conditioning, adding immense pressure on electricity infrastructure. The deployment of adaptive strategies and design interventions is critical to prevent increased energy use associated with space cooling.

As classified by the national building code of India, the warm-humid climate zone occupies the largest settled land area in the country, and it is the toughest to design climate responsive buildings for [5]. This zone is also called a tropical wet-dry climate by Köppen-Geiger classification [6] due to the distinctive characteristic of clear-cut seasonal summer wet and winter-dry periods with annual rainfall averages between 90 and 180 centimeters, almost all coming during the months of the high-sun season [7]. The guidelines and tools available to architects for climatic design tend to favor hot-humid design responses. For instance, Victor Olgyay's Design with climate [8] suggests light heat capacity walls are best in this climate, for thermal lag may cause night re-radiation of heat and morning condensation. Mainstream climate analysis tools such as energy plus's Climate Consultant 6.0 also suggest lightweight construction as a vernacular strategy for this climate. However, the reality is more nuanced than theory. While designing for adaptive comfort in the tropical wet-dry climatic zone of coastal India, one has to consider three distinct climatic conditions of hot-dry summers with design temperatures of 37°C, warm-humid monsoons, and cool- humid winters. The design principles for these seasons are different, often conflicting with each other and impacting economic and spatial aspects of design.

This paper presents Humanscapes Habitat, an applied research and demonstration project for adaptive comfort and reduced energy consumption in the Tropical wet-dry climatic zone of coastal India.

2. HUMANSCAPES HABITAT – SUSTAINABLE ARCHITECTURAL DESIGN

Humanscapes Habitat was undertaken as an applied research and demonstration project for "Sustainable and Integrated Urban Living" for benchmarking in habitat as a course correction for a sustainable and harmonious mode of development, an imperative need in a present global energy crisis climate change. Located in the international township of Auroville, India, this three-storey mixed-use development of residences, community, and workspaces cater to 44 residents with a built-up area of *1963 sqm.* Using passive solar principles in site planning & architectural design combined with photovoltaic on-site energy generation, on-site passive rainwater harvesting using natural soil – vegetation systems, biological sewage recycling plant, and appropriate materials and technology, the project addresses three of the five housing challenges faced by State.

This paper's scope will focus on the sustainable architectural design interventions in Humanscapes that lead to adaptive comfort and lowered operational energy consumption. The three design principles and the following interventions are as given below:

1. Minimizing heat gain: The site planning minimizes paved areas and creates a cooler microclimate through landscaping. The buildings are oriented with long facades in the north-south direction and mutually shaded with vertical upward draft ventilating spaces in between. The shape of the building and layout of spaces is done for the least solar gain by minimizing surface exposures to the sun during the hottest part of the day using reflective surface material on the roof and wall shading overhangs.
2. Maximizing natural ventilation: Design and placement of windows in proportion to room size and activity. The north and south facades are oriented at 45 degrees of prevailing wind direction, NW at night (land breeze), and SE during the day (sea breeze). The windows are placed along these facades facing each other with manually operated window shutters to manipulate the area of opening depending on the wind direction, smaller aperture to the windward side and larger to the leeward side to enhance the air speed. The larger windows open out to a shaded balcony /veranda to flush out the spaces in the evenings.
3. Appropriate materials: use of low embodied energy building materials with low thermal conductivity and high time lag.

These strategies work moderately successfully for the three distinct seasonal challenges of the tropical wet-dry climate of coastal India, achieving adaptive comfort throughout the year and thereby reducing the operational energy consumption.

3. METHODOLOGY

Post occupancy, the buildings were monitored for a period of 13 months, a cycle of 2 summers, and one monsoon season. Sensors were placed in relation to the various strategies adopted like building orientation, natural ventilation, shading, and materials. The data collected for air temperature, relative humidity, surface temperature, and operational energy consumption for this period was used to analyse indoor conditions for

adaptive comfort and reduction in operational energy consumption.

3.1 Monitoring strategy

After the project was completed (2018) and apartments had been occupied by the residents for a minimum of 3 months, 11 sensors were placed in critical areas like West facing exposed roof (WFER) apartments from Second floor and east facing unexposed roof (EFUR) apartments from Ground floor to monitor inside and outside air and surface temperatures, and relative humidity.

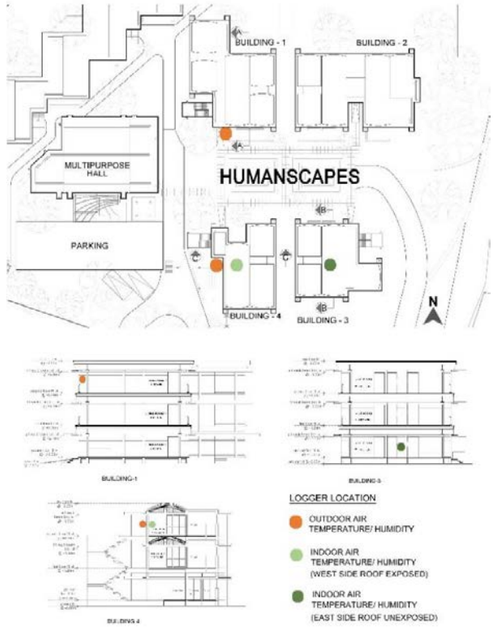


Figure 2: Site plan and sections of phase 1A – Humanscapes with sensor locations

Figure 3: Floor plan of WFER apartment (Second floor) in phase 1A with the sensor location

3.2 Indoor conditions

To get an overall picture of indoor conditions throughout the year, the months of June, September, December, and March were chosen for month-specific and hourly averages parameters results. Furthermore, the west-facing exposed roof apartment from the second floor was chosen for data analysis, having the highest temperatures, and was the most critical space in Humanscapes habitat.

When people wear light clothing, the MRT (Mean radiant temperature), which is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure, has double the effect of air temperature [5] on adaptive comfort, and keeping down the air temperatures is not enough.

To keep a lower mean radiant temperature which indirectly keeps the indoor air cool through convective heat transfer, the building envelope of humanscapes provides high time lag and thermal damping, thus delaying the indoor surface temperature peak time to late evening when the surrounding air is already cool. The building envelope in humanscapes habitat consists of four major elements namely, the 24cm thick Poured earth concrete (PEC) wall, the waste Cuddapah Stone wall, concrete columns and the 35 cm thick insulated vault roof. The strongest thermal impacts occur on the roof [5] in this climate, and the surface temperatures elevate due to solar gain input on the roof. Undue increase of surface temperatures in Humanscapes is prevented by using reflective roof surface of white ceramic tiles of reject quality, ensuring appropriate ventilation of space as well as under the roof, use of resistive insulation on the outside of the roof and active use of thermal mass offered by PEC walls, Waste Cuddapah stone walls, Concrete columns and brick vault roof.

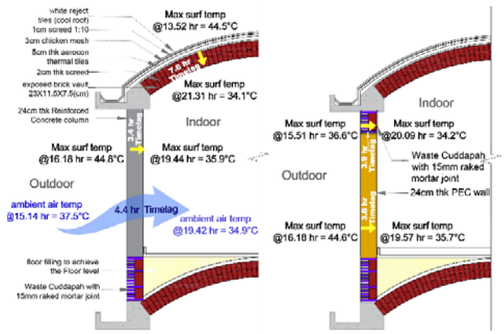


Figure 1. Average Maximum surface and air temperature with their time of occurrence for all the four elements from WFER apartment, in June 2019.

In June, the maximum outside surface temperature of roof reaches 44.5°C at 13.52hrs, while the indoor surface temperature (ceiling) reaches its maximum of 34.1°C at 21.31hrs. Due to a time lag of 7.6 hrs, the upward draft ventilation under the roof dissipates the heat as ambient air temperature is lower. Similarly, for the west-facing, unshaded and unpainted walls outside surface temperature reaches its maximum of 44.6°C at 15.51hrs while the insides reach a maximum of 35.7°C at 20.09 hrs with a time lag 3.6 hrs and damping of 8.5°C. The concrete column being adjacent to PEC wall, behaves very similar due to thermal bridging. The Cuddapah walls outside reach a maximum of 36.6°C, which is attributed to its overhang shading and providing a time lag of 3.9 hrs. The thermal mass located in the WFER apartment cooled at night, absorbs heat, and provides cool indoor surfaces and air temperatures during the day in the hottest month of June.

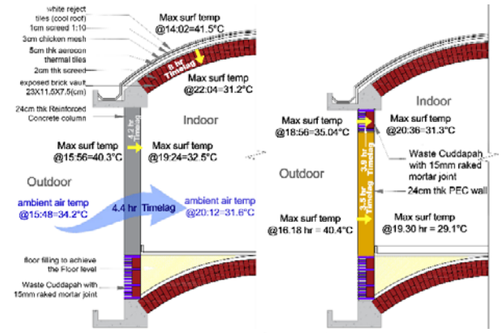


Figure 2. Average Maximum surface and air temperature with their time of occurrence for all the four elements from WFER apartment, in September 2019.

In September, the envelope functions very much like that in June with lowered air and surface temperatures.

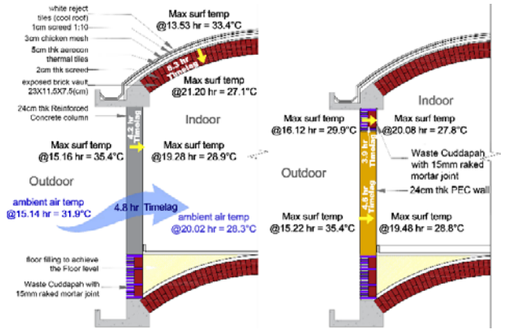


Figure 3. Average Maximum surface and air temperature with their time of occurrence for all the four elements from WFER apartment, in December 2019.

The building envelope with high tag and thermal damping works excellent during hot and dry summer days with open windows in the night and creates warm indoor conditions. For the cold December nights the High time lag brings in the heat from the day, and with windows closed during the night, creates comfortably warm indoor temperatures.

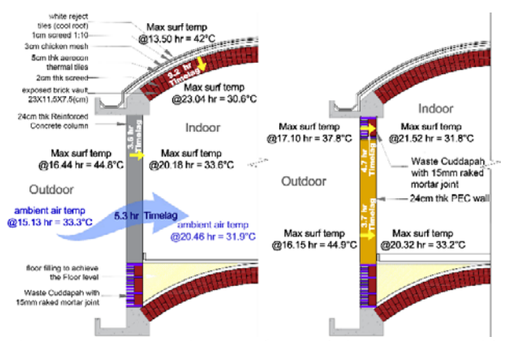


Figure 4. Average Maximum surface and air temperature with their time of occurrence for all the four elements from WFER apartment, in March 2020.

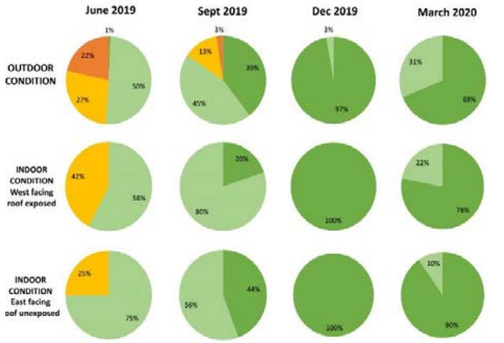
In March, the insulated vault roof and waste Cuddapah wall reported their highest time lags of 9.2 hrs and 4.7 hrs respectively. The ambient air temp also shows its highest time lag of 5.3 hrs.

Further, thermal comfort modelling was conducted to consider the effect of relative humidity simultaneously with dry bulb temperature and conclude adaptive comfort.

3.3 Thermal comfort analysis

Limits of comfort vary considerably according to studies carried out in India and abroad. In hot-humid climates, air flow is one of the few ways to produce a cooling effect on the human body by increasing the rate

of evaporation, drying the skin allowing a sense of wellbeing. As natural ventilation does not reduce the dry-bulb temperature a certain minimum desirable wind speed is needed for achieving thermal comfort at different temperatures and relative humidity [9]. The Desirable wind speed table 9 for Thermal comfort conditions and Minimum Wind Speed table 10 for just acceptable warm conditions from Clause 5.2.3.1.2 of the National Building Code (NBC 2016) were used to analyse thermal comfort distributions in indoor and outdoor conditions over the monitoring period. WFER and EFUR were chosen as representatives of worst- and best-case scenarios, respectively. The comfortable and acceptably warm hours need the desirable wind speeds mentioned in tables 9, 10 from Clause 5.2.3.1.2 of the National Building Code. The very comfortable conditions do not need any air movement, and uncomfortable hours are not acceptable even with air movement.



	COMFORT LEVEL	RANGE			COMFORT LEVEL	RANGE	
	VERY COMFORTABLE	31 °C @ 30% RH	28 °C @ 90% RH		ACCEPTABLY WARM	36 °C @ 40% RH	33 °C @ 90% RH
	COMFORTABLE	35 °C @ 30% RH	31 °C @ 90% RH		UNCOMFORTABLE	37 °C @ 30% RH	34 °C @ 90% RH

Figure 5: percentage distribution of conditions outside and inside WFER and EFUR apartment – comfort analysis

The outdoor conditions are uncomfortable for 22% of hours in June, whereas the indoors conditions are acceptably warm for 42% of hours and comfortable for 58% hours using Air movement in the most critical WFER apartments.

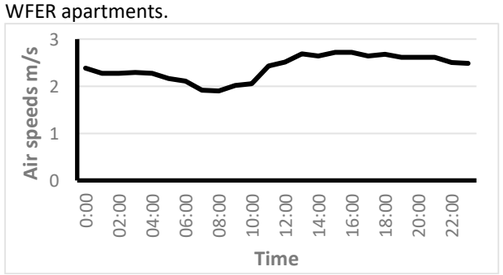


Figure 6: Monthly Average Air Speed Requirement inside a WFER apartment (Wind velocity vs. Time) in June
Note: Air velocity was not monitored in post-occupancy study. Air speeds requirement is as per desirable wind speed tables from NBC, and these can be generated using natural ventilation and installed ceiling fans.

The required airspeed data, monitored Dry bulb temperature (DBT), and Relative humidity (R.H) data were then used to calculate the Tropical Summer Index (TSI). This index is based on extensive studies conducted in the Indian context by Central building research Institute (CBRI) Roorkee and is used to measure the comfort levels during Hot-Dry and Warm-Humid indoor conditions. TSI is defined as the temperature of calm air, at 50% relative humidity, which imparts the same thermal sensation as the given environment [10]. The thermal comfort of occupants lies between 25-30°C TSI with optimum conditions at 27.5°C. The TSI values are applicable for clothing insulation of 0.3 – 0.45 clo. Mathematically, TSI (°C) is expressed as Equation (1):

$$TSI = 0.745tg + 0.308tw - 2.06\left(\sqrt{0.9v + 0.841}\right) \quad (1)$$

where TSI – Tropical summer index (°C);
*t*g = globe temperature (°C);
*t*w = wet bulb temperature (°C)
v = Air speed(m/s) and

Tw is calculated using the psychometric chart from the known variables following the ASHRAE standards. Globe temperature was considered equal to DBT because of indoor conditions. The velocity is multiplied with a factor 0f 0.9 because the high efficiency fans installed in humanscapes can generate wind speeds up to 2.7 m/s. and not 3m/s.

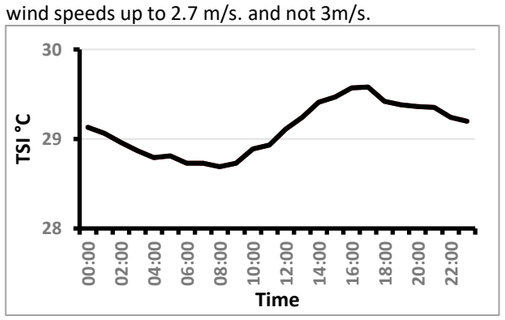


Figure 7: Average TSI values during June for WFER apartment

For the most critical month of June having 22% of uncomfortable hours, the design interventions along with required air speeds, resulted in TSI (indoor temperature of calm air and 50% R.H) between 25 to 30°C, which are thermally comfortable conditions for the occupants.

3.4 Operational Energy reduction

The monitoring of operational energy was done monthly from the installed meter of the local grid. Besides using design interventions and building material technology for adaptive comfort, energy-efficient lights, ceiling fans and appliances were also used for reducing operational energy consumption. The energy performance index (EPI) of Humanscapes is 7.14 kWh /year m2. This reduced operational energy consumption was easily met using 12.21 kW grid-connected rooftop Solar Photo Voltic panels.

4. CONCLUSIONS

This investigation demonstrated that the design intervention of humanscapes habitat led to overall adaptive comfort and reduced operational energy consumption from the analysis of monitored thermal comfort parameters and energy use.

1. Inside the WFER apartment, which is the most critical space in Humanscapes, the insulated vault with its high time lag of 7.6 hrs, PEC wall with its time lag of 3.6 hrs, Waste Cuddapah wall with its time lag of 3.9 hrs, and concrete columns with its time lag of 3.4 hrs, maintain low indoor surface temperatures during the hottest part of the day. Alongside this, the indoor air temperature remains 2.6°C lower than the outside maximum air temperature with a time lag of 4.8 hrs.
2. The thermal comfort distribution shows that the design interventions in Humanscapes along with ceiling fans create comfortable indoor conditions throughout the year without the use of air conditioning. In June, the indoor conditions of WFER apartments are acceptably warm for 42% of hours and comfortable for 58% hours using Air movement. The design interventions, along with Required airspeeds, result in TSI between 25 to 30°C, which are comfortable thermal conditions for the occupants.
3. The design achieves a very high Energy Performance Index of 7.14 kWh/m2 due to the design interventions and energy-efficient appliances. With this reduced operational energy consumption, the building progressively becomes net positive with a 12.21 kW on-grid photovoltaic system.

ACKNOWLEDGEMENTS

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CLIMATESCOUT® A design tool for low carbon architecture

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ABSTRACT: Understanding climate and developing an appropriate architectural response is the first step in the design process to design low carbon buildings. CLIMATESCOUT® is a web-based climate analysis application that helps its users design buildings that uniquely respond to a site by providing climate-specific design advice at the building scale. After clicking on a world map to select a climate zone, the application takes the user to a page to build a section combining appropriate strategies for a selected climate. During the design, we pre-selected the strategies by comparing 27 building scale strategies from the 2030 palette with the 30 Köppen-Geiger climate subtypes to determine their applicability for each of them. As they are selected, they appear in real-time overlaid in diagrammatic form, providing an immediate visual connection between the climate and the architectural idea. The application was developed by CRTKL, is free and is being used in practice in academia worldwide as well as in professional practice.
KEYWORDS: Climate Analysis, Design Process, Passive Strategies, Low Carbon Architecture

1. INTRODUCTION

An increasingly warmer planet requires buildings that adapt to changing conditions, while also reducing greenhouse gas (GHG) emissions to slow down and reduce the rate of related changes. Such passive adaptation is not typically possible in many buildings of the past century, especially all glass buildings, many of which are designed to solve overheating problems by using more energy for mechanical cooling. Even if in the future, the electrical grid is powered by renewables, buildings must be designed to be future-proof and resilient by ensuring the thermal safety and health of occupants when grids fail. Passive strategies appropriate to the climate are an important part of this.

There are multiple approaches to achieve a high-performance envelope integrated with passive strategies and a low carbon building. However, all of them must include some form of climate analysis. In fact climate analysis is the first step in any architectural design process.

This paper will describe CLIMATESCOUT®, a design tool that helps to achieve a low carbon building by suggesting passive strategies that are climate appropriate.

2. CLIMATE ANALYSIS

The amount of energy used in a building is a direct result of the interactions between the external environment, the building's program, and the building's form. Buildings should be able to regulate outdoor conditions and harness available energy to achieve internal comfort with minimum energy use and emissions.

The first step in this process is to perform what is traditionally called a climate analysis. In this process we analyze climate information to determine the most effective architectural design strategies to harness natural forces and achieve thermal comfort.

Probably the first modern text that studied the relation between climate and buildings was Olgyay's Design with Climate [1] in which he proposed the term "bioclimatic design" to identify potential building design strategies that use natural energy resources and minimize conventional energy usage to achieve thermal comfort. In this book, Olgyay also proposes the building bioclimatic chart to indicate design strategies that can be used for outdoor combinations of temperature and relative humidity to achieve indoor thermal comfort. It is called bioclimatic because it connects climate with human thermal comfort.

Givoni [2] [3] developed the building bioclimatic chart (BBCC) and then further developed with Milne [4] to address the problems associated with Olgyay's charts. This chart is based on the temperatures inside buildings (expected based on experience or calculations) instead of the outdoor temperatures. Givoni used the psychrometric chart as the base of his BBCC for plotting the comfort zone and its extension.

In the past, bioclimatic and climate responsive guidelines were typically organized as guidelines in books and reference guides for specific climates. One of the first is Koenigsberger, Mahoney, and Evans's [5] "Climate and House Design," which proposed a relationship between climatic regions and the recommended design strategies to achieve thermal comfort in each of these. Additional examples are "The Passive Solar Energy Book" [6], "Climatic Building Design" [7], "European Passive Solar Handbook" [8], "Proyecto Clima y Arquitectura" [9] and "Climate Considerations in Building and Urban Design" [10].

In the last twenty and especially in the last ten years, several climate analyses tools have been developed, which are proficient in producing a robust graphical visualization of climate data and provide the user with quantified information on the impacts of the passive strategies on thermal comfort. Digital climate analysis tools can process yearly data that are available in several weather file formats such as EnergyPlus Weather (EPW) and Weather (WEA) and present this data graphically so that it is easier to process and understand. This analysis, when done correctly, provides much insight on the appropriate passive strategies for a given climate. The ability to process yearly data files is the main advantage of these digital tools; however, it is also their main limitation. If a yearly climate data file is not available, then it is not possible to do any analysis at all unless data are interpolated from nearby stations or data are used from a similar location and organized in a readable format by these programs, such as EPW. Furthermore, not everybody has the level of knowledge required to study these climate variables appropriately, combining them in different ways to obtain conclusions regarding appropriate strategies.

Climate graphs and charts can now be created from yearly data using climate analysis software. There are several examples of climate analysis tools: Climate Consultant, developed at the University of California Los Angeles (UCLA) by Murray Milne and Robin Liggett [11] and CLIMA tool developed by Giovanni Betti and his team at UC Berkeley.

These are powerful analysis tools that provide useful information on the climate being analyzed; however, for the many that lack specialized training it is hard to connect the results of the climate analysis with the required architectural response.

2. CLIMATESCOUT®: A CLIMATE DESIGN TOOL

Climate graphs and charts created from existing climate analysis software illustrate relationships between the climate variables and in some cases, as in Givoni's psychrometric chart, between climate variables and design strategies. CLIMATESCOUT® is a web-based application developed in 2021 by CallisonRTKL that allows selection of building design strategies in real-time overlaid on a diagram, providing an immediate visual connection between the climate and the architectural idea. The emphasis is on the selection and combination of the design strategies based on selected climate instead of creating graphical analysis of specific climates.

2.1 Design of CLIMATESCOUT®

CLIMATESCOUT® helps its users design buildings that uniquely respond to a site by providing climate-specific design advice at the building scale. To achieve this, it uses the Köppen-Geiger climate classification and building scale design strategies from Architecture 2030's Palette. Fig 1 shows one of the first concept sketches

One of the key criteria to be effective in the design process is ease of use. CLIMATESCOUT® is very easy to use ensuring that it can be used by any designer, student and even users that are not trained in architecture or the design professions.

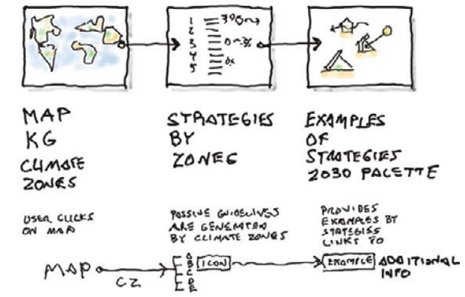
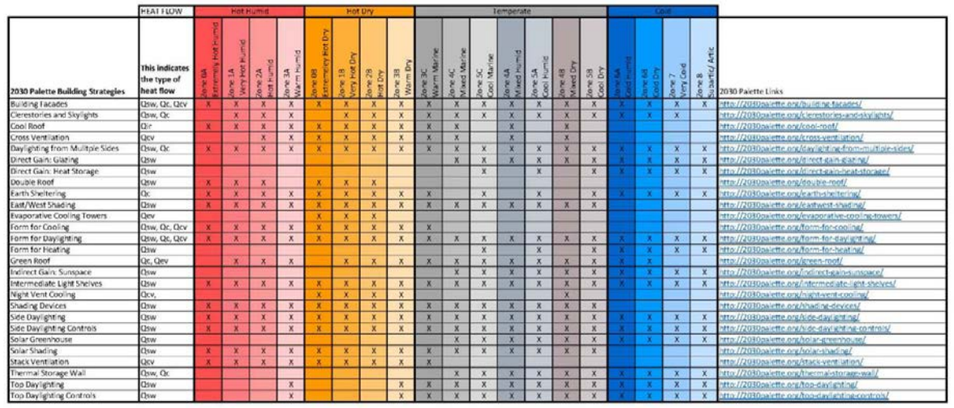


Figure 1: Author's first concept drawing for CLIMATESCOUT®

The Köppen-Geiger climate classification system empirically maps biome distributions worldwide, organizing regions by similar vegetation characteristics. Developed in the late 19th century, it is still widely used today for applications that must consider different climates, such as ecological modelling or climate change impact assessments. Using Köppen-Geiger instead of other classifications that focus only variables that affect thermal performance and primarily support heating and cooling relying on degree days, such as the ASHRAE climate zones, allows for a broader understanding of the relationship between the building and its surrounding environment and allows the possibility to establish additional connections between the building and its surrounding ecology in future versions.



2030 Palette Building Strategies	This indicates the type of heat flow	Hot Humid: zone 0A Extremely Hot Humid	zone 1A Very Hot Humid	zone 2A Hot Humid	zone 3A Warm Humid	Hot Dry: zone 0B Extremely Hot Dry	zone 1B Very Hot Dry	zone 2B Hot Dry	zone 3B Warm Dry	Temperate: zone 3C Warm Marine	zone 4C Mixed Marine	zone 5C Cool Marine	zone 4A Mixed Humid	zone 5A Cool Humid	zone 4B Mixed Dry	zone 5B Cool Dry	Cold: zone 6A Cold Humid	zone 6B Cold Dry	zone 7 Very Cold	zone 8 Subarctic/ Arctic	2030 Palette Links
Building Facades	Qsw, Qc, Qcv	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/building-facades/
Clerestories and Skylights	Qsw, Qc		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		http://2030palette.org/clerestories-and-skylights/
Cool Roof	Qir	X	X	X	X	X	X	X	X	X	X		X		X						http://2030palette.org/cool-roof/
Cross Ventilation	Qcv			X	X	X	X	X	X	X	X		X		X						http://2030palette.org/cross-ventilation/
Daylighting from Multiple Sides	Qsw, Qc	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/daylighting-from-multiple-sides/
Direct Gain Glazing	Qsw										X	X	X	X	X	X	X	X	X	X	http://2030palette.org/direct-gain-glazing/
Direct Gain Heat Storage	Qsw											X		X		X	X	X	X	X	http://2030palette.org/direct-gain-heat-storage/
Double Roof	Qsw	X	X	X		X	X	X				X		X		X	X	X	X	X	http://2030palette.org/double-roof/
Earth Sheltering	Qc	X	X	X	X	X	X	X	X	X		X		X		X	X	X	X	X	http://2030palette.org/earth-sheltering/
East/West Shading	Qsw	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					http://2030palette.org/eastwest-shading/
Evaporative Cooling Towers	Qev					X	X	X	X												http://2030palette.org/evaporative-cooling-towers/
Form for Cooling	Qsw, Qc, Qcv	X	X	X	X	X	X	X	X	X											http://2030palette.org/form-for-cooling/
Form for Daylighting	Qsw, Qc, Qcv	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/form-for-daylighting/
Form for Heating	Qsw											X		X		X	X	X	X	X	http://2030palette.org/form-for-heating/
Green Roof	Qc, Qev		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X			http://2030palette.org/green-roof/
Indirect Gain Sunspace	Qsw									X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/indirect-gain-sunspace/
Intermediate Light Shelves	Qsw	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/intermediate-light-shelves/
Night Vent Cooling	Qcv,					X	X	X	X						X						http://2030palette.org/night-vent-cooling/
Shading Devices	Qsw	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					http://2030palette.org/shading-devices/
Side Daylighting	Qsw	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/side-daylighting/
Side Daylighting Controls	Qsw	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/side-daylighting-controls/
Solar Greenhouse	Qsw											X		X		X	X	X	X	X	http://2030palette.org/solar-greenhouse/
Solar Shading	Qsw	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					http://2030palette.org/solar-shading/
Stack Ventilation	Qcv	X	X	X	X	X	X	X	X	X											http://2030palette.org/stack-ventilation/
Thermal Storage Wall	Qsw, Qc										X	X	X	X	X	X	X	X	X	X	http://2030palette.org/thermal-storage-wall/
Top Daylighting	Qsw				X				X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/top-daylighting/
Top Daylighting Controls	Qsw				X				X	X	X	X	X	X	X	X	X	X	X	X	http://2030palette.org/top-daylighting-controls/

Figure 2: Pairing of 2030 design variables with Köppen-Geiger climate zones.

The Köppen-Geiger system classifies climate into five main classes and 30 sub-types. The five main climate groups are A (tropical), B (dry), C (temperate), D (continental), and E (polar). Each group and subgroup include different seasonal precipitation and temperature patterns. All climates are assigned a primary group represented by the first letter. Next, climates, except those in the E group, are given a seasonal precipitation subgroup (the second letter). Finally, a temperature subgroup, assigned for all groups except A, indicated by the third letter for climates in B, C, and D, and the second letter for climates in E.

Twenty-seven building scale strategies taken from the Architecture 2030 palette were paired with the 30 climate subtypes to determine their applicability for each of the Köppen-Geiger climates (Fig.2). This initial filtering of appropriate strategies was done during the development phase of the program. Only clearly inappropriate strategies were blocked in this initial selection process, to avoid obvious mistakes. For example, it is not possible to select passive heating in a hot and dry climate. The user can select and combine from these curated strategies for a selected climate. As they are selected, they appear in real-time, providing an immediate visual connection between climate and building response. Most climate analysis tools effectively visualize climate data and quantify the effect of some strategies on thermal comfort. Still, they do not provide a visual image of these strategies integrated into an architectural response. CLIMATESCOUT® does this, providing a more integrated and coherent vision of the design strategies working in unison.

The strategies for each climate are well known and some options that can be selected with the tool are listed below. For hot climates: passive cooling, natural ventilation, shaded walls/windows, indirect daylighting, light-colored walls/surfaces, double glazing. For temperate climates in the warm season: passive cooling, shaded windows, indirect daylight and in the cold season: passive solar heating, daylighting, double glazing. In cold climates: passive solar heating, daylighting, double glazing.

2.2 Using CLIMATESCOUT®

When you first go to CLIMATESCOUT® a world map with the climate zones is shown (Fig. 3). Clicking on any location opens a diagram with strategies in this case in a BWh climate zone such as the Sahara desert (Fig. 4).

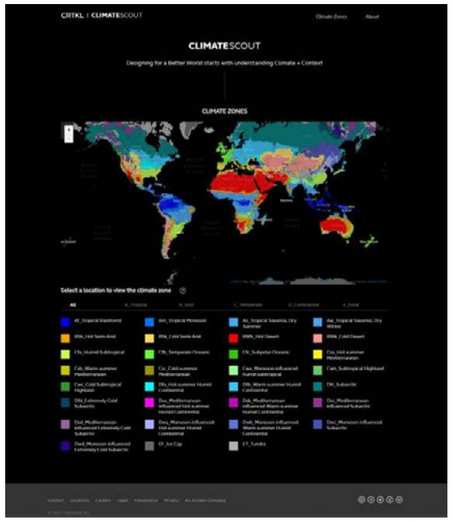


Figure 3: Climate selection page in CLIMATESCOUT®

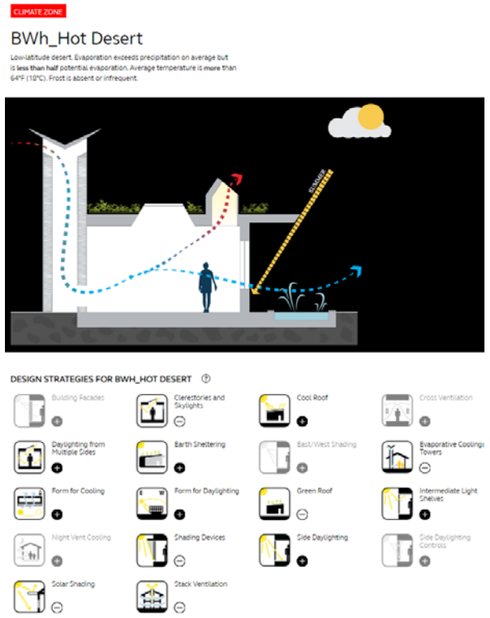


Figure 4: Example of strategies in climate zone BWh

The diagrams that are generated using the application have been developed by the team to represent envelope relationships with different strategies, and the icons have been developed to better illustrate the strategies. Selecting an icon (Fig. 5) shows additional information regarding a selected strategy, in this case evaporative cooling. At the bottom of the page, it provides a link to Architecture's 2030 palette where additional information, including design rules of thumb, is provided.

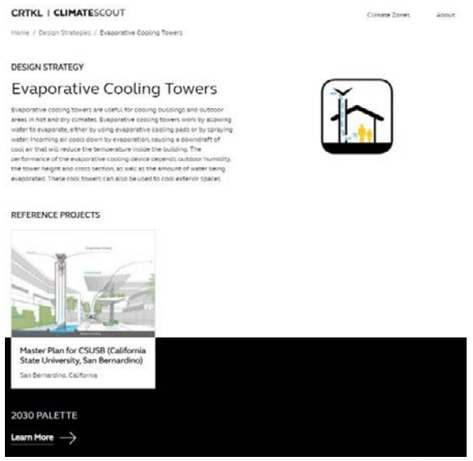


Figure 5: Additional information on evaporative cooling

CLIMATESCOUT® provides an integrated vision of passive design strategies working in unison. It presents visual images and information with embedded passive strategies for each of the 30 climate subtypes; determined by the Köppen-Geiger classification system. It was developed by CRTKL, is accessible for free, used by architects worldwide, with more than 200,000 unique page views in the 15 months since it was launched on April 23, 2021. The link for the current version is available at https://www.callisonrtkl.com/climate-scout/. It is also accessible in the Society of Building Science Educators (SBSE) website and is used by faculty in architecture schools in the United States as a teaching tool.

2.3 Examples of Application

CLIMATESCOUT® is being used as a teaching tool in universities and in the design profession in practice. In academia, it has been used in design studios, large lecture courses on environmental control systems and seminar courses. Figure 6 shows a snapshot of a concept board for Solar Energy Systems, a course taught online in the Fall of 2002 at the Lyle Center for Regenerative Studies at Cal Poly Pomona University. In this course students designed a carbon neutral home using different tools including using CLIMATESCOUT® to propose ideas based on their location and climate.

Figure 6: Concept Board image for course RS 4300

CLIMATESCOUT® has also been used in professional practice to propose ideas based on climate. The following are examples of how it was used in three projects.

Merlata Bloom Milano is an innovative project with numerous facets and uses, among them an urban farm on the roof that will become a new amenity for the city (Fig. 7). Among the strategies selected are passive heating, shade for solar control in the summer, and daylight. Figure 8 shows the integrated design, sustainability, and digital processes, in which CLIMATESCOUT® was used in the first phase, while other tools such as Rhino combined with grasshopper and ladybug tools were used for further analysis. Figure 9 shows the skylight as it was further analysed.

Figure 7: Merlata in Milan Cfa climate

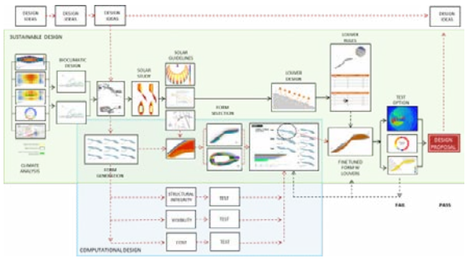


Figure 8: Design process

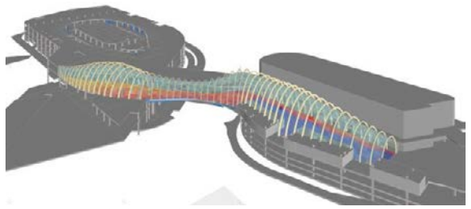


Figure 9: Skylight analysis

For an expo Center in Harbin, China (Fig.10) it was important to provide a well-lit interior year-round while efficiently heating and cooling the building. The climate analysis suggested best strategies to combat the hot humid summers and severe dry winters and the design team used the application to visualize design strategies during concept design. The team implemented well insulated façades, direct solar gain with heat storage, shade, natural ventilation, and daylighting from multiple sides. Additional studies were done to maximize solar radiation and daylight in appropriate areas.

For the Caohejing office tower competition in Shanghai, China (Fig 11), the climate analysis indicated shade would be necessary to improve performance and reduce carbon emissions. Further studies indicated that the south and west elevations were more critical, and a shade system was designed integrated in the façade to maximize daylight and minimize negative solar gains. Additional studies were done to maximize solar radiation and daylight in appropriate areas, while providing daylight year-round.

Figure 10: Harbin Expo Center Dwa climate

Figure 11: Caohejing office competition

3. CLIMATESCOUT® FUTURE VERSIONS

Simplicity and ease of use will always be important as future versions of the program are implemented. Figure 12 outlines the user workflow with the application. The user selects a location in a map and proposes appropriate strategies while being able to link to other pages for more information. This structure will be maintained in the new version, the goal is to provide more information on the applicability of the specific strategies in Mandarin and Spanish languages so that the program is accessible to more people. Another feature is the effectiveness of the selected strategies in different climates, which would provide the user with more precise information on the impact of the strategies on skin and internal load dominated buildings in the different climates. To achieve information on the impact of the strategies these will be modelled individually.

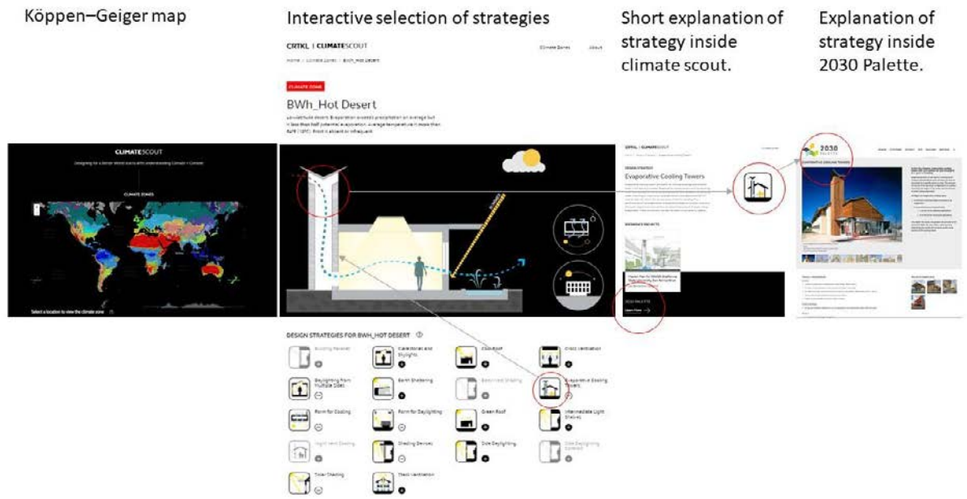


Figure 12: CLIMATESCOUT® workflow

The users will then have information on the impact of a strategy on thermal comfort, using the Predicted Mean Vote (PMV) and Adaptive Comfort metrices. Daylit will be estimated based on the percentage of annual hours the space will be sufficiently daylit using spatial Daylight Autonomy (sDA) metric and Annual Sunlight Exposure (ASE). Better thermal comfort performance and adequate daylighting will reduce mechanical heating-cooling and electric lighting loads and greenhouse gas emissions caused by a building.

The ability to download images and validated information from the tool will allow better use for presentations by architects in practice and students and instructors in academia. The tool will be a good resource for design studios and courses in building sciences like, Environmental Control Systems. We envision that it will empower the users to make quick decisions on strategy selection while finalizing their design concepts.

4. CONCLUSIONS

Recent experiences of catastrophic heat waves and cold snaps clearly point to the need for mechanical heating or cooling sometimes. However, not only does climate responsive design make a huge difference extending the length of time people can be comfortable in buildings without mechanical systems, reducing the carbon impacts of buildings and costs of remaining comfortable while improving the health and safety of occupants, but it may also provide a lifeline for the many who do not have, or cannot afford to operate, mechanical systems.

In the future, natural forces must play a more important role in shaping our buildings, re-connecting with ecosystems around them, implementing locally appropriate passive cooling strategies to provide zero carbon thermal comfort for much of a year.

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Benchmarking buildings in the context of Net-Zero targets

Tracking energy performance of a case study from design to operation

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ABSTRACT: To keep on track with the net-zero targets for the building sector, building energy benchmarking is essential. Benchmarking compares the building energy performance to established standards based on historical energy usage, and these benchmarks become aspirational goals. However, existing building energy data reveal a different consumption trend in recent times. Thus, actions are required to assess current benchmarks' relevance, development, and applicability so that buildings comply with the net-zero target. This paper compares the design and operational performance of a newly constructed building with existing benchmarks. Further, the feasibility of net-zero targets in an operating building is investigated using a calibrated energy model. Findings show that the building used 2.1 times more energy than design estimation. A key factor for this deviation was the change in operating hours, increasing from 10 hours per day during design to 24 hours in operations. This space-time utilisation increase made the building unable to achieve the performance needed for current net-zero benchmarks. This is one of the challenges that benchmarking systems need to address. The current benchmarks (to enable net-zero pathways) lack a broader range of maximum hours and should include a time normalisation factor to avoid penalisation for better space-time utilisation.
KEYWORDS: Energy Performance, Energy Benchmarks, Building Operational Stage, Net Zero Carbon

1. INTRODUCTION

By 2050, the UK must achieve its zero-emission objective under the Climate Change Act 2008, as amended in 2019 (The Climate Change Act, 2019). As part of the UK's climate change target, the London Energy Transformation Initiative (LETI) proposes that by 2025, all new buildings should have low Energy Usage Intensity (EUI) and low space heating demand so that net-zero carbon emission from new buildings can be achieved by 2030 (LETI, 2020). To keep on track with the energy target, energy benchmarking of the buildings is required.

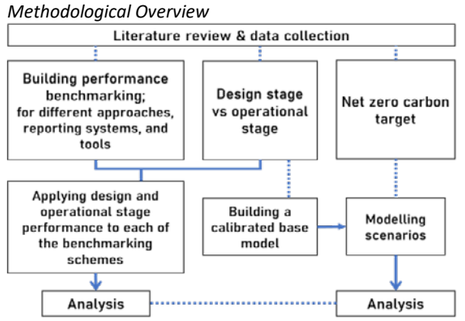
Energy performance benchmarking is a strategy for assessing a building's energy performance by comparing its energy consumption to a specified target or criteria based on historical energy consumption or established energy standards (Hong et al., 2013). Benchmarks can be derived in two ways: top-down and bottom-up. The top-down analysis examines macro or building-level energy before focusing on more specific variables such as the end-uses of the building. On the other hand, bottom-up evaluation accumulates the performance of a particular building at the system level, which is then aggregated into a single EUI representing a hypothetical building's overall performance (Hong, 2015).

In the UK, CIBSE Guide F (CIBSE, 2012), CIBSE TM46 (CIBSE, 2008), and the Energy Consumption Guides (ECG) Series (EEBPP, 1997) can be used to evaluate building energy consumption as the top-down benchmarks. Additionally, CIBSE Guide F also includes end-use benchmarks for bottom-up evaluation. These documents are industry-standard guidance protocols that inform local government regulatory needs while also providing benchmark values for building energy consumption. However, discrepancies in benchmark values from various sources make building performance evaluation more challenging. Furthermore, current building energy statistics show a different consumption pattern than these relatively dated energy benchmarks (Hong et al., 2013). Analysing data over time indicates that the building's energy consumption trend will certainly change, making the current benchmarks outdated (CIBSE, 2019). Additional research is needed to determine the relevance and development of these benchmarks and their suitability for buildings' design and operations as they move towards net-zero targets.

2. METHODOLOGY

In this paper, we used a newly built case study building to assess its performance against all the relevant benchmarks from the design stage to operation. We compared the targeted and achieved performance of the building, factoring in its various changes over time with various benchmarks. This helped us evaluate the benefits and limitations of benchmarks being used in the industry. Also, using a calibrated energy model, we were able to undertake scenario testing and assess the practicality of meeting the net-zero targets in this already operational building. An overview of the proposed method is shown in Figure 1.

Figure 1:
Methodological Overview



2.1 Literature Review and Data Collection

Initially, three key interrelated topics need to be studied as a part of the research.

- *Performance Benchmarking*

Thorough study and desk research of the energy performance benchmarking was conducted. It includes the understanding of benchmarking approaches (top-down and bottom-up), benchmarking systems and reporting in the UK, such as the CIBSE Guide F, CIBSE TM46, and ECG54, and the CIBSE Benchmarking Tool (Table 1).

- *Design Stage vs Operational Stage*

Benchmarking is explored using a case study building. Fundamental causes of the difference between the estimated and actual performance of the case study are identified. The data is collected from design documentation and modelling reports for CIBSE TM54, a modelling guide and reporting protocol for design stage energy projections (CIBSE, 2013). TM54 divides the parameters used in energy consumption prediction into low-end, mid-range, and high scenarios to provide a wider range of estimates. The mid-range scenario represents the typical energy use of a building. Meanwhile, the operational stage data is typically collected from post-processed and cleaned actual metered and monitored data of the building's electrical metering.

- *Net Zero Carbon Target*

As a response to the UK's environmental objectives in the future, the Climate Emergency Design Guide (CEDG) from LETI gives guidance on how to attain the carbon-neutral target by 2030. Additionally, the UK Green Building Councils (UKGBC) has created a feasibility study report to implement new net-zero carbon buildings (UKGBC, 2020).

The literature review aims to present a comprehensive overview and chronological evolution of the UK's benchmarking systems and their relevance towards future development.

Table 1:
Benchmarking Systems and Reporting in the UK

Benchmarking System & Reporting in the UK	Description
ECG54 – Energy Use in Further & Higher Education Buildings (Energy Consumption Guide Series) - 1997	It offers an energy usage and cost assessment approach and examines the primary influences on energy use in academic and auxiliary buildings and space functional categories.
GPG321 – Energy Efficiency for Further and Higher Education (Good Practice Guides) - 2002	The objective of this Guide is to educate universities and colleges on the potential for implementing energy efficiency, as well as to offer methods for doing so.
CIBSE Guide F – Building Energy Efficiency - 1996 (1st edition), 2004 (2nd edition), 2012 (3rd edition)	CIBSE Guide F provides energy efficiency principles and benchmarks. It comprises 'typical' and 'good practice' energy benchmarks for a wide range of available data on buildings, components, and end-uses.
CIBSE TM46 – Energy Benchmarks - 2008	The CIBSE TM46 is a publication of the Display Energy Certificate (DEC) benchmarks that are based on the original CIBSE Guide F and ECG 19 data with a significant simplification of values drawn from many sources as well as engagement with the industry. It allows the use of options to account for separate energy uses and longer occupancy.
CIBSE Benchmarking Tool - 2013	CIBSE Benchmarking Tool is an online platform that offers a more dynamic approach for more up-to-date and accurate benchmarks to understand current energy usage patterns in buildings. It aims is to progressively revise and update the energy benchmarks in CIBSE Guide F.
Climate Emergency Design Guide (CEDG) by LETI - 2020	The Climate Emergency Design Guide (CEDG) from LETI gives guidance on how to achieve the zero-emissions target by 2050 (The Climate Change Act, 2019).

2.2 Case Study Performance Against the Various Benchmarking Schemes

A comparison of the case study's energy consumption between the design and operational stages up to the subsystem level is carried out to identify which parameters are significantly causing the difference between the targeted and actual performance. The energy consumption for each stage is then compared against current relevant benchmarks to see which benchmarking system is the most appropriate or suitable for the design and operational stages.

2.3 Building a Calibrated Base Model

Using the DesignBuilder software (DesignBuilder, n.d.), a base model is created according to the mid-range scenario of the CIBSE TM54 (design stage reference) and detailed engineering drawings (operational stage reference) of the case study. After the simulation results of the base model from the design stage input have been obtained, it is then compared and fine-tuned with the actual measurement of energy usage so the model can be calibrated, which in this case are lighting, power, and HVAC system with its auxiliary.

2.4 Modelling Scenarios

Two scenarios are applied to the calibrated model;

- *Scenario 1: Actual Operational Hours and Utilisation at Design Stage*

One of the causes of discrepancies between the estimated and actual energy consumption is the change in building utilisation after the building is operational. By replicating actual operational occupancy numbers and hours on the base model for the design stage, attempts to reduce the energy used can be focused on design parameters that are unlikely to alter after the building operates. The significance of the operational hours for the overall energy consumption can also be evaluated. This scenario modifies the calibrated model with real operating hours and 100% building utilisation.

- *Scenario 2: Achieving Net Zero Operational Target*

The goal of Scenario 2 is to assess the feasibility of achieving net-zero operational carbon without significantly altering the building's current utilisation. Scenario 2 is a follow-up to Scenario 1, where further simulations are performed to achieve better building performance closer to the net-zero operational target. It modifies the final model input of scenario 1 by applying better values of several parameters than the CIBSE TM54 low-end scenario on the model; higher heating COP, higher cooling setpoint, and using low-end scenario for power and equipment density by reducing on-site server and IT loads as suggested by UKGBC on their feasibility study (UKGBC, 2020). The proposed LETI energy consumption target was used as the building's net-zero carbon target. According to LETI, Schools and offices should have an EUI equal to or less than 65 kWh/m^2/year and 55 kWh/m^2/year, respectively.

2.3 Result Analysis

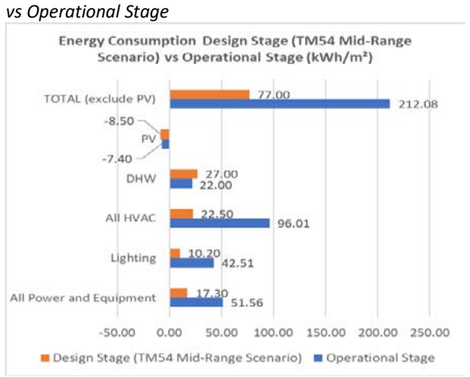
After comparisons and simulations of the case study were completed, related analysis was carried out regarding; the difference and relevance of each benchmarking scheme for design and operational stage, effects of operational hours and building utilisation on building energy consumption, and building capability in achieving the net-zero operational target.

3. CASE STUDY

The case study building is an educational building that aims to achieve the highest possible grade for environmental, social, and economic sustainability.

Compared to its design stage assumptions, several significant changes occurred during the operational stage, including the building's operational schedule, changing from ten to twenty-four hours per day. Also, the Demand Control Ventilation (DCV) system failed to operate properly, resulting in the building's mix mode operation being run inefficiently during actual usage. With this change, and after the raw data has been cleaned, the total energy used in the operational stage (212.08 kWh/m^2) is 2.75 times higher than the design stage projections (77.00 kWh/m^2) (Fig.2).

Figure 2:
Comparison of Energy Consumption Design Stage (TM54) vs Operational Stage



With all the differences between the two stages, Figure 2 illustrates that PV provides 87% of the estimated design stage at the operational stage. For power, the increase in the energy utilised is about three times. Meanwhile, the increase in lighting and all HVAC system end-uses for the operational stage are about 4.2 and 4.3 times higher than the design stage, respectively.

4. BENCHMARKING

Different benchmarks evaluation approaches serve distinct purposes in the building procurement process yet complement one another. A top-down assessment that compares the overall building's energy consumption with a similar building can encourage more energy efficiency at the design stage, while a bottom-up assessment help identifies inefficient subsystems when the building has operated. In the UK, Although CIBSE Guide F and CIBSE TM46 are considered out of date and need modification, their availability in terms of allowed maximum operating hours and separate energy end-uses makes them remain the primary guide for building energy consumption benchmarks.

In evaluating the top-down approaches in benchmarking, benchmarks that are comparable for this case study building are selected, considering the building's functionality and value of the benchmarks. Given the significant difference between the energy used in each stage, the benchmark comparison is also separated as seen in Figure 3. The considered comparable benchmarks for the design stage are the benchmark values that are more or less 30% than the energy used prediction of the case study building. At the design stage, it can be seen that the comparable benchmarks have a similar building typology with the case study, which is an academic or higher educational building. However, none of the benchmarks is from the CIBSE Guide F, not even its 'Education' building category. Meanwhile, at the operational stage, the figure expresses that the closest comparable benchmarks are the energy consumption of typical offices from Guide F and TM46. It was also found that none of the Guide F for educational buildings or TM46 for university campuses with the maximum hours is comparable for either the design or operational stage.

Figure 3:
Top-Down Benchmarks for Design and Operational Stage

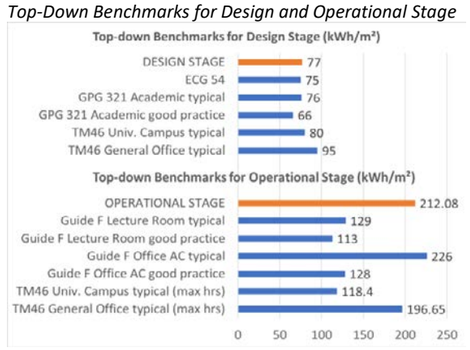
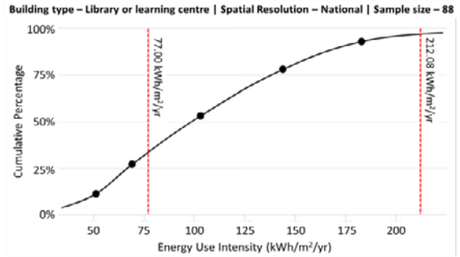


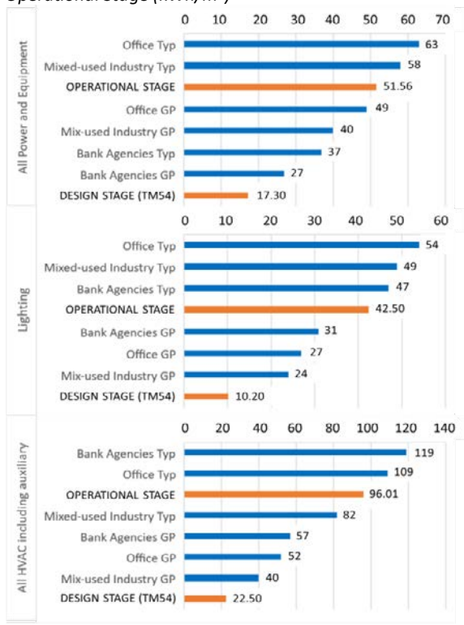
Figure 4:
Energy Consumption of Design and Operational Stage in the CIBSE Benchmarking Tool



Building Type	Good Practice Electricity	Typical Practice Electricity	Source
Library or learning centre	69	103	DEC

In another perspective of how the case study building performs, CIBSE Benchmarking Tool is used to locate where the building stands within the more updated typical building stock. Figure 4 shows that energy used in the operational stage (212.08 kWh/m^2) is at the higher end of the 88 building samples in the tool, while for the design stage (77.00 kWh/m^2), its energy consumption still does not comply with the good practice benchmark (69 kWh/m^2). The current building sample shows that the case study building's performance is still inferior to its peers, most likely because the comparison is not with identical operational conditions. However, this tool is currently in development; thus, data comparisons to other building typologies, such as offices, are not available yet.

Figure 5:
Bottom-Up Benchmarks for Design (TM54) and Operational Stage (kWh/m^2)



For bottom-up benchmarks, no building category from existing benchmarking schemes fits the functionality of the case study building. Thus, a few combinations of building categories are presented for comparison as an approach in identifying the closest category that might fit the case study building, then the energy end-uses in the design and operational stage are compared to the selected benchmarks. After considering the building's functionality from the building typologies available in Guide F, three categories with good practice (GP) and typical (Typ) benchmarks were selected, namely, office (standard and air-conditioned type), banks and agencies (agency with all-electric with cooling type), and mixed-use and industrial building (standard and air-conditioned office type).

Since the data collection of the case study building has a low granularity, the benchmarks are simplified into three categories for comparison; all power and equipment, lighting, and all HVAC system, including the auxiliary. Figure 5 compares

three end-use benchmarks for design and operational stages. It shows that the design stage's end-uses are too low compared to all selected benchmarks (roughly half of the closest benchmark value). Whereas for the operational stage, when viewed more extensively and comprehensively, the figures show that all of the case study building's end-uses fall within the office's benchmark range for good practice and typical. However, a broader range of building classification is required to get a more accurate building performance objective. Furthermore, to optimally perform bottom-up benchmarking, new data collection/protocols with a certain level of submetering are required to facilitate more accurate evaluation.

5. RESULTS AND ANALYSIS OF MODELLING SCENARIOS

5.1 Scenario 1: Actual Operational Hours on Design Stage

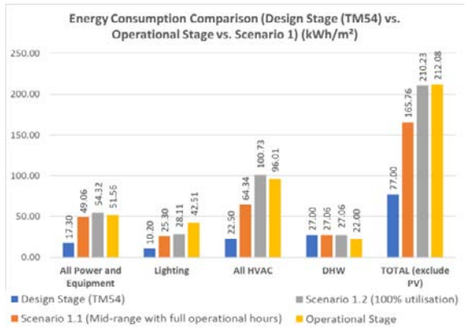
Table 2:
Changes in Parameter for Each Scenario

Parameter Used or Changes in Parameter	Base Model	Scenario 1		Scenario 2	
		1.1	1.2	2.1	2.2
TM54 mid-range value for all input data (incl. operating hours and utilisation)	v				
TM54 mid-range input data but with real operating hours as conditions (no DCV)		v	v		
TM54 mid-range input data but with 100% building utilisation			v		
TM54 mid-range input data except for HVAC (low-end) with real operating hours as conditions (no DCV) and 100% utilisation				v	
Better value for HVAC parameter and power density than scenario 2.1					v

As seen in Table 2, Scenario 1, two simulations were performed; Scenario 1.1 modifies the calibrated model (with TM54 mid-range input data) with real operating hours as conditions, whereas Scenario 1.2 applies both actual operational hours and 100% building utilisation. As seen in Figure 6, the overall building's energy used increases 2.15 times compared to the design stage after applying the twenty-four-hour operation and without the mixed-mode ventilation in use (Scenario 1.1). This rises to 2.73 times over the design stage estimate after 100% of equipment utilisation is applied (Scenario 1.2). Scenario 1.2 result comes out comparable to the operational stage performance except for the lighting that only consumes 66.13% of the actual measurement energy. It is most likely caused by the actual lighting density when the building operated is higher than the input data for the 100% utilisation scenario.

Scenario 1 asserts that high energy consumption does not always indicate inefficient operation; increased operational hours also play a significant role. Moreover, through operational modelling, inefficient building components can be identified and improved.

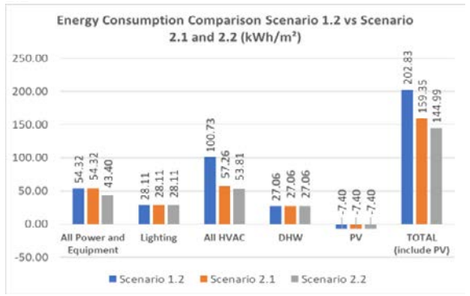
Figure 6:
Scenario 1 Energy Consumption Comparison with Design (TM54) and Operational Stage



5.2 Scenario 2: Achieving Net Zero Operational Target

The energy consumption target used is the LETI target for commercial offices (55 kWh/m^2/year). LETI targets are limited to various archetypes not directly linked to the case study use. However, according to the benchmarking evaluation on the case study and its twenty-four operational hours, the case study building is more equivalent to an office than a university facility. Compared to the LETI target, the actual energy use of the case study building is 3.85 times higher. However, the LETI target, which considers NABERS modelling guidance (LETI, 2020), still only represents standard office hours. To make the target more contextual with actual conditions of the case study building, an increase of electricity consumption by 107% for office maximum hours (8760 hours/year) based on CIBSE TM46 is applied to the LETI target, which takes the target to 113.85 kWh/m^2/year.

Figure 7:
Energy Consumption Comparison of Scenario 1.2, 2.1, and 2.2



Two simulations were undertaken for Scenario 2 (Table 2). The first one (Scenario 2.1) is modifying Scenario 1.2 (which uses TM54 mid-range input data) to use the TM54 low-end input data for the HVAC input parameter. The second simulation (Scenario 2.2) is adjusting the Scenario 2.1 model, with better value for HVAC parameters; higher heating COP, higher cooling setpoint, and using low-end scenario for power and equipment density by reducing on-site server and IT loads.

Figure 7 shows a gradual energy consumption towards the final simulation. Applying low-end building specifications for HVAC (Scenario 2.1) decrease 21.4% of energy consumption due to the energy used by the HVAC being reduced by roughly half. Meanwhile, compared to Scenario 2.1, Scenario 2.2 achieves a 9% decrease in energy consumption through a 6% reduction in HVAC and a 20% reduction in power and equipment energy consumption.

Table 3:
Energy Used of Scenario 2 Results Compared to Net Zero Operational Carbon Target

Target Benchmark / Scenario	Energy Used (kWh/m²)	Remaining Energy to Reach Target (kWh/m²)
LETI Commercial Offices	55.00	-
Increase of 107% LETI target	113.85	-
Scenario 1.2	202.83	88.98
Scenario 2.1	159.35	45.50
Scenario 2.2	144.99	31.14

Based on the results of the Scenario 2.1 simulation, it was determined that optimising the HVAC system is the first approach to decrease building energy consumption without changing the physical or functional configuration of the building. While this is a decent start, it can only cover 48.86% of the remaining energy to be reduced to achieve the LETI customised target (Table 3). After the calibrated model applies the actual building conditions and a scenario of improving the quality of the HVAC system and decreasing the IT loads is simulated, there is still 35% (31.14 kWh/m^2) of remaining energy that needs to be covered to achieve the target. Applying DCV System and improving renewable energy sources can increase more energy saving. Finally, the remaining energy should be offset using a recognised offsetting framework.

6. CONCLUSION

The significance of operating hours in defining the design target is indicated by the spike in building energy consumption, which climbed to 2.15 times the design intention when operating hours were raised from ten to twenty-four hours per day. It also affects the benchmarks' evaluation, as evidenced by the top-down assessment, which indicates that while the case study's performance at the design stage is comparable to that of a similar building typology, i.e., educational buildings, the closest comparable benchmarks at the operational stage are the energy consumption of typical offices from CIBSE Guide F and CIBSE TM46, which took twenty-four operational scenarios into account (Fig. 3).

In conclusion, it is important to analyse the building's performance during the design and operational stages to determine the net-zero carbon target. It's difficult to maintain a compromise between net zero objectives and a building's optimal space-time use. According to the evaluation of existing benchmarks, the current benchmarks lack a broader range of allowed maximum hours for each building typology. LETI's target should include a time normalisation factor as a buffer against substantial changes that may occur during the operational stage.

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CFD simulation on ventilation performance of existing apartment buildings in Indonesia

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ABSTRACT: Natural ventilation has been considered as a cost-efficient solution to promote energy-saving, indoor air quality and improve occupants' thermal comfort in residential building. However, the implementation of natural ventilation often fails to meet the expectation due to internal and external factors. The external factors such as urban form and climate are difficult to control. On the other hand, the internal factors such as the floor plan and opening configurations are still under control of the building's stakeholders but their detail information are still lacking in the major building guidelines. This study aims to reveal how the internal factors, particularly the floor plan and opening configuration, affect the natural ventilation performance. Firstly, a typological study was carried out to obtain a representative unit's floor plans and opening configurations of public apartments in Indonesia. Secondly, Computational Fluid Dynamic (CFD) simulation was performed on the representative building models to assess their ventilation performances. The study found that a desirable ventilation performance could be achieved by designing floor plan with minimum obstacles for airflow, proper room layout and opening configuration. The opening configuration also covers the effect of its location, area, and form.
KEYWORDS: CFD Simulation, Natural Ventilation, Residential Building, Ventilation Performance

1. INTRODUCTION

Indonesia still faced a huge housing backlog of 11.5 million units in 2015 due to the rapid growth of urbanization [1]. Therefore, the Indonesian government launched the one million housing program to narrow the housing backlog [2]. This program aims to provide one million housing units per year, one of which is in the form of vertical housing. On the other hand, previous studies found that many apartments in Indonesia were designed without considering passive design principles, and therefore, thermal comfort is difficult to achieve without relying on Air Conditioner (AC) [3]. If the number of these highly energy-dependent apartments increases, the energy demand for cooling would rise and further exacerbate the carbon emission. Therefore, it is important to design an energy-efficient building by considering occupants' thermal comfort and indoor air quality (IAQ). This will benefit the occupants due to the lower building's operational cost.

Natural Ventilation (NV) has been broadly recognized as one of the promising strategies to achieve energy efficiency as well as to secure indoor air quality and thermal comfort. The study in China proved that NV could reduce energy consumption by up to 78% [4]. Moreover, the NV could reduce around 20-47% of CO_2 concentration in the Portugal building [5]. However, the implementation of NV often fails to provide a sufficient cooling capacity for buildings in hot-humid climate areas [6]. Hence, design improvement and further study are necessary in order to enhance the effectiveness of NV performance.

In general, the effectiveness of NV is affected by external and internal factors. The external factors are the environment surrounding the building that influences the ventilation performance (e.g., urban form, microclimatic condition). Meanwhile, the architectural design, such as the floor plan and opening configuration, are categorized as internal factors. In the apartment building, the floor plan and opening configuration are commonly uniformed throughout the building regardless of the location and orientation of the units.

Previous studies had investigated the influence of floor plans on ventilation performance. The study by [7] shows that changing the shape of the interior partition could enhance the air speed up to 33%. Moreover, an open-layout floor plan that allows a connection between each space could improve indoor air speed performance [8]. Nevertheless, the ventilation performances of the existing apartment's floor plans in Indonesia have not been investigated yet.

Another influential internal factor is the opening configuration. This factor covers opening position and/or location, area/size, form, and window type. In regards to the opening position, NV is divided into cross and single-sided ventilation [9]. Under cross ventilation mode, the openings are located in two or more walls. Meanwhile, for the single-sided ventilation, the opening(s) is located only on one side of the wall. Theoretically, cross ventilation provides better ventilation than single-sided ventilation. Nevertheless, it is difficult to secure cross ventilation in public apartments due to some reasons such as security, privacy, cost, etc. Therefore, several design improvements of the existing apartments are necessary to improve the ventilation performance.

This pilot study aims to reveal the ventilation performances of the existing unit's floor plans and opening configuration as the basis for future improvement. A typological study and CFD simulation were carried out in this study.

2. METHODOLOGY

2.1 Typological Study

A typological study on the existing apartments in Indonesia was conducted to obtain the typical design features for unit's floor plan as well as opening configuration. An internet-based survey was employed by collecting drawings and photos of 200 existing middle-class apartment buildings (built between 2007 and 2020) in Indonesia. In general, the apartment buildings have two major unit types, i.e., the single type (24m^2) and the family type with two bedrooms (2BR) (36m^2). This paper focuses on investigating the 2BR unit types.

2.2 Computational Fluid Dynamic (CFD)

The CFD simulations were carried out using scSTREAM v2020 to evaluate the ventilation performance. In general, this software works based on the cylindrical structured mesh method to solve the thermal-fluid problems of the indoor as well as outdoor environment.

A simplified 5-storey building model representing the typical public apartment was created to reduce the computational time of CFD simulation (see Fig. 1). The CFD model setting is listed in Table 1. As shown, the grid size is defined as 0.075 m and the total generated mesh ranges from 28-36 million (depending on the simulated cases). In addition, the isothermal condition was assumed considering the small temperature differences between the indoor and outdoor environments. Moreover, the Standard k-ε was used as the turbulence model in the steady-state analysis. The boundary condition is also determined based on the actual condition. In regards to the inflow velocity profile, the power-law equation was used in this model (see Eq. 1).

$$\frac{U_Y}{U_{ref}} = \left(\frac{Y}{Y_{ref}}\right)^{\alpha} \quad (1)$$

where U_{ref} is the average velocity at reference height, Y_{ref} is the reference height and α is the power law exponent.

Moreover, in order to investigate the influences of the floor plan and opening configuration, a parametric study was performed by changing the opening components (i.e., window and door) close/open conditions under several typical floor plans of apartment in Indonesia. In total, four opening conditions are evaluated in each representative floor plan, i.e., simple opening-only (i.e., hole only, without window), cross ventilation mode, single-sided ventilation mode, and window-only (i.e., balcony door and entrance door are closed), respectively (see Table 2).

2.3 Evaluation parameters

In order to analyze the ventilation performance, common key parameters were evaluated, which are the air-flow pattern, ACH and indoor air speed.

In general, the ACH requirement could be categorized based on its purpose, which are the ACH for indoor air quality and heat removal, respectively. Firstly, the ACH for indoor air quality aims to achieve the indoor air quality that is associated to the occupant's health. Referring to the Indonesian National Standard (i.e., SNI 03-6572-

Table 1:
CFD simulation setting

Parameters	Descriptions
Wind characteristic	• 2 m/s at ref. height of 10m • Power law with exponent of 0.27, represent the urban area • Wind direction (90° from building mass)
Analysis type	Steady state
Thermal	Isothermal condition
Turbulence	Standard k-eps model
Mesh number	• Total mesh = 28-36 million • Standard length = 0.075 m (x, y, z)

Figure 1:
Simulation building model (a) front view and (b) isometric view and (c) side view, and (d) building floor plan

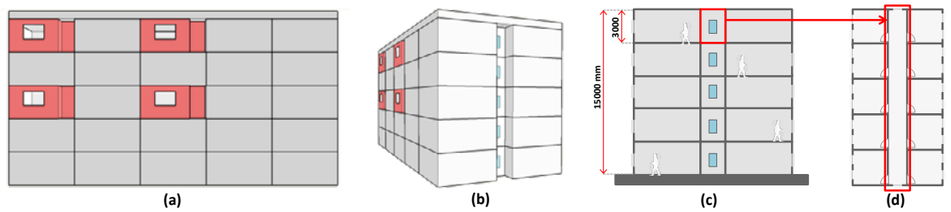


Table 2:
Simulation case design.

Cases	Without windows	With windows									Descriptions
		LDK			BR-1		BR-2		Toilet		
		Entrance	Window	Door	Door	Window	Door	Window	Door	Window	
1	○										Opening only
2		○	○	○	○	○	○	○	○	○	Cross-vent.
3		✕	○	○	○	○	○	○	○	○	Single-sided vent.
4		✕	○	✕	✕	○	✕	○	✕	○	Window only

Note:
BR-1 = Larger room; BR-2 = Smaller room, LDK=Living Dining Kitchen
○ = Open ✕ = Close (if the opening is available)

Figure 2:
Typical unit's floor plans of public apartments.

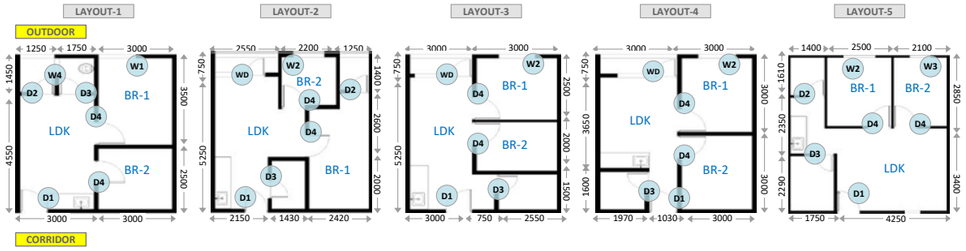
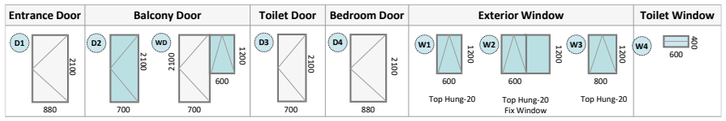


Figure 3:
Typical doors and windows design.



2001), the minimum ACH value is 4 ach for common living space [10]. Secondly, the ACH requirement for heat removal aims to provide sufficient ACH to remove the heat due to internal heat gain inside the room. The study [11] shows that by using the heat balance approach, the required ACH to remove the heat inside of the typical studio room in Indonesia is between 150-200 ach.

Furthermore, the indoor air speed is evaluated by referring to the Singapore's green building guideline. In the guideline, the average wind velocity of 0.2, 0.4, and 0.6 m/s are classified as 'moderate', 'good' and 'best' categories, respectively. Those average wind velocities are calculated from the wind speed at horizontal plane of 1.2 m above the floor level [12]. This standard is basically in accordance with the ASHRAE's adaptive comfort index for naturally ventilated space. It is described that the elevated air speed of 0.6 m/s can raise the upper limit of thermal comfort acceptability by 1.2°C [13].

3. RESULTS

3.1 Typical unit's floor plans and opening configurations

The typology survey of the public apartments shows that there are five floor plans for 2BR unit that are commonly found in the apartment building in Indonesia, namely Layout-1 to Layout-5, respectively (see Fig. 2). In general, most surveyed buildings have floor-to-ceiling height of 2800 mm. Based on the survey, Layout-1 is the most common floor plan where 23.1% of the samples apply this layout. Meanwhile, the others Layout-2, -3, -4, and -5, accounts for 10.3%, 12.8%, 10.3%, and 5.1% of the sample. The 2BR unit typically consists of Living Dining Kitchen (LDK), a large bedroom (BR-1), a smaller size bedroom (BR-2), and a bathroom. In regards to the corridor type, around 90% of the surveyed apartments are dominated by the double-loaded which is equipped with two openings at the end of the corridor (see Fig. 1).

The typical opening configuration in the public apartment was also investigated. As shown in Fig. 3, the apartment doors have a similar opening type and only differ in size and materials. In regards to the door size, LDK and BR have larger size door (W880 x H2100) than the ones in the balcony and bathroom (W700 x H2100). A solid opaque door panel is commonly used for LDK, BR, and bathroom doors. Meanwhile, an aluminium window frame with a transparent glass panel is frequently used for the balcony door.

In addition, the top-hung window is commonly used in the BR and LDK of the existing public apartments (i.e., 31% of the samples). In general, the top-hung window is dominated by the size of (W600 x H1200) and (W800 x H1200). Moreover, a top-hung window is also commonly combined with a fixed window (with the size of W600 x H1200) in order to increase the amount of natural daylight.

3.2 Effect of the unit's floor plan on ventilation performance

Figs. 4 and 5 show the airflow distribution on the horizontal plane at 1.2 m above the floor level in the windward and leeward units on the 3rd floor of the building model for all test cases. In general, the windward units receive greater incoming wind flow than the leeward unit. As shown in Fig. 4, in most of the cases, especially under cross ventilation, all layouts receive a large amount of airflow into the room. This is due to a high-pressure difference between the outside wall of the windward unit and the corridor space. In contrast, the leeward units experience a small pressure difference between the outside wall and corridor space, thus inducing slower airflow (see Fig. 5). This condition is a major drawback of the leeward unit in an apartment with a double-loaded corridor configuration. In the other words, it is difficult to secure a uniform ventilation condition in all units.

Furthermore, Figs. 6 and 7 show the percentage of units in the building that experience particular ranges of ACH and indoor air speed, respectively. The given ranges for ACH and indoor air speed have been discussed in the previous section. As shown in Fig. 6a, most LDKs in all layouts experience sufficient airflow under cross ventilation. In regards to the ACH, the LDK under cross ventilation also could meet the required value for IAQ (more than 50% of total units) and heat removal, respectively. However, the percentage of ACH more than 150 ach in the LDK is less than 50% of the total units (see Fig 6a).

Meanwhile, in regards to the indoor air speed, only the LDK can obtain a large percentage of units experiencing the indoor air speed of 0.2-0.4 m/s (Fig. 7a). A fair ventilation performance in LDK is probably due to the availability of openings on the façade and minimum obstacles in the interior due to the partition or wall. Hence, the incoming wind could smoothly flow through the LDK. Moreover, although the LDK in Layout -1 and -5 have a

Figure 4:
Air flow distribution at horizontal plane of windward unit which located in the 3rd floor under all cases.

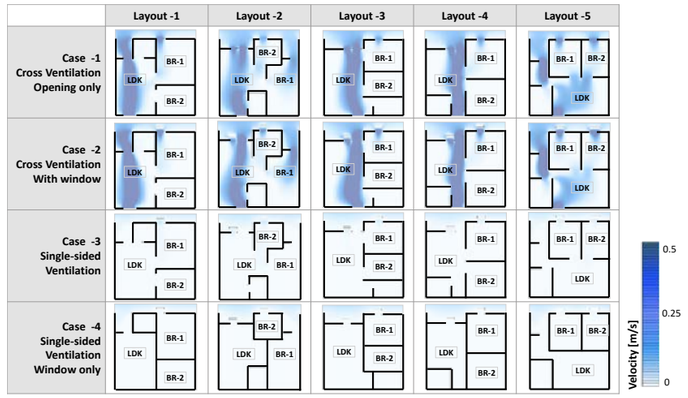


Figure 5:
Air flow distribution at horizontal plane of leeward unit which located in the 3rd floor under all cases.

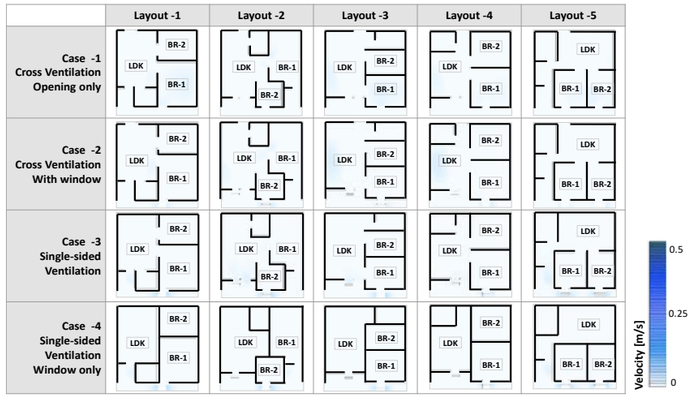


Figure 6:
Percentages of units with specific air change rates (a) LDK; (b) BR-1; and (c) BR-2.

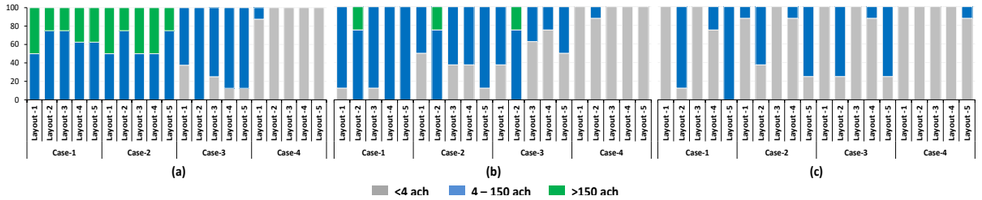
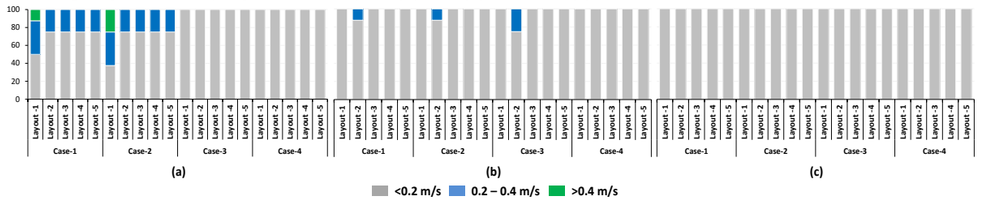


Figure 7:
Percentages of units with specific indoor air speed (a) LDK; (b) BR-1; and (c) BR-2.



relatively smaller size of exterior openings, the LDK in these layouts still could perform well due to the airflow from other spaces under cross ventilation (i.e., when the BR's door opens). In addition, only Layout -1 could provide the indoor air speed of more than 4 m/s. This is probably due to a reduction of the fluid pressure around the opening that enhances greater indoor air speed. This pressure reduction is created by the narrow space in the balcony that creates the *Venturi* effect.

In contrast, under single-sided ventilation, most of the LDK in all layouts have relatively lower ACHs and indoor air speeds compared to the cross ventilation mode. Interestingly, even under the same single-sided ventilation, the ACHs in Case-3 and -4 show a significant difference. In Case-3, more than 62.5% of the total units have LDK that satisfies the ACH more than 4 ach. Meanwhile, under Case-4, most LDKs are dominated by ACH smaller than 4 ach. This is probably due to the influence of the number of openings as well as the interior door (i.e., bedroom's doors). In Case-3, the window and balcony door are open and the interior doors are also open. This shows that the number of openings on the outer wall as well as the air permeability between rooms is the important factors to secure better ventilation for an apartment unit with single-sided ventilation.

Furthermore, the BR-1 has sufficient airflow under cross ventilation due to the availability of openings facing toward the outdoor space. As shown in Fig. 6b, more than 50% of the units could meet the required ACH for indoor air quality under cross ventilation. Nevertheless, most of the units in all layouts are not able to receive the desirable indoor air speed of more than 2 m/s.

Moreover, most of the BR-1 has poor ventilation performance under single-sided ventilation. Nevertheless, although most layouts have poor ventilation performance, Layout-2 shows exceptional results. The simulation results show that under the cross and single-sided ventilation (i.e., Cases -1, 2, and 3), Layout-2 could provide the required ACH for heat removal and 'moderate' air speed in around 25% of the units in the building. This condition occurs most probably due to the *Venturi* effect in the narrow balcony of BR-1 in Layout-2.

Furthermore, most of the BR-2 in Layout -1, -3, and -4 encounter poor airflow due to the absence of any direct opening towards the outdoor. Therefore, the ventilation of BR-2 under these layouts strongly depends on the airflows from LDK and BR-1. In contrast, the BR-2 in Layouts -2 and -5 still could receive sufficient airflow because these layouts place the BR-2 at the outdoor side and equip it with a window towards the outdoor. In regards to the ACH under cross ventilation, almost all layouts could meet the required value of ACH for IAQ, except in Layouts -1 and 3 (see Fig. 6c). Moreover, under single-sided ventilation, Layouts -2 and -5 still could perform better than the other layouts, mainly due to the availability of windows. In addition, the BR-2 in all layouts have indoor air speed of less than 0.2 m/s in any ventilation mode.

3.3 Effect of opening configuration on ventilation performance

The simulation results show that most units perform better under cross ventilation than single-sided ventilation in all layouts. It clearly shows the importance to secure proper openings as inlet and outlet for the airflow, respectively. In the case of single-sided ventilation, providing two or more openings on the outer wall could create a pressure difference between openings, thus enhancing better air circulation. In addition, the air permeability between rooms significantly enhances the airflow even in a unit under single-sided ventilation.

As shown in the previous section, the BR-1 in Layout-2 has the best ventilation performance (see Figs. 6b and 7b). This is mainly due to the effect of the opening configuration, particularly the opening size. As shown in Fig. 2, the exterior opening of BR-1 in Layout -2 is actually a balcony door (W700 x H2100 mm), while the other layouts use windows (W600 x H1200 mm). Therefore, the BR-1 in Layout -2 could allow more air to enter the room due to a higher effective opening area.

In regards to the effect of opening type, the ACH in BR-1 under Case-2 (i.e., with window) is generally lower than in Case -1 (without window). This condition is occurred most probably due to the smaller effective opening area of the top-hung window in Case-2 than the simple opening in Case-1, which are 0.5 m^2 and 0.72 m^2 for the top-hung and simple opening, respectively.

Moreover, the effect of window type in the LDK varies between the types of floor plan. For example, the window in LDK could increase the ACH (i.e., in Layout-4) or decrease the ACH (i.e., in Layout-5) compared to the ACHs under the simple opening. This is probably due to the top-hung pane of the combined window and door in Layout -4 obstructing the incoming airflow. Hence, the obstructed airflow directly flows into the next door opening with a high air speed. While the ACH reduction in Layout-5 is mainly due to the top-hung pane in BRs blocking the incoming airflow, thus decreasing the airflow in the LDK.

4. CONCLUSION

In general, the results from this study show that the ventilation performances under natural ventilation conditions are greatly influenced by the selection of floor plan or layout of the unit. More detailed findings are summarized as follows:

1. The availability of exterior openings in each room is necessary when designing the floor plan of the unit in order to provide sufficient ventilation in the room.
2. Any airflow obstructions, such as the interior wall and furniture, need to be minimized in order to optimize the air circulation in the unit.
3. The balcony can be designed to optimize the incoming wind in order to create the *Venturi* effect, which could improve the ventilation performance.
4. The availability of openings in two or more walls could enhance the airflow rate. In this case, a permanent opening in the outer and corridor wall has improved the ventilation performance.
5. A large effective opening area at the inlet could improve ventilation performance under cross ventilation.
6. Under the single-sided ventilation mode, it is recommended to provide more than one opening on the outer wall, which acts as an inlet and outlet, respectively. In addition, it is also important to provide air permeability between rooms.
7. The selection of suitable window types also needs to be considered in order to optimize the overall ventilation performance.

The findings from this study would be useful for designing an affordable public apartment with better indoor air quality, energy-saving, and thermal comfort. Further study on other possibilities of the unit's floor plan and opening configuration is necessary to optimize the benefits of natural ventilation in public housing.

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13. ASHRAE Standard 55-2017. Thermal Environmental Conditions for Human Occupancy.

The literature review on boundary conditions of use for non-residential buildings

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ABSTRACT: This paper describes the results of qualitative and quantitative literature reviews on boundary conditions within educational buildings, emphasising the users' perspective. The reviews were performed before and during the COVID-19 pandemic using Scopus, Taylor& Francis, Web of Science databases. The boundary conditions understood as special characteristics for use and or precondition, determining specific features of buildings are investigated in the categories of energy, space use and user behaviour, and lighting. The reviews demonstrate that in the case of study investigations, a relation between different indicators helps define the boundary conditions. B/C are type of building/ user/ situation-pandemic / locations/ simulation inputs-values and methods- specific. The results of the papers published during the ongoing pandemic indicate that the perception of an indoor environment is changing along with its boundary conditions. This has consequences on the design, maintenance, and operation routines of educational buildings to limit the risk of transmission and contagion from airborne respiratory viruses.
KEYWORDS: Boundary Conditions, Energy, Use of Space, Lighting, Covid-19

1. INTRODUCTION

Under pressures of energy transition postulates, UN sustainable development goals (SDGs) [1] and COVID-19 pandemic confinement rules [2,3], it is crucial to identify the main boundary conditions (B/C) for the use of non-residential buildings. Boundary conditions indicate essential preconditions and particular characteristics for building design, operation and maintenance [4]. So far, little has been published on the B/C of non-residential buildings such as schools and university buildings before and during the COVID-19 pandemic. This paper provides a comprehensive literature review on B/C from the users' perspective conducted for Task 61 SHC IEA (International Energy Agency): *Solutions for daylighting and electric lighting* [5] and work done after completing the task. The research includes a mixed-methods approach based on quantitative, systematic and the experts' qualitative literature reviews and the online questionnaire. Main findings on B/Cs are described in four main areas: energy, users' behaviour and the use of space and lighting. The results suggest that standardised data used for calculations is often insufficient because of underestimating the actual user behaviours or changing circumstances like a pandemic outbreak.

The exact identification of boundary conditions or their factors in educational buildings can help develop a deeper understanding of interrelations between energy aspects, users' behaviours, and lighting and help to examine how boundary conditions within educational buildings changed due to the spread of COVID-19.

This paper aims to present the findings on boundary conditions of the educational buildings in the following categories: energy, building users' behaviour lighting in pre-pandemic and pandemic times. In this paper, the boundary conditions are understood as unique characteristics for use and or precondition, determining specific features of buildings [4]. The educational buildings include primary and secondary schools' premises, kindergartens, day-care buildings, university buildings, including libraries. The educational building is understood as a building exclusively used for more than 8 hours per day for educational purposes. The predominant users include children, students, and teachers.

2. BACKGROUND

The outbreak of the SARS-CoV-2 virus led to significant changes in the lifestyles of many people who use educational buildings. The regulations on self-isolation, quarantines and limited freedom of movement were introduced in different times and pandemic stages. They affected the use of educational buildings. One of the results of confinement regulations were educational building closures [6], which impacted 80% of children worldwide. According to the UN Educational, Scientific and Cultural Organization, one hundred thirty-eight countries have closed schools nationwide for different periods [7]. Many pupils and university students experienced distance learning and strict lockdowns, which brought about in-home space reinterpretations, different treatments of personal space and changes in perception of boundary conditions. Due to the unprecedented scale of the pandemic in modern times [8], the outbreak of COVID-19 has vast socio-economic implications and detrimental effects on almost every aspect of human life [9–11]. Consequently, it impacted the built environment. The paradigm to reduce potential risks and the spread of the virus becomes visible in many proposed solutions and research, forming a need for better air quantity, modular construction, and hygienic building materials [12]. The reopening of educational buildings also gave rise to many questions on strategies how to do it [13] and how to continue education assuring preventive COVID-19 measures, for example, in a context of HVAC (heating, ventilation, air conditioning) solutions [14]. The authors decided to focus on the B/C in the educational buildings due to their importance for better design of education premises. *"Education is one of the strongest predictors of the health and the wealth of a country's future workers, and the impact of long-term school closure on educational outcomes, future earnings, the health of young people, and future national productivity has not been quantified"* [6]

3. METHODS

The extensive literature review on B/C within non-residential buildings was based on a quantitative review, a systematic review and a qualitative experts' literature review. These reviews were performed by a team of international experts working together on the IEA task. The scope of the first quantitative review carried out in 2019 included peer-review papers and reports from the last 20 years (one exception). The second quantitative review was carried out at the beginning of 2022 during the ongoing global pandemic of coronavirus disease 2019 (COVID-19). This review was focused on the B/C in educational buildings only.

3.1 B/C pre-pandemic reviews

The first method was a qualitative literature review in the following databases: Scopus, Web of Science, Taylor and Francis, Google Scholar. The information was sought in all accessible sources of information – databases and libraries in May of 2019. The general search topic for the review was boundary conditions of use for non-residential buildings, emphasising user needs and requirements. The filters of searching were keywords, types of non-residential buildings and thematic categories: energy, use of space/ user behaviour, lighting, acoustic comfort, thermal comfort). 21 papers were selected for complete analysis, but only two of them discussed conditions within educational buildings and two in specific places- libraries.

The database, where the systematic review was conducted in 2019, was Scopus. Due to its broad spectrum of available scientific information, the search focused on peer-reviewed papers from the last five years. The search was limited to the following categories: engineering, computer science, environmental science, mathematics, energy, agricultural and biological sciences, medicine, earth and planetary sciences, materials science, and social science. The search was divided into three main stages. In the first stage, the total number of 93 143 documents were analysed. Afterwards, documents referring to the phrases "residential, dwelling, housing" and duplicates were excluded resulting in 388 papers. They were skimmed to check in accordance with the topic. Two hundred six articles were irrelevant. Afterwards, 52 primary documents were scanned, out of which 45 occurred to be irrelevant. Only seven articles were chosen for detailed analysis as a result of this systematic quantitative review. Six of them discusses conditions in educational buildings.

The third method was a qualitative review into only categories: energy, usage of space, lighting, acoustic and thermal comfort, and the search was carried out with an emphasis on building types: offices, schools, universities, hospitals, commercial buildings, libraries, and factories. It was carried out by international teams of experts from the IEA SHC Task 61 during two meetings in 2019 and 2020. Only 13 papers were related to boundary conditions in educational buildings.

3.2 B/C review during the pandemic

Qualitative literature review during the COVID-19 pandemic in February 2022 included papers found in Scopus, Taylor& Francis, Web of Science. The search categories were limited to energy, space use, occupants' behaviour, lighting; and had to refer to the COVID-19 pandemic. The words alternations like COVID-19, pandemic/s, infection were added to a search. This additional literature review aimed to compare main tendencies concerning B/C according

to global shifts associated with the COVID-19 pandemic.

4. RESULTS AND DISCUSSION

4.1 B/C indicators in the pre-pandemic era

The pre-pandemic reviews on B/C (qualitative, systematic and experts) resulted in the selection of 23 papers (Table B1). Twenty-one papers were written after 2010 with two exceptions related to the use of daylight and electrical light dated 2002 [15] and 1979 [16]. In the experts' review, acoustic and thermal comfort categories were added into the initial review categories: energy, use of space, user behaviour, lighting. The categories were further expanded into subcategories such as energy demand/modelling/consumption; widow control/ use; occupancy detection/prediction/modelling; daylighting and electrical lighting preferences/control as well as energy savings; acoustic comfort, sound levels/control; thermal comfort, ventilation, heating, cooling control, building envelope design (Fig. A1).

Table 1: B/C indicators in the reviewed papers.

ENERGY	USE OF SPACE	OCCUPANTS' BEHAVIOUR	LIGHTING
1. ENERGY DEMAND, CONSUMPTION - energy demand [17] - measured [18] and simulated [18] energy consumption - electricity consumption [19] **2. ENERGY EFFICIENCY** - energy-saving potential and operation daylight, electric light [20] - improvement of building energy efficiency**:** lighting [19], occupancy [21]	**1. INDOOR ENVIRONMENTAL QUALITY** - noise, smell, temperature, ventilation, air quality [22], daylight [23] **2. PHYSICAL PARAMETERS /** -academic progress [24] - an interplay between building users and physical environment, spatial ambience, and the users' behaviours [25] - building stock performance/ renovation [25] - aircraft noise /[26]/ thermal comfort [27] - comfort/climate change [28]	**1. OCCUPANCY PATTERNS** -predictions [17] - monitoring, understanding [21] **2. OCCUPANTS' BEHAVIOUR** - users' mood and saliva cortisol concentration [19] - energy-related occupant behaviour [27] - relation between occupancy & energy [29], lighting [30] - behaviour: use of daylight and electric light [31]	**1. LIGHTING USE & PREFERENCES** - light environment & perception [19] - lighting performance gap [30] - occupants' use of lighting systems [16,19] - use of daylight vs electric [31] **2. LIGHTING CONTROL** - reduction of incident solar radiation, glare levels, distance to windows daylight control [20,22], shadings [23] **3. VIEWS, DAYLIGHTING** - window views [32] greenery/ students' attention restoration [33] - presence of daylight/ academic performance [15]

Most of the reviewed papers (20) were case studies, including on-site monitoring cases. The B/C case studies were mainly held in Europe, with only two in North America and two in Asia. Other research methods included computer simulation methods, surveys, statistical analysis. The case study results were based on monitoring in 1 building (a few classrooms or a few parts of the building) to 80 buildings. The monitoring times ranged from hours to month depending on occupancy hours for the respective building type (i.e., day-care, kindergartens, schools/university- school schedule and school year; libraries: working days). The types of occupants vary from children to pupils, students, teachers, staff members. The number of occupants in the investigated buildings ranged from 84 to 3766 but was often not indicated (Table B1).

The B/C and their indicators and factors include energy consumption data, control of heating, ventilation, electric lighting, or window openings. Often operating schedules, physical characteristics of interior spaces were investigated with users' behaviour and energy demands (Table 1). The reviewed B/C and their factors range from values, conditions to particular indicators (aircraft noise [26]), user profiles, or operating hours. The results indicated that boundary conditions and indicators are often building type-, user- or situation-specific.

The literature review results indicated that many B/C indicators relate to a specific use of spaces and school routines. The indoor quality indicators like fresh air, ventilation, temperature, daylighting [15], lighting control, access to view [32] could influence educational performance or young users' attention restoration [33]. Educational building's types and styles differ and their operational times, occupation patterns, routines, and users. These diversities contribute to the multiple B/C values.

Few studies accentuated the importance of electric lighting flexibility [24], daylight control and outside views as conditions related to academic performance [15] or stress levels [33] (Table 1). The other factors influencing the educational environment and its users are health and safety standards, energy policies, and educational curricula.

4.2 B/C indicators' changes

The qualitative review of B/C indicators in educational buildings during pandemic resulted in 19 papers. However, most articles described the short-run effects of the COVID-19 pandemic on the educational built environment and users and could only predict long-run implications [34]. The research methods include reports, short monitoring, or case studies descriptions. The review results illustrate that pandemic and the ways to mitigate it altered boundary conditions within education buildings concerning energy, use of space and users' behaviour, ventilation, and lighting (Fig. A2).

The school closures have significant social, economic and health consequences for the users of educational buildings [7]. There is no reliable data on the relative contribution of school closures to transmission control [13]. Some researchers suggest that school closures alone would prevent only 2–4% of deaths, much less than other social distancing interventions.

COVID-19 pandemic triggered changes in overall energy use, posing significant challenges to the energy sectors in many countries due to fluctuations in energy use of buildings [35]. In some places, electricity demand was reduced around 10-30 % during the lockdowns but climbed after a reopening due to increased window opening [35,36]. Researchers noted that during COVID-lockdown, the energy system in many buildings was operated inefficiently [35]. In some cases, the operation of closed educational institutions followed the weekend patterns. The school closures are also associated with extended use of various digital screen devices [37] and increased domestic electricity use. Researchers describe decreased electricity use in public buildings [38] and public schools. M.S. Geraldi reports mean electric energy reductions in Florianópolis (BRA) in elementary schools by 50.3 % and nursery schools by 50.4 %, compared to the same period in the last two years [38]. It is observed that unoccupied buildings present considerable energy consumption due to stand-by loads and viral loads, such as lighting for safety and computer servers [38]. Researchers noted that despite redundancy in occupancy patterns in Norwegian educational buildings, the heating system's operation remained on the same level [35]. Inflexible sustainable approaches partly explained it.

Boundary conditions concerning HAVAC (heating, ventilation, and air conditioning) have been changed to meet the goals of occupants' health and to comply with new hygienic-sanitary rules- the air changes with fresh (uncirculated) air [39]. Considering a high crowding index in educational buildings and new pandemic related restrictions and rules, higher ventilation rates with fresh air are required, leading to increased primary energy use [39]. Researchers noted a need for new energy-management solutions and high energy-efficient ventilation to limit COVID-19 contagion in schools [40]. Furthermore, they also emphasise a need for indoor air quality (IAQ) improvements in classrooms, a central HAVAC management system to respond quickly to an internal source of contamination, improved filtration system [14].

The changings in educational institutions' routines and social distancing rules also had consequences on space use and people's behaviour [13]. The COVID-19 spread resulted in different strategies for educational buildings in terms of returning to on-site lessons, school social distancing, testing, and contact tracing practices [6,13]. The disturbances of school life, social isolation and remote learning, with increased screen time among children [37], also impacted school children, their caregivers [41] and teachers. The pandemic has affected the perception of the surrounding environment and its barriers [10]. The reopening of educations buildings also brought new ideas on how to mitigate the spread of the virus and reduce airborne transmission indoors. In terms of use of space, intermittent occupancy of classrooms or schools combined with ventilation was proposed [42]. The room's occupancy capacity and times were reduced. The users were encouraged to leave the classroom periodically to guarantee access to outdoor air [42]. One study points out a possible evolution of households' long-term decision making due to the COVID-19 crisis: the ability to 'work from home' and online schooling might influence people to live further away from downtown, increasing suburbanisation trends [43].

Lighting researchers noted an increase in the importance of windows as providers of external view, visual social connections with other people [44] and fresh air. They also pointed out that electric lighting had a significant share in energy consumption in educational buildings despite lockdowns because of stand-by and emergency lighting. Thus, behavioural changes and more efficient lighting systems could reduce basal energy consumption [38].

5. CONCLUSIONS

Defining border characteristics helps to understand the role of users within spaces and their impact on the building's functioning. COVID-19 is a new variable that impacted users and educational building spaces. Consequently, a completely new B/C emerged. The learning process gained new actors such as caregivers, and remote learning made home the new learning environment space. The use of spaces in educational buildings changed to prioritise users' health and mitigate the spread of the virus. In the first phase of the pandemic, energy savings became marginalised, and despite worldwide schools' closures, the decrease in heating and lighting was not significant.

The pandemic caused shifts in understanding of boundary conditions. An increased interest in indoor air quality (IAQ) improvements was noticeable [14,42]. The energy efficiency/ renewable energy generation indices were less studied. Conditions for the use of space have been changed to accommodate the needs of distancing, different space routines, and hybrid learning practices. Users of educational buildings experienced many effects of remote education and new social distancing rules like mandatory mask-wearing. In lighting, access to views outside and greenery started to be more important and widely studied [44]. One of the researchers noted that the perception of an indoor environment changed with immediate consequences on the design, operation, and maintenance of HVAC systems to limit the risk of transmission and contagion from airborne respiratory viruses [39].

The review demonstrated that B/C are building type/ user/ situation (pandemic)/ location specific. Therefore, they are not easily transferable, but they

help understand correlations between various factors shaping the educational built environment.

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APPENDIX A

Figure A1: Categories and subcategories of search themes during the experts' review.

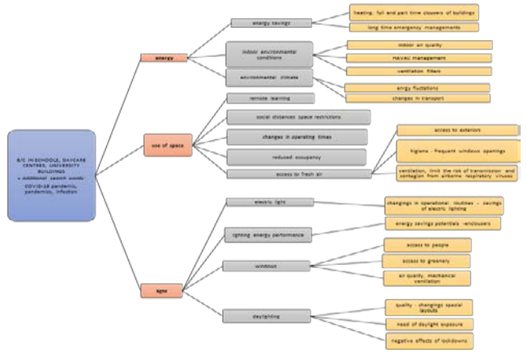

Figure A2: Categories and subcategories of search themes during the qualitative review during COVID-19.

APPENDIX B

Table B1: Results of the qualitative, systematic and experts' review before the COVID-19 pandemic.

	Investigated paper	CATEGORY OF INVESTIGATED B/C FACTORS				APPLIED METHOD OF INVESTIGATION			GENERAL BUILDING DATA						GENERAL OCCUPANCY DATA		
									INVESTIGATED BUILDING TYPE			BUILDING LOCATION					
		Energy	Use of space	Occupants behaviour	Lighting	literature review	case study, on-site monitoring	other	school	university	library	City	country ISO3166	NUMBER OF ANALYSED BUILDINGS	NUMBER OF ANALYSED OCCUPANTS	MONITORING DATES	TOTAL MONITORING TIME
1st method	Wauman 2015 [17]	Ed	+		EL	+	+	Representational school building model based on 35 buildings	+			Flemish Region	BEL	35	250	1. Sept.-30. June	±1200 hours
	Hunt 1979 [16]			+	EL, DL		+		+ & office			N/A	N/A	1	N/A	(Jan–Jun, Jul–Dec)	6 months
	Sufar 2012 [45]		+	+	EL, DL	+					+	N/A	MYS	N/A	N/A	N/A	N/A
	Wang 2017 [21]	Ee	+	+	EL		+				+	Reading	GBR	1	N/A	N/A	30 days, 24h/day: 2x15 days (term, vacation)
2nd method	Mateus 2017 [18]		+				+		+			Lisbon	PRT	2	N/A	N/A	N/A
	Delvaeye 2016 [20]	Es, Ec			DL		+		+			Haacht	BEL	1	N/A	1.12.2013 – 30.11.2014	Total: 1140 hours
	Gentile 2018 [19]	Ee, Es		+	EL		+		+			Helsingborg	SWE	1	116	21.11.2012 – 09.04.2013	N/A
	Cortiços 2018 [25]	Es	+			+		+	+			Lisbon	PRT	1	300	N/A	N/A
	Calama-González 2019 [23]	Ee			DL, EL			+	+			Seville	ESP	1	N/A	May 2017 – April 2018	Annual hours 2nd floor: 2394h 1st: 1680h
	van Someren, 2018 [30]	Ee, Es			DL, EL			+	+			N/A	GBR	3	N/A	2012–2013	N/A
3rd method	Barret 2015 [24]		+	+			+		+			Blackpool, London Borough of Ealing, Hampshire	GRB	27	3766	N/A	visits
	Li 2016 [33]			+	DL		+		+			Illinois	USA	5	94	N/A	9 am and 5 pm
	Vásquez 2019 [32]			+	DL		+		+ preschool			Florianópolis	BRA	1	84	N/A	1 pm-5 pm various seasons
	Wauman 2014 [17]	Ed			EL			model	+			N/A	BEL	35	N/A	N/A	N/A
	Sekki 2015 [29]	Ee	+	+			+	+	+ day-care			Espoo	FIN	74, 80	>2205 Ch	2011, 2012	Different energy audit times
	Montazami 2011 [26]		+	+			+	+	+			London	GRAB	18	92 T, 163 S	06, 07 2005, 2007, 2008	June & July
	Puteh 2014 [28]				EL/DL			Questionnaire	+			Malacca	MYS	3	917-6 S	N/A	N/A
	Salleh 2015 [22]		+	+	EL/DL			POE questionnaire, field observations	+ kindergartens			N/A	MYS	240	404	N/A	N/A
	Heschong 2002 [15]		+	+	DL, EL			Multivariate regression analysis math and reading test results, and the demographic characteristics	+			Orange County, CA; Seattle, WA; and Fort Collins, CO	USA	2000 classrooms	6000-8000 S	N/A	Sample visits
	Almeida 2016 [27]		+	+			+	Measurements & questionnaires	+	+	+	Viseu	PRT	6	487 S	2014	March & May
	Delvaeye 2018 [20]	Es, Ec	+	+	DL, EL		+	Lighting controls	+			Haacht	BEL	1	N/A	2013-2014	Dec. till Nov.
	Bernardo 2017 [46]	Ee, Ec	+	+	DL, EL		+	Smart controls, models	+			Central PRT	PRT	1	955 S, 99 T, 30 Stf	Sep. 2012-Aug. 2013	visits April 3rd - April 16th
	Lourenço 2019 [31]	Ec	+	+	EL, DL		+	Statistics, simulation models, POE	+			N/A	PRT	90/8/4	N/A	2013-2015	Cold &warm seasons

Abbreviations: Ee – energy efficiency; Ed – energy demand; Ec – energy consumption/use; Es – energy-saving, EL – electric lighting; DL – daylighting; T – teachers; S – students; Ch – children; Stf - staff

Keep It, Grow It, Mix It

Urban densification with a focus on reuse, mixed-use and extension of existing buildings

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ABSTRACT: Climate neutrality coupled with an overall positive ecological footprint is still a distant dream for new construction. The German building sector is directly and indirectly responsible for about 40% of all German CO2 emissions and has so far failed its CO2 reduction goals. For the German building sector, the key to climate neutrality lies not only within sustainable new construction but in its existing building fabric. The embodied carbon of new construction needs to be reduced as well as the amount of new construction itself. In this paper, we present three projects of the office Sauerbruch Hutton, in order to not only highlight the potentials but also the problems that planners face in different parts of the world. All three projects seek to create benefits for the urban surroundings, therefore changing the perception of a building not only as an individual object, but as part of the urban tissue.
KEYWORDS: Density, Responsibility, Timber, Reuse, Life-Cycle-Analysis

1. INTRODUCTION

To achieve the most recent climate action plan goals by 2050, CO2 emissions must be reduced drastically, aiming for climate neutrality. This might be achievable under current economic and regulatory circumstances. However, all other phases in a building's life cycle need to be considered and become much more ecological. On average, 25-40% of a building's CO2 emissions over a life span of 50 years evolve from new construction processes [1]. This proportion increases up to 100% if the building operation is CO2 neutral or plus energy. The CO2 life cycle footprint of retrofits amounts, on average, to 10-25% [2].

In order to understand the impact of the CO2 footprint of reused or new construction, as well as the differences between material choices, Sauerbruch Hutton produces life cycle analyses (LCA).

By reusing buildings to meet current and future spatial demands, we reduce construction as a whole. Architects should provide arguments for politicians to strengthen the relevant branches of industry and inspire clients and other planners to tender and implement a new reuse building culture.

Likewise, in order to reduce the footprint of new construction, the processes of manufacturing, transportation, construction, maintenance and disassembly should use renewable energy and local, reused, recycled or renewable materials. Compared to a conventional building, CO2 emissions can be reduced by ca. 40% [4] by using sustainable materials such as timber. This would be a big step towards sustainable construction, but not sufficient. We also need to make sure that what is built is robust and beautiful so it can be used for a long time as to minimize new construction.

The densification of cities can be part of the solution when harnessing the potential of existing built environments, designing for future flexibility and social well-being while carefully growing with a reduced spatial demand. If the cities are expanded upwards rather than outwards [5], land is saved, journeys are shortened and, with ground floor public use, the public realm is enlarged.

At the PLEA conference, three key-projects from Sauerbruch Hutton will be presented that showcase these strategies. The first project, Munich Re, focuses on restructuring the façade and interior of an existing building through careful extraction and reshaping, giving it a completely new appearance. The second project, the extension of the Berlin Metropolitan School, comprises rooftop additions to three of the existing structures through a light weight timber construction. The third project, Puerta los Andes, a mixed-use complex (in planning) in Santiago de Chile, takes maximum advantage of this inner-city location.

2. KEEP IT — MUNICH RE

This refurbishment and retrofit of a 1980s office block in Munich in 2014 provided a rare opportunity to thoroughly reuse an existing building, minimising the overall energy consumption and improving levels of workplace comfort and environmental quality. The complete renewal of the façade was used as an opportunity to give a previously faceless building on the city ring road an elegant and unexpectedly dynamic presence. The solid spandrel panels were removed to allow full-height glazing, and the building's overall form was modified to conceal the formerly projecting staircases and to create a new, dynamic entity.

Figures 1 and 2:
Before and After © Sauerbruch Hutton

2.1 Design for reuse

Converting a structure previously designed for a different purpose is challenging. In this case, the building was made to host huge computing machines. The deep floor plans allowed for a dark central area with space for the computers, which were really enormous in those days, with daylit office spaces around the perimeter. As the central area was neither naturally ventilated nor lit by daylight, it was decided to take out some ceilings and create a central atrium. This allowed for an office design with standards comparable to those of new-built offices.

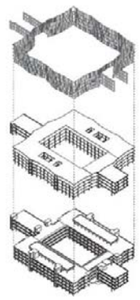
Although the main structure was retained, the façade was completely replaced. The non-load-bearing concrete balustrades and the lintels above the windows were removed and replaced by large windows with low balustrades. Both measures – the creation of daylit atriums in the middle of the floor plan and the extension expansion of glazed area - result in a great improvement in the amount of daylight.

2.2 Lessons learnt

When the decision of tearing down the slabs in the middle of the floor plan was made, the impact on the structure had to be analysed. The 1980s structure was conceived using the minimum amount of concrete, resulting in a lean structure without any buffer for additional loads. By taking out the middle slab, the static system of the load bearing structure was changed and weakened, and additional reinforcement was therefore required. To leave the remaining concrete slabs intact, a fibre reinforcement was bonded into the soffit.

Following the fire safety regulations, the four upper floors of the main structure were divided into units with a maximum area of 400 m². Direct access to these areas is provided via the main staircases and lifts – which were kept. Thanks to the atrium, there are no gloomy core areas in the units situated in the middle of the north and south wings. The "conference bridges" (leftover structure spanning over the atriums) create spatial situations that increase the scope for communication between the floors.

Figures 3 and 4:
Left: © Sauerbruch Hutton / Right: © Jan Bitter



2.3 Life cycle analysis

The creative reuse of this building proved to be the most economical solution. Around 2,800 m³ of concrete were removed in the process and roughly 3,800 m³ of new reinforced concrete elements were added. To erect a new structure of the same volume and in a comparable form of construction, roughly 23,000 m³ of concrete would have been necessary.

The saving of roughly 19,000 m³ of reinforced concrete leads to a significant saving of embodied carbon. A new structure would have caused more than 32,000 MWh because of the high energy input in the concrete and steel production. This was reduced down to 6,000 MWh thanks to the conversion of the existing building structure. The

saving of 26.000 MWh prevents the emissions of up to 9,600 tons of CO2.

Additionally, CO2 emissions were saved due to the minimum demolition works, and the entire savings reached 10,175 CO2 as seen in figure 5, *Energy balance*. The operational energy demand was optimized by the new outer skin providing thermal insulation and solar protection, as well as natural lighting and ventilation in the offices. With these measures and the connection to the district heating of the *Stadtwerke München*, the CO2 emissions produced by heating were reduced to 36% compared to conventional gas-heating systems. Because of the *Stadtwerke München* produces energy out of renewable sources (such as geothermal, wind, sun or water), the CO2 emissions produced by electricity, especially for cooling the building, were reduced by 95% approximately.

Figure 5:
Energy Balance ©Sauerbruch Hutton

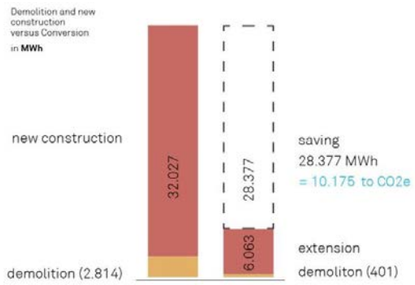
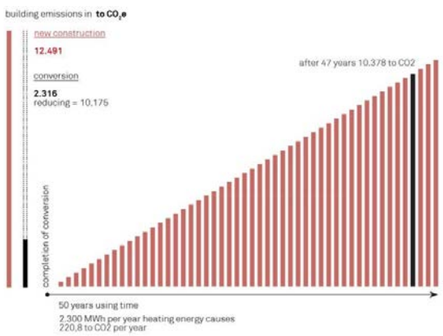


Figure 6:
Accumulated heating energy © Sauerbruch Hutton

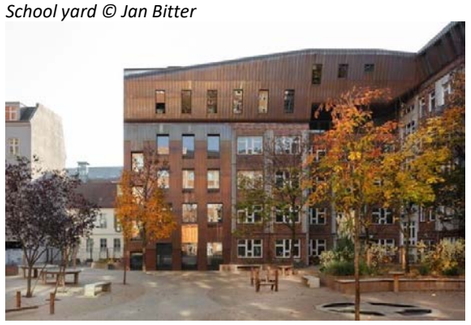


3. GROW IT — BERLIN METROPOLITAN SCHOOL

Berlin Metropolitan School was founded in 2004 and is located in an existing prefabricated building from the GDR era that was erected in 1987, using the then widely available building types of *Schulbaureihe 80* [3].

In order to implement their advanced educational concept and accommodate their recently established senior classes, the school required additional floor space. Four building sections cluster around a generous schoolyard inside the block. The scheme consists of rooftop extensions to three of the existing buildings, as well as a lateral annex that continues all the way down to ground level. The new spaces provide additional classrooms, music rooms, a library with access to a roof garden, administration offices as well as a large auditorium where the main events of the school year are hosted.

Figure 7:
School yard © Jan Bitter



The construction work needed to be executed during school hours and was realised in stages. Therefore, the extension was designed as a prefabricated timber system that ensured a fast assembly with a minimal disturbance. On account of its low self-weight, the timber construction required neither additional foundations nor alterations to the supporting structure of the existing fabric.

The light and sustainable building material timber is clad, but left visible on the inside, creating healthy, pleasant workplaces for students and teachers alike. Seen from the outside, the copper cladding matches the warm tone of the brick slips of the existing prefabricated modules, and at the same time distinguishes the new intervention from the existing building. Applied as a circular construction, the copper façade is both durable and reusable, not losing its value over time.

Figure 8:
Auditorium © Jan Bitter

3.1 Design for extension

The initial challenge was to adapt the existing structure to support extra loads and keep a harmonic aesthetic. The load-bearing structure of the extension was adapted in small parts to the existing structure in order to be as economical as possible.

In terms of design, it was important to break up the extremely monotonous grid of the façade without negating the load-bearing grid of the existing building.

The centre piece of the extension is an urgently needed meeting place that could not be realised in the existing building due to its narrow structural grid. It is housed in a large roof that hardly reveals its size from the outside due to its various angles. Sustainable design in dense cities implies that buildings could be used as much as possible and for different purposes allowing frequently vacant spaces to satisfy spatial needs and avoid new urban land use and new construction as much as possible. The school's auditorium was conceived as a meeting place for 1,150 people after school hours. It can thus be handed over to external parties and used for very different events.

In the extension, the corridors are to be actively used and supplemented with solid oak furniture. They are to be used for learning or just for meeting to exchange the latest news.

The new staircase in the annex to Lienistrasse also addresses the approach of multiple uses. There are windows where you can sit in pairs and have a good view of the schoolyard. Lienistrasse has very few public uses in this section, as the ground floor of many buildings are elevated. Therefore, it was important to bring the school together with the public life of the city and to open it up instead of closing it off.

3.2 Lessons learnt

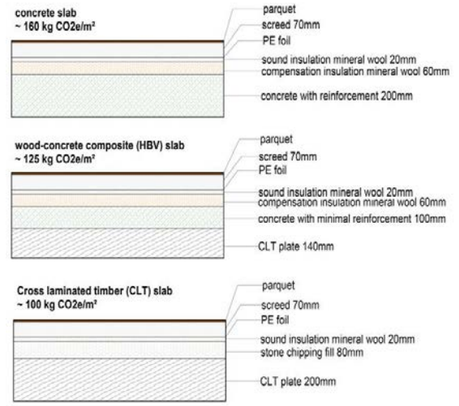
One goal was to use as little new material as possible. This had to be agreed in advance with the approving authorities, as flammable surfaces cannot be approved for its building class. The first step was therefore to avoid using cladding for fireproof, such as plasterboard, and to determine the combustibility of the surfaces with the authorities in order to make it fireproof without treatment but through burn-off. In total, this resulted in 33 applications for deviation in the fire protection concept with regard to timber visibility.

The timber shell should remain visible as far as possible. In order to meet the requirements for sound insulation and building services installations, two walls in each classroom had to be covered with additional cladding. In order to protect the raw wood surfaces from damage, only a pigmented wax was applied. The new ceiling system consists of hollow box ceilings with split fill and spans of 10.80m. This is the distance from bracing wall to bracing wall in the existing building. This ceiling system has a high proportion of wood and can be reused. The façade material is a standard copper sheet that is available on the market in rolls. The width of 35 cm results in a façade grid of 30 cm. The copper sheet is back-ventilated and can be easily recycled.

3.3 Life cycle analysis

Urban densification through rooftop extensions avoids the sealing off of new ground and saves infrastructure. As existing structures can often only handle light weight additions, timber structures are more suitable than heavy massive construction. In this project, almost 1,000 m^3 of wood were used for the new storey. The wood used for the roof extension stores around 720 tons of CO2 in total. Timber comes with the benefit of renewable, CO2 binding growth and a considerably less energy-intensive production than other conventional materials such as concrete or steel. Timber constructions have up to 50% lower CO2 footprint over the life cycle than conventional construction types.

Figure 9:
Life cycle analysis CO2 © Sauerbruch Hutton



By combining conventional building materials, such as concrete, with wood systems, significant CO2 reductions can be achieved, though still less than for timber alone. Composite ceilings often allow for more flexibility in height and span, which is sometimes needed in retrofits, which often have more restrictions than rooftop extensions. As a result, the types of construction are currently developing rapidly and new CO2 reduction potentials are being tapped. The reuse or recycling of wood concrete composites however is difficult if the concrete is cast onto the wood and on site; prefabrication with a separate cast can be applied

as a solution. Also, for timber construction with glued components, such as cross laminated timber, solutions for recycling have yet to be found in order to avoid downcycling or burning of the wood.

4. MIX IT — PUERTA DE LOS ANDES

This mixed-use complex - which will be sustainable, energy efficient, powered by renewable energy and LEED certified - will consist of a three–level low-rise building acting as a plinth for a 20-storey compact office tower, a long 17-storey residential building to the west and nine underground levels. The mostly commercial plinth houses a large atrium and public plaza space at level 3 and at street level.

This project acts as a "vertical city", where large, easily accessible and integrated common spaces are proposed on different levels, with façades and views towards the city.

Figure 10:
View of the vertical city © Sauerbruch Hutton

4.1 Design for densification

The competition brief asked for a high-density mixed-use program with large quantities of public space on a site located at the intersection of three important avenues in the Las Condes neighbourhood, in the Santiago Metropolitan Region. Located alongside the *Alameda-Providencia-Apoquindo* axis, one of Santiago's major arterial roads, the site is characterised by a high urban density, while the short distance to the mountains range gives the site a strong presence of the San Ramón Mountain, an icon in the Santiago Valley.

Our proposal for the new development and urban spaces takes maximum advantage of this inner-city location with its unique character and strong relationship to the landscape, while being firmly rooted in the immediacy of the urban intensity evident at this place. The amount of large developments done in the recent years around *Apoquindo* and *Presidente Riesco*, the commercial center to the south of *Apoquindo*, as well as the busy traffic explain this condition (Metro Line 1, which runs along Apoquindo Avenue, is the busiest line in the Santiago Metro network with a daily ridership of 700,000).

A generous funnel-shaped atrium connects Puerta Los Andes to the immediate urban surroundings and the landscape beyond. This atrium is oriented to the heart of the *Las Condes* neighbourhood in the North and offers direct access to the Metro station.

This project is aimed to operate 24/7, and for this reason, it will articulate a continuous living-commercial life.

Figure 11:
Public space © Sauerbruch Hutton

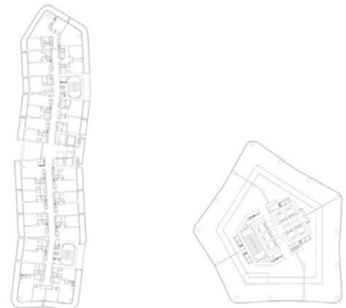
4.2 Sustainable strategies

In general, Sauerbruch Hutton aims for robust strategies. For this project, together with Transsolar we have developed a scheme adapting to the local conditions (very dry, very hot and sunny during the day, very cold at night). Mixed use, compact shape, exposed thermal mass and passive sun shading are some of the elements and strategies planned for Puerta de los Andes.

The new quarter is a composition of mixed-use with office, co-working, housing and retail. An around-the-clock use is making the area safe and lively at different times of the day. This is a diverse block conceived for a vibrant community that is likely to support business activity and engage with the retail and commercial offers allocated in the public plinth.

In the floor plans great attention is paid to the façade surface versus square meters. A compact layout assures good daylight without excess façade surface. In the offices, all work spaces are adjacent to the façade to allow for maximum natural light and views. The residential block is divided east-west and all units have an exterior area with the larger units placed in the corners, offering fantastic views in two directions.

Figure 12:
Floor plans © Sauerbruch Hutton



To allow for use of thermal mass, the soffit is exposed concrete. The design team flagged early on in the process that it would be beneficial to used robust and massive materials such as concrete or brick for the structure in order to achieve the necessary thermal mass. Water activated slabs reduce peak cooling loads and energy demand. It also allows for higher room height as there is no suspended ceiling.

The façade is using vertical and horizontal louvres to optimize daylighting while reducing solar gain. The roof over the public plaza creates a canopy that keeps rain and solar gain out but allows for pleasant levels of daylight, avoiding the otherwise very bright exposure of Santiago's sun.

5. CONCLUSION

Germany's existing building fabric reflects still a building culture anchored in the past. Today's challenge is not only to build new and sustainable, but to find a building culture and an architectural language which can be in dialogue with the old. The existing needs to be continuously adapted to the needs of the next generations.

In Munich Re it became soon clear that the deep floor plan was not suitable to be used in a contemporary office layout. Therefore, some floor plates were removed to create large atrium spaces to bring light and enhance communication. When building with existing structures, it is crucial to analyse the original plans, understand the realm of what is possible, of how the building has aged and how the surrounding circumstances have changed (e.g. ground water level, subsidence of parts of the building). Planning risks often arise from not knowing the exact built circumstances due to a lack of documentation and investigation.

Based on previous experiences, one should anticipate patterns of common problems and shortcomings in existing structures. For instance, the buildings from the 70s and 80s have often been built with reduced material use to minimize loads. Such buildings often need new fire protection and structural retrofit due to the degraded quality of building elements (e.g. too little concrete covering of steel reinforcement) or a changing of loads during the retrofit. The Berlin school example, on the other hand, showed an over dimensioned structure, in this case due to its standardized prefabrication, and thus has a great potential for structural adaptations and light weight extension.

When facing the challenge of an unknown building and the less common re-use of materials, all project actors have to work together with a common understanding and goal. The decision to re-use a building or its individual materials needs to be undertaken early in the design process in order to have enough time to investigate diverse re-use possibilities with the client and construction firms. Likewise, there also needs to be a common understanding of the limits an existing structure has to offer. Together the planning team needs to identify weaknesses and turn them into positive assets of the design. Building authorities need to get involved in order for them to trust and support the process.

The standards of today's norms can be a big challenge for the re-use alternative, when in reality their revision to allow more re-use would need to be encouraged. Regulations must ensure safety on site but not exaggerate planning risks. Such norms, when dealing with the existing, should encourage and reassure clients that it is more reliable, faster and less expensive to re-use buildings rather than incentivise new constructions.

The processes of building with the existing are challenging and not (yet) conventional, but solutions can be found and benefits created not only by saving resources and CO2 emissions, but by enabling an appreciation of our past building culture and finding a new architectural language that enhances the old with the new.

In large densification projects it is vital that mixed use is achieved as to ensure safe and future-proof business.

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Passive low energy earth architecture

Sustainable buildings for anyone and everyone, anywhere

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ABSTRACT: This paper sets out a case for embracing Passive Low Energy Earth Architecture (PLEEA) as the best practice solution to providing the buildings we need to provide the sustainable homes, villages, towns and cities of the future. Passive Low Energy Earth Architecture comprises unfired earth and natural materials, appropriate climate responsive design, natural ventilation and conditioning, adaptive comfort, safety, health and resilience and renewable technology for full LCD zero carbon performance. Two homes on the South Coast, NSW are examined. The benefits of PLEEA in a thirty-one-year-old mudbrick home is compared with that of a new code compliant project home. The comparison is explored through discussion of thermal performance, health and safety, embodied energy, and LCD using various tools and metrics. Secondly, the climate change resilience of the homes is explored using CSIRO Climate Analogue Towns data to provide weather file predictions into the future.
KEYWORDS: earth building, passive design, mudbrick, thermal performance, climate-resilient

1. THE CHALLENGE - one world's resources, addressing climate change and building resilience

We are utilising the world's resources at the rate only 1.7 worlds can provide and unless we act to reduce that already unsustainable equation our actions will lead to ecological and human collapse (1).

As the world's population reaches 8 billion, we have exceeded our sustainable capacity. The wealthy 20% are consuming 80% of the world's resources and we are showing virtually no progress in regard to sustainable development (2).

In Australia, homes consume around 22.8% of total electricity use, are responsible for more than 10.1% of greenhouse gas emissions (3) and contain embodied energy in the order of 53% of the total energy use over a 50-year life (4).

1.1. THE SUSTAINABLE SOLUTION - Passive Low Energy Earth Architecture (PLEEA)

This paper proposes that Passive Low Energy Earth Architecture is a sustainable approach to new building available to all, anywhere in the world. In Australia, our buildings need to be resilient in warming climates, able to cope with more unpredictable and unsettled weather patterns, more pronounced and frequent storms, droughts, floods, bushfires, cold snaps and heat waves.

How appropriate are modern "envelope efficient", high-energy dependent, lightweight, high embodied energy buildings in warming climates, pandemics, black-outs, and wildfires? Is BAU practice sustainable?

Passive Low Energy Earth Architecture comprises unfired earth and natural materials, appropriate climate responsive design, natural ventilation and natural conditioning, adaptive comfort, safety, health and resilience, and renewable technology with zero carbon performance.

1.2. Why build in unfired earth?

Earth building is appropriate, renewable, and sustainable technology. Ancient yet relevant today.

How Appropriate? Earth is an abundant, locally available, resource with the lowest possible embodied energy and very low environmental impact able to be used for building in multiple ways. It can be utilised for footings, floor, walls and roof, fireplaces, ovens, chimneys, stairs, and furniture. It can be the structural element, insulation, fabric energy storage, the lining and cladding all in one. Earth is naturally fireproof, soundproof, and resistant to pests, and rot. It is available to anyone anywhere, rich, or poor alike.

What about hazards and disasters? Earth is non-combustible and complies with Australian Standards with the highest Bushfire Attack Level rating - Flame Zone. It also has a fire rating of up to 4 hours. It can be used safely in places with high seismic hazards. (UTS, EBS) and may withstand category 4 cyclones.

Earth building is the ultimate renewable technology. Ideally, the earth material is sourced from the building's footprint or on-site, otherwise it can be sourced locally often disrupting waste streams. Earth building materials are infinitely recyclable.

Well-designed earth buildings use fabric energy storage which negates or reduces HVAC energy demand or at least time shifts the demand for heating and cooling, thereby reducing the peak load and helping the transition to renewable electricity generation. It is decentralised energy storage.

This energy storage capacity and the excellent hygrothermal properties inherent in earth elements absorb, store and release both heat and moisture stabilising and balancing internal temperature and humidity. Internal mass also provides radiant surfaces that offer a high level of comfort.

The earth elements can be optimised for any climate by varying density and thickness, which adjusts thermal characteristics. Generally, lower densities achieved by adding natural fibres (straw, hemp hurd, sawdust) and light weight aggregates (expanded clay, foamglass, pumice) are suited to colder climates and higher densities to hotter climates where added thickness increases thermal lag and storage capacity.

Insulation, whether bulk, reflective or optimised dynamic mass insulation, needs to be appropriate to the climate. Considerations are solar gain and night sky cooling potential, maximum and minimum temperatures, the seasonal temperature differentials between inside and outside, including diurnal fluctuation and humidity.

Earth buildings are managed and operated through mass-linked ventilation and natural conditioning. Natural ventilation is enabled and ensured as the operational strategy in passive low energy earth 'design' efficient buildings. In 'envelope' efficient buildings natural ventilation is often sacrificed for energy efficiency.

In passive low energy earth buildings, natural gains are maximised through design rather than focussing on the minimisation of conditioning losses through envelope efficiency. PLEEA doesn't rely on HVAC, are low energy, low cost, healthier and safer, as well as, climate change resilient.

2. CASE STUDIES – Two approaches

The benefits of PLEEA are examined using a case study of a passive solar designed mudbrick home and comparisons made with what is known about typical code compliant project brick veneer homes. We will explore the predicted thermal performance and full LCD of the two approaches to energy efficiency plus likely future performance for the life of the buildings given climate change predictions. We will discuss the two approaches in terms of space heating/cooling energy, carbon, comfort and IAQ of each approach.

Home 1 is well known to the author and has been assessed thoroughly. The paper presents monitoring and assessment of actual performance using various tools and metrics, as well as, and thirty-one years of lived experience in the home.

The author has constructed many project homes and understands the process from construction through demolition. Though having the benefit of a thorough analysis and discussion on thermal performance of both homes is known about Home 2 in some areas. The author also draws on research into similar buildings when necessary. More will be presented on comparative the LCDs of earth and common wall assemblies at the conference.

Both homes are built on the South Coast New South Wales, Australia in Climate Zone 6. It is characterised by mild temperate conditions with four distinct seasons, generally comfortable in spring and autumn, hot summers with moderate humidity, cool winters with low humidity, and significant rainfall throughout the year. Summers are short and mild, however there are significant heating requirements in the winter as there is an average minimum temperature below 10℃ for five months.

2.1. Home 1 – Mudbrick home (Figures 1&2)

Home 1 was designed and built by the author on small rural site in a bushfire prone area. It was designed and built by the author for their young family with modest financial resources and was completed in 1991. It is not perfect though that is partly why this study is so interesting. We will discuss what is required to make the building code compliant today and its new resilience modeling.

The 225 m2, 3-bedroom home is orientated with the long axis east-west to maximise and solar gain in winter and shading in summer. Walls and windows to the east and west are minimised and shading control is through vegetation both trees and deciduous vines growing over a pergola along the north and wrapping around the sides of the home. Living areas are zoned to the sunny northern side and bedrooms, bathroom, WC and laundry to the cooler southern side. Sun angles are 34 and 78 degrees at midday in winter and summer respectively.

The building is ground coupled and there is 200t of effective thermal mass in the mudbrick walls, concrete slab and tiled floors. Local hardwood was used for posts, Douglas Fir for beams and rafters and Radiata Pine for stud wall frames and ceiling, eave and timber framed wall linings. Recycled materials include beams, fired bricks for the chimney and paving, some western red cedar single glazed windows and redwood internal doors. The roof is corrugated steel with R 1.5 50mm thick foil/fibreglass blanket insulation between the roof and raked timber ceilings over exposed rafters.

Mudbricks were hand-made onsite from material sourced from the footprint of the building, sundried and laid with the same mud mix used as mortar. The density is 1750kg/m3.

The home relies on simple passive solar design. Occupants operate the windows and doors to achieve good levels of adaptive comfort during summer, autumn and spring without added energy. Mass-linked ventilation and natural conditioning achieve nine months of adaptive comfort through maximising gains from external conditions. For about three months of winter, solar gain is inadequate to always keep the home warm, so heating is supplemented by a solar

space heater and a wood heater. Fresh air is provided by air leakage, natural ventilation and a 40W fan introducing solar heated or night cooled air via the Ecoheat unit. The control panel is set, and it operates automatically when internal comfort may be improved by more favourable external conditions.

The home is simple to operate with daily set up, mainly the opening and/or closing windows, curtains and doors, taking about five minutes in the morning and in the afternoon. In Winter, a once only twenty-minute set up which involves closing the clearstory windows and removing the shade cover from the skylight and switching on the EcoHeat unit to winter mode. Though the solar heater is automatic, the wood heater needs to be lit and fire maintained as required.

The home is fitted with a grid connected 4.5 kWh PV array and electric boosted solar hot water service.

Figure 1: MUDBRICK HOME 1 - South Coast NSW, Australia

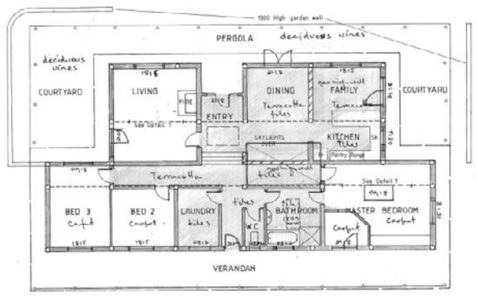

Figure 2: HOME 1 Plan - South Coast NSW, Australia

2.2. Home 2 – Brick veneer home (Figures 3&4)

Home 2 is a typical brick veneer (BV) project home of a similar size to Home 2 with a cement tiled roof and a polystyrene insulated concrete slab. Structurally, it is light timber framed with plantation pine (chemically treated) gang nailed trusses. It has a 2400 level ceiling. The external walls are required to have a R value of 2.5 and ceiling/roof R4.0. Walls and ceiling linings are plasterboard. The external walls are single skin 110mm extruded fired brick laid in sand cement mortar. The windows are aluminium double glazed with canvas awnings to west. Doors and windows are weather stripped and exhaust fans have draft stopping self-closing baffles. This is an effectively light weight home with exposed mass limited to tiled floor area (dark areas). Generally, space heated and cooled by RCAC and this is the government recommendation. The home isn't orientated or designed well from a passive solar design point of view though it has the perfect opportunity to do so. It meets the energy efficiency code.

Figure 3: BV HOME 2 - South Coast NSW, Australia (Tony Isaacs Consulting)

Figure 4: BV HOME 2 Plan - South Coast NSW, Australia (Tony Isaacs Consulting)

3.0 COMPARATIVE ASSESSMENT – various tools and metrics

3.1 The Nationwide House Energy Rating Scheme (NatHERS) – Problems with envelope compliance

NatHERS is a predictive thermal modelling tool used to demonstrate Energy Efficiency compliance with the National Construction Code (NCC). The home is rated based on the amount heating or cooling that is predicted to be needed in a typical year to keep the home within a set comfortable range. In most parts of Australia, new homes require a minimum star rating of 6 stars in 'Regulation Mode' for building approval.

Home 1 achieves a retrospective 3.2-Star rating and the predicted cooling energy is 11.3MJ (3.1kWh/m2) in NatHERS 'Regulation Mode' (Figure 5) which is more than three times better than the 6-Star project home (6).

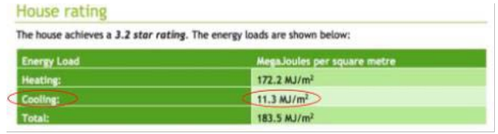

Figure 5: NatHERS Home 1 rating (Tony Isaacs Consulting)

Figure 5 shows that an assessor has no control over ventilation - a simple logic is used. Mass buildings are managed and operated through mass-linked ventilation and it is likely that the cooling demand is inflated. In terms of predicted energy, it is all about heating loads. Heating thermostat settings may be inappropriate according to research (7). The roof mounted solar space heater achieves a lift in temperature of 2-3°C internally which negates the need for wood heating on reasonable winter days, not nights, although this passive low energy space heating/cooling design feature isn't considered in modelling, nor is carbon intensity of energy source.

NatHERS 'Free Running Mode' can't be used for certification, though models how the home responds naturally to its climate, how well it achieves adaptive comfort and maintains safe conditions without energy. The frequency of the occurrence of temperatures for 3°C temperature bands in four defined areas of the home (Figure 6). Firstly, adaptive comfort is achieved meeting occupant expectations without energy for all but winter. Secondly, the home maintains safe limits of 12-30°C, marked by vertical red lines, without energy. It is clearly safe without power in a heat wave or cold snap. Thirdly, it indicates climate change resilience to warming climates.

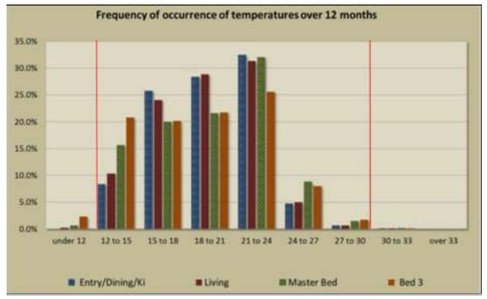

Figure 6: Home 1 assessment (Tony Isaacs Consulting)

Home 2 has almost equal predicted heating and cooling loads (Figure 7). It requires less energy to warm it in winter though can easily overheat any time (Figures 8, 9 & 10).

Energy Load	MegaJoules per square metre
Heating:	43.0 MJ/m²
Cooling:	37.6 MJ/m²
Total:	80.7MJ/m²

Figure 7: NatHERS Home 2 rating (Tony Isaacs Consulting)

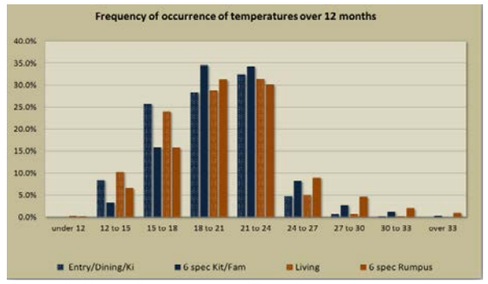

Figure 8: House 2 assessment (Tony Isaacs Consulting)

Home 2 is 5°C warmer on the day of lowest minimum temperature. Of interest, occupants of Home 1 find > 20°C too warm in winter perhaps due to surrounding radiant heat (Figure 9).

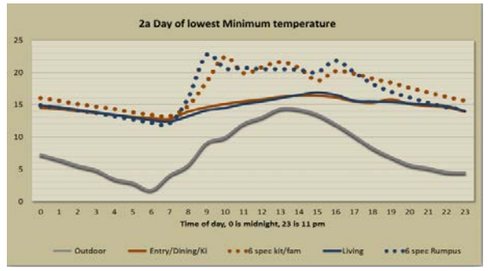

Figure 9: Free running coldest day (Tony Isaacs Consulting)

Home 1 exhibits an even predictable comfort and ability to balance temperature fluctuations, both diurnal and wild that mass building is recognised for (Figures 8 & 9). Earth buildings are also able to balance and condition the building's humidity through mass-linked ventilation though NatHERS doesn't model hygrothermal characteristics of building materials.

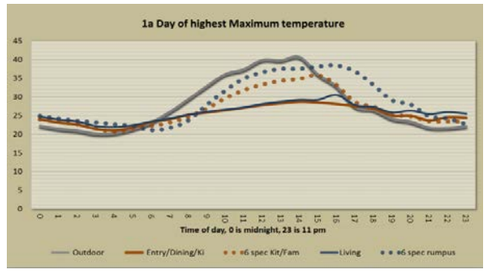

Figure 10: Free running hottest day (Tony Isaacs Consulting)

In summer, Home 2 is 10°C hotter than House 1 on the day with the highest maximum temperature (Figure 10). Close to outside, nudging 39°C inside when 41°C outside. It is reliant on RCAC and power.

The author lived for 9 months in a well- insulated and sealed conditioned building and noted occupants using RCAC for heating and cooling in the same day.

House 2 is clearly not a naturally conditioned passive low energy building so modelling to at least reduce likely energy use may be appropriate.

Whether or not NatHERS adequately or accurately assesses passive low energy design-efficient buildings is widely debated. However, what is clear is that Home 1 isn't reliant on cooling, and that despite it having a high heating demand, adaptive comfort is achieved with a carbon neutral fuel and sunshine. Furthermore, it is naturally ventilated not reliant on mechanical ventilation. The combined result is that space heating/cooling and ventilation is achieved with zero carbon impact. With highly rated envelope-efficient homes the opposite is true and reliability, safety and zero carbon becomes more difficult to achieve.

3.2 Adaptive Comfort, Health and Safety

Natural mass-linked ventilation is the driver of the performance of Home 1 ensuring fresh air and adequate air changes. Night-time purging in the summer, daytime operation of the solar space heater in the winter, and varied use in the autumn and spring generally maintain comfort plus IAQ. In a thermally lightweight "envelope efficient", building efficiency and IAQ are often mutually exclusive so that MVHR units are required. That energy is considerable.

Home 1 achieves good indoor air quality, and adaptive comfort for a large proportion of a year and will achieve safe conditions in a cold snap or heat wave through design. Biomass provides 17 - 20℃ comfort desired by the occupants in the living areas in the winter, and generally 2-3℃ less when sleeping). In autumn and spring comfort conditions are perfect. In summer the inside temperature rarely reaches 24℃ and sits between 19-23℃. Inside the maximum recorded in heatwaves is 28℃ and then only for a short period on the last day. House 2 exhibits overheating that can occur anytime of year. It wouldn't be safe to occupy in a heat wave without RCAC. Ventilation can be utilised only when external conditions are favourable otherwise efficiency is out the window when a building has no thermal reserves.

3.3 eTool Global LCA

eTool Global is a life cycle assessment tool. Home 1 achieved an eTool Global Emissions Certificate. Embodied carbon is down by 41% compared to the base building and operational carbon is down by 152% through minimising operational energy and carbon and with the addition of a 4.5kW photovoltaic array on the roof. Excess electricity exported to the grid achieves a 113% saving equating to beyond zero carbon (8). Home 2 is likely to be all electric with gas instantaneous gas hot water option for hot water. Reviewing other projects on the eTool website it will have zero savings in embodied energy so will struggle to meet full LCD carbon zero when fitted with PVs. There is too much embodied energy and due to the materials and construction techniques used in BV construction, on demolition, very little can be salvaged. It all goes to landfill some of it as toxic waste.

3.4 Climate change resilience

CSIRO predicts a generally warming climate and more extreme and unpredictable weather events. Climate Analogue Towns allow us to look at weather predictions into the future from 2030 to 2050 to 2090. The weather files from analogue towns are substituted for current files in resilience modelling.

Figures 11&12 show NatHERs modelling of a different local 5.4-star mudbrick home into the future. The heating loads decrease steadily from 75 MJ (20.8 kWh)/m2/yr now (2021) quickly dipping below the Passivhaus maximum heating energy demand in maybe 10 years and continues to fall as this south coast climate resembles warmer climates further north up the coast with minimal heating by 2050 and zero heating by around 2090 (9).

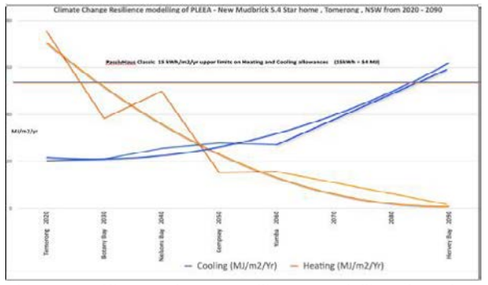

Figure 11: Climate change resilience modelling (based on modelling by Michael Purtell)

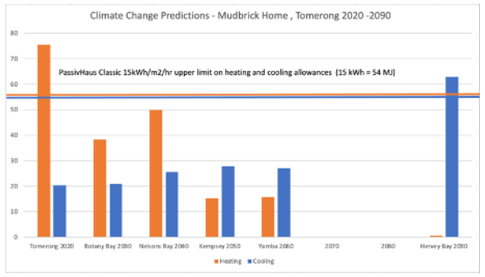

Figure 12: Climate change predictions modelling (graph based on modelling by Michael Purtell)

Cooling loads increase gradually from a low 20.3 MJ (5.6 kWh)/m2/yr through mid-north coast NSW to southern Queensland where the design is ideal for climate through to Hervey Bay above Brisbane where it rises just above Passivhaus criteria cooling energy demand allowance for the first time around 2090.

The NatHERS star rating improves overtime. CSIROs Evaluation of NatHERs 5-Star homes concluded that modern envelope efficient homes work well in winter in all climates though they use more energy in summer for cooling, more than predicted and the more "energy efficient" the envelope the more energy used in cooling. Studies show that PassivHaus and envelope efficient buildings are also prone to overheating. Does "envelope efficiency" achieve climate change resilience for the life of the building? Is the impact of climate change considered in simulations or legislated standards?

5. CONCLUSION

We are faced with a climate emergency that needed to be resolved as quickly as possible.

The safest and lowest energy option is to build a passive solar home that uses little or no energy for heating and cooling and will be resilient to more extreme climate conditions and blackouts and to an increasingly hot climate.

Natural ventilation ensures IAQ as VOCs and CO2 are less likely to build up and the risk of airborne contagion is much lower than with mechanical ventilated air-conditioned buildings. In envelope efficient buildings it is a battle between lost design efficiency, higher energy and cost or indoor air quality.

Australia is transitioning to renewable electricity and will likely increase envelope efficiency to 7-stars and is encouraging air-conditioning. The intent is to lower the potential heating and cooling energy usage and rely on 'guilt-free' air-conditioning powered by renewable energy. This doesn't address the impacts of air-conditioning: peak load demand, the GWP of refrigerants or safety of occupants in heat waves and bushfires when power is lost. It doesn't resolve the negative relationship between indoor air quality and efficiency. It doesn't consider embodied energy, climate change resilience of new buildings or whether designs assist rather than hinder the transition to renewable economies. It doesn't respect CSIRO's negative assessment regarding performance gap of the NatHERS approach to date or climate change resilience modelling (10).

The assumption of air-conditioning and setting minimum R or U values for envelopes is simplistic. Thermal modelling through sophisticated simulation is a useful tool for optimising design. Using it incorrectly as a regulatory tool can lead to negative consequences such as compliance difficulties for passive low energy buildings. Consider the latest in techno optimism thinking. Say we were to build a PassivHaus and it was assumed to have a lifespan of 60 years. Roughly 50% of the energy would be operational and at least 50% would be embodied energy (11). The embodied energy is released into the atmosphere now as an immediate 'carbon burp' (12). How does this address our sustainable future, if acting immediately is late?

Passive Low Energy Earth Architecture is an answer to a sustainable built environment. PLEEA can provide safe, healthy, comfortable, affordable, desirable, ecologically sound, zero carbon, climate change resilient buildings for the future, now.

The solution is available to anyone and everyone anywhere utilising the resources of one world.

ACKNOWLEDGEMENTS

We acknowledge the Traditional owners on whose unceded lands we live. We acknowledge their frontier wars, their fallen warriors and their elders past present and emerging.

I have borrowed from PLEA to describe PLEEA. Marci Webster-Mannison, architect, helped with this paper.

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November 22 - 25, 2022

SUSTAINABLE URBAN DEVELOPMENT

DAY 01
16:45 — 18:15

CHAIR
CLAUDIO CARRASCO

PAPERS
1208 / 1461 / 1517 / 1207 / 1180 /
1159

24TH PARALLEL SESSION / ONLINE

WILL CITIES SURVIVE?

Carbon footprint, LEED criteria and cost effectiveness

Comparative analysis of 5 technical solutions for the design of the non-potable water network of the MIND area in Milan

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[1] DEERNS Italia SpA – Milan

ABSTRACT: This paper describes a consultancy delivered to the Real Estate developer of a wide area in the north of Italy, aimed at calculating the overall site water balance and focusing on the non potable water network, in order to identify the most appropriate technical solution according to several criteria, ranging from local authorities requirements to LEED certification, through technical constraints and Client's desiderata.
Five alternative technical solutions of Non Potable water networks are compared in terms of CAPEX, OPEX, Embodied carbon (RICS scopes A1-A5), Operational carbon, LEED achievable points and other Additional qualitative criteria.
KEYWORDS: Carbon Footprint, Water Consumption, LEED, Embodied Carbon, Operational Carbon

1. INTRODUCTION

As part of the Real Estate development of the MIND - Milano Innovation District area in Milan (Italy), on the site that hosted EXPO2015, an area of 620'000 m^2, LendLease Firm is developing office buildings, residences and commercial units, setting challenging sustainability criteria for all project teams in terms of carbon footprint, energy efficiency, preservation of natural resources and resilience to climate change.

This paper describes a consultancy delivered to the client, aimed at calculating the overall site water balance and focusing on the non potable water network, in order to identify the most appropriate technical solution according to several criteria, ranging from local authorities requirements to LEED certification, through technical constraints and Client's desiderata.

2. THE CONSULTANCY

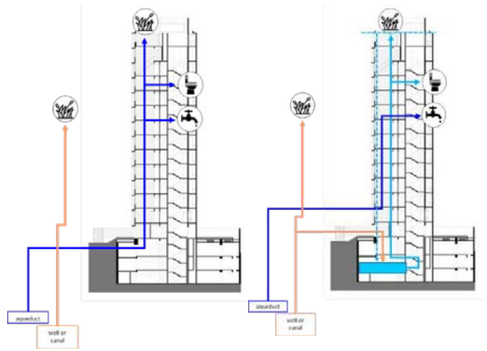
Water networks currently available on site, inherited from EXPO2015 and to be refurbished/integrated, are:

- Drinking water network;
- Rainwater network and a perimeter canal, which work together to reduce the storm water peak flow discharged by the entire site.
  The perimeter canal (about 5 km with a total water surface of about 79'000 m^2) connects to 2 local water courses at opposite sides of the site.
- Foul water network;
- Firefighting network;
- Well water network;
- Non potable and irrigation network;

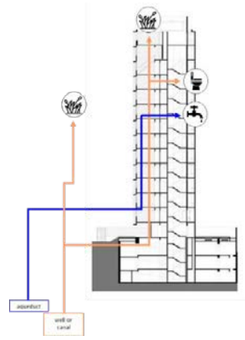
The consultancy focuses on the drinking, non-potable and irrigation networks. The following alternative technical solutions are identified and compared in terms of:

- CAPEX
- OPEX
- Embodied carbon (RICS scopes A1-A5)
- Operational carbon
- LEED achievable points
- Additional qualitative criteria.

Figure 1:
Technical solutions compared: schematic



1A 1B ***2***



3A 3B

3. SITE WATER BALANCE

A sitewide water balance calculation was performed, in order to appropriately quantify water needs and water discharge rates. The water balance was carried out considering the following needs:

- Drinking water needs
- Non potable water needs
- Irrigation needs

The balance considers several water sources:

- Drinking water (public network)
- Well water and canal water discharged after thermal use in the energy center
- Harvestable rainwater

3.1 Water Needs

The following table summarises annual drinking water and non potable water need estimations.

Table 1:
Water needs

Use	Vol (m^3)
Drinking water	352'078
Non potable water	453'663
Green roof irrigation	32'193
Softscape irrigation	128'611

3.2 Water Availability: Drinking

Drinking water must always be provided by the public aqueduct to ensure potability; its availability is assumed to be unlimited since the public aqueduct of Milan can provide almost any type of request thanks to appropriate redundancy (244 extraction wells).

3.3 Water Availability: Well water and Canal Water

To feed non potable uses well water or canal water networks can be used (water discharged after thermal use in the site's energy center).

The following table summarises water volumes consumed by the energy center, available for reuse in non potable network.

Table 2:
Water Availability: Well water and Canal Water

	Days	Well water m^3	Canal water m^3
January	31	401'760	1'473'120
February	28	362'880	1'088'640
March	31	321'408	401'760
April	30	233'280	259'200
May	31	214'272	669'600
June	30	311'040	907'200
July	31	374'976	1'071'360
August	31	374'976	1'071'360
September	30	207'360	777'600
October	31	214'272	267'840
November	30	336'960	518'400
December	31	401'760	1'339'200
TOTAL		3'754'944	9'845'280

3.4 Water Availability: Harvestable Rainwater

The following table summarises harvestable rainwater volumes for the site.

Table 3:
Water Availability: Rainwater

	Total rain mm	Rainy days n°	Volume available for reuse m^3
January	59	7	3'863
February	49	5	3'238
March	65	7	4'278
April	76	8	4'969
May	96	9	6'285
June	67	8	4'390
July	67	5	4'396
August	89	7	5'844
September	93	6	6'127
October	122	8	8'056
November	77	6	5'048
December	62	6	4'061
TOTAL	920	83	60'556

Different water sources can be considered for different uses, and will be compared as described above.

Table 4:
Technical solutions compared

			NEEDED	AVAILABLE
1A	**Unitary network and no water reuse inside buildings**			
	USE	**WATER SOURCE**	**m³**	**m³**
	Drinking water	Public aqueduct	352'078	unlimited
	Non potable water	Public aqueduct	453'663	unlimited
	Green roof irrigation	Public aqueduct	32'193	unlimited
	Softscape irrigation	Well water	128'611*	3'754'944
1B	**Unitary network and no water reuse inside buildings**		**NEEDED**	**AVAILABLE**
	USE	**WATER SOURCE**	**m³**	**m³**
	Drinking water	Public aqueduct	352'078	unlimited
	Non potable water	Public aqueduct	453'663	unlimited
	Green roof irrigation	Public aqueduct	32'193	unlimited
	Softscape irrigation	Canal water	128'611*	9'845'280
2	**Dual network and reuse of rainwater in each building**		**NEEDED**	**AVAILABLE**
	USE	**WATER SOURCE**	**m³**	**m³**
	Drinking water	Public aqueduct	352'078	unlimited
	Non potable water	Rainwater reuse	453'663	60'556**
	Green roof irrigation	Rainwater reuse	32'193	60'556**
	Softscape irrigation	Well water	128'611*	3'754'944
3A	**Dual network without rainwater reuse in each building**		**NEEDED**	**AVAILABLE**
	USE	**WATER SOURCE**	**m³**	**m³**
	Drinking water	Public aqueduct	352'078	unlimited
	Non potable water	Well water	453'663	3'754'944
	Green roof irrigation	Well water	32'193	3'754'944
	Softscape irrigation	Well water	128'611*	3'754'944
3B	**Dual network without rainwater reuse in each building**		**NEEDED**	**AVAILABLE**
	USE	**WATER SOURCE**	**m³**	**m³**
	Drinking water	Public aqueduct	352'078	unlimited
	Non potable water	Canal water	453'663	9'845'280
	Green roof irrigation	Canal water	32'193	9'845'280
	Softscape irrigation	Canal water	128'611*	9'845'280

** Gradually reduced from day 0 to year 2050*
*** Gradually reduced according to RCP 8.5 scenario*

COMPARISON CRITERIA QUANTIFICATION

4.1 CAPEX

The following table summarises capital costs required to operate on assessed water networks.

Table 5:
CAPEX overview

scenario	CAPITAL COST (€) drinking water network	non potable water network
1A	1'170'000 €	600'000 €
1B	1'170'000 €	800'000 €
2	900'000 €	1'000'000 €
3A	900'000 €	1'000'000 €
3B	900'000 €	1'200'000 €

4.2 OPEX

Water operational costs consist essentially in the following items:

- Billed cost of water
- Pumping costs in pumping stations
- Maintenance costs of tanks and pumping station

The following table summarises operational costs considered.

Table 6:
OPEX overview

network	OPERATIONAL COST (€/m³) bill	pump	maintenance	total
drinking water network	0.60	0.05	0.04	0.69
non potable water network	0.00	0.06	0.04	0.10

4.3 Embodied carbon (RICS scopes A1-A5)

To quantify embodied carbon associated with materials production and installation, reference values coming from several databases have been considered.

- To assess Scopes 1 to 3 reference values from EPDs of possible manufacturers have been considered.
- To assess Scope 4 possible local producers, around Milan area, have been considered. Specific CO_{2eq} emissions due to transportation have been estimated with reference to UK DEFRA 2020 GHG conversion factors.

The following total values related to scopes A1-A4 are calculated:

Table 7:
Embodied Carbon overview

Item	$kgCO_{2eq}/kg$
Steel pipe	2.047
Concrete	0.113
Reinforcement steel	0.673
HDPE pipe	2.087

Scope 5 is not quantified, as it is considered that installation will occur contextually to other site's general installation activities. The following table summarises material quantities required to operate on assessed water networks.

Table 8:
Material quantities (internal and external networks) overview

scenario		MATERIAL QUANTITIES (kg) EXTERNAL NETWORKS drinking water network	non potable water network
1A	HDPE pipe	19'451	6'972
1B	HDPE pipe	19'451	6'972
2	HDPE pipe	14'962	11'621
3A	HDPE pipe	14'962	11'621
3B	HDPE pipe	14'962	11'621

MATERIAL QUANTITIES (kg/m² gfa) INTERNAL NETWORKS

SCENARIO		RESIDENTIAL	COMMERCIAL	RETAIL	LIGHT INDUSTRY	HOTEL
1A	steel pipes	0.079	0.014	0.014	0.014	0.106
1B	steel pipes	0.079	0.014	0.014	0.014	0.106
2	steel pipes	0.185	0.049	0.049	0.049	0.283
	concrete	4.726	3.848	3.848	3.848	5.506
	steel	0.189	0.014	0.154	0.106	0.106
3A	steel pipes	0.185	0.049	0.049	0.049	0.283
3B	steel pipes	0.185	0.049	0.049	0.049	0.283

4.4 Operational carbon

To quantify operational carbon associated with water networks, reference values coming from several sources have been considered.

The following values are assumed, based on Italian averaged values:

Table 9:
Operational Carbon overview

Potable water supply	Water treatment (sewage)	NON potable water supply
$kgCO_2eq/m^3$	$kgCO_2eq/m^3$	$kgCO_2eq/m^3$
0.735	0.880	0.377

4.5 LEED

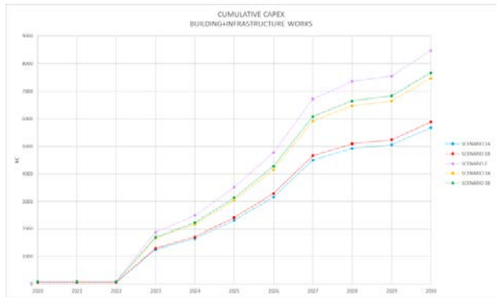
On MIND site both LEED BD+C – campus (for buildings) and LEED for Cities and Communities certifications are being carried out. Credits related to water management for both certifications are studied.

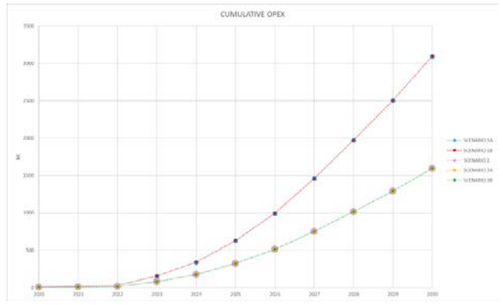
Table 10:
LEED involved credits

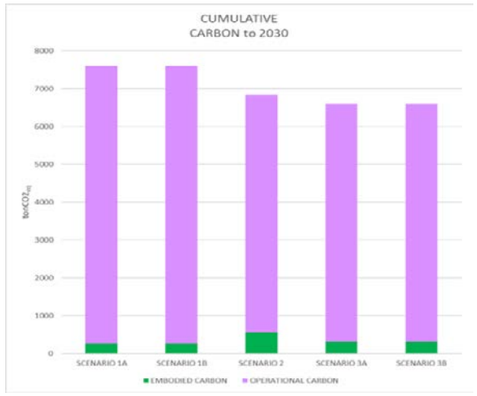
LEED BD+C	
SSc4	Rainwater Management (2 credits)
WEp1	Outdoor Water Use Reduction (prerequisite)
WEp2	Indoor Water Use Reduction (prerequisite)
WEc1	Outdoor Water Use Reduction (2 credits)
WEc2	Indoor Water Use Reduction (6 credits)
LEED for Cities and Communities	
WEp1	Integrated Water Management (prerequisite)
WEc2	Stormwater Management (5 credits)

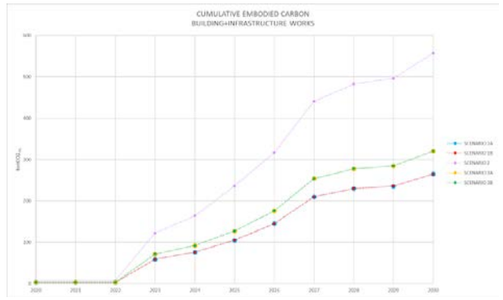
5. RESULTS

The following graphs show the main outcome of the consultancy focusing on the years 2020 to 2030, i.e. the years related to construction activities on site.







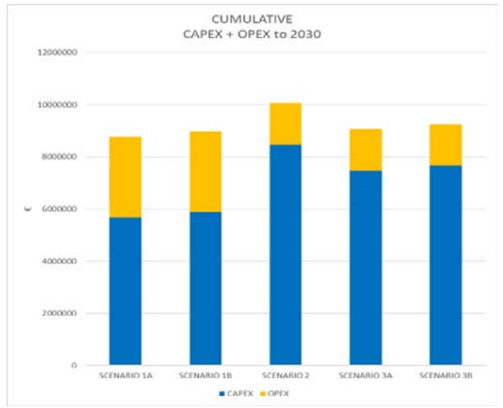


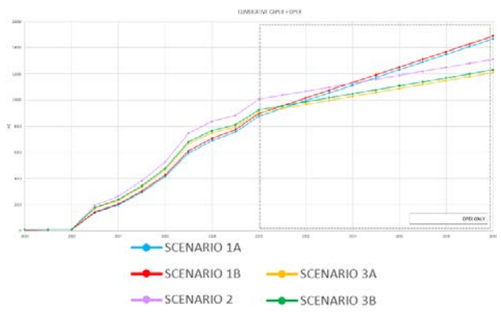
scenario	SSc4	WEp1	LEED BD+C WEp2	LEED BD+C WEc1	LEED BD+C WEc2	LEED for Cities and Communities WEp1	LEED for Cities and Communities WEc1	TOTAL
1A	0	ok	ok	2	3-4	ok	5	10-11
1B	0	ok	ok	2	3-4	ok	5	10-11
2	2	ok	ok	2	5-6	ok	5	14-15
3A	0	ok	ok	2	5-6	ok	5	12-13
3B	0	ok	ok	2	5-6	ok	5	12-13

The graphs show that both OPEX and CAPEX sensibly differ from one scenario to the other, however in all cases OPEX is a fraction of CAPEX.

Considering that OPEX associated to Scenarios 1A and 1B are clearly higher than the others, the following graph shows the overall costs on a timespan extended to 2040 (considering a fully operational site after 2030).

The graph shows that in the best case scenario, after 2035 1A and 1B become the most expensive scenarios among the 5.





6. CONCLUSIONS

Results show that Scenario 2 is characterized by a higher cumulative CAPEX, due to the installation of both a dual network and rainwater harvesting tanks.

Scenarios 3A and 3B, where a dual network is considered only, are slightly cheaper, while scenarios 1A and 1B allow for the highest savings, thanks to a slight increase in the main potable water network only.

On the other hand, in terms of OPEX, the most cost-effective scenarios are 2, 3A and 3B, which rely on non potable water coming from well or canal, and therefore is not paid to the municipality.

The same trend is detected on carbon side, i.e. results show that Scenario 2 is characterized by a higher embodied carbon, due to the installation of both a dual network and rainwater harvesting tanks.

Scenarios 3A and 3B, where only a dual network is considered, are slightly better, while scenarios 1A and 1B allow for the highest savings in CO2 emissions, thanks to a slight increase in the main potable water network only.

On the other hand, in terms of operational carbon, the most effective scenarios are 2, 3A and 3B, which rely on non potable well or canal water.

A Different behavior is however detected in the relationship between expenses and carbon in the long term, in fact, if years 2020 to 2030 are considered:

- On the economics side, the incidence on the total expenses is higher for CAPEX, therefore if the driver is economical, the most cost-effective scenario is 1A.
- On the carbon side, the incidence on the total emissions is higher for operational carbon, therefore if the driver is carbon emissions, the most cost-effective scenarios are 3A and 3B.

Considering that from 2030 onwards only operational values are to be considered (OPEX, operational carbon), the most cost-effective solution can be identified in 3A-3B, due to both OPEX and operational carbon reduced values compared to other scenarios.

Along with carbon and economic considerations, it should be noted that scenario 2 allows the achievement of a higher number of LEED credits with reference to the certifications attempted by the buildings under development, followed by scenarios 3A-3B, and 1A-1B.

Additional comparison parameters are included in an overall weighted comparison table: Technical resiliency, Maintenance difficulty, Existing infrastructure reuse, Innovative approach compared to business as usual, Difficult of approval from local authorities.

A performance value ranging from 1 (worst performance) to 5 (best performance), and a weighting factor defined with the Client are assigned to each parameter.

The overall score shows that highest rating is achieved by scenario 3A, closely followed by scenario 3B.

Figure 2:
Weighted results

		SCENARIO				
	Weight	1A	1B	2	3A	3B
CAPEX	14%	5.0	4.7	1.0	2.4	2.2
OPEX	17%	1.0	1.0	5.0	5.0	5.0
Embodied Carbon	14%	5.0	5.0	1.0	4.2	4.2
Operational Carbon	20%	1.0	1.0	5.0	5.0	5.0
LEED Cities	-	-	-	-	-	-
LEED BD+C	10%	1.0	1.0	5.0	3.0	3.0
Technical resiliency	4%	4.0	4.0	5.0	5.0	5.0
Maint. difficulty	5%	5.0	4.0	2.0	4.0	3.0
Existing Infr. reuse	4%	1.0	1.0	3.0	3.5	3.5
Innovative approach vs business as usual	4%	1.0	1.0	3.0	4.0	4.0
Difficulty of approval from local authorities	8%	1.0	1.0	5.0	3.0	3.0
	100%					
		2.4	**2.3**	**3.6**	**4.0**	**3.9**

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ESG Trends in real estate investment in Europe

Drivers, challenges, and good practices

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ABSTRACT: The main objective of this study is to qualify the ESG criteria of the financial real estate stakeholders and associated trends, drivers and challenges. The ESG criteria (Environment, Social and Governance) supports the harmonization and integration of sustainability practices in buildings. This topic has gained influence among financial sector in the last years and few comprehensive studies have taken it into account. This paper takes a comparative approach as different European regions and different real estate financial roles (investors, fund managers and asset managers) are studied. It was conducted by the authors together with 10 different European national real estate associations between June 2020 and June 2021. The results highlight the importance of ESG criteria for the real estate sector. At the same time the lack of monitoring practices for social and governmental criteria is observed. Results also showed that regulations are seen as drivers of sustainability, although different critics are mentioned.
KEYWORDS: ESG, Real Estate, Investment, Carbon, European market

1. INTRODUCTION

Cities and their built assets are pushed to become more sustainable. Instead of rules and regulations intervening at the building stage, favouring ESG criteria at the investment stage is a main lever.

ESG concerns have taken an increasingly important place in the investment and asset management strategies of professional real estate investors (Diab/Martin Adams 2021). In the past years, market demand has required investors to define clearer methodologies and policies that also respond to new regulatory frameworks for investment, under an ESG (Environmental, Social and Governance) umbrella (Kumar 2022) within a global agenda of countries' commitments towards carbon neutrality and environmental performance and sustainability.

This paper presents the results of a European overview of sustainable real estate investment practices and policies at corporate and fund levels, and identifies the key challenges and drivers regarding ESG integration. The study encompasses the analysis of existing practices and trends from entities with a total of 787 billion euros of real estate direct and indirect assets under management (AuM), as of 2019.

1.1. Context

Nowadays, and responding to environmental pressure, different investor stakeholders who contribute to the financing of real estate projects are more concerned on the impact and exposure of their investments. They are some of the most important stakeholders in cities today, as they intervene at all different stages of urban development. Today, ESG integration will have major consequences on investment choices in the development of cities and their buildings. Nonetheless, few studies address the real estate sector as to identify ESG practices (7 out of 2000 studies on ESG consider sustainable real estate according to Friede/Busch/Bassen 2015).

Moreover, real estate players need to respond to public authorities and regulators, that have developed a more and more stringent framework for sustainable investments (European taxonomy, Renovation Wave Strategy, Energy Performance of Buildings Directive). A mapping of trends is ever more relevant in light of the European Union's objective of carbon neutrality by 2050.

Observing that many practices are voluntary in nature and new issues are integrated (i.e., data collection/security, biodiversity or circular economy, etc.), the present study aims to identify trends in the context of existing ESG policies and investment practices.

2. IMPLEMENTATION

2.1. Scope definition and partner selection

Contributors to the study were grouped geographically and by professional category. One real estate association per country was chosen and meetings were held with all partners during the course of the study. The European supporters and partners to this study were, at European level, European Public Real Estate Association (EPRA) and INREV (Investor in non-listed Real Estate Vehicles), and at national level, the Investment Property Fund (IPF) from the United Kingdom, the German Property Federation (ZIA), the Dutch association for institutional property investors (IVBN), Women in Real Estate in Spain, as well as the Norwegian, Danish and Finish Property Federations Norsk Endom, Ejendom Danmark and Rakli *(Figure 1)*.

The professional categories of respondents identified were either fund managers, institutional investors or property companies. The study takes into account entities with headquarters in Europe. The following countries were analysed: France, the United Kingdom, Germany, the Netherlands, Spain, Denmark, Norway and Finland. The choice of countries is credited to the size of the real estate investment market and their connection to the 2 leading European associations EPRA and INREV.

This study is based on a quantitative survey which was later followed up with qualitative interviews for better insights. For both the survey and the interviews, participants agreed to disclose their identity.

2.2. Design of the data collection process

The questionnaires were co-constructed with the partner organisations in order to raise macro and local market insights. These organisations also helped distribute it among their national networks in order to incite more responses.
The study was conducted between October 2020 and March 2021. In total, 162 entities contributed. 91 respondents completed the survey entirely and 2 respondents completed a sufficient number of questions to be included in the scope of the survey. (i.e., 93 responses are included in total).

Figure 1:
Regional scope of study and partners involved

The study was sent out using an online survey tool from October 2020 to January 2021.

The questionnaire was composed of 4 parts: 1) Personal information; 2) information on member's activity and investments; 3) Current sustainable investment practices / sustainability policies and 4) Prospective view: Challenges & drivers. The quantitative questionnaire included 33 questions to be answered in English. The answer process took about 30 minutes as questions were of different formats (multiple choice questions, drop down questions, ranking questions and open questions).

The survey was limited by the number of people who responded. In addition, we acknowledge that leading players in ESG and largest companies in terms of human resources were more likely to contribute to the survey.

2.3. Implementation and Analysis of quantitative and qualitative data

The questionnaire was sent to respondents by the various European real estate associations through an email campaign to their members. The responses were aggregated, analysed by country, and by professional category.
25 qualitative interviews were conducted following the same interview scheme. The interviewees were chosen to be representative in terms of country typology, ESG maturity and company size. The interviews were conducted between December 2020 and March 2021 and lasted about 30 to 45 minutes. 5 questions were asked:

- What are the current ESG priorities of the real estate investment sector?
- What are the market opportunities/new business models linked to sustainable real estate investment?
- What obstacles do you identify to sustainable finance applied to real estate? (in particular in relation to legislation/taxonomy and certification/label/reporting standards)
- How do you prepare for the EU taxonomy? What public or private sector initiative would accelerate the preparation for its implementation?
- In your experience, which initiatives bring today the most value to the real estate investment players for ESG integration

As the interviews were semi-directive, the notes were analysed using the technique of "coding" which consists of labelling and organizing the qualitative data to identify different themes and the relationships between them. Several themes and sub-themes with key challenges and initiatives were identified.

3. RESULTS

The results will be presented in an order following first: ESG frameworks and reporting schemes, second: ESG issues taken into account, third: challenges and drivers and finally priority issues and initiatives taken.

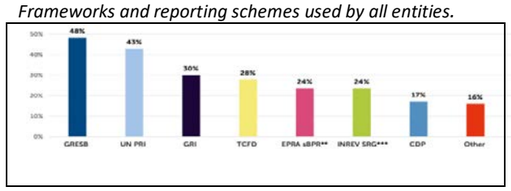
3.1. ESG frameworks and reporting schemes

94% of all surveyed entities have a defined ESG policy for their real estate investments. Institutional investors are generally the most advanced in their inclusion of ESG policy for investment portfolios. Whereas 95% of institutional investors portfolios are currently covered by an ESG policy, only 75% of fund managers portfolio are covered. Additionally, fund managers are also less ambitious in terms of how much funds they aim to be covered by ESG policies in the next 5 years. Only 58% target >3/4 of assets to be covered compared to 70% and 66% for institutional investors and property companies. Paradoxically to the numbers above, fund managers declare the highest percentage of existence of a designated person responsible for ESG governance (97%).

Furthermore, these policies rely on existing frameworks and reporting schemes for the design and implementation in the investment and management phases (reference to fig.2). When analysing the frameworks used, GRESB is the reference tool most used (48%) followed by UNPRI (43%). The GRI (30%) and the TCFD (28%) frameworks are also widely used. Nonetheless 13% indicated they do not use any of these frameworks. Some entities indicate that the GRESB framework could improve its processes to enable a more efficient response and ensure transparency on the methodology and use of data.

The frameworks used by each professional category differ. EPRA Sustainability BPR is the framework most used by property companies, which contrasts with fund managers and investors who use UNPRI. Interestingly, even though 55% of the respondents declare they assess their impact across the UNSDGs (the UN Sustainable Development Goals) framework was not mentioned in the "Other" category.

Figure 2:
Frameworks and reporting schemes used by all entities.



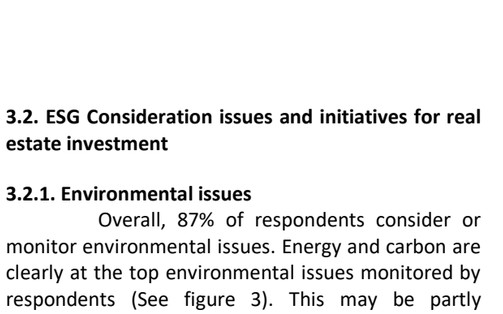
3.2. ESG Consideration issues and initiatives for real estate investment

3.2.1. Environmental issues

Overall, 87% of respondents consider or monitor environmental issues. Energy and carbon are clearly at the top environmental issues monitored by respondents (See figure 3). This may be partly explained by the fact that today's regulations are very much oriented towards environmental issues more than social aspects. Out of the issues mentioned in the survey, biodiversity and circular economy are the issues least taken into account by respondents. Both issues are considered difficult to implement according to interview partners.

The issues monitored or targeted by each professional category appear alike, with the exception of "resilience to climate change", which is more closely monitored by institutional investors and fund managers than property companies. Carbon and energy issues are most monitored by property companies (by 10%), which might be due to tenant demand. Institutional investors surveyed do not have any monitoring indicators related to biodiversity.

Figure 3:
Integration of metrics for environmental issues by all respondents



3.2.2. Social issues

Compared to environmental issues, social issues are largely considered but only few respondents have quantitative targets. On average, 85% of all types of survey respondents take into account social issues. But they have little objectives or indicators associated with these issues. Health and safety of occupants and access to transportation (public transportation, sustainable mobility solution, etc.) are among the top three social issues closely monitored by all entities. Community engagement, human rights and inclusion and diversity are least monitored by all entities. Out of the three groups, property companies tend to take into account social issues the least, but have more quantified objectives and indicators for health and safety and access to transport.

3.2.3. Governance issues

Governance issues are the most considered by all respondents out of the three ESG criterias. But they have little targets or indicators associated. Among the highest ranked governance issues are: tenant engagement and anti-bribery and anti-corruption. Among the issues adressed in interviews were the issues of European and national regulations.

Property companies seem to be more advanced in setting up specific targets and monitoring indicators compared to fund managers and institutional investors, maybe because listed property companies have had legal reporting obligations for longer.

59% of respondents believe that the importance of governance evaluation criteria will increase in the next year.

3.3. Challenges and drivers for ESG integration

3.3.1. Main challenges

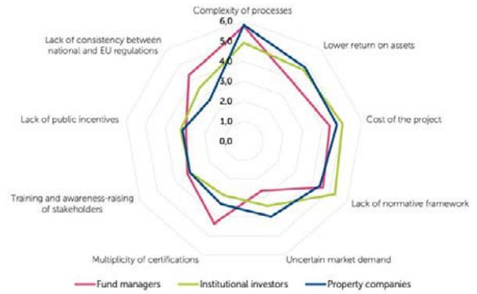
8 key issues came up as challenges for ESG integration (figure 4). Complexity of processes was considered one of the biggest challenges. Time and resources consuming reporting requirements that market players have to abide by hinder efficiency and may ask for organisational changes according to interviewees. Some respondents have actually mentioned fears that the European taxonomy may slow down the refurbishment of existing building stock, as its requirements are extremely high and only few assets follow the high requirements for now. On the other hand, the lack of frameworks is considered a challenge. Respondents especially highlighted biodiversity, circular economy or data management where frameworks are missing.

Furthermore, availability and/or quality of data appear to be among the main barriers for ESG integration, as it ranked first among the open answers provided by respondents. Fund managers, as a group, are additionally concerned with the multiplicity of environmental certifications and the lack of consistency between national and EU regulations.

Lack of public incentives on the other hand is the issue least considered by respondents.

Main challenges tend to be similar in all countries with differences in importance. For instance, lack of normative frameworks is more perceived as barriers for ESG integration in UK/Germany/Nordic countries rather than in France/Spain. Lower return on assets in Spain/Benelux rather than in France/UK/Nordic countries. Complexity of process is perceived as a major barrier in all countries.

Figure 4:
Classification of main challenges by all entities

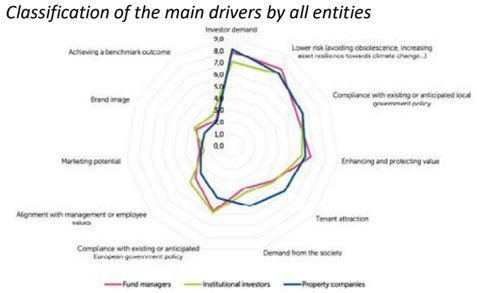


3.3.2. Main drivers

The different entities mostly share the same view on the four main drivers of ESG integration: Investor demand, lowering risks, compliance and value creation all ranked high as drivers (See figure 5). Enhancing and protecting value is more important for fund managers than for other types of respondents whereas tenant attraction is more important for property companies.

Once again regional differences become visible. All regions but France and Spain see Investor demand as a main driver. Enhancing and protecting values is another key driver in all countries but Norway and Germany. German based respondents are the only ones concerned with compliance with European policy whereas on the Spanish market tenant attraction ranks highest in the main drivers, showing *some regional specifities.*

Figure 5:
Classification of the main drivers by all entities

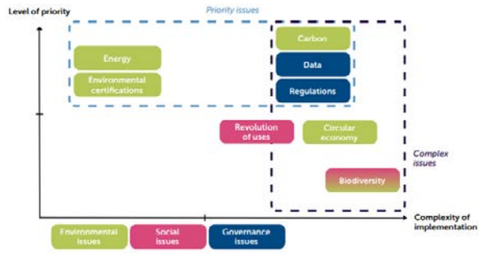


3.4. Prospective ESG trends for the real estate investment

3.4.1. Priority ESG issues

8 real estate ESG investment issues were identified based on their complexity and priority, where environmental issues generally have the highest representation (see figure 6).

Figure 6:
Classification of main challenges by all entities



The building and construction sector is one of the sectors most concerned by the challenges of carbon emissions reduction. In this manner energy, carbon and environmental certifications ranked as top priorities over circular economy and biodiversity. There is a consensus among real estate players that GHG emissions and the adaptation to climate change is a top priority. Bioclimatic and passive buildings are seen as a solution for the future of the sector. Because they take into account the immediate environment of the building, demand in energy for heating or cooling is reduced. Passive solutions linked to adaptation are also: revegetation, awareness raising and change of uses, biodiversity, fight against urban heat islands. The environmental issues carbon, circular economy and biodiversity are considered complex to implement.

On the topic of biodiversity stakeholders ask for harmonized approaches to define objectives and monitoring relevant indicators. While some mapping and data collection approaches exist, biodiversity is considered to be a topic that needs to be dealt at neighbourhood rather than at asset level.

Energy efficiency remains a top priority for market players to address the carbon footprint issue. Although a voluntary process, the environmental certification of buildings remains a priority tool for real estate players as this measure allows to create benchmarks. It is observed as a sign of quality and improves asset performance.

In regards to social priorities, the sector considers shared and evolving services as part of building use and an important ESG issue. In this sense, the complexity arises with the different type of usages: mixed uses, modularity, reversibility, sustainable mobility, and inclusion with positive social impact. Fund managers are for instance looking at the flexibility and reversibility of spaces while investors and property companies are considering bioclimatic buildings. There is a strong tenant demand (13, 14, finding of the study) for this type of building as large companies are looking to locate their headquarters in them.

There is a consensus among market players that the European taxonomy, as regulatory priority, will move the real estate sector forward. 58% of respondents have prepared for the taxonomy regulations whereas there are different levels of preparedness. Some are on track with a detailed action plan, whereas others consider their current criteria will suffice requirements and some are only in a brainstorming stage. Especially its impact on creating a unified market standard and a common language is appreciated. Real estate market players expect the taxonomy to address in priority the issue of the refurbishment of existing buildings and to clarify its application according to local legislation.

3.4.2 Stakeholder Initiatives

Generally, the initiatives and issues mentioned by participants respond to the two highest issues in the environmental part of ESG: carbon and energy.

According to stakeholders, proven solutions to reduce energy consumption are energy performance certificates for buildings and energy and environmental mapping of real estate portfolios with targets on consumption reduction. The solutions interviewees propose are both passive and related to adaptation measures like: more biodiversity, fight against urban heat islands, insulation of buildings, revegetation.

Stakeholders of the market have made data collection and management a priority. Fund managers and property companies are for example implementing systematic environmental data collection policies that are ensured via cross referencing.

As regulations are perceived as both a complex and priority issue, one participant raised the idea of a more efficient European carbon tax. For the tax to be efficient in the real estate sector it should be about 10 times higher than currently, according to him. Stakeholders are also wishing for clearer guidelines from regulatory authorities and standardised frameworks for all market players to harmonise practices and establish common definitions.

Innovations in the social sphere include public-private partnerships with local municipalities that some companies have set up in order to enable low-income people to stay in city centres, where housing is very expensive. Another trend is the development of funds specialising in intermediate housing for people whose incomes are too high to qualify for social housing but too low for them to buy a property on the private market.

4. CONCLUSION

The paper identifies key ESG trends that impact the financial real estate market. A significant insight is that organisations surveyed indicated their plan to extend their ESG policy coverage to more assets in the near future. The main drivers for ESG integration are : investor demand, lowering risks, compliance and value creation.

All in all, carbon, regulation as well as availability and quality of the data are priority ESG topics but also among the most complex to address.

On the environmental pillar (E), renovations of existing assets, multi-use of assets or integration of biodiversity and circular economy in projects are some of the trends that were found. The European environmental taxonomy will probably accelerate the mobilisation to address topics of biodiversity or circular economy, as it will provide and/or harmonize ESG indicators and criteria.

On the social pillar (S), a European social taxonomy could have the same effect on social issues mentioned through the study that were also largely considered but rarely monitored because seen as complex. The interview partners mentioned the affordable housing issue as a priority they are looking at which needs to be pushed. The reason health and security of users is the first social issue taken into account by the respondents, might be driven by regulation and enhanced by the current health crisis context. Access to transportation is well monitored.

Finally, on the governance pillar (G), as business ethics is one of the fundamental aspects of good corporate governance, one would have expected market players to be more advanced in terms of targets and monitoring indicators in this area, but it ranges last among all three types of respondants. Anti-corruption and tenant engagement are more closely monitored by all entities.

Regulatory and bureaucratic issues are generally seen as more challenging than financial aspects. Our study found that regulations drive sustainability best practices in the real estate sector. Regulations are considered by stakeholders as an opportunity to allow convergence. Nevertheless, participants asked for a more positive approach of rewards instead of a correction-based approach.

Note that 36% of the institutional investors or fund managers that responded to the survey are signatories to the UN Principles for Responsible Investment (PRI) and almost half of the property companies participate in the GRESB benchmark, with an average evaluation of 85/100. As such, the results of the study may be biased towards the best practices of the European market.

ACKNOWLEDGEMENTS

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Validating a cycle-based IoT sensor for mapping intra-urban air temperature and humidity

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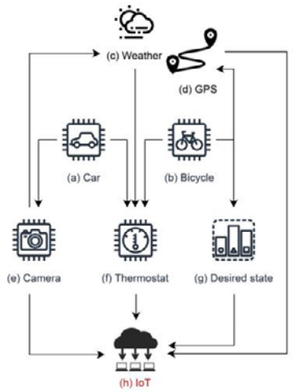
ABSTRACT: Crowdsourced weather data has been increasingly used to provide the input data for the boundary conditions in the microclimate models as well as to validate the modelling outputs. MeteoTracker (MT) is an Internet of Things (IoT) application for domestic vehicles that can contribute to the intra-urban air temperature database for meteorology enthusiasts as well as research and design communities. To promote green and healthy mobility, we have validated the MT device on bicycles and evaluated its monitoring performance with 2 other Kestrel heat stress trackers (KT) at low travelling/wind speed. The pre-planned cycling route cuts through the EUR district in Rome, Italy in September 2021. The dual-sensor design and the radiation error correct system (RECS) in the MT devices demonstrate good abilities in probing air temperature and humidity nuances when passing through different urban areas, as the three devices remain highly synchronised (Pearson r > 0.86). However, the MT device may overshoot the response time (> 41 s) if the cycling speed is less than 3 m/s. We have suggested some strategies for improvement in reducing the response time of probing the ambience under nuanced thermal variability.
KEYWORDS: Citizen weather stations, cycling, IoT, intra-urban, air temperature map, humidity map

1. INTRODUCTION

Crowdsourcing methods have enabled real-time monitoring of urban climate through citizen weather stations (CWS), smart wearables, and mobile devices [1]. These smart applications based on Internet of Things (IoT) technology have greatly incentivised the sharing of individual-environment data with the vast urban design and research communities. Some well-calibrated CWS provide reliable and real-time roof weather data that is useful for urban heat island (UHI), microclimate, and outdoor thermal comfort studies. Wunderground (US), Weather Observation Website (WOW), and METEOLAZIO are a few well-known crowdsourced online weather services (ITALY) [2]. Although the intra-urban thermal maps contoured based on these roof-level CWS are useful for mesoscale research [3], they are limited in reflecting the ground-level thermal conditions, such as the air temperature in deep street canyons [4], beneath tree canopies [5], or around water bodies. To overcome this technical challenge, the automobile lidar sensor, which measures the surface temperatures of street canyons in massive volumes, supplements the shortage of ground-level thermal data. However, the thermal imaging techniques do not provide ambient air temperature (Ta), relative humidity (Rh), and wind speed (U).

We have employed a mobile weather station, 'MeteoTracker' (MT) to test the monitoring accuracy of the air temperature and humidity variations across heterogeneous urban fabrics and thermal conditions at walking/cycling speeds. Initially, MT was manufactured to capture thermal variability for driving and fast cycling only. Hence, the scope of this study was narrowed to assessing the data quality by low-speed sampling. We tested a thermal-biking campaign [6] in the Esposizione Universale Roma (EUR) district in Rome, Italy. The data quality was assessed by finding the time lag of sampling nuanced Ta and Rh variations below the driving speeds (< 6 m/s). Any technical issues due to the decreasing headwind at cycling speeds were also investigated. One motivation is to raise citizens' awareness of the exacerbated heat and cold stress associated with climate and urban landscape, as well as to engage in green mobility and active behaviour [7] (Figure 1).

Figure 1:
The vehicle- versus the cycle-based CWS system

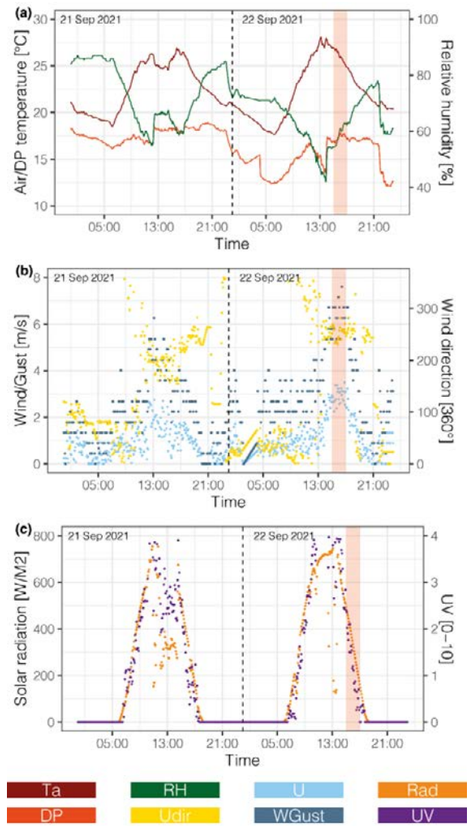


Note: (a) and (b) are two mobility types with CWS applicability for collecting (c) weather and (d) GPS data. Three extension packages, (e), (f), and (g) have been sampled but have not been used in analyses in this paper.

2. MATERIALS AND METHODS

Rome is in the western part of Lazio province in Italy and has a typical Mediterranean climate. Our thermal-cycling campaign took place in the EUR district where Ta is more than 3°C lower than the central area of Rome primarily due to the urban heat island (UHI) effect [8]. The measurement campaign was scheduled for a sunny afternoon in late September when the air was noticeably cooler for outdoor activities. The measurement started at 3 pm when the ground wind reaches its daily maximum when the sea breeze disperses from the west coast of Rome (Fig 2-b, U < 4 m/s, WGust < 8 m/s, 200° < Udir < 300°). The increase in air speeds created diverse convective conditions to assess the stability and accuracy of MT devices in monitoring air temperature and relative humidity on bicycles.

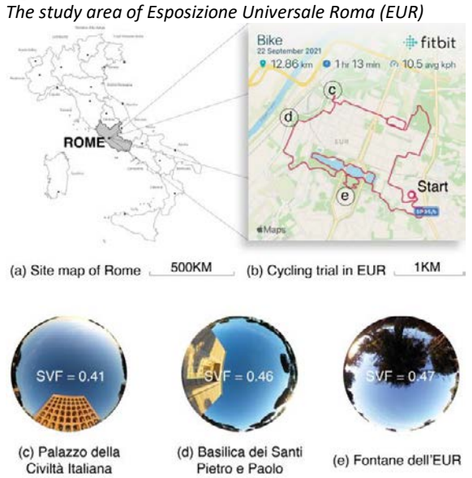
Figure 2:
The meteorological records from the roof weather station (meteoregionelazio.it) were installed near the cycling campaign (Fig 3-b), on the day and the day before the measurement campaign (21 and 22 Sep 2021).



Note: The rose ribbon denotes the two-hour window for the measurement campaign (15:00 - 17:00) on 22 Sep 2021. (a) shows the air temperature (Ta), dew point temperature (DP) and relative humidity (RH); (b) compares the wind speed (U) and the gusting wind (WGust), and wind direction (Udir); (c) compares the global radiation (Rad) and UV index.

The choice of the thermal-cycling routes is important. To cover a variety of microclimate conditions in the study area, the entire cycling route was designed in a circuit that began in a residential area in the east of the EUR district and proceeded anti-clockwise around the central Piazza Guglielmo Marconi, passing through piazzas with varying sizes, low- and mid-rise building clusters, pocket parks, iconic landmarks, waterfront areas, and large green infrastructures on the south of EUR lake (Fig 3-b, c, d, e). The overall cycling distance covered was 12.86 kilometres; The total distance reached by bicycle was 12.86 kilometres, and the average cycling speed was 10.5 kilometres per hour.

Figure 3:
The study area of Esposizione Universale Roma (EUR)



Note: (a) shows the study area in Rome, Italy, and b) is a screen of the Fitbit device that records GPS and cyclists' physiological information along the cycling trail (not discussed in this paper). Three spherical photographs were taken along the cycling route: (c), (d), and (e). The geo-tagged Fitbit data will be further analysed to audit the MeteoTracker GPS data.

2.1 Validation tools

The Kestrel 5400 Heat stress trackers (KT), manufactured in the USA, were documented as a laboratory-grade portable weather station with a calibration period of two years. It has been widely applied to validate simulation results in urban climate and biometeorological studies. Two KT devices were used in this study to validate and

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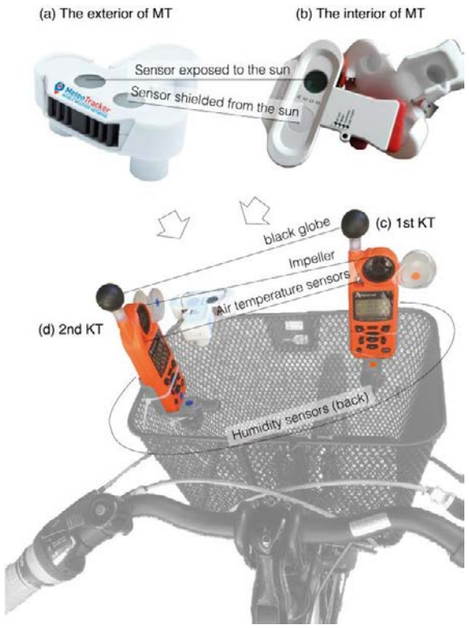
calibrate the MT device. Usually, the KT device can be fixed on a rotating base on a tripod, however, we did not use wind vanes on bicycles because the accelerations may cause errors in finding the actual wind direction. To estimate the wind directions for cycling, one KT device was mounted in the front of the basket and the other perpendicularly on the side. (Figure 4).

Figure 4:
Three sensors were mounted to a bike basket.



Note: (a) and (b) show dual sensors of the MT device which was mounted on the frontal-left; (c) shows the composition of three devices, one KT was oriented forward and (d) the other KT was oriented perpendicularly on the left edge of the basket.

The MT device is equipped with dual sensors that measure Ta, Rh, and pressure (Pres). One sensor is exposed to the sun and the other is shielded from it (Figure 4-a/b). The radiation output data are documented to be calibrated using a patented 'dual-sensor differential' system (Radiation Error Correction System, RECS), which corrects for solar radiation-induced errors. The RECS also addresses the convection-induced error when a very low moving speed is detected from the GPS data. Due to the lack of the RECS documentation for the MT device and the unavailability of the raw uncorrected data from its dual sensors, this paper takes the RECS as a Blackbox correction method.

2.2 Measurement accuracy

We have sampled five environmental parameters: air temperature (Ta), relative humidity (RH), barometric pressure (Pres), dew point temperature (DP) and altitude (Alt). The sampling inaccuracy and resolution of two signals of time series are compared to prepare for the following data interpolation and correlation analysis between the MT and KT device (Table 1).

Table 1:
The accuracy and resolution of two device

Samples	Inaccuracy		Sampling rate	
	MT	KT	MT	KT
Ta	< 0.5 °C	< 0.5 °C	depends on the moving speed	1 s to 1 h
RH	< 2 %	< 2 %		
Pres	< 3 Pa	< 1.5 Pa		
DP	N/A	< 1.9 °C		
Alt	< 10 M	< 7.2 M		

Note: MT is the device being validated and two KT devices are the validators.

2.3 Validation methods

The Pearson correlation and the time-lagged cross-correlation (TLCC) are used to examine the accuracy of the monitoring results from the MT against KT devices [9]. All missing data due to the inconsistent sampling rates was added using the linear interpolation method every single second. After data cleaning and smoothing, the new sample size grows to 4207 (s), corresponding to 70 minutes. Second, the Pearson correlation is used to analyse the global synchrony of two-time series signals in a snapshot fashion for all five microclimate samples. Third, a TLCC analysis is used to estimate the lagging/leading time between the MT and KT devices, and finally, the accuracy results are visualised on a cycling map to take into account the variance in accuracy with cycling speed, wind speed, and the built environment along the biking routes.

3. FINDINGS

In this section, we present our validation results from the cycling campaign and the spatial variations of sensors' accuracy in measuring the intra-urban Ta and Rh on the bike.

3.1 Overall synchrony

A total of five meteorological variables were analysed and showed good agreement among the three devices, which takes the entire biking samples into account. Yet, the dew point temperature (DP) is the one that yields a poorer correlation, mainly because it is a compound thermal variable based on Ta and RH. The MT device showed good agreement in validation against KT_f (Pearson r > 0.85) and KT_s (Pearson r > 0.87) (Table 2).

Table 2:
The overall correlations between MeteoTracker (MT), and two Kestrel Heat stress Tracker, mounted on the basket front (KT_f) and the side (KT_s) respectively

Pearson r	MT vs KT_f	MT vs KT_s	KT_f vs KT_s
Ta [°C]	0.864	0.878	0.813
RH [%]	0.945	0.943	0.949
Pres [pa]	0.939	0.956	0.958
DP[°C]	0.504	0.462	0.752
Alt[M]	0.968	0.987	0.959

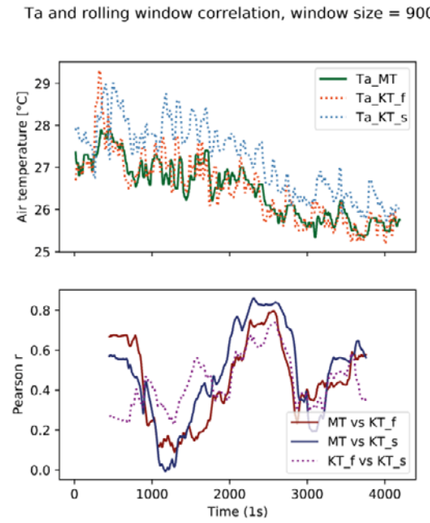
Note: Sample size along the biking route - 4207

3.2 TLCC analysis

1. Air temperature (Ta)

The monitoring of Ta is well synchronised among the three devices (Figure 5-a). The difference in the means of Ta between MT and KT_f is hardly noticeable: 0.13 °C, compared to 0.82 °C between KT_f and KT_s. The difference was probably caused by the inadequate ventilation via the Ta sensor.

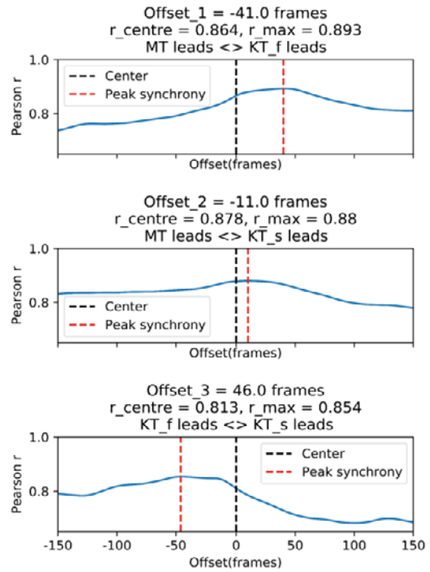
Figure 5:
Rolling window correlation (partial correlation).



Note: (a) shows the raw Ta data sampled by the three devices and (b) shows the partial correlation using the rolling window method (TLCC).

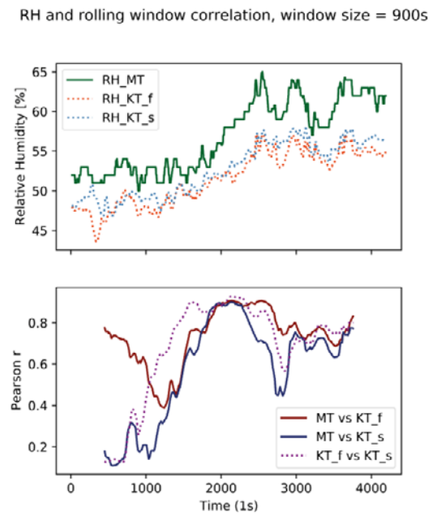
The partial correlation coefficients (Figure 5-b) between each of the three devices change greatly, ranging from 0.02 to 0.86. This indicates that the MT devices changed greatly in probing sensitivity throughout the whole cycling session. The partial correlation method is effective at estimating the lag time of one device by offsetting the signal until the highest synchronisation is found. The correlation coefficient improves from 0.864 to 0.893 when the MT signal is offset 41 seconds ahead, meaning a maximum of 41 seconds of delay in response to the instantaneous Ta variations, compared to the KT_f signal, which was almost in real-time (Figure 6-a).

Figure 6:
Rolling window correlation (partial correlation).



Note: (a) shows a lagging time of 41 seconds in MT behind KT_f; (b) shows a lagging time of 11 seconds in MT behind the KT_s; (c) shows a leading time of 46 seconds in KT_f ahead of KT_s.

Figure 7:
Rolling window correlation (partial correlation).

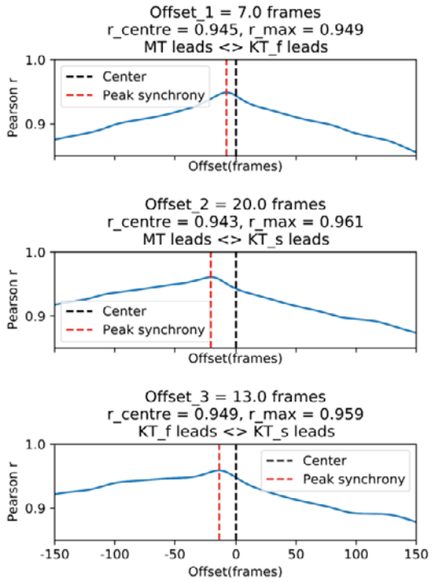


Note: (a) shows the raw Rh data sampled by the three devices and (b) shows the partial correlation using the rolling window method (TLCC).

2. Relative humidity (Rh)

The rolling window approach (TLCC) was also used to validate the Rh variations along the cycling route. Generally, the sampling accuracy of RH follows a similar pattern to that of Ta, which peaks between the 30th and 45th minutes of the cycling trial (Figure 7-b). Yet, the time-lagging effect in RH was much less than Ta for an estimated 7 seconds of maximum leading time (Figure 8-a).

Figure 8:
Rolling window correlation (partial correlation).

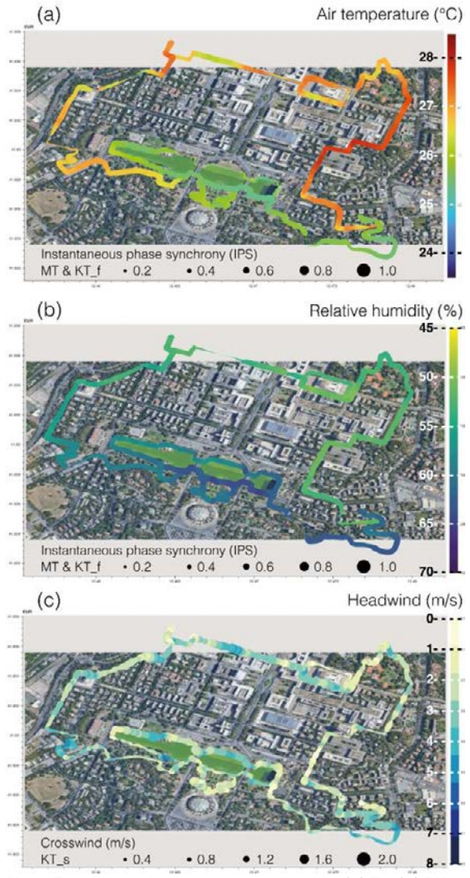


Note: (a) shows the MT device has a leading time of 7 seconds ahead of the KT_f; (b) shows the MT device has a leading time of 20 seconds ahead of the KT_s; (c) shows KT_f has a leading time of 13 seconds ahead of KT_s.

4. DISCUSSIONS

Since the partial correlation approach is unable to compute results at the beginning and end with fixed sizes of rolling window, we have explored instantaneous phase synchrony (IPS) utilising Hilbert transformations for spatial mapping (Figure 9-a/b). The IPS enables the quantisation of second-to-second synchrony between two-time series. The results of IPS show great variance in the spatial mapping. The variance was probably caused by the airflow dynamics during cycling. The instability in headwinds (Uhd) might reduce the probing sensitivity. As more air with varying temperatures reaches the probe, the measurement performance could be either positively or negatively affected, which warrants further investigations, possibly using controlled experiments in thermal chambers.

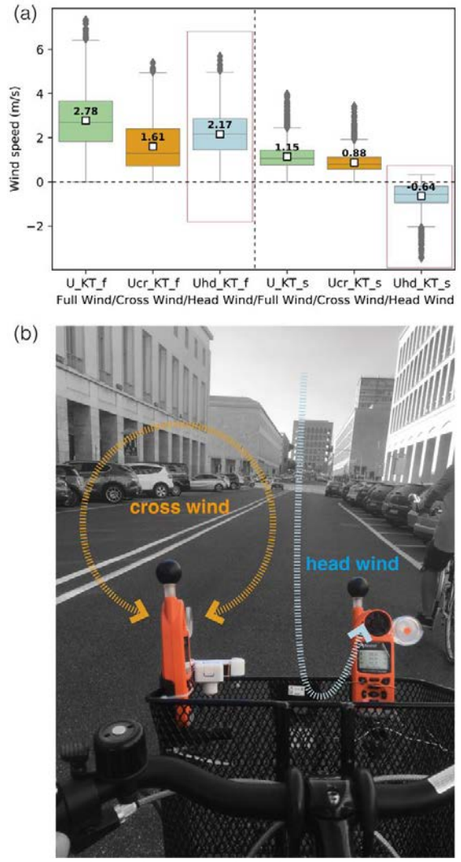
Figure 9:
Mapping of Ta and RH; Instantaneous phase synchrony (IPS) mapping; headwind and crosswind mapping.



Note: The data points are colour-coded by (a) Ta, (b) RH, and (c) Uhd and are sized by (a/b) Pearson r and (c) Ucr.

However, the crosswinds (Ucr) have a much smaller effect on RH and are almost imperceptible on Ta (Figure 9-c). Huge Rh differences are shown between KT_f and KT_s as the impellors (headwind directions) are perpendicularly placed (Figure 10) to estimate the irregular turbulent winds in street canyons. This also challenges the probing of the actual air humidity as the sensors are facing the frontal wind. For the MT device, the crosswind-induced errors are reduced to a great extent, thanks to the internally built sensors with a one-way venting path. Further improvements could be made by increasing the number of air inlets and outlets of the MT to accommodate a wider angle of wind directions, i.e., an omnidirectional anemometer. Yet it awaits further investigations into the instability of wind directions caused by the turbulent effects, especially during low-speed cycling and brisk walking.

Figure 10:
Ta and RH monitoring errors may be either mitigated or exacerbated by the headwinds and crosswinds in the street canyons



Note: (a) shows the ranges of wind speeds during the cycling campaigns from KT devices and (b) depicts the in-situ wind and turbulent effects in an urban street canyon.

5. CONCLUSIONS

Our work in EUR demonstrated a vehicle-based CWS application to sample the ambient microclimate. We evaluated its monitoring performance at walking and cycling speeds. One essential motivation behind the functional modification is also to promote active behaviour and green mobility, as well as to raise citizens' awareness of the changing urban climate. Using TLCC, rolling window correlation, and spatial mapping approaches, the sensor shows good synchrony with two kestrel devices (Pearson r >0.86). However, we also identified the insensitivity and inaccuracy issues with the MeteoTracker device's probing dynamic Ta and RH at lower air speeds. The 5 cm wide air inlet is essential to reduce the error in MT's monitoring Ta when varying degrees of convective cooling are available at acceleration or deceleration. We believe that reshaping the venting paths across the internal probes could provide great potential to reduce the response time (currently > 41 s) even under nuanced Ta variations.

There are also limitations in this study. The black globe sensor of the KT device requires at least two up to ten minutes to acclimatise itself from the sun to shade, and vice versa. As a result, the delayed response to the sunlight of two KT validators, as well as the radiation error from MT's dual sensors, were not evaluated. The scope is hence limited to any convection-induced errors from the air temperature and humidity measurements, thanks to the fast response of wind impellors. Secondly, we had only carried out one measurement campaign in late summer. The campaign was conditional on good weather, the availability of instruments, and traffic conditions. Further exploration will be necessary for high-resolution urban microclimate mapping using cycling and walking methods. Additional human-physiological experiments during colder seasons are also beneficial to filling gaps in the relevant fields of urban climate and outdoor thermal comfort studies.

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Measuring impact of building height randomness on daylight availability

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ABSTRACT: Studies indicate that indoor daylight can influence occupant health and productivity, besides improving the energy performance of buildings by reducing artificial light demand. Past studies have explored the impact of urban form on daylight using heuristic-based or optimization-based approaches. However, most studies have used solar insolation on building as an indicator of daylight performance, rather than directly measuring daylight inside the building. Additionally, previous studies have provided limited guidance on the impact of urban development parameters on daylight. As the world urbanizes and cities become denser, daylight availability will reduce if the urban design fails to adequately consider daylight during the prototyping phase. This study investigates the impact of the degree of vertical randomness among buildings in a regular grid-style neighborhood. Scenarios with different footprint sizes and mean floor counts are developed, and daylight during a year is simulated using Radiance. Useful daylight illuminance is then used to quantify the daylight performance of the scenarios. The findings show that while vertical randomness in an urban form improves daylight, the expected improvement in daylight due to vertical randomness depends significantly on footprint cover and floor count.

KEYWORDS: Daylight, Urban Form, Parametric Design

1. INTRODUCTION

One of the primary objectives of urban design and building regulations is ensuring optimal natural light access to its inhabitants. While urban design regulations are concerned with maximizing daylight access to the entire neighborhood, individual building developers try to maximize available daylight (Strømann-Andersen & Sattrup, 2011). Access to natural light is associated with improved health outcomes and increased workplace productivity (Boyce et al., 2003). Additionally, natural light within optimal range reduces building energy consumption by reducing artificial light energy use (Chi et al., 2018; Yu & Su, 2015).

Climate-based daylight modeling (CBDM) (Brembilla & Mardaljevic, 2019; Mardaljevic, 2006) is a framework for evaluating individual buildings or neighborhoods based on their daylight performance. It falls under the broader category of performance-based design (Baker et al., 2006), which aims to present a flexible alternative to prescriptive planning. Under CBDM, a building or neighborhood is judged based on cumulative or time-series based daylight performance, defined using one or more daylight metrics.

With or without explicit reference to CBDM, many studies have investigated design heuristics for increasing daylight availability (Eltaweel & Su, 2017). However, most studies have focused on improving access to a single or small group of buildings for different use, location, or style of architecture. Only a few studies have explored improving daylight in a neighborhood as a whole, and thus there is limited guidance for the initial stage of the urban design process. Studies that focused on neighborhood-scale have generally examined façade exposure, the orientation of streets, building and street shapes, courtyard styles, and the building density's impact on daylight (Yu & Su, 2015).

In urban morphology studies, a typology-based approach has often been adopted to simplify complex forms into comparable classes. Using the typology-based approach, Ng (2005) investigated how building height variation influenced daylight availability in otherwise identical towers in a high-density neighborhood. Cheng et al. (2006) extended this concept to include both vertical and horizontal randomness, where vertical referred to building heights, and horizontal referred to the locations on the ground. They compared daylight in 'uniform', 'horizontal random', 'vertical random', and 'horizontal plus vertical random' urban forms and concluded that random urban form improved daylight access.

Unlike the heuristic studies by Ng (2005), and Cheng et al. (2006), Vermeulen et al. (2015) explored the related issue of increasing solar irradiation on building facades as an optimization problem. They explored the application of genetic algorithms on a regular grid layout where a building in a plot could have different footprint dimensions, location, height, or rotation. However, the application of an optimization approach is still in the nascent stage while insights from heuristic studies continue to be deployed in architecture and urban design practice (Schumacher, 2009).

Past heuristic studies have improved the understanding of the influence urban planning and design decisions have on daylight availability. However, most studies did not explicitly measure randomness and instead classified urban form in 'uniform' and 'random' categories. Thus, while improvement in daylight availability from randomness in urban form is shown, it is unclear how much improvements in daylight can be expected and the extent of randomness after which diminishing improvements become insignificant. Additionally, most studies used solar irradiation on façades as an indicator of indoor daylight quality. While irradiation on façade and indoor daylight is positively correlated, the relationship between the two depends on the dimension of the building itself.

Thus this study investigates the effect of randomness in an urban form on daylight availability inside buildings. In the study, randomness refers to vertical randomness, i.e., differences in relative building height or floor count, assuming each floor is of the same ceiling height. The standard deviation of floor count is used to quantitatively measure the randomness in each neighborhood scenario.

Six hundred and twelve neighborhood scenarios with different mean floor count, randomness in floor count, and building footprint dimensions are constructed. These are passed on to Radiance (Ward, 1994) to execute daylight simulation, the results of which are then used to construct a measure of daylight performance of the scenarios.

2. METHODOLOGY

2.1 Geometric Model

While architectural models of individual buildings are often accurately detailed, urban planning and design rely on the general street layout and structure massing, especially in the early stages of prototyping. Thus, a generic urban neighborhood is developed, consisting of regular grids of 25 m side length, where each square represents a parcel inside which a building can exist (Fig. 1). The 7x7 neighborhood consists of a 6x6 interior grid for potential new development, and a single row of the exterior grid for pre-existing development. This creates a depiction of new development within a pre-existing context.

Each parcel can contain one building of a different floor count or side length, with the building's center coinciding with the parcel's center. For the purpose of daylight simulation, it is assumed that this geometric model is located in Seoul, Korea.

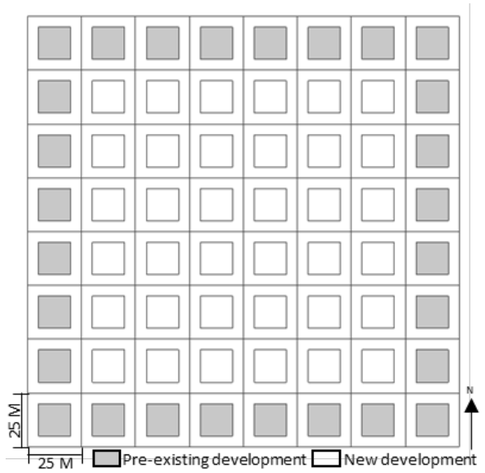

Figure 1:
Geometric model of the study.

2.2 Parametric Design Setup

The study uses a parametric approach with 612 neighborhood scenarios representing different side lengths and extent of randomness. These scenarios are categorized into four sub-scenarios, A, B, C, and D, representing building side lengths of 10, 15, 20, and 25 m, respectively, where each sub-scenario consists of 153 models (Figure 2). The minimum side length is decided based on the assumption that a cover ratio below 0.15 is uncommon in urban areas. In contrast, the maximum side length represents a cover ratio of one.

Each sub-scenario is further categorized into three sets, 1, 2, and 3, representing mean floor count of 6, 11, and 16, respectively. These floor counts are chosen based on typical floor count in moderate to high-rise areas in Seoul. Each set consists of one uniform model where all the buildings have the same floor count, and 50 random models where all the buildings can have different floor count. These 50 random models are categorized into five sub-sets with a standard deviation of one to five. Random building heights for each set are generated using a truncated normal distribution with distribution parameters described in Table 1. The truncated normal distribution is used because in a neighborhood, building height generally only varies within a predictable extent.

The contextual buildings' footprint dimensions are specified to the same value as sub-scenario's dimensions, and contextual buildings' floor count is specified to the same value as the set's mean floor count.

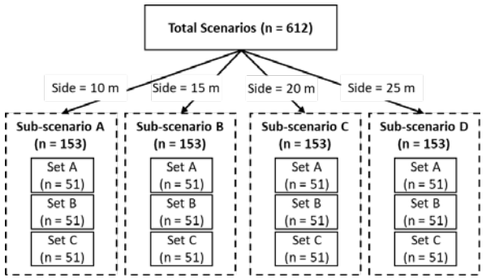

Figure 2:
Categorization of neighborhood models.

Table 1:
Parameters for the sets.

Set	x̄#	a	b	σ#	No. of models
Set 1	6	1	11	0	1
				1-5	10 for each σ
Set 2	11	6	16	0	1
				1-5	10 for each σ
Set 3	16	11	21	0	1
				1-5	10 for each σ

Notes:
x̄: mean of floor count, a: left side truncation,
b: right side truncation, σ: standard deviation.
#: x̄ and σ are parent normal distribution parameters.

3. SIMULATION SETTINGS AND DAYLIGHT METRIC

Radiance (Ward, 1994) is used for daylight simulations. It is a widely used backward raytracing physically-based renderer which has been extensively validated (Reinhart & Walkenhorst, 2001). Specifically, the two-phase daylight coefficient method is used since detailed fenestration design is generally not of concern at the urban design stage. Pezer sky model (Perez et al., 1993) with the luminance of typical meteorological year is generated from the energy plus weather file. Other assumptions for simulation are:

- Location: Seoul, Korea (37.56° N, 126.97° E)
- Building wall and roof material: concrete with the reflectance of 0.3
- Window: glass with the transmittance of 0.5
- Window to wall ratio: 0.4
- Location: Seoul, Korea (37.56° N, 126.97° E)
- Building wall and roof material: concrete with the reflectance of 0.3
- Ground: asphalt with the reflectance of 0.07
- Period of occupancy: 7 AM to 7 PM
- Radiance parameter setting: Fast (Kharvari, 2020)
- Sensor resolution: 3 x 3 m
- Sensor Height: 0.8 m from floor
- Ceiling Height: 3.5 m

Illuminance (lux) is typically used to specify the amount of light. Many metrics to relate space, time, and illuminance have been developed within the CBDM framework. Useful daylight illuminance (UDI) (Nabil & Mardaljevic, 2006) is one such metric that has seen increased adoption in daylight studies (Brembilla & Mardaljevic, 2019). UDI categorizes illuminance into bins of lower and upper thresholds. Typical bins specified are UDI-n (0–100 lux), UDI-s (100–300 lux), UDI-a (300–3000 lux), and UDI-e (>3000lux), representing non-sufficient, sufficient, autonomous, and excessive daylight conditions, respectively (Brembilla & Mardaljevic, 2019). The UDI value of a sensor is defined as the percentage of occupancy hours when illuminance is in the bin's range. The average value of all the sensors represents the UDI value of a neighborhood model.

In this study, UDI-a, which represents conditions where no artificial light is required without causing significant thermal or glare discomfort, is used to measure the daylight performance of each neighborhood model. Thus the evaluation metric can be stated as the average percent of the time between 7 AM to 7 PM when illuminance is between 300 to 3000 lux.

4. RESULTS

The UDI-a results for four sub-scenarios are shown in Figure 3. Each graph in Figure 3 shows results by sets of mean floor count of 6, 11, and 16 at zero to five standard deviations of floor count. The scatter plot shows the UDI-a value of each neighborhood model, and the line plot shows the mean value at a specific standard deviation.

It is observed that for a given side length, an increase in the floor count of buildings results in a lower UDI-a. Similarly, at a fixed floor count, an increase in the side length of buildings results in a lower UDI-a.

In sub-scenario A, where the side length is fixed at 10 m, UDI-a without any vertical randomness is 75.21%, 66.65%, and 55.15% for floor count 6, 11, and 16, respectively. As the side length of buildings is less than half of the side length of plots, the broad canyon keeps daylight performance value relatively high. The average difference between uniform (σ = 0) and maximum randomness (σ = 5) is 0.97%, 2.88%, and 2.75% for floor count 6, 11, and 16, respectively. The improvement in UDI-a from vertical randomness is minimal, with most benefits achieved by one standard deviation.

In sub-scenario B, where the side length is fixed at 15 m, UDI-a without any vertical randomness is 46.04%, 30.29%, and 21.62% for floor count 6, 11, and 16, respectively. The average difference between uniform and maximum randomness is 13.73%, 8.74%, and 5.61% for floor count 6, 11, and 16, respectively. In sub-scenario C, where side length is fixed at 20 m, UDI-a without any vertical randomness is 18.71%, 10.26%, and 6.99% for floor count 6, 11, and 16, respectively. The average difference between uniform and maximum randomness is 14.22%, 7.38%, and 5.16% for floor count 6, 11, and 16, respectively.

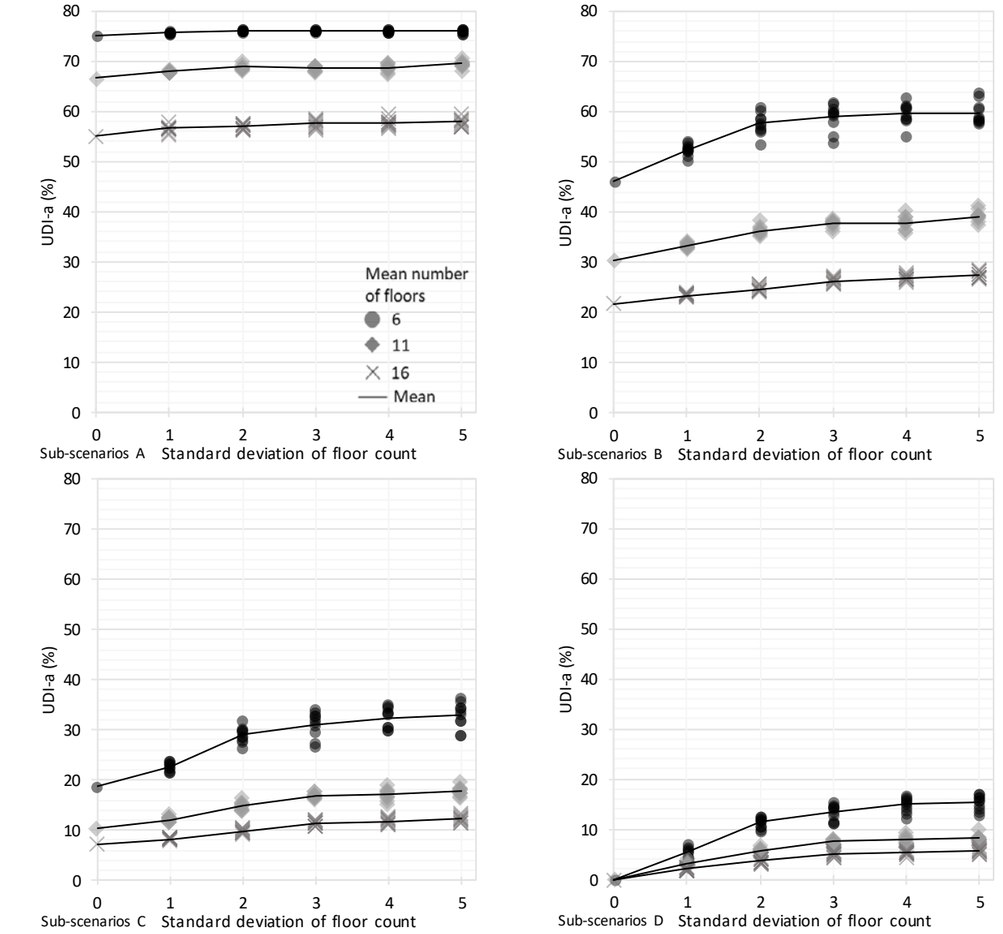

Figure 3:
UDI-a for side lengths 10, 15, 20, and 25 m (sub-scenarios A, B, C, and D, respectively).

In both B and C sub-scenarios, as the side length of the buildings increases, the deeper canyon decreases daylight performance. Improvements in daylight performance from vertical randomness are substantial and similar for a given floor count in both the B and C sub-scenario.

Sub-scenario D, where the side length is fixed at 25 m, represents an unlikely urban morphology when buildings and plots' side lengths are equal. Since there is no space between buildings, the daylight performance is 0% without any vertical randomness. The average difference between uniform and maximum randomness is 15.47%, 8.19%, and 5.74% for floor count 6, 11, and 16, respectively.

5. DISCUSSION AND CONCLUSION

The parametric experiment shows that daylight performance can be improved by introducing vertical randomness into urban form. Although building and plot dimension ratio, as well as building floor count, are relatively bigger factors that determine the daylight performance of a design, vertical randomness can substantially improve daylight performance as cities densify.

Although in scenarios B, C, and D, an increase in vertical randomness substantially improves average daylight performance, the incremental improvements show diminishing returns. Assuming that the difference between daylight performance at the standard deviation of zero and five represents a maximum improvement, 24%–45%, 52%–84%, and 81%–93% of maximum improvement is achieved by the standard deviation of one, two, and three, respectively (Fig. 4). Thus additional vertical randomness at standard deviation four, and five only marginally improves daylight performance.

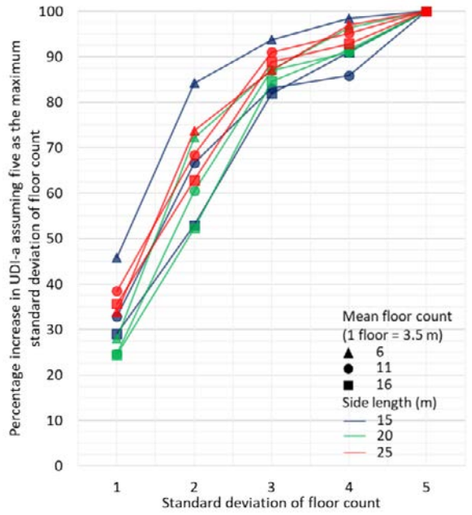

Figure 4:
UDI-a with incremental increase in standard deviation of floor count, assuming five standard deviation as maximum randomness.

It is also observed that while an increase in vertical randomness improved average daylight performance, neighborhood models with the same side length as well as the same mean and standard deviation of floor count can have a significant variation in daylight performance. For example, in the case of sub-scenario C, designs with a mean floor count of six and a standard deviation of two had the UDI-a range from 26.22%–31.69%. Thus, in this sub-scenario, while average daylight performance improved when the standard deviation is increased to three where UDI-a ranges from 26.72%–34.01%, not all designs with higher standard deviation had better daylight performance than designs with a lower standard deviation. This highlights the importance of parametric experimentation and avoiding overt reliance on general heuristics and guidelines.

This study investigates the impact of vertical randomness in an urban form on daylight duration in the UDI-a range of 300 to 3000 lux. It is observed that when the street canyon is deeper, either due to building footprint dimension or mean floor count, vertical randomness substantially improves daylight performance. This improvement is observed across different sets of scenarios consisting of building with different side lengths and mean floor counts. However, the improvement in daylight performance diminishes beyond three standard deviations in building floor count, by which 80% of expected improvements from vertical randomness are achieved.

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PLEA SANTIAGO 2022
Will Cities Survive?

Thermal assessment of an urban canyon in Brazil

A chrono-morphological approach from 1940 to a future scenario

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ABSTRACT: Climate changes and the intensified urbanization in modern cities often result in the creation of urban heat islands, a phenomenon that decreases the quality of life in various cities throughout the world. Among the factors that cause the creation of heat islands, urban morphology has a primal role in the pedestrian's thermal sensation. Urban canyons, streets framed by high buildings can reduce the solar incidence and local wind speeds, altering the heat exchanges between buildings and the air and interfering with thermal comfort. The present paper aims to evaluate to what extent the modifications on an urban canyon affected outdoor thermal comfort over time. For this, the Ladybug Suite Tools software was used to model and simulate an urban canyon of Juiz de Fora city's central area in Brazil. The findings showed that although the urbanization process over time resulted in small differences in thermal comfort, the verticalization phenomenon reduced the windspeeds at the pedestrian level.
KEYWORDS: Thermal comfort, computational simulations, urban canyons, urban heat islands, urbanization

1. BACKGROUND

The currently intensified urbanization processes are causing the creation of Urban Heat Islands (UHI), that is, urban spaces in which the air temperature is higher when compared to the peripheral areas of the cities [1]. In addition, the climate changes have contributed to the intensification of the UHI's phenomenon, creating extreme heatwave events, which modifies the thermal conditions of the city's microclimates [2].

Several studies have shown that urbanization processes have a more direct impact on the manifestation of the UHI phenomenon than the climate changes. This is noted in two studies that indicated a gradual increase in temperature in areas that became denser over time [3,4]. Some studies have assessed the development of the city's heat islands. A study in Phoenix, Arizona [5], which analyzed climatic data from 1900 to 1995 and performed on-field measurements, found that the peripheral locations presented temperatures 3°C to 8°C higher in central areas. It was also found that the UHI phenomenon increased the air temperature by 0.5°C per decade evaluated. Other research [6,7] conducted in New York analyzed climatic data from 1900 to 2002. They found out that the urbanization process was responsible for about one-third of the warming that the city has been experiencing since 1900. This happened due to the verticalization process, which reduced the wind speed in the urban boundary layer.

Another study [8] in Granada addressed the development of nocturnal UHI from 1901 to 1990 and found out that the phenomenon was worse in densely built areas of the city, getting almost 3,5°C warmer in comparison to the rural areas. Near the city parks, the temperature difference was only 1°C, showing the capability of green areas to soften thermal discomfort. In tropical climates, the nocturnal heat island can be more expressive in dense and tall areas of cities. Hence, research found an increase of 2°C in the air temperature of canyons in the city of Passo Fundo during the nighttime [9].

Other works analyzed the impact of the urbanization processes in tropical areas, such as a study done in Goiania, Brazil [10]. In this case, the surface temperatures varied spatially and temporarily. While in 1986, temperatures between 26.1 to 28°C occupied 0.6% of the total area analyzed, it reached 24.2% in 2010. Another study in Rio de Janeiro [11] explored the evolution of the city's UHI through 31 years, from 1984 to 2015. The analysis found that the phenomenon increased the air temperature by 1.9°C and 0.9°C in high and low dense land use areas, respectively.

However, urbanization and verticalization processes can benefit thermal comfort at the pedestrian level, especially in tropical climates and during hot moments of the day. In Fortaleza, Brazil, a work found out that shaded areas reduced air temperature by 3°C, as more sunrays were blocked by taller urban geometries [12].

The UHI phenomenon can be intensified due to the following factors: i) anthropogenic heat (heat released by pedestrian movement, cars, public lighting, etc.), ii) properties of urban surface materials (albedo, thermal absorption, etc.), iii) changes in vegetative cover and iv) urban morphology, being the latter one of the factors that affect the most the thermal conditions in urban environments. One of the aspects that modifies the urban morphology is the verticalization process, which creates the urban canyons: areas where the street is flanked by buildings on both sides, creating an environment that resembles the natural formation of canyons [13].

Although it is well known that the urban morphology can change the distribution of winds and solar incidence received by the building's facades, creating local thermal conditions [14], it is still essential to understand how the urbanization processes have been impacting local thermal conditions over the years; and what are the projections for the future. It is important to highlight that few analyses have been done on the same kind of climate of this research or used a historical approach to assess how the built density and the verticalization processes affect outdoor comfort conditions. Therefore, this study aims to evaluate to what extent the modifications on an urban canyon affected the outdoor thermal comfort over time. For this, an urban canyon of the central area of Juiz de Fora city in Brazil was evaluated.

Juiz de Fora has approximately 570k inhabitants [15], and its center has an orthogonal urban layout (Figure 1). Halfeld St. is one of the city's main commercial streets and underwent a verticalization process, currently having a morphology that configures as an urban canyon. This study was conducted through a computational simulation that analyzed and compared the street's thermal comfort in four different periods: 1940, 1980, 2020, and a hypothetical future scenario.

Figure 1: Google Earth photo with Halfeld Street canyon highlighted.

The city has a dry-winter humid subtropical climate according to Köppen and Geiger climate classification, with two well-defined seasons: a humid and hot summer and dry and cold winter. During cold seasons (from May to August), the mean radiation levels are higher, reaching 190W/m², and air temperature levels are at a lower level, reaching, on average, 16,4°C. During the summer, the average air temperature reaches 21,8°C, and the average horizontal radiation levels reach the lower value of 123,9W/m² in November. Precipitation and humidity levels are lowest in July and August (60% and 72,5mm on average, respectively). On the other side, humidity peaked at 86% during hot seasons, and accumulated precipitation reached 300mm. The city's predominant wind direction is north-south, reaching an average velocity of 3m/s.

2. METHODS

The study used computational simulations to evaluate the thermal conditions of the four moments analyzed. The methods used were adapted from previous works [16,17], which performed outdoor thermal comfort analysis using the Ladybug Suite Tools software. This freely available software was used with the Rhinoceros 3d CAD. The models created using were inserted into the Grasshopper environment.

Each moment's physical configurations (building heights and footprints) were modeled on the Rhinoceros 3d software. For the past moments (1940 and 1980), data were collected from the city's cadastral plans and historical photo archives. For the 2020's morphology, data from cadastral plants from the city's data archives and Google Streetview were used. The future case scenario was generated parametrically using Grasshopper components, the land occupation rate and the height of the buildings were modeled to their maximum allowed, according to the current local legislation. It is crucial to notice that some buildings would have their height decreased in this scenario, given that the maximum height permitted by the local legislation is lower than most original building heights. The historical buildings were preserved as they currently are. Table 1 shows the parameter used for the future scenario. It is important to highlight that the future scenario is hypothetical and represents a situation in which the street buildings would use the maximum land occupation and heights.

Table 1: Parameters used in the future scenario

Max. building height	Max. occupancy rate	Max. floor utilization rate
21m	1st to 3rd stories – 100% Other stories – 65%	6,5

The urban canyon (Figure 2) has approximately 11,5m of width and 700m of length, and a snippet of 195 x 700m was delimited for the modeling. The model considered all the buildings of the canyon and the surrounding buildings that may influence the thermal conditions of Halfeld Street in two blocks offset from it. A pattern height of 3m was stipulated for each story of the buildings modeled.

Figure 2: Snippet delimited for the modeling.

The climatic data used were collected from the Energyplus website and the International Institute of Meteorology. The Urban Weather Generator (UWG) component embedded within Ladybug's toolset transformed the file according to the four analyzed periods. Thus, the output morphed files characterize the urban heat island effect on a local scale. The UWG component allows the user to assign parameters such as sensible heat and soil and façade albedo. Table 2 presents the parameters defined. According to previous works, albedo and sensible heat were adopted accordingly [18,19], and assumptions were made from the analyzed historical photos. It was identified that the urban paving and building façade materials of the 1940s had higher albedo. So, from 1980 onwards, the albedo of those surfaces was reduced. Regarding the sensible heat, in 1940, there was no heavy car traffic, public lighting, or other heat-emitting sources as nowadays. Thus, a lower value was assigned compared to the other moments.

Table 2: Parameters used in the UWG component.

Year of Analysis	Albedo (soil)	Albedo (building façades)	Sensible Heat – w/m²
1940	0.2	0.6	4
1980	0.1	0.4	10
2020	0.1	0.4	20
Future	0.05	0.2	50

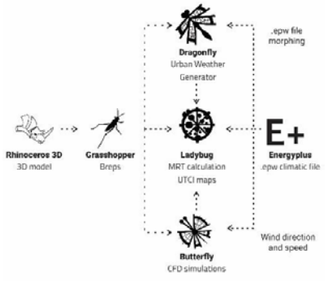
The simulations were carried out in winter and summer solstices and results from 8 a.m., 12 a.m., 4 p.m., and 8 p.m. were extracted. The thermal comfort index Universal Thermal Climate Index (UTCI) was selected for the analysis. The UTCI is a human biometeorology parameter used to assess the linkages between the outdoor environment and human well-being. The UTCI index is defined as the standard for the "feels like" temperature sensation [20]. The index is based on a single equation and accounts for human variables such as activity and clothing insulation [20]. The UTCI has already been considered in canyon studies [21,22] as an acceptable way to determine thermal comfort. The index is calculated based on four main climatic variables: mean radiant temperature, air temperature, relative humidity, and local wind speeds. The temperature scale is categorized in stress levels, as shown in Table 3.

Table 3: UTCI stress scale [20].

UTCI scale (ºC)	Stress category
Above +46ºC	Extreme heat stress
+38 to +46 ºC	Very Strong heat stress
+32 to +38ºC	Strong heat stress
+26 to +32ºC	Moderate heat stress
+9 to +26ºC	No stress (comfort zone)

The workflow assembled for generating the UTCI maps using Ladybug Suite Tools software was structured in Figure 3.

Figure 3: Workflow assembled for the simulations.



The wind speed was simulated using Butterfly (a CFD (Computational Fluid Dynamics) plugin embedded in Ladybug Suite Tools). A total of 32 CFD simulations were carried out, one for each period analyzed. The geometry was rotated according to the wind direction of each moment. The wind speed and directions were assigned according to Table 4.

Table 4: Wind direction and speed extracted from .epw file.

Period of analysis	Hour	Wind direction (degrees)	Wind velocity (m/s)
WINTER SOLSTICE	8 a.m.	319	3.3
	12 a.m.	295	2.5
	4 p.m.	317	2.2
	8 p.m.	331	3.4
SUMMER SOLSTICE	8 a.m.	79	2.5
	12 a.m.	78	0.6
	4 p.m.	103	3.2
	8 p.m.	75	4.0

Each case ran for about 500 iterations for the CFD simulations, and the simulation parameters such as cell size and refinement levels were configured according to Table 5.

Table 5: Parameters used in the CFD simulations.

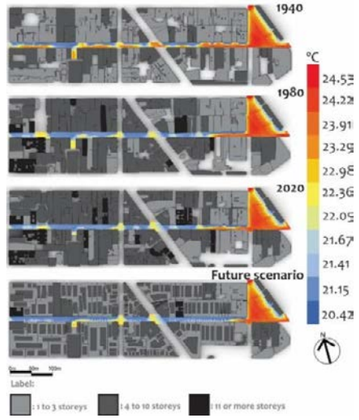
Analysis Year	Cell size (m)	Refinement levels min and max (dimensionless)
1940	5	2 - 3
1980	4	2 - 3
2020	3	2 - 3
Future	2	2 - 3

The analysis was carried out in the winter and summer solstices. The results are presented in the following section. It shows the average UTCI bioclimatic maps for winter and summer solstice days. They show the UTCI values projected into a gradient-colored mesh (offset at 1.1m from the ground). Furthermore, it was possible to extract a dataset containing UTCI and wind speed data from the simulations. This dataset was created by using 700 probing points that were linearly distributed in the middle of the canyon. The dataset supported the comparison of data between each timestep that was analyzed. Therefore, it helped to identify the changes in the UTCI and the alterations in the wind flow over time.

3. RESULTS

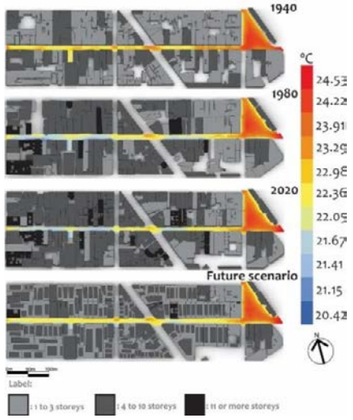
Results indicated that, as the urban morphology on the Halfeld street arose over time, more shaded spots were created, and therefore, less solar radiation reached the pedestrian level. This resulted in lower temperatures within the canyon, especially from 1940 to 1980, as shown in Figure 4, which presents the daily average UTCI values obtained on the winter solstice in the analyzed years.

Figure 4: Daily average UTCI map on the winter solstice in the analyzed years.



In the summer solstice (Figure 5), this scenario was also observed from 1940 to 2020, although less expressive. This is due to the higher solar angle by this time of the year. Therefore, the shaded areas are more expressive closer to the buildings, and more sunlit places were registered throughout the day. The hourly average UTCI values indicated that by 8 a.m., the comfortable temperatures decreased by 16,5% and 2,5%, on the winter and summer solstices, respectively, from 1940 to the future scenario. By 4 p.m., those values were reduced to 8,0% and 4,2%. Lower solar angles can explain the comfort reduction during the morning and afternoon periods, especially in the wintertime. This creates more shaded areas, decreasing the comfortable temperatures. On the other hand, by 12 a.m., those values raised in 6,9% and 4,6%, as the sun is on a higher angle and fewer shaded areas are created. These results are similar to those found in the work carried out in by Park, Tuller, and Jo (2014), that found out that the period from 2 p.m. to 4 p.m. had a stronger heat stress level. Hence, shaded areas that was previously thermally comfortable presented moderate heat stress (according to the UTCI scale). Areas shaded by buildings had a reduction of 1°C in comparison to the areas exposed to the sun. However, in the present work, the difference between shaded and sunlit areas resulted in 7°C of variation in the summer and 3°C in the winter. This shows how the urban heat island phenomenon can be expressive in tropical climates.

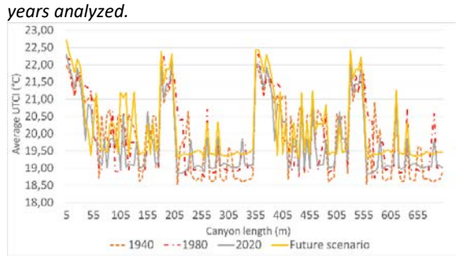
Figure 5: Daily average UTCI map on the summer solstice in the analyzed years.



On the other hand, the night period presented a different behavior. In the winter solstice, the average UTCI values decreased by 13,2%, while they increased by 3,4% in the summer solstice. This is explained by heat gained during the day and released from the building fabric in the evening. The results are like those found in the study done by Furlani *et al*. (2021) in the city of Passo Fundo. The authors identified an increase of approximately 2°C in air temperature during the evening on urban canyons of dense areas of the city. However, the canyon morphology analyzed here is not as tall as the ones assessed in Passo Fundo, which explains the the increase of approximately 1°C.

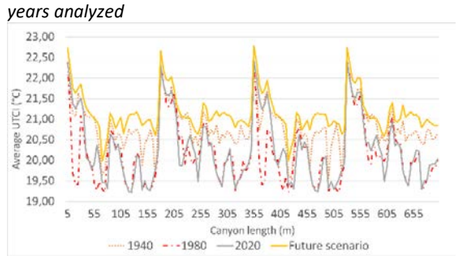
When comparing the daily UTCI changes between the timesteps (1940 to the future scenario), a raise of 0,76 and 0,94% on such values were observed between both moments in wither and solstice, as can be seen in Figure 6. However, the two most significant changes were observed between 1940 and 1980, following the verticalization process of the street, which created more shading and lowered the indexes by 0,41 and 0,81%, respectively.

Figure 6: Average daily UTCI on the winter solstice in the years analyzed.



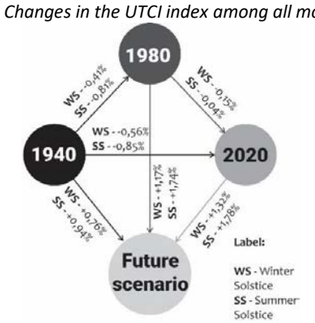
The second most noteworthy change in the UTCI in both solstices was between 2020 and the future scenario, following the city's densification. As shown in Figure 7, the temperature range reaches higher values on the summer solstice, and the UTCI values for the future scenario are at its highest throughout the canyon compared to previous timesteps. The index would raise 1,32% and 1,78% on the winter and summer solstices, respectively.

Figure 7: Average daily UTCI on the summer solstice in the years analyzed



In the future, if the buildings are built at their maximum extent and height, sensible heat will be at the highest value, and the albedo will be at the lowest, explaining the difference in the comfortable temperatures between then and the previous decades. The diagram shown in Figure 8 summarizes the changes in the UTCI index between all years analyzed. Notably, there would be a rise in temperatures of the future scenario when compared to the previous years (1940, 1980, and 2020). It can be noticed that although the values in percentage are not expressive, the increase in temperatures may be sensitive to people's well-being. Regarding the wind influence on the thermal comfort, the CFD simulations showed that the wind was more effective when its direction was aligned to the canyon's axis, given that the urban morphology can act as a barrier, and hence, it can lower the wind speeds. Over time, the wind speed showed a decrease of 25,5 and 40,7% between 1940 and the future scenario. This shows that the urban densification process would made the urban canyon less permeable to the local wind flow.

Figure 8: Changes in the UTCI index among all moments.



4. CONCLUSION

This study evaluated to what extent the modifications on an urban canyon in Brazil affected the outdoor thermal comfort over time. Results have shown that the shading created by the urban canyon lowered the comfort index, especially during the winter. As the canyon's morphology arose, more shaded spots were created. However, in this study, the differences in comfortable temperatures among the years analyzed, from 1940 to a future scenario, were not expressive. This can be due to the low building height when comparec to other studies and to city's mild climatic conditions.

Nevertheless, some of the tallest buildings would be removed from 2020 to the future scenario, less shading will be created, and therefore, the temperatures found were not expressively higher for this moment. However, it is essential to observe that the urbanization process will make the nocturnal heat island effect worse, especially during the summer. This shows that densifying and verticalizing cities can have both positive and negative impacts. Deep canyons can create shading during hot moments of the day, but also worsen the nocturnal heat island effect once it hinders the heat dispersion to the sky vault. This will also be affected by the reduction in the soil and façades albedo and the rise in the sensible heat.

This study did not consider the effects of vegetation in the environment but only the effect of urban morphology on urban comfort. Finally, it can be noted that computational simulations can be a valuable tool to evaluate the thermal conditions of urban canyons, in addition to estimating the magnitude and intensity variations on the spatial

thermal comfort of urban spaces over time. Hence, this approach can support the development of further urban legislation and design guidelines to mitigate thermal discomfort.

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Simulation study on the thermal effects of vertical greening system under the influence of local climate zones in Shanghai

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ABSTRACT: Vertical greening system (VGS) can make use of building facades and thus add "green" to dense urban areas with increasingly tight land use. The urban geometry and surface materials affect the local thermal conditions, acting on the VGS thermal process. However, few studies have focused on the impact of local-scale urban climate differences on the thermal effect of VGS. Based on the framework of Local Climate Zone (LCZ), the study evaluates the VGS summertime cooling, humidifying, and energy-saving performances in Shanghai, using an integrated simulation with ENVI-met and EnergyPlus. In general, the coupling models can reasonably explain the VGS cooling and shading effects, with average RMSEs of ~0.8°C and ~1.5°C. The simulation results revealed mean cooling of ~0.2 °C and energy-saving of 6%~12% of VGS under the five LCZ contexts of built types with heat island and moisture differences of 1.4°C and 6.2%. Among them, LCZ 2 and 3 show highest cooling effects, while energy effects in LCZ 2 and 5 are more prominent. The daily energy savings of 134–152 Wh/m^2 are largely due to the shading of vegetation and growing substrate (nearly 92%), while the contribution of air temperature reduction is about 8%. Whereas the humidifying effect may negatively (-11%) affect the energy performance. The findings help to better understanding on the Influences of built environment difference on VGS cooling mechanism and energy saving potential, and provide support to VGS application in urban design or renewal practice.

KEYWORDS: Vertical greening system, Local climate zone, Coupling models, Cooling effect, Building energy saving

1. INTRODUCTION

The dual impact of urbanization and climate change has made thermal problems of urban heat island and energy shortage increasingly prominent. Urban greening can effectively improve the quality of the habitat through canopy shading and transpiration. However, the development pattern of the high-density and compact intensified the shortage of construction land, and it is undoubtedly difficult to substantially increase the ground green cover. The vertical greening system (VGS) has a plant and soil structure similar to that of natural greening [1]. It can take advantage of the idle space on the building facade to replenish urban green quantity, and extend the greening to three-dimensional space [2], and has gradually become a key part for small- and medium-scales to moderate global problems.

By affecting the ventilation and shelter conditions, the built environment causes the exchanges of cold and heat sources, long- and short-wave radiation, and other meteorological changes. This will further impose the mechanism of VGS, which prevents it from exhibiting the same thermal performances [3]. The local climate zones (LCZ) fully considers the differences in the built environment and divides the urban areas into 10 built types and 7 land cover types according to the thermal response ability of the underlying surface [4]. The homogenized urban fabrics in the same LCZ generally produce similar microclimate features in the weather conditions of sunny, breezy, and less cloudy, and they are widely used in urban study on thermal problem [5-6]. Therefore, applying an objective and universal LCZ system, it is more conducive to explain the relationship between the urban physical elements and the thermal effects of VGS.

The diversity of building forms in urban built areas lead to local micro-climate differences. This difference gradually acts on the outdoor environment, building surfaces, and indoor spaces [7]. The VGS is attached to the building perimeter and affects the heat transfer process from outside to inside. In order to explore how VGS responds to the influence of local micro-climate in three-dimensional (3D) space, and how its cooling and energy saving performances may differ, it is necessary to carry out coupled simulations of VGS thermal effect under the LCZ background.

This study aims at evaluating the thermal performances of VGS applied in various LCZ contexts. 1)

It explored and verified the simulation effectiveness of "green facade" module and models coupling results; 2) it assessed the micro-climate differences between different LCZs and their impact on VGS; 3) and it analyzed the contribution of the cooling and energy effects of VGS.

2. METHODOLOGY

The study integrated the micro-climate model ENVI-met and the building energy simulation tool EnergyPlus to investigate the cooling, humidifying, and energy effects of VGS. We conducted a field measurement to evaluate the models accuracy, which was then adopted to simulate the outdoor micro-climate of VGS under the LCZs background. ENVI-met generates hourly based NetCFD data of air temperature (T_a), relative humidity (RH), and building surface temperature (T_s) of each scenario in 3D space. These data are used to configure the EPW files (.epw) in EnergyPlus to provide modified boundary conditions, simulating the daily energy saving rate in comparison with modified urban local climates.

2.1 Study area

Shanghai (121°04'E, 31°20'N) is located in the lower reaches of the Yangtze River in China, and belongs to the Cfa of Köppen-Geiger climate classification. The city has distinct four seasons, with hot summers and cold winters. The summer T_a can exceed 37.7 °C [8], and the cooling energy use accounts for 43.3% of the total electricity consumption [9]. Therefore, cooling in summertime and building energy savings is a vital issue in climate-adaptive urban design.

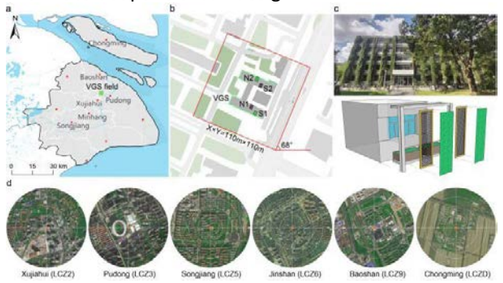

Figure 1: LCZ sites and VGS observation field.

The LCZ classes of National Weather Stations (NWS) in Shanghai (Figs. 1a, d) are matched by remote sensing images and street view maps. Taking into account the homogeneity of built environment within a radius of 500 m and the repeatability of the LCZ types, a total of 6 out of 11 NWS (including five built types and one referential land cover type) were selected as the LCZs environment samples for subsequent analysis.

2.2 Field measurement

The field measurement was carried out on summer thermal performance of VGS on a 5-storey campus building. Two pairs of office rooms on the 4th floor were monitored (Figs. 2b, c). Each pair features one masonry (bare facade) and one green facade with the same orientation. And it was continuously measured for 15 days, including cavity of T_a, exterior and interior of T_s, and indoor thermal comfort, etc. The complete program, sensor placement, and empirical parameters has been presented in detail in Ref. [10].

2.3 Coupling simulation

The VGS building and its adjacent space were constructed in a 130 × 130 grid model domain in ENVI-met, with a 1 m × 1 m resolution. The thickness, reflectivity and leaf area density (LAD) of VGS were respectively set to 15 cm, 0.2 and 3.0 [10]. The other spatial features (layout, scale and height-to-width ratio and) and building attributes (shadow, materials and window-to-wall ratio) are consistent in the ENVI-met and EnergyPlus models (Figs. 2).

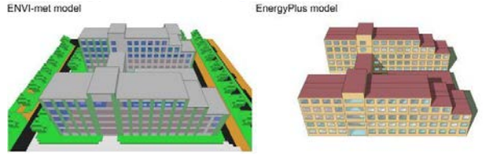

Figure 2: Simulation scenarios in ENVI-met and EnergyPlus.

The simulation scenarios used the typical summer data (the hourly average under consecutive 3 days of sunny and breezy of Shanghai NWSs [8]) as the forcing conditions, including T_a, RH, average wind speed at 10 m height, etc. The configuration of solar radiation, cloudiness, and soil temperature and wetness are referred to a study in the same climate as Shanghai [2]. The configurations of material and construction of building envelope are based on the specifications of the China public building energy codes in 2015s (current) and 1980s (previous) [11]. (Table 1)

Table 1 Main input parameters for the simulation.

Configuration	Parameters	Values and access
	ENVI-met	
Meteorology	Solar radiation	36.88
	Wind direction	145°
	Cloudiness	1 octas
	Soil temperature	307, 305, 298 K
	Soil wetness	10%, 20%, 30%
Building	Reflection	Wall 0.4, roof 0.3
	Thermal conductivity	Wall 0.8, roof 0.5 W/(m²K)
Plant	Greening facade	albedo 0.2, LAD 3.0 m²/m³
	EnergyPlus	
Run settings	Set points	26 ◦C (00:00–24:00)
	Internal heat gain	24 W/m²
	Occupancy	10 m²/person
	Activity	134 W/person
	Outdoor air	30 m³/(h·person)
	Infiltration rate	1 ACH
Construction	Wall/Roof (U-value)	Curr. 0.8/0.5, Prev. 1.0/0.7
	Window (SHGC)	Curr. 0.3, Prev. 0.4

U-value, heat transfer coefficient, W/(m²K); SHGC, solar heat gain coefficient.

3.4 Coupling models verification

The T_a of outdoor, T_s of exterior ($T_{s\text{-}ex}$) and interior ($T_{s\text{-}in}$), and T_a of indoor ($T_{a\text{-}in}$) are verified to completely indicate the heat transfer process of VGS from outdoor to indoor. The microclimate variables and coupled energy results are captured at the receptors, to evaluate the accuracy of ENVI-met's T_a and T_s, and EnergyPlus's $T_{a\text{-}in}$ with hourly measured data using the root mean square error (RMSE).

Fig. 3 compares the RMSE changes of the difference (bare-green) between the measured and simulated values before and after vertical greening, respectively. The results show that the simulated and measured values are more consistent at night than during the day. The RMSE of the measured T_a difference between the bare wall and the green wall during the day is about 0.2 °C higher than the simulated value, while the difference at night is about 0.3 °C lower than the simulated value. The RMSEs of the $T_{s\text{-}ex}$ and $T_{s\text{-}in}$ difference between bare and green wall are larger than the simulated value (0.8–2.3°C) during the day, and it is smaller than the simulated value at night (0.2–0.9 °C). The simulated and measured indoor scenarios are forced by the outdoor temperature and humidity and the external T_s of the building, so it is consistent with the outdoor environment during the day, and the difference law of the external surface of the building continues at night. the RMSE of the $T_{a\text{-}in}$ difference before and after VGS is 0.82 °C. Since the bare and the green facades have the similar underestimation biases, the overall difference pattern of simulation is as expected, reflecting the cooling effect and shading effect of the VGS. And the simulated results can still be considered reliable and can be used for subsequent exploration of relative differences of the thermal effect of VGS under different micro-climates.

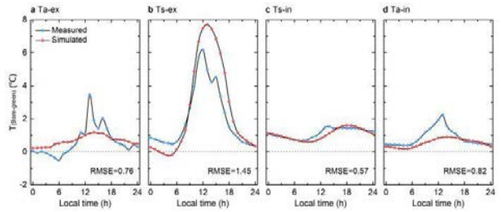

Figure 3: Comparison between measured and simulated T_a

3. RESULTS AND DISCUSSION

3.1 Thermal performances in LCZs

3.1.1 Ta and RH pattern differences

In virtue of Shanghai NWSs data, the hourly T_a and RH differences between the LCZ classes (ΔT / ΔRH = LCZ X–LCZ D) in Jul. 1–Aug. 31, 2020 are plotted as heat maps (Fig. 4a, b). The heat island effect becomes obvious after sunset, and this trend continued until 2 h after sunrise the next day. Comparatively weak cool island often appears during the daytime. Meanwhile, the ΔRH variations exhibited a close inverse relationship with the ΔT. The largest difference of T_a and RH in the LCZ classes mainly occurred on non-rainfall days, with the maximum at 23:00–03:00 (7.8 °C) and the minimum at 10:00–14:00 (-21.5%), respectively.

As expected, the most pronounced heat island is observed in LCZ 2 and 3 with higher land use intensity, where the frequency of heat island occurrence (the proportion of hours with ΔT > 0) even reached between 73%–78%. The frequency in LCZ 5 and 6 of moderate built intensity both are close to 62%, and fewer cooling phenomena can be exhibited during the daytime. LCZ9 is the sparsely built area with the highest greening rate, and its heat island frequency is about 39%, and there are obvious "cool island" during the daytime.

Although they are all in urban built-up areas, the development intensity and underlying surface cover type are different, and there is a significant temporal and spatial distinction in local climate, which further affects the thermal effect of vertical greening.

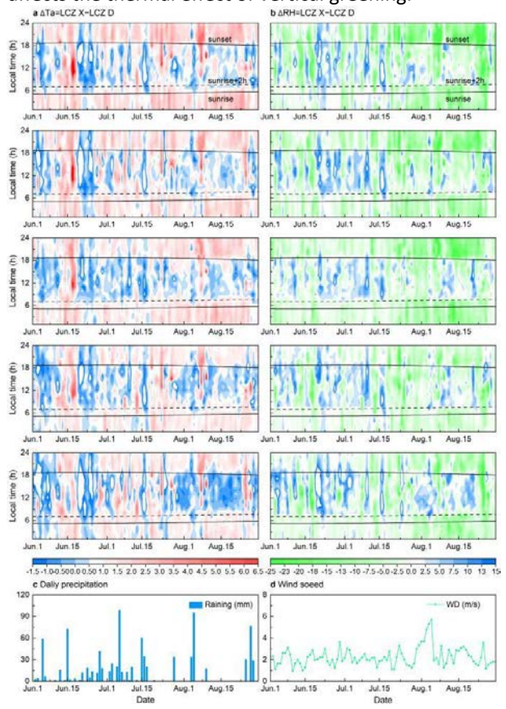

Figure 4: Hourly T_a and RH patterns between the LCZs.

3.1.2 Ta and RH differences for ideal days

The greater thermal inertia inside the canopy on cloudy and rainy days makes it difficult for the hot and cold air masses to penetrate to the underlying surface [5]. The five built LCZs usually last for a whole day as a heat or cool island. To accurately compare the diurnal patterns of thermal environment, the 51 ideal meteorological days favorable for the development of heat island and moisture difference [6] were screened by daily accumulated precipitation (< 1 mm) and mean wind speed (< 3 m/s) for following analysis (Fig. 4c, d).

For the mean diurnal ΔT during nighttime (sunset to sunrise +2h), the LCZ classes with compact buildings and relatively little vegetation (LCZ 2 and 3) record the highest ΔT values (1.5–1.8 °C), while LCZ 5 and 6 are intermediate (0.9–1.3 °C); LCZ 9 is the lowest (0.7 °C). Because anthropogenic heat was proved to be a major contributor to urban heat island formation [12]. For the mean ΔT during the daytime (sunrise+2h to sunset), the T_a differences among the LCZ classes are negligible, with the values within ± 0.5 °C (Fig. 5a). The shading from high-rise or high-density building areas can offset the daytime heat islands differences. For an LCZ, the higher the heat island intensity, the lower the RH. The nighttime mean diurnal ΔRH ranged from -8.1% to -3.7%, and ΔRH differences were relatively small during the daytime, ranging from -6.5% to -1.9% (Fig. 5b).

The heat island effects and moisture changes for most of the urbanized LCZ classes are still significant in summertime, with mean ΔT and ΔRH of greater than 1.4 °C and lower -5.2%. High-density built-up areas have larger heat islands and lower humidity, while dispersed built areas with a higher percentage of green coverage tend to have the least thermal environmental problems. This also verifies that there is a fitting correlation between the LCZ classes and their thermal environment.

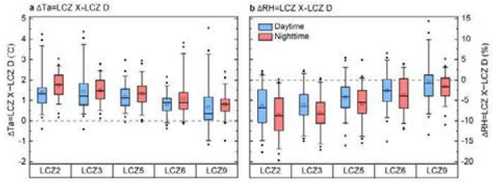

Figure 5: Diurnal T_a *and RH differences between the LCZs.*

3.2 Thermal Effects of VGS

3.2.1 Cooling and humidifying effects of VGS

To better compare the cooling and humidifying differences before and after VGS, we select the grids as far as 5 units from the building facade, and extract the average value. The results indicate the cooling air generated by VGS evapotranspiration sunk along the building facades and gathered near-ground, which can alleviate the thermal pressure of pedestrian space. The maximum difference of T_a reduction between five built types of LCZs is approximately 0.16 °C at 15:00 (Fig. 6a). The cooling periods are mainly concentrated in the afternoon (13:00–18:00), and the cooling ranges are between 0.11–0.26 °C, with an average value of about 0.16 °C; The cooling effect is not significant in the nighttime, and there is even a slight warming trend in some periods. The humidifying (RH increasing) and cooling effects of VGS have similar hourly variation patterns (Fig. 6b); the ranges of humidifying during the day are between 0.5% and 1.7%, with an average value of nearly 1.2%.

The results between different LCZs also show that in areas with worse thermal environment or higher heat island, VGS actually has a greater thermal mitigation. Besides, the building density has a more sensitive influence on the cooling and humidifying effects than the building height. The two high-density sites (LCZ 2 and 3) generally exhibited larger T_a reduction and RH increasing than their low-density counterparts (LCZ 5, 6, and 9). For similar density, the differences of T_a and RH between different heights are obviously smaller.

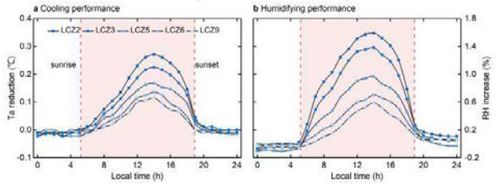

Figure 6: Hourly differences of T_a and RH between LCZs.

3.2.2 Shading effects of VGS

Fig. 7 shows the hourly T_s reduction for the green facades of the four orientations in comparison with the bare facades. The solar altitude and irradiance during the daytime caused considerable variations in the magnitude and time of the peak T_s reduction between the four orientations. The west walls have the highest maximum T_s reduction, ranging from 12.6 to 18.3 °C and occurring at 15:00–16:00. The west walls are followed by the east walls, with maximum T_s reductions ranging from 11.3 to 14.3 °C and occurring at an earlier time at 10:00–11:00. The south and north walls both experience the daily peak T_s reduction at 13:00–14:00, with ranges of 8.6–12.0 and 6.5–9.2 ◦C, respectively.

The five scenarios of built LCZs context exhibited nearly identical results in T_s reduction. Due to the shading effect of the neighboring closely-spaced, high-rise buildings, the cooling effect of LCZ 9 is attenuated and consistently has the lowest T_s reduction. Shading is especially noticeable on the east walls in the morning and the west walls in the afternoon in summertime. In contrast, the LCZ 2 always has the highest T_s reduction because the built areas are low and widely spaced. The differences in the maximum T_s reduction between the LCZ 2 and LCZ 9 are 4.3, 3.7, 6.5, and 3.5 °C, respectively, for the east, south, west, and north walls. The ranking of the mean T_s reduction between the LCZ2 and 9 is LCZ3, 5, and 6, indicating that cooling and humidifying effect are in opposite order.

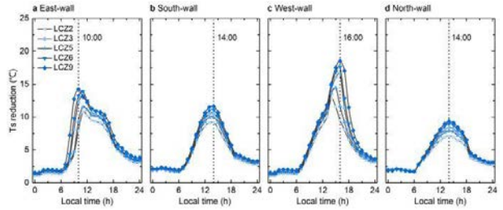

Figure 7: Hourly T_s reductions of between the LCZs.

3.3 Energy effects of VGS

3.3.1 Daily energy savings

Fig. 8 presents the daily energy saving rate of the green facade scenarios. Current buildings code (2015s) had a rate range of 6.2%–7.6%. Under the same simulation settings, the rates of previous buildings code (1980s) were much higher, with a range of 10.4%–12.1%. Buildings constructed for the 2015s specification not only had the lower rate values, but the differences in the rate between the LCZ classes were also smaller.

Furthering, the daily energy saving and energy saving rate of vertical greening per unit area were calculated under the influences of different LCZ context. Buildings constructed under the 2015s and 1980s specifications has energy saving ranges of 134–152 and 284–326 Wh/m^2, respectively. If we assume a summer cooling period of 92 days, annual cooling energy savings of 11.8–13.6 kWh can be achieved for every m^2 of facade greening on buildings constructed in 2015s specification. These values for 1980s specification is 27.6–31.7 kWh. The results also suggest that the current specification with lower U-value of the building envelope structure inhibits heat conduction and effectively reduces the cooling energy consumption.

The LCZ 9 consistently had the lowest daily energy saving rate and energy savings in two specifications. Dense, high-rise buildings result in a greater shading effect, thus limiting the ability of green facades to reducing the cooling demands. The LCZ 2 and 5 had the highest energy savings due to the relatively low building density. Compared to LCZ 9, the daily energy savings of LCZ 2 is 18.4 and 41.6 Wh/m^2 higher for buildings of 2015s and 1980s specification.

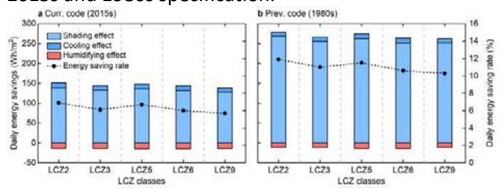

Figure 8: Daily energy savings differences between the LCZs.

3.3.2 Contribution of cooling, humidifying and shading

The daily energy savings are largely due to the shading of the vegetation and the soil (nearly 91.6%) that reduce the exposure of building walls to intensified solar radiation in summer, while the contribution of T_a reduction is about 8.4% (Fig. 8). This finding indicates that buildings with few nearby obstructions are more favorable for VGS from the perspective of energy conservation. Besides, the negative humidifying effect of -11.3% increases the latent cooling load of the buildings, thus counteracting the energy performance of VGS. Only considering the thermal effect of VGS on the outdoor environment, while ignoring the impact on the building surface (T_s), has few positive influence on building energy savings. Although similar results also presented that moisture from vegetation caused an increased cooling loads, the most studies have focused on the positive effects of shading and transpiration of trees or parks [13]. In cities with humid climates, the negative effects of green spaces should be considered when assessing their energy effects.

3.4 Cost-benefit of VGS

A cost-benefit analysis is carried out in combination with the investment per unit area to evaluate the economic feasibility of VGS. The construction cost of double-skin vertical greening is about 225 yuan/m^2 (plant + frame + labour), and the annual maintenance fee is 5 yuan/m^2 [14]. The energy savings benefits of VGS in summer mainly include two aspects: one is the reduction of electricity consumption for air conditioning; the other is the reduction of carbon emissions of power plant. With the average energy saving of 12.5 kWh/m^2, the total income is about 9.8 yuan/m^2, based on the commercial electricity fee of 0.78 yuan/kWh [15]. The baseline emission factor of the power grid is 0.81 kg/kWh in Eastern China, and the economic value of carbon is calculated at 0. 77 yuan/kg [16], resulting in a carbon emission reduction benefit of 7.5 yuan/m^2. Adding the above two items, the benefits of energy saving and carbon emission reduction of VGS is ~17.3 yuan/m^2.

The financial net present value (*NPV*) of VGS per unit area in year *t* is:

$$NPV = \sum_{t=0}^{n} (CI - CO)_t (1+i)^{-n}$$

In the formula: *i* is the financial benchmark rate of return in the building trades, taking 3% [15]; $(CI\text{-}CO)_t$ is the net cash flow in the *t* year, *CI* is the cash inflow, *CO* is the cash outflow; *n* is the project life cycle.

Calculated only based on summertime benefits, the payback period of double-skin VGS is about 18 years. The total income of VGS in the service life of 35 years is ~205.5 yuan/m^2.

4. CONCLUSION

This study investigated the potential of VGS to alleviate thermal problems in a humid subtropical city in China. We linked the thermal effects of VGS under different LCZ background, while previous studies were largely Ignored differences in local climate caused by the urban form within built areas. We also analyzed the cooling, humidifying, and shading effects of VGS to the overall energy savings, whereas previous studies mainly investigated a single benefit. The results can provide an shed some light on the underlying mechanism of VGS thermal and energy effects:

1) The ENVI-met and EnergyPlus coupling models can reasonably evaluate the VGS cooling effect and energy effect, with an average RMSE of about 1.1 °C. Overall, the simulations underestimated cooling and humidifying effects and slightly overestimated shading effect of VGS. It is also difficult to reflect peak changes caused by instantaneous changes in radiation and surroundings in real situation.

2) The law of gradient distribution of Ta and RH among LCZs preliminarily verified the feasibility of LCZ classes according to the characteristics of built environment. This law is most pronounced during non-rainy days and winter nights. The T_a and RH differences between LCZ classes can reach 7.8 °C and -21.5%, and the average difference under ideal weather days is 1.4 °C and -5.2%. These differences are most obvious during the nighttime. Simultaneously, it is not negligible in the daytime when people have a higher production and living frequency, and it can still produce an average heat island of 1.1 °C and a dehumidification of 4.5%.

3) The VGS has been proven to be effective in cooling, humidifying and shading. The VGS can produce cooling of 0.3 °C and humidifying of 1.7%. Among them, LCZ 2 and 3 show a highest cooling and humidifying effect, while energy effect in LCZ 2 and 5 is more prominent. The T_s reduction caused by shading effect accounts for the largest contribution to the building energy savings. If the VGS is widely applied to the renovation of old buildings with more sensitive envelope structures that enforced the previous specification during 1980−2015, the energy effect will be more significant.

The high computing cost of ENVI-met only allowed us to model one weather scenario. For a more comprehensive understanding on the long-term thermal performance of VGS, the energy effect on winter heating loads should also be evaluated. Given the limitations in model and the resulting uncertainty, the reported thermal effect should be regarded as an approximation rather than an absolute estimation. And some input variables were directly adopted from the model default values due to resource limitation. Both coupling model have some assumptions that may not fully represent the real situation. A more sophisticated verification of green facade module and field-based observational experiments in future work will lend greater credibility to our findings.

ACKNOWLEDGEMENTS

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WILL CITIES SURVIVE?

The impact of urban forms on psychological restoration and bioclimatic performance in high-density neighbourhoods

An integrated analysis in Shanghai

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ABSTRACT: This article presented an integrated study of the impact of urban form on the psychological restoration and the bioclimatic performance in high-density neighbourhoods in Shanghai. 24 typical urban layouts in Shanghai residential areas were studied in terms of the built period, location, and several architectural characteristics. First, a psychological experiment was conducted among 90 participants to test their responses to the visual stimuli of these urban layouts. Seven psychological variables were used including Restoration Likelihood, Familiarity, Complexity, Enclosure, Being Away, Fascination and Preference. A multiple mediation analysis can show that there were significant effects of urban form on restoration likelihood and preference, while these effects were partially or fully mediated by other psychological variables (e.g., familiarity, complexity, being-away). Second, the bioclimatic performance of these urban forms can be indicated via an analysis of Sky View Factor, which was achieved using Radiance simulation. It can be found that there was positive correlation between the Sky View Factor and the canyon width/height. Finally, it could be worth noting that improving the bioclimatic performance in these urban forms would benefit their psychological restoration. This integrated analysis was proved as an innovative approach to achieve a psychologically and physically sustainable urban development.
KEYWORDS: Urban Form, Psychological Restoration, Bioclimatic City, High-density Neighbourhood, Shanghai

1. INTRODUCTION

A rapidly growing urbanization combined with climate change has given rise to profound environmental problems in cities, such as land use shortage, urban heat island, energy crisis, air and noise pollutions, waste disposal, and relevant public health issues [1]. These are still the big challenges faced by municipalities and urban planners today.

As for the health issues, the urban design for mental health and wellbeing is being recognized as a new research focus in urban studies [2, 3], especially with the current situation of COVID-19 pandemic [1]. This research topic targets to inspire, motivate, and empower policymakers and practitioners to build mental health into their urban planning projects for a healthier, happier urban future [2]. Urban form, the key design issue in urban planning, refers to the main physical elements that structure and shape the city including streets, public spaces, street blocks, plots, and buildings [4]. It has been preliminarily noticed that there is influence of urban streets and buildings on environmental determinants of the public health (e.g., walkability) [3, 5]. However, it is still not fully understood how concrete configurations of specific urban form can impact on residents' mental health [5]. A psychological study has preliminarily exposed the opportunities to improve restorative quality of streetscapes in a low-density residential area [6], while a practical approach to investigate visual properties and affective appraisals in residential areas with only houses was produced [7]. It would be useful to further test the achieved findings from these studies [6, 7] in a highly dense urban neighbourhood (e.g., high-rise buildings in some mega cities in Asia).

On the other hand, the bioclimatic urban design has been well studied over 30 years, which generally focuses on the assessment of climatic implications of various physical structures of the city, such as street orientation, canyon height-to-width ratio, building density, and street shading [8, 9]. As mentioned in one study [9], the human thermal stress influenced by the urban form is the typical topic studied in this field. Depended on the urban form, the Sky View Factor can indicate that how much the urban area is shielded from the sky, which would response to the human thermal comfort and heat stress [9]. Studies in several cities have proved that the Sky View Factor had a linear relationship with urban heat island intensities [10, 11]. This has exposed a practical method to figure out the relationship between urban form and urban heat island effect in a high-density city.

This article presented an integrated study of the effect of urban form on the impact of urban form on the psychological restoration (linked to the potential to improve mental health) and the bioclimatic performance in high density residential neighbourhoods in Shanghai. 24 typical urban layouts were studied in terms of location, built period, and other characteristics. A psychological experiment was conducted to test their restoration likelihood and preference, while the bioclimatic analysis was achieved using the simulation. This integrated analysis can be applied as an innovative way to achieve a sustainable urban development.

2. METHODS AND MATERIALS

Three various methods are presented in this section, including urban layout, psychological experiment, and bioclimatic analysis.

2.1 Urban residential layouts studied

This article selected 24 typical urban layouts in residential areas of Shanghai, with their characteristics and rendering images given in Table 1 & Figure 1, respectively. These layouts were first chosen as representatives in terms of the period when they were built, such as No.1 (1950s), No.4 (1960s), No.7 (1980s), No.11 (1990s), No.16 (2000s), No.20 (2010s), etc. These layouts were numbered according to their built periods. In addition, their locations were considered as another factor for this selection, varying in the distance to the centre of Shanghai city (e.g. Renmin square).

Table 1: Characteristics of 24 urban residential layouts.

No.	Built Period	Height (m)	Floor-Area-Ratio	Building-Coverage-Ratio	Canyon width/height ratio
1	1950-1955	9	1.11	0.37	1
2	1955-1960	15	1.40	0.28	1.47
3	1955-1960	12	1.08	0.27	1.33
4	1960-1970	18	1.68	0.28	0.5
5	1970-1980	42	2.52	0.18	0.31
6	1980-1985	18	1.14	0.19	0.56
7	1980-1985	42	2.38	0.17	0.31
8	1985-1990	18	1.38	0.23	1.3
9	1985-1990	18	1.14	0.19	0.94
10	1985-1990	18	1.20	0.20	1.2
11	1990-1995	18	1.44	0.24	1.11
12	1990-1996	18	1.14	0.19	0.54
13	1995-2000	15	1.40	0.28	1
14	1995-2000	30	1.60	0.16	2
15	2000-2005	54	2.88	0.16	0.44
16	2000-2005	69	4.31	0.17	1.39
17	2000-2005	15	1.65	0.33	1.2
18	2005-2010	72	2.40	0.10	0.21
19	2005-2010	45	2.40	0.16	1.16
20	2010-2015	93	3.72	0.12	0.29
21	2015-2020	96	4.48	0.14	0.4
22	2015-2020	60	2.80	0.14	0.55
23	2015-2020	21	1.88	0.29	1.05
24	2015-2020	51	2.67	0.30	0.82

Four characteristics of these urban residential layouts [12] can be found as building height, floor-area-ratio (FAR), building-coverage-ratio and canyon width/height ratio (Table 1). Three types of residential layouts were studied in terms of building height [12] as: high-rise buildings (> 27 m), mid-rise buildings (> 10 m and ≤27 m), low-rise buildings (< 10 m). Mid-rise buildings were applied in half urban layouts (12), while only one layout (No. 1) used the low-rise building. Over 50% of the layouts had a FAR < 2.0 and the building coverage ratios of most layouts were < 0.30 (22). As for the canyon width/height ratio, half layouts had a value < 1.0.

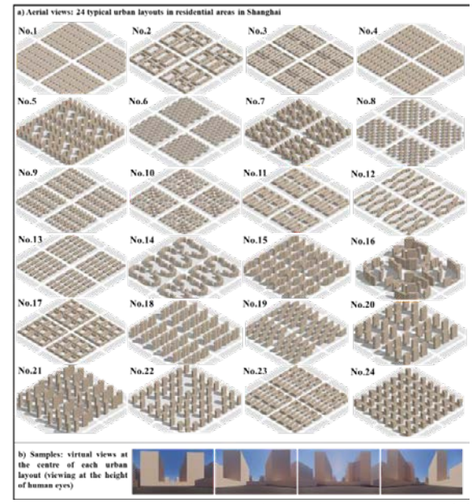

Figure 1: 24 typical urban residential layouts studied (a); samples of virtual view at the centre of one layout (b).

As shown in Figure 1, two types of virtual images of the 24 layouts were produced as the visual stimuli used in this study. Figure 1 (a) shows aerial views of these urban residential layouts, while figure 1 (b) presents samples of views at the centre of one layout. From 1950s to 2010s, there were three main types of urban form in these residential neighbourhoods: slab, enclosed and tower. In 1950s, most residential buildings were slabs and enclosed blocks. From 1960s to 1980s, the slab type was the main form. Some complex slab types can be found, such as serrated (No. 9) and curved types (No. 10). The types of urban form varied from 1990s to early 2000s, including slab, semi-enclosed, and complex enclosed types. Since 2000, no big changes can be found between the types of urban form applied in Shanghai high-density neighbourhoods. The most common types applied in this period were the high-rise slab and the high-rise tower. Over the 70 years, the urban form in Shanghai high-density neighbourhood has evolved from the simple models to the more complex models.

2.2 Psychological experiment

A psychological experiment was implemented to test human responses to the 24 urban forms (Table 1 & Figure 1). Seven psychological variables tested for each urban layout were: 1) Restoration Likelihood [6] ('Imagine that you are walking alone in this

neighbourhood. You are mentally tired from intense concentration at work, and you appreciate having a chance to stroll and recover before you have to go home to solve various matters. how do you feel ?'); 2) Familiarity [7, 13, 15] ('how you are familiar with this layout'); 3) Complexity [6, 7] ('how complex is this layout'); 4) Enclosure [6, 13, 14] ('how open is this layout'); 5) Restoration – Being Away [6, 15] ('how do you feel relaxed when living in this neighbourhood'); 6) Restoration – Fascination [6]: ('how do you feel relaxed when living in this neighbourhood'); 7) Preference [6, 14, 16]: ('how do you like this neighbourhood'). Each question was to be rated with an 11-point scale (0 = not at all, 10 = completely).

A total of 90 participants (age: 19.81±1.65) was recruited from a university in Shanghai to attend the psychological test. For each layout displayed by two types of visual stimuli (Figure 1. a & b). Participants were first asked to rate on the seven variables. After rating on all 24 layouts, they have completed a questionnaire to collect their background information, including demographics, and socioeconomics.

2.3 Bioclimatic analysis: Sky View Factor

For the bioclimatic analysis in an urban area, the Sky View Factor (SVF) was adopted as an indicator of urban heat island effect and human thermal stress [10, 11]. SVF can reflect the amount of sky that can be seen from the ground in an urban area and was also found to be correlated to the formation of urban heat island effect [10]. Several studies [10, 11] have found there is a linear relationship between SVF and urban heat island effect as follows:

$$UHI_{max} = a - b*SVF \quad (1)$$

Where, UHImax – maximum urban heat island (◦C); SV*F* – sky view factor; *a* – constant, relating to the climate condition at the location [10, 11]; *b* – constant, relating to the vegetation and climate condition at the location [11]. Thus, at a specific location, an increasing SVF can indicate a decreasing trend of the maximum urban heat island effect.

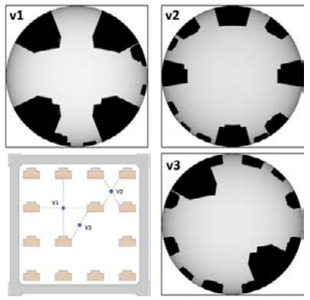

Figure 2: Radiance rendering hemispheric images used for SVF analysis in an urban layout (example: Model 22).

In this article, the urban heat island effect was not analysed directly, but the SVF values in various urban models were calculated using a method based on Radiance simulation under the uniform sky [17]. For each urban layout (Figure 1), typical positions were defined according to street orientation, canyon height-to-width ratio, building density. The SVF was calculated at each position and thus an average value was achieved based on these positions. The average SVF was used as a representative of this urban layout. Figure 2 presents a sample of SVF analysis of urban layout No. 22.

3. RESULTS

3.1 Psychological restoration: effect of urban form

Figure 3 displays the mean scores of restoration likelihood of the 24 urban layouts.

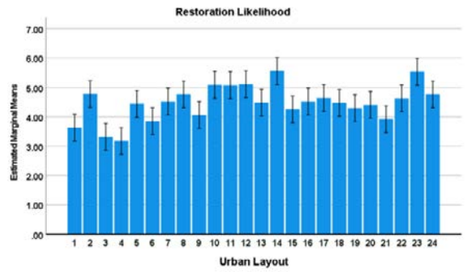

Figure 3: Mean scores of restoration likelihood on 24 urban layouts.

It can be found that the layouts 10, 11, 12, 14, and 23 can deliver a higher score of restoration likelihood (> 5.0), while the lower scores are for the layouts 1, 3, 4, 6 and 21. The highest scores are found at the layouts 14 and 23, which are contemporary enclosed type. Three layouts (No.1, 3 & 4) have the lowest scores than the other 21 layouts, two of which are simple slabs in the period of 1950 -- 1970. For the 12 layouts (No.2, 7, 8, 10 ,11, 12, 14, 16, 17, 18, 23, 24) with higher scores, eight are enclosed or semi-enclosed layouts. It seems that the enclosed layout can receive a relatively higher restoration likelihood than other urban forms.

A multiple mediation analysis of the effect of urban form on the restoration likelihood is displayed in Table 2 & Table 3. In Table 2, Model1 shows that the urban form has a significant predicting role for the restoration likelihood (β = 0.0361, p < 0.01), while several covariables also express similar effects, including age and gender, and three housing conditions (height, floor, and size) (p < 0.05). When five psychological variables (familiarity, complexity, enclosure, being away and fascination) are added into the regression (Model2), the predicting effect of urban form can be still found as significant (β = -0.0141, p < 0.01). However, this effect has been clearly reduced. Except for the gender, covariables have the significant predicting effect. The variables in Model 2 can explain 63.34% of the variance in restoration likelihood.

Table 2: Multiple regression analysis with Restoration Likelihood as outcome variable.

	Model1		Model2	
Predictors	B	β	B	β
Constant	8.8642		0.4308	
Age	-0.2828	-0.2092**	-0.0765	-0.0566**
Gender	-0.1934	-0.0426*	0.1105	0.0243
Hometown	-0.0216	-0.0130	-0.0579	-0.0348*
Housing_status	-0.1411	-0.0093	0.5828	0.0385**
Housing_height	-0.1957	-0.1212**	-0.0845	-0.0523**
Housing_floor	0.1792	0.0961**	0.0986	0.0528**
Housing_size	0.4786	0.1173**	0.2570	0.0630**
Urban_form	**0.0361**	**0.1119****	**-0.0141**	**-0.0438****
Familiarity			0.1079	0.1290**
Complexity			0.1268	0.1257**
Enclosure			0.1040	0.1013**
Being_Away			0.4652	0.4630**
Fascination			0.1353	0.1526**
R^2		*0.0763*		*0.6334*

*Significant: * p<0.05; ** p<0.01*

In addition, the indirect effects of the association between urban form and restoration likelihood were estimated using 5000 bootstrapped sample with the 95% bias-corrected confidence interval (Table 3). Clearly, there are partial mediating effects found at Familiarity (0.0032 0.0097), Complexity (0.0019 0.0082), Enclosure (0.0026 0.0103), Being_Away (0.0106 0.0263), and Fascination (0.0034 0.0133).

Table 3: Indirect effects of the association between urban form and restoration likelihood, through five variables.

		Bias corrected 95% Confidence Interval	
	Effect	Lower	Higher
Total	0.0502	0.0396	0.0609
Familiarity	0.0045	**0.0025**	**0.0068**
Complexity	0.0047	**0.0025**	**0.0074**
Enclosure	0.0068	**0.0031**	**0.0108**
Being_Away	0.0260	**0.0190**	**0.0338**
Fascination	0.0083	**0.0044**	**0.0126**

3.2 Psychological preference: effect of urban form

Figure 4 shows the mean scores of preference on the 24 urban layouts.

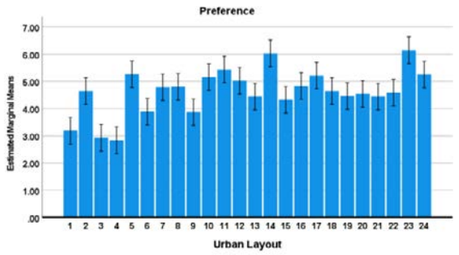

Figure 4: Mean scores of preference on 24 urban layouts.

It can be seen from Figure 4 that the layouts 14 & 23 have the highest scores of preference (≥ 6.0) while the layouts 1, 3 & 4 can receive the least preference (< 3.2). The layouts 5, 10, 11, 12, 17, 24 are still found with a higher preference score (> 5.0). In addition, other 13 layouts have a medium preference score (> 3.5 and < 5.0). For the layouts with high preference (No.5, 10, 11, 12, 14, 17, 23, 24), the enclosed or semi-enclosed types are applied.

Table 4 & 5 indicate a multiple mediation analysis of the effect of urban form on the preference.

Table 4: Multiple regression analysis with Preference as outcome variable.

	Model1		Model2	
Predictors	B	β	B	β
Constant	10.0423		-0.0756	
Age	-0.2332	-0.1575**	0.0166	0.0112
Gender	-0.3350	-0.0674**	0.0463	0.0093
Hometown	0.0821	0.0450*	0.0310	0.0170
Housing_status	-1.3708	-0.0826**	-0.3535	-0.0213*
Housing_height	-0.1160	-0.0656*	-0.0097	-0.0055
Housing_floor	0.0367	0.0180	0.0020	0.0010
Housing_size	0.1066	0.0239	-0.0768	-0.0172
Urban_form	**0.0610**	**0.1726****	**0.0027**	**0.0076**
Familiarity			0.4954	0.0935**
Complexity			-0.0367	-0.0332**
Enclosure			-0.0259	-0.0230
Being_Away			0.4946	0.4494**
Fascination			0.4954	0.5102**
R^2		*0.0728*		*0.8052*

*Significant: * p<0.05; ** p<0.01*

In Table 4, it can be found in Model1 shows that the urban form has a significantly positive predicting effect on the preference (β = 0.1726, p < 0.01). The significant predicting role is also found at age, gender, hometown and two housing conditions (p < 0.01). When five psychological variables (familiarity, complexity, enclosure, being away and fascination) enter the regression (Model2), the predicting effect of urban form tends to be insignificant (β = 0.0076, p > 0.05). For the covariables, only the effect of house status is significant (p < 0.05). The variables in Model1 can only explain 7.28% of the variance in the preference.

Table 5: Indirect effects of the association between urban form and preference, through five variables.

		Bias corrected 95% Confidence Interval	
	Effect	Lower	Higher
Total	0.0583	0.0453	0.0719
Familiarity	0.0035	**0.0020**	**0.0054**
Complexity	-0.0014	**-0.0028**	**-0.0001**
Enclosure	-0.0017	-0.0045	0.0011
Being_Away	0.0276	**0.0203**	**0.0357**
Fascination	0.0302	**0.0222**	**0.0387**

Table 5 gives the indirect effects of the five mediators, which were estimated using 5000 bootstrapped sample with the 95% bias-corrected confidence interval. The Enclosure cannot deliver significant effect (-0.0045 0.0011), while other variables have significant effects: Familiarity (0.0020 0.0054), Complexity (-0.0028 -0.0001), Being_Away (0.0203 0.0357), and Fascination (0.0222 0.0387).

3.3 Sky View Factor and urban form

Figure 5 indicates the SVF values of the 24 urban models, calculated using Radiance simulation [17].

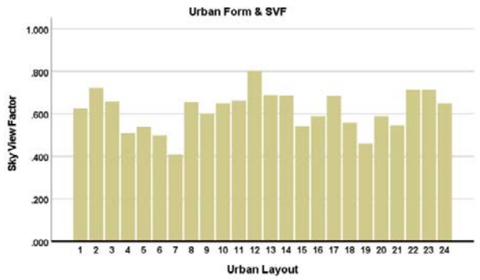

Figure 5: Variation of SVF of 24 urban layouts.

It can be found the distribution of SVF as: low SVF (< 0.5), urban model 7 & 19; medium SVF (> 0.5 and < 0.7), urban model 1, 3, 4, 5, 6, 8, 9, 10, 11, 13, 14, 15, 16, 17, 18, 20, 21, 24; high SVF (> 0.7), urban model 2, 12, 22, 23. Most urban models (18) have the medium SVF, while only two and four models can see the low and high SVF values, respectively.

Table 6: Correlation matrix of five characteristics of 24 urban layouts (Pearson correlation, 2-tailed).

	Building Height (m)	Floor-Area-Ratio	Building-Coverage-Ratio	Canyon width/height ratio	SVF
1	1	0.932**	-0.696**	-0.485*	-0.353
2		1	-0.528**	-0.364	-0.351
3			1	0.387	0.361
4				1	0.451*
5					1

Significant correlation: ** p<0.01, * p<0.05

Table 6 gives the correlation analysis of five characteristics of 24 urban forms, including building height, floor-area-ratio, building-coverage-ratio, canyon width/height ratio, and SVF. SVF can significantly correlate with the canyon width/height ratio ($r = 0.451$, $p < 0.05$), but not other four values ($p > 0.05$).

3.4 Correlation: psychological performances and SVF

Table 7 shows the correlation analysis of SVF, restoration likelihood, and preference.

Table 7: Correlation matrix: restoration likelihood, preference and SVF (Pearson correlation, 2-tailed).

	Restoration Likelihood	Preference	SVF
1	1		
2	0.708**	1	
3	0.135**	0.113**	1

Significant correlation: ** p<0.01, * p<0.05

Apparently, the positive correlations can be found between the three values: SVF & Restoration Likelihood ($r = 0.135$, $p < 0.01$), SVF & Preference ($r = 0.113$, $p < 0.01$). Thus, a higher SVF would deliver higher scores of restoration likelihood and preference, particularly for the layouts of 12, 14, 23.

4. DISCUSSIONS AND CONCLUSIONS

This article shows that the urban form has significant effects on psychological performance (psychological restoration & visual preference) and bioclimatic performance (SVF) in 24 high-density neighbourhoods in Shanghai.

4.1 Psychological effects of urban form

First, the evidence achieved from this study can well support that there is the association between urban form, and psychological restoration and visual preference in terms of these typical urban layouts. This association has been clearly exposed in one study in low-rise residential buildings [6] and another study with general urban settings [14]. This study [6] concluded that urban residential areas with higher levels of architectural variation and lower building height have been proved to be more restorative. In the present study, we found similar trend that the higher SVF (a larger sky view) and complex layout types would lead to higher restoration likelihood. In addition, the positive correlation between SVF or larger sky view and preference can be considered to agree with the key findings [6].

Second, the effects of urban form on restoration likelihood and preference can be partially or fully mediated by relevant visual properties and affective appraisal (familiarity, complexity, enclosure) and restorative items (being_away and fascination). The mediation effect of being away and fascination has been well exposed for the relationship between physical factors of residential buildings and restoration potential [6]. The positive effects of being away and fascination on the preference were also in line with the findings of several studies [6, 14, 18].

4.2 Bioclimatic effects of urban form

It is normally found that SVF positively correlates with the canyon width/height ratio in these typical urban layouts. An urban neighbourhood with a larger canyon width/height ratio will have a bigger average SVF, indicating that there would be a lower maximum urban heat island effect [8, 9]. Thus, the canyon width/height ratio can take direct effect on the thermal comfort condition for residents in dense urban neighbourhoods, as mentioned in a study [8]. In urban design, the canyon width/height ratio can be regarded as a useful physical feature according to the aim to create comfortable thermal environment in a high-density residential area.

4.3 Urban form: an integrated analysis

Given the discussions in section 4.1 & 4.2, it can be found that there is a link between the physical and psychological performances in these high-density urban areas, both of which receive effects of configurations of urban form. It could be worth noting that improving the bioclimatic performance (e.g. Sky View Factor) according to the optimization of urban form will directly benefit the psychological performance (e.g. psychological restoration).

However, in an urban area, only the green space or green infrastructure has been broadly investigated in terms of its impact on the health and wellbeing (e.g. mental, physiological), and the physical environmental performance (e.g. noise, air pollution, heat reduction) [19]. It is necessary to promote more studies into the effect of urban form, especially for the psychological performance (mental health).

4.4 Research limitations

For the psychological experiment, the method of rendering images enabled the creation of highly realistic urban environments, in combination with the systematic manipulation of independent variables and control for confounding variables [16]. However, for such complex urban neighbourhoods, the application of rendering image (2D) may still need a further validation.

The participants to attend the psychological experiment were recruited from current university students, which may have brought in limited sample diversities in age and socioeconomic status. It cannot be denied that there might be some divergence of psychological responses between students and other groups (e.g., professionals).

The 24 urban layouts used in this study were achieved based on current situation of Shanghai city and some available literatures. They might not be able to fully cover all possible typical urban forms found in the urban area of Shanghai.

4.5 Future work

Further studies will be carried out to test more possible urban forms and apply more psychological variables relevant to mental health problems in high-density neighbourhoods with various locations and socioeconomic statuses. To improve the participants' experiences during the experiment, the use of a complex audio-visual system could be considered at the next stage. In addition, the diversity in research participation would be enhanced through the applications of various recruitment approaches.

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Sustainable construction in humanitarian action

Criteria for humanitarian building sustainability

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ABSTRACT: Humanitarian organisations have an interest in improving the sustainability of buildings that support the assistance provided to people affected by conflict and disaster. Yet, usual means of assessing building sustainability - e.g., labels such as LEED and BREEAM - are not suited to the priorities and contexts of humanitarian action. This paper describes research seeking to identify building sustainability criteria that are relevant and feasible in relation to building in the context of humanitarian programs. A comprehensive master list of building sustainability criteria is developed and presented in a novel graphic format that supports comparison and analysis. Then, consultations with humanitarian construction practitioners support development of a ranked short list of criteria that are particularly relevant to the priorities and contexts of humanitarian assistance. The research is the first stage of a project developing an analytic framework and digital tool to support building sustainability assessment in the context of humanitarian action.
KEYWORDS: building; sustainability; assessment; criteria; humanitarian;

1. INTRODUCTION

Humanitarian assistance entails saving lives, alleviating suffering and protecting the dignity of people affected by conflict and disaster. The urgency of humanitarian response contrasts with the duration of construction and the durability of built work. Yet, construction – of health facilities, schools, etc. - is an important function of many humanitarian organisations.

The urgency and relatively short funding cycles of humanitarian assistance also contrasts with the long-term consideration of sustainability. Yet, sustainability is increasingly important for humanitarian organisations, due, *inter alia*, to donor concerns and recognition of links between sustainability, climate change and the incidence of humanitarian crises. Recently, numerous initiatives have aimed to improve the social, economic and environmental sustainability of humanitarian organisations and their operations (e.g., [1]). Improving the sustainability of humanitarian construction is one aspect of this broader emphasis on improved sustainability of humanitarian assistance.

Improved construction sustainability is typically supported by assessments of building and infrastructure designs and operation. Various methods and systems have been developed to support such assessments. Numerous sustainability labels (e.g., Leadership in Energy and Environmental Design, LEED) are available that define sustainability assessment methodologies and provide certification for buildings and infrastructure. Notwithstanding limitations, they are widely recognised and provide an accessible means of assessing and comparing sustainability, thereby promoting improvements in sustainability performance.

However, in general, sustainability labels are not readily applicable to the work of humanitarian actors. In particular, widely-used labels such as LEED and the Building Research Establishment Environmental Assessment Method (BREEAM) have been developed with regard to buildings and infrastructure in developed economies with relatively sophisticated building industries (and exported to socially and economically comparable markets). Notwithstanding international use of these labels, the criteria, priorities and benchmarking data they employ may be less relevant to less-developed and unstable contexts of humanitarian assistance [2]. Further, label assessment methodologies require expertise and data about buildings and contexts that may not be readily accessible for humanitarian organisations nor available for the countries in which they work.

This paper addresses the applicability of building sustainability labels and the criteria they use to construction work of humanitarian organisations. It reports research aimed at identifying criteria that are most relevant and feasible, or adaptable, in relation to assessment of building sustainability in the contexts of humanitarian assistance. This research is the initial stage of a collaboration between EPFL, ETH and the International Committee of the Red Cross (ICRC), which aims to support improved sustainability of humanitarian construction. The subsequent stage involves development of an analytic framework and digital tool tailored for building sustainability assessments within the arena of humanitarian action.

2. METHODOLOGY

While the research has focussed on the work of the ICRC, it is intended to address a broader scope of humanitarian construction. The ICRC's mandate of assisting those affected by conflict encompasses various forms of assistance, including provision of protection, healthcare and basic services such as water and sanitation. While ICRC operations encompass a large proportion of humanitarian crises internationally, disaster-related situations not involving conflict are not explicitly addressed here.

A large range of building sustainability assessment labels are available (Bernardi et al. list 63 labels [3]). These labels are distinguished by different priorities, criteria, and scoring systems. Yet, many apparent differences are attributable to variations in terminology and structure rather than substantial differences in ways that sustainability is defined and assessed. Eight labels are addressed here:

1. LEED (New Construction, v.4.1)
2. BREEAM (International, New Construction)
3. EDGE (https://edgebuildings.com/)
4. SBTool (www.iisbe.org/sbmethod)
5. DGNB (New Buildings, International)
6. SNBS (v. 2.1) (www.snbs-batiment.ch)
7. HQE (International, Non-residential Buildings)
8. QSAND (www.qsand.org/)

In addition, criteria defined in standard ISO-21929-1:2011 – *Sustainability in Building Construction (Sustainability Indicators)* [4] are also taken into account.

The research comprised two components: 1) development of a weighted master list of building sustainability criteria, and 2) editing of the master list into a short list of criteria that are particularly relevant to buildings associated with humanitarian action.

The first component involved development of a weighted criteria master list through review of the group of nine labels. The review first involved comparison of criteria from each label. Given differences in structure, and terminology, a consistent hierarchy was adopted that distinguished between *criteria*, *indicators* and *categories*. Here, *criteria* refers to specific aspects of building sustainability (e.g., operational energy consumption). *Indicators* refers to measurements of performance in relation to each criterion (e.g., annual energy consumption). *Categories* refers general topics under which criteria are grouped (e.g., energy). Criterion weight was defined as the weighting of the criterion in relation to maximum score available in the label. For example, LEED (New Construction, v.4.1) has a maximum score of 110 points and allows a maximum of 4 points for *Renewable Energy*, resulting in a weight of 0.045. Definition of weight also highlighted non-scored prerequisite criteria.

The nine label-specific criteria lists were then combined into a single master list. This involved a process of comparison of criteria and indicators, taking into account differences in terminology and categorisation of criteria and indicators. For each criterion, aggregate weight was defined as the sum of label-specific weights. The definition of aggregate weight also highlighted criteria that are non-scored prerequisites in any of the labels.

The second research component involved practitioner consultations that informed editing of the master list into a short list. Building professionals (i.e., architects, engineers, and project managers) from ICRC and other humanitarian organisations were engaged in three phases of consultation. Consultations addressed the *relevance* and *feasibility* of building sustainability criteria in relation to humanitarian assistance. Here, *relevance* refers to the importance of criteria in relation to the functions of humanitarian buildings and the priorities of stakeholders. *Feasibility* relates the availability of project-specific and context-specific data, computational tools and expertise required to measure the criteria via associated indicators.

The first preliminary consultation sought to remove from the master list criteria that are clearly incompatible with contexts and functions of humanitarian assistance, to provide a group of criteria to be addressed effectively in more-detailed consultations. A focus group discussion involving two senior humanitarian construction practitioners informed this initial edit (which was later reviewed and adjusted in the larger focus groups during the third round of consultation).

The second consultation addressed in greater detail the feasibility of the remaining criteria. In an online survey, 48 humanitarian construction practitioners rated the feasibility of implementing 30 building sustainability criteria in the context of humanitarian assistance programs. Feasibility scores (from 0 to 5) were assigned by each respondent and then combined into aggregate feasibility scores (from 0 to 1) for each of the criteria.

In the third round, a consultation workshop addressed together the relevance and feasibility of the criteria from the master list. 11 participants were asked to position criteria in a field indicating relative relevance (vertical axis) and feasibility (horizontal axis). Assessments of relevance and feasibility addressed in the questionnaire survey (i.e., the second consultation)

were first adjusted by participants. Then, additional relevant criteria from the master list were added and positioned in relation to relevance and feasibility determined by practitioner participants.

4. RESULTS

Review of each of the nine sustainability assessment labels identified criteria that are represented for each label in **Annex 1**. Combination of the criteria from each label identified 108 building sustainability criteria, which are listed with aggregate weights in **Annex 2**.

The 108 criteria are presented graphically in **Figure 1**, in which each node represents a sustainability criterion. Node sizes represent aggregate weight, with the width of grey circular bands representing weighting of the criteria in individual labels. Node colours represent dimensions of sustainability – green represents environmental conservation, orange represents social development, blue represents economic development. Nodes are positioned in segments representing generic categories that have been defined taking into account the various categories of the nine labels.

The results of consultations are presented in **Figure 2**, which highlights the 40 sustainability criteria deemed by informants to be particularly relevant to building in with regard to humanitarian assistance. Weights of these criteria – i.e., the size of the nodes – take into account workshop adjustments from the third round of consultation. **Annex 3** lists these criteria with adjusted weight/relevance and feasibility scores, which were modified from original aggregate weights and original feasibility ratings.

5. DISCUSSION

Figure 1 suggests a preponderance of environmental conservation in sustainability assessment labels. Of the 108 criteria, 72 (67%) are associated with environmental conservation, while 46 (42%) are associated with social development and 24 (22%) with economic development. Moreover, of nine of the ten highest aggregate weighted criteria are associated with environmental conservation. This reflects broader societal perspectives and priorities regarding sustainability as well as the evolution of assessment labels, with prominent labels (e.g., LEED and BREEAM) originally addressing environmental conservation only [3]. Despite the evolution of more holistic sustainability concepts, environmental conservation retains prominence compared to social and economic development.

In general, criteria are distributed evenly across the nine categories in **Figure 1**. One exception to this is the category of *Culture*, which comprised only two criteria addressed in SBTool, SNBS and ISO-21929.

Notwithstanding this distribution, the inordinate weighting of a small group of criteria highlights specific priorities. Among the range of 108 criteria, inordinately weighted criteria include:

1. Assessment and minimisation operational energy demand (C2),
2. Assessment and reduction of GHG emission from operation (F7),
3. LCA and optimisation of life-cycle impacts (operational and embodied energy) (C3, E5),
4. Design and provision for healthy air quality (G3),
5. Reduction of operational water demand (D4),
6. Selection of an appropriate site that has positive impacts on the land and surrounding area (B1),
7. Management of surface water, inc. collection and recycling (D1),
8. Adaptability to new uses and functions (H4),
9. Protection of site ecology, inc. flora & fauna (B5),
10. Design and provision of comfortable user-controlled heating and cooling (H1).

The consistently high weight allocated to these criteria across labels suggests a consensus that these criteria are particularly significant aspects of building sustainability.

Development of a short list of criteria that are particularly relevant and feasible in relation to humanitarian action entailed omission of many criteria from the master list. From 108 criteria in the master list, 40 criteria remained in the humanitarian-specific short list presented in **Annex 3**. The extent of omissions is in part attributable to the formats of consultations that restricted the depth of consideration of the wide range of criteria in the master list. Yet, the format of consultations also permitted informants to focus on criteria considered particularly relevant to their work.

The 68 omitted criteria may be characterised in several ways. 11 of the omitted criteria (16%) pertained to functions deemed irrelevant (or not significantly relevant) to humanitarian objectives, such as cold storage, laboratory and residential functions. 10 of the omitted criteria (15%) relate to features of sites and surrounding neighbourhoods. In excluding these criteria, practitioners cited the lack of control humanitarian organisations have over site selection. 7 of the omitted criteria (10%) relate to building systems that were deemed irrelevant to humanitarian action due to inordinate complexity and/or excessive cost; this included criteria relating to mechanical HVAC systems. Finally, criteria were omitted that were not deemed irrelevant, though were assessed as being of low significance in light of pressing needs characterising humanitarian assistance; this included criteria addressing, e.g., water temperature, light and noise pollution, as well as acoustic and olfactory conditions.

The resultant short list retains the preponderance of environmental conservation that characterised the master list. The short list also generally maintains the distribution of criteria across the nine categories, with the exception of the category of *Location and Site*, which is less represented in the short list, reflecting the limited control of humanitarian actors over site characteristics.

Adjustments to criteria relevance scores during workshops entailed changes to relative weight of these criteria in response to constraints and priorities of humanitarian action, compared to general building contexts addressed in assessment labels. These adjustments included increases in the relevance scores of 16 criteria, reductions in the relevance scores of six criteria, and the addition of 11 new criteria from the master list. No trend is apparent in these three groups of criteria regarding associated dimensions or categories.

Adjustments of feasibility scores during consultations entailed changes from the feasibility assessments derived from the questionnaire survey. The discursive character of the workshops enabled informants to consider in greater detail the factors affecting feasibility and to arrive at an improved assessment. Adjustments included increases to feasibility scores of seven criteria and reductions in feasibility scores of 13 criteria. As with changes to relevance scores, no trend is apparent in these two groups of criteria in relation to the associated dimensions or categories. Yet, the preponderance of reductions suggests that, in general, assessing building sustainability in humanitarian contexts is less feasible (i.e., more difficult) compared to usual contexts.

The manner in which these scores of relevance and feasibility are presented – specifically, the numerical precision – suggest a degree of accuracy that is not actually provided by the methods employed. The scores are determined from subjective assessments of a group of practitioners that occupy similar roles – architects, engineers and project managers working for humanitarian organisations. Rather than precise ratings, the scores allow relative positioning of the criteria from the perspective of expert practitioners.

Despite this limitation, this identification of criteria that are particularly relevant to building in relation to humanitarian assistance is a useful contribution to improving sustainability in this specific arena. The criteria identified in this study provide a foundation for the ongoing development of an analytic frame and digital tool that will enable the ICRC and other organisations to assess the sustainability of their building activities. Specifically, the findings of this study serve to focus attention on criteria that are the most relevant and feasible aspects on sustainability in relation to humanitarian construction.

6. CONCLUSIONS

A review of eight building sustainability assessment labels and one related standard informed development of a comprehensive range of 108 criteria and associated label-specific weights. These weights are taken to indicate the relative importance attributed to each criterion. Thus, aggregated weights across the group of labels are taken to indicate a consensus on the relative importance of each criterion as an aspect of building sustainability. The novel graphic format developed to present these criteria highlights the preponderance of the dimension of environmental conservation over those of social and economic development.

A consultation process engaging humanitarian construction professionals (i.e., architects, engineers and project managers) served to identify from this master list a short list of criteria that are particularly relevant and feasible in relation to construction in humanitarian action. *Relevance* here refers to relative importance in relation to the objectives and priorities of humanitarian assistance and the actors involved in its provision, while *feasibility* refers to the availability of project-specific and context-specific data, tools and requisite expertise to measure the criteria. 40 building sustainability criteria were highlighted as being particularly relevant/important in relation to buildings in the context of humanitarian assistance.

The process of consultation highlighted in the short list a smaller group of around ten criteria that were inordinately weighted – i.e., assessed by practitioners as being additionally important aspects of building sustainability in the context of humanitarian action.

The consultation process entailed subjective assessments of a relatively small group of practitioners. Nevertheless, the short list focusses attention on sustainability criteria that are particularly relevant to construction in the context of humanitarian action. This short list of criteria will inform ongoing research and development of a building sustainability assessment framework and digital tool tailored to the requirements of humanitarian organisations.

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Figure 1: *Graphic presentation sustainability criteria master-list including aggregate weight and categorisation*

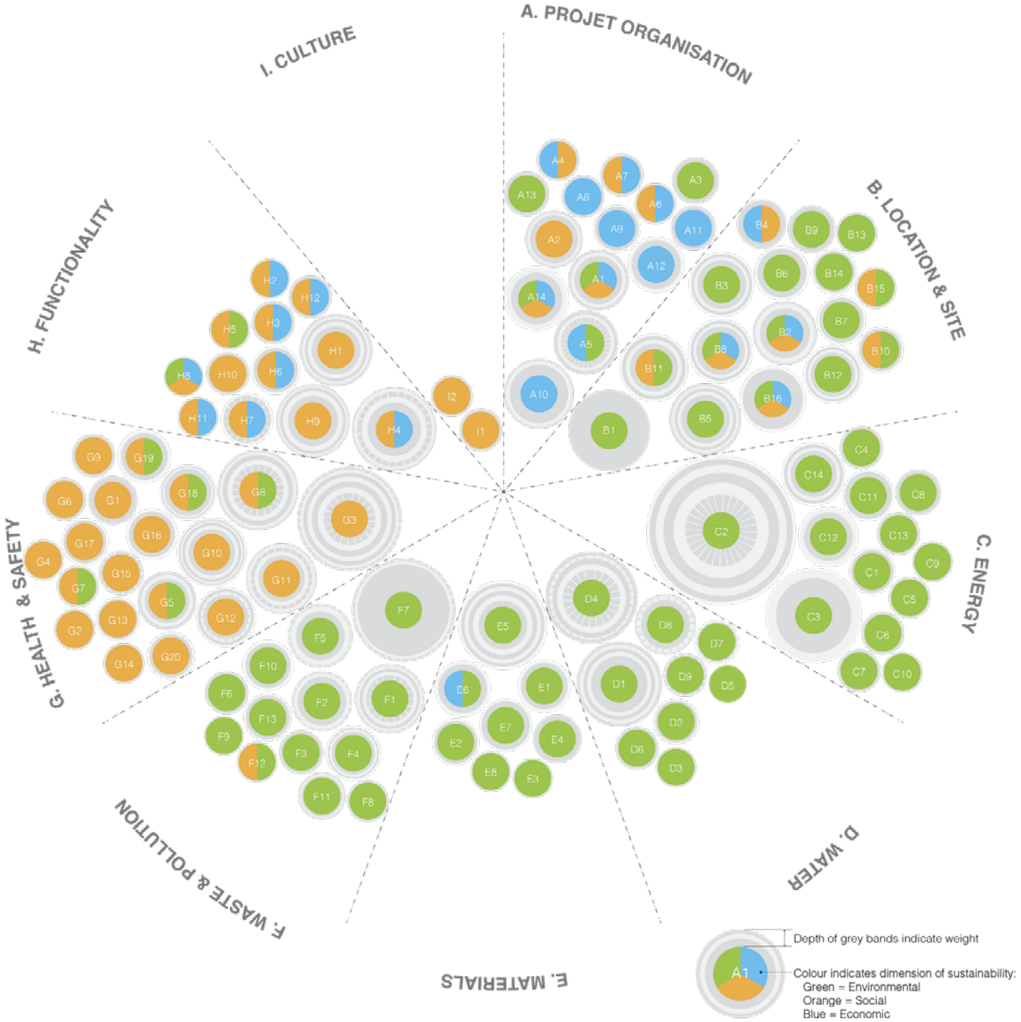
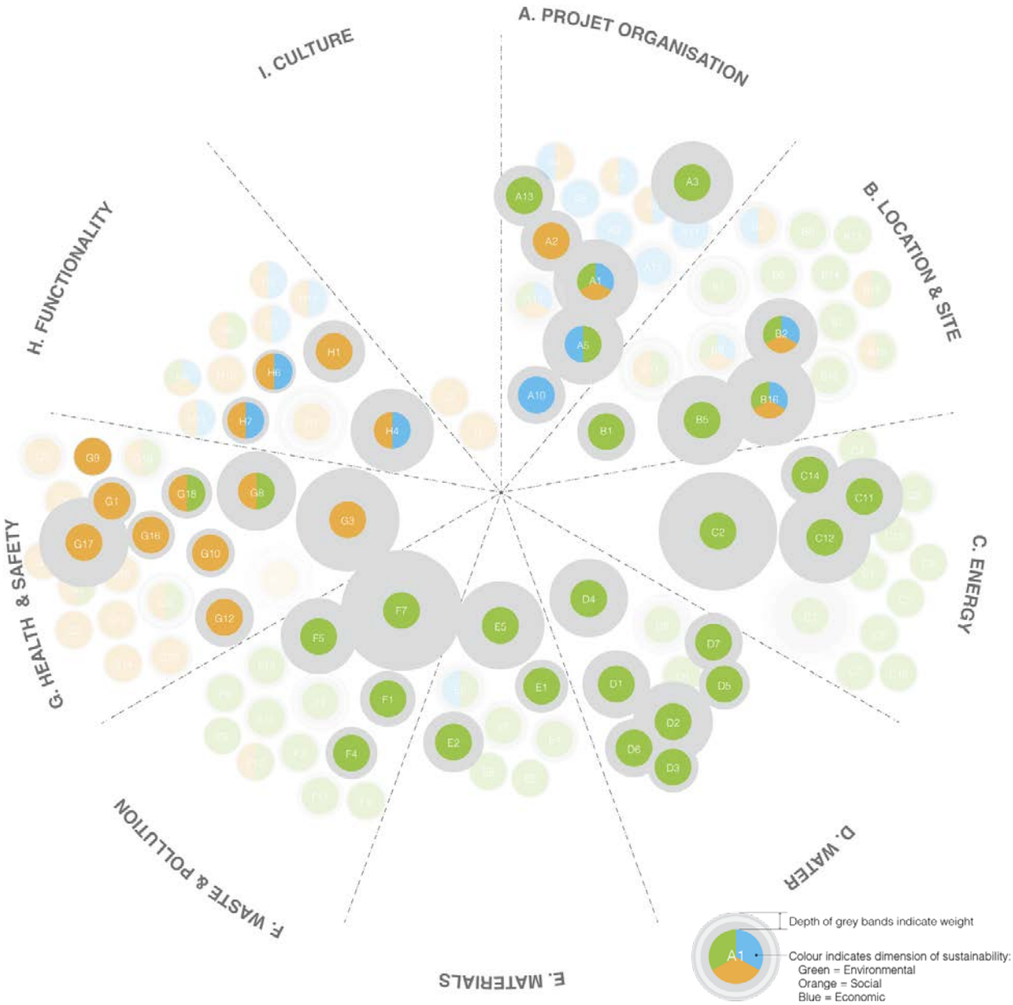


Figure 2: *Graphic presentation sustainability criteria short-list with adjusted weight reflecting relevance to humanitarian action*



A1	Comprehensive & consultative project brief	C2	Assessment and minimisation operational energy demand	D7	Installation of water metering with data collection and display	G8	Design and provision of comfortable user-controlled heating and cooling
A2	Participative design process (disciplines & users)	C11	Arch. design to reduce radiant and conductive heat gain/loss	E1	Assurance of resp. sourcing & efficient use of raw materials	G9	Architectural design to optimise thermal comfort
A3	Monitoring & reporting env. impacts during construction	C12	On-site renewable energy production	E2	Specification and use of recycled building material	G10	Design and provision of comfortable acoustic conditions
A5	Commissioning planned and undertaken	C14	Install. of energy metering w. data collection and display	E5	LCA and optimisation of life-cycle impacts (embodied energy)	G12	Design for comfortable natural lighting
A10	Life-cycle cost (LCC) calculation	D1	Management of surface water, inc. collection and recycling	F1	Assessment and reduction of construction waste	G16	Spec. of user control systems for ventilation, thermal & lighting
A13	Assessment of project impacts on local economy	D2	Assessment and reduction of landscaping water demand	F4	Provision for operational waste recycling	G17	Design & prov. for safety & security in relation to personal threat
B1	Selection of approp. site that has pos. impacts on surrounds	D3	Reduction in construction water demand	F5	Prov. of facilities for operational waste management & disposal	G18	Design & prov. for safety &security in relation to natural hazards
B2	Avoidance of negative impacts on local properties	D4	Reduction of operational water demand	F7	Assessment and reduction of GHG emission from operation	H1	Design & prov. for accessibility throughout the building and site
B5	Protection of site ecology, including flora and fauna	D5	Installation of operational water recycling	G1	Design and provision of sanitary health conditions	H4	Adaptability to new uses and functions
B16	Compliance with planning policies and regulations	D6	Installation of a leak detection system	G3	Design and provision for healthy air quality	H7	Design and provision for ease of maintenance & cleaning

Community resilience during time of crisis
Case of Mahdibagh Colony, Nagpur

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ABSTRACT: The Covid-19 pandemic has caused devastation in cities around the world. Communities have been at the frontline of this disaster as the infection spread from home-to-home leading to health emergencies as well as social and economic difficulties. It is opportune to document the innovative approaches taken by communities to respond, adapt and rebuild after the crisis. This can help in future capacity building. The present research investigates a unique and sustainable neighbourhood in the Covid hotspot of Nagpur, India for its response to the disease and the ensuing lockdown. It studies the colony on four factors that influence community resilience: I) vulnerable population; ii) built environment; iii) income levels; and iv) mutual trust. Primary data is collected through online resident survey and interviews. Details of built environment are mapped by a visual survey. The initiatives are calibrated against the percentage of patients, the COVID mortality rate and general wellbeing of the residents. The colony has shown high resilience to the pandemic that has translated into lower infection rate and quick recovery. The developed framework can be used to assess communities for their resilience and also document best practises.
KEYWORDS: *Community; Colony; Resilience; Best Practises; Covid*

1. INTRODUCTION

Community forms the starting point for urban disaster response. Increasing the capacity to handle crisis at this level can ultimately strengthen cities. Communities that are sustainable and resilient are those that can confront changing conditions, absorb disturbances with flexibility, and utilize existing resources and local partnerships to achieve community goals without compromising the ability of future generations to meet their own needs (TN Department of Environment and Conservation, 2021). As India emerges from the devastation caused by the pandemic, a study of community approaches is required to see how they have shaped response and recovery.

1.1 Community Disaster Resilience

The COVID-19 pandemic is found to be similar to natural disasters in its ability to disrupt social and organisational practices and for which a society must show resilience (Tanl et al., 2021; H, 2020; M & H., 2020). Resilience is the capacity of a social system to adapt to a disturbance and recover from the damage quickly and with minimal losses. The concept and assessment of Community Disaster Resilience (CDR) is widely studied (Nguyen & Akerkar, 2020; Sonny S. Patel, 2017) with a list of factors and indicators that broadly fall within those defined by Norris et al (2007):i) Economic Development; ii) Social Capital; iii) Information and Communication; and iv) Community Competence. Xu et. al. (2021) analyse the factors to determine the key criteria that influence community resilience during the Covid-19 pandemic. They define them as i) vulnerable members; ii) built environment; iii) income level; and iv) mutual trust. These are taken as criteria for the present study and a framework of indicators is developed from prior studies.

Vulnerable Members: The key to making a community strong is by protecting those who are most at risk. The World Health Organization (WHO, 2021) identifies that Covid-19 is more severe in people above 60 years or with underlying health conditions or comorbidities. These are thus considered as indicators.

Built Environment: Xu et. al. (2021) find that the robustness of the physical environment during the pandemic depends on the density and condition of the building environment and the provision of emergency facilities. Open spaces act as breathing space between the houses and affect the health of the residents.

Income Level: Research has established that the pandemic led to an extremely negative effect on economic activities and employment (Cotofan et al., 2021). The job loss during this period caused a decline in income levels. Households with high Socioeconomic status (SES) are more resilient against COVID-19 than those with low SES due to better sources of income (Rahman et al., 2021). Poor households are more likely to fall into poverty when faced with any external shock to their source of livelihood. Household income levels and unemployment are thus considered for study.

Mutual Trust: Prior studies on community resilience establish that along with individual strengths it is important to consider the community perceived collective resources in assessing CDR (Norris et al., 2007; Tariq et al., 2021; Rapaport et al., 2018). Mutual trust between members is an essential resource. It refers to the belief that others can be relied upon and the willingness to act on the assumption of the other's benevolence (Cohen et al., 2013). When members are closely connected to each other, it can invite collective beneficial action.

Trust between the members and the community leadership increases the public's positive response to crisis communication during adverse times. It also leads to more involvement of the members in the pre-disaster strategic planning and post-disaster recovery.

2. STUDY AREA

Nagpur is a city of 4.65 million located in Central India. It is a major commercial and political centre of the region. Since 2020 it has rated highly for its cleanliness (Chakraborty, 2020). India is reported to have the second-highest total COVID cases in the world (BBC News, 2021) and in 2021 Nagpur was one of its hotspots (Maitra, 2021). The city faced a strict lockdown from March 2021 to June 2021 (Kamble & Bahadure, 2021).

Figure 1*: Map locating Mahdibagh in Nagpur, India*

Mahdibagh, a gated colony in the northeast of the city is taken as a case study to assess community resilience during these trying times (Figure 1). The community was established in 1891 and consists of members of the same faith under the guidance of a Spiritual Head. It has a population of almost five hundred with varied income levels, education and occupations. The residents share a strong social and religious bond which is evident in their way of life. The colony manmade and natural assets are efficiently managed and maintained by a core committee of volunteers who are elected every year in a general meeting. Surawar & Surawar (2021) establish the sustainability of the colony's design approach.

A hypothesis is formed that Mahdibagh was able to face the peak duration of the pandemic with minimum loss and recover from it quickly due to good practices which should be recorded.

3. METHOD AND DATA COLLECTION

This work investigates the study area for community disaster resilience on basis of the four identified criteria and compares the results to the infection and mortality rate witnessed during the peak period of the pandemic from 1st March 2021 to 31st July 2021. An online form was circulated among the residents to collect demographic background of the respondents and details of their residences. It also includes questions about COVID infection and vaccination. The random sample of residents who answered the survey consists of 361 people with variation in age, income and gender as seen in Figure 2.

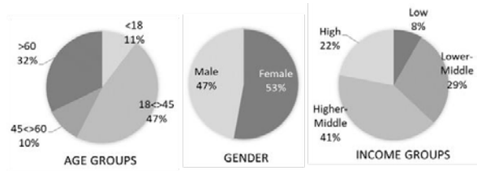

Figure 2: *Profile of residents surveyed*

Further, three focus groups consisting of community elders (above 60 years), youth (between 18 to 29 years) and doctors were interviewed to collect details of decisions and steps taken to control the infection and support residents during the lockdown. The interviews were conducted informally either telephonically, through online meets or in person following social distancing norms. A five-point Likert scale from 1-Very low to 5-Very high, is used to gauge the resident's opinions. Lastly, a visual survey is carried out to map the built and unbuilt environment. The primary data is collected under the developed framework. Benchmarking is defined for each of the indicators (Table 1).

Table 1 : *Benchmarking for observed data*

Parameter	Criteria	Community Disaster Resilience Ranking					Remarks
		5	4	3	2	1	
		very high	high	moderate	low	very low	
Vulnerable Population	Percentage of individuals above 60 years	<5%	5-7.5%	7.5-10%	10-12.5 %	>12.5 %	As per the report by United Nations Population Fund (2014) the percent-age of senior citizens in Maharashtra is 10%. This is taken as average
	Percentage of individuals with comorbidities	<5%	5-7.5%	7.5-10%	10-12.5 %	>12.5 %	The range is followed from criteria 1
Built Environment	Mean number of people per sleeping room	1	2	3	4	5	Having one person per room is most preferable for quarantine situations
	Ratio of total built to total open space	1:3	1:2	1:1	2:1	3:1	The ratio of built to unbuilt is typically 1:1.35 for non-congested areas. It is thus taken as average
Income Level	Percentage of household having annual income of highest-earning member < 2.5 Lakhs	0-20%	20-40%	40-60%	60-80%	80-100%	
	Percentage of unemployment due to COVID	<3%	3-4%	4-5%	5-6%	>6%	Urban Maharashtra reported minimum 3.5% & maximum 5.8% unemployment rate from March to July 2021 (CMIE, 2022)
Mutual Trust	How much do you trust your neighbours?	Very Highly	Highly	Moderately	Less	Very less	Uses Likert scale to gauge people's perception
	How much do you trust the community leadership?	Very Highly	Highly	Moderately	Less	Very less	Uses Likert scale to gauge people's perception

3.1 Vulnerable Population

A large part (32%) of the population of Mahdibagh is above sixty years and 17% of the population suffer from chronic illness, most of whom are senior citizens.

3.2 Built Environment

The density of the houses is measured by the number of persons sharing a sleeping room since private spaces became of great importance during lockdown especially for quarantining patients. Built and unbuilt area is mapped to determine the density of built area (Figure 3).

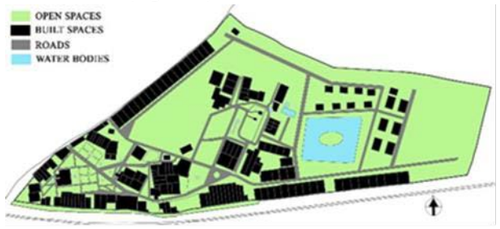

Figure 3: *Built and unbuilt areas in Mahdibagh Colony*

3.3 Income Level

The online questionnaire collects the monthly income of the household head under five categories; i) Low: less than Rs 25K; ii) Lower-middle:25K-50K; iii) Upper-middle: 50K-1Lakh; iv) High: Above 1 Lakh. The change in employment status after March 2020 is also noted in the survey.

3.4 Mutual Trust

The respondents are asked to rate their trust in their neighbours for support during a disaster. They were also questioned about their trust in the committee.

4. ANALYSIS AND RESULTS

During the second wave while the city reported a positive test rate of 24-32% (Anparthi, 2021), the highest percentage of new positive cases in Mahdibagh was 7.5% (4). The total mortality rate was 6% of the infected patients while the city recorded its maximum deaths in April 2021. Thus, it is concluded that the residents of the colony were protected from the brunt of the pandemic.

Community resilience depends on social, economic, physical, demographic and institutional factors (Xu et al., 2021). Four important criteria specified by Xu et.al. and reiterated by studies in India (Pathak et al., 2020; Acharya & Porwal, 2020), are taken for the study of Mahdibagh. Community actions to counter existing vulnerabilities are identified and discussed (Table 2).

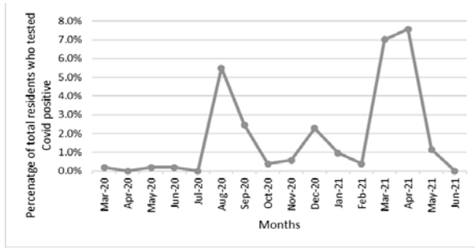

Figure 4: *Percentage of Covid infections in Mahdi Bagh Colony from May 2020 to June 2021*

4.1 Vulnerable Population

The community has a sizeable vulnerable population which decreases its resilience during the pandemic. The community was able to restrict the number of Covid deaths during the period in consideration. This is because a majority of the elderly (85%) live in joint families and remained safely indoors with the help of other household members. For the elderly who live alone, the younger members volunteered to run errands.

On instructions by the Head of the community a number of steps were taken to protect the vulnerable population during the second wave. During peak periods of the pandemic, a youth initiative allowed residents to order vegetables and fruits once a week using a google form. The vendor delivered the goods at the entrance gate and these were distributed to the doorstep by volunteers. This enabled the vulnerable to minimise contact with the outside world. The community kitchen cooked and home delivered meals to those who were unable to manage on their own. Also, a group of community doctors and volunteers was formed to monitor the infected, especially the elderly. Oxygen concentrators and PPE kits were purchased and kept on standby for emergency patients.

Table 2*: Study of community resilience of Mahdibagh using identified indicators & sub-indicators with discussion on action taken. Refer to Table 1 for Benchmarking*

Parameter	Criteria	Source	Data	Ranking	Action Taken
Vulnerable Population	Percentage of individuals above 60 years	Online survey	32%	1	Volunteer systems enabled elders to minimise contact with the outside. Infection was only 28% in this age group.
	Percentage of individuals with comorbidities	Online survey	17%	1	A doctors' group was established to monitor the health and wellbeing of these members.
Built Environment	Mean number of people per sleeping room	Online survey	1.85	4	Home quarantine was possible. Patients were monitored by resident medical professionals. Portable oxygen concentrators were made available.
	The ratio of total built to total open space	Mapping	1:2.8	5	Every household has access to private as well as public open spaces that have helped in maintaining wellbeing even during the lockdown
Income Level	Percentage of household having monthly income of highest-earning member < 25000	Online survey	8%	5	Members with lesser resources, who were hit financially by the lockdown are supported in their recovery by other community members
	Unemployment due to COVID	Focus groups	1.1%	5	Professional advice and support is readily available to younger members enabling them to overcome difficulties. The community members help each other find employment, even providing jobs to those in need
Mutual Trust	How much do you trust your neighbours?	Focus groups	Very Highly	5	The residents consider themselves to be a part of an extended family and have a strong bond
	How much do you trust the community leadership?	Focus groups	Very highly	5	The members show full trust in their organizing committee since it is guided by the Spiritual Head
		CDR Score		4	

4.2 Built Environment

Houses in the colony are either individual bungalows or row houses. All of them have access to drinking water and sanitation. The mean number of persons per sleeping room is found to be two and on average one toilet is available for every two persons. Standard of hygiene is high. Also, most people were able to home quarantine when infected. Except for a few of the old houses, all residences have a front garden and many (87%) have a porch. There are two large open playgrounds and a golf course so the built to unbuilt ratio of the colony is high (1:2.8).

The openness in built environment is also aided by the absence of compound walls so residences are directly open to the road and the adjacent plots. This allows people to connect with their natural surroundings and talk to the neighbours while maintaining social distancing.

Figure 5*: The main playground in Mahdibagh*

4.3 Income Level

Only 8% of the residents fall in the low- income group. They are supported by the other members through financial assistance or even employment. Only 4 of the 361 respondents (1.1%) reported that they have lost their jobs during the period in consideration. On the other hand, the unemployment rate in urban Maharashtra rose to 7.62% in April 2021.

4.4 Mutual Trust

Mahdibagh is unique in its social bonding. All the residents know each other on first name basis and participate together in celebrations and sorrow. People who were either bereaved or faced a financial setback were able to recover quickly because of strong support from the community.

The community lays deep faith in their Spiritual Guide who personally oversaw the management of community resources including volunteers, available hospital beds and oxygen concentrators, both before and during the second wave. The resident doctors were brought together in an advisory group to issue warnings and advice. All the members are linked through a WhatsApp group so that community awareness is high.

5. CONCLUSION

Community is defined as group of people with diverse characteristics who are linked by social ties, share common perspectives, and engage in joint action in geographical locations or settings (Ostadtaghizadeh et al., 2015; Tariq et al., 2021). Communities are the building blocks of a city. Social connections can be found to be strongest here and they form the lowest level of informal decision making. Recent studies have shown that conversations and considerations on resilience should be shifted from the top institutionalized level (national, state and city) to local community levels (Magis, 2010; Pfefferbaum et al., 2013; Rapaport et al., 2018). This can be beneficial in reducing response time and recovery can also be quickened by strengthening people at the community level.

The Covid pandemic is a recent worldwide disaster that has created an unprecedented situation where during lockdown cities and even neighbourhoods were cut off from each other to stop the spread of the disease. This led to community-led innovative approaches to counter the crisis and recover from it. People have intuitively realised the strengths and weaknesses of their localities. The present study formulates a framework that can be used to study Community Disaster Resilience (CDR) during pandemics in cities of India. It is used to study Mahdi Bagh, a community in Nagpur which is found to display high resilience. The walled colony is studied under the four defined parameters. It shows that it has strong community ties and sustainable planning but its weakness lies in its relatively high percentage of the vulnerable population. The community through its able leadership and strong bonding has been able to overcome the setback by protecting the elderly and sick through voluntary medical and social aid.

As cities face a new threat of pandemics in the foreseeable future it is necessary to strengthen our local communities and neighbourhoods. The developed framework reveals that the four parameters of CDR even if not intrinsically present in the community, can be reinforced through timely decisions and planning. The research method thus advocates the assessment and documentation of best practices that other communities can adopt for future action.

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Will favelas survive?

A study of urban heat islands and climate emergency in Maré, Rio de Janeiro

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ABSTRACT: Rio de Janeiro's metropolitan area, home to more than 10 million people, is becoming increasingly hotter. Rising temperatures, due to intense industrialisation, urbanisation and anthropogenic heat lead to 'urban heat islands'. Seen as a key feature of the urban climate and one of the main socio-environmental problems of the 21st century, the warming of cities, enhanced by climate change, can pose serious risks to the health of their populations. The main objective of this research is to evaluate the relationship between the urban environment and variations in intra-urban temperatures in Maré, a densely populated complex of favelas *in Rio de Janeiro. The methodology involved data measurement through mobile transects, thermal sensation calculation and analysis of historical, geographic, environmental, and urban changes in the territory. Results show that intra-urban temperatures are higher where there is less access to ventilation, in streets that have a reduced sky view factor, as well as parts closest to industrial areas. By comparison, temperatures are lower in vegetated and shaded areas. Understanding the causes of urban heat as well as climate change and producing specific changes in these spaces can mitigate urban overheating, while also empowering citizens to demand a healthier city.*
KEYWORDS: Urban Heat Island, Climate Emergency, Favela, Maré

1. INTRODUCTION

Before developing into a city, Rio de Janeiro had an exuberant nature composed of clean rivers and abundant vegetation of the Atlantic Rainforest, the *restingas* and mangroves located by the sea. This natural landscape was responsible for maintaining an environmental balance in relation to population growth and pre-industrial anthropogenic production in that tropical climate location. In the last century, the rapid and uncontrolled urbanisation process gave rise to a large city and the emergence of *favelas*, when "infrastructure and public health lost the race for population growth" [1]. *Favelas* have become an inseparable part of Rio's urban landscape.

In addition, the Rio de Janeiro Metropolitan Area is home to more than 10 million people and is becoming increasingly hotter. Over a period of 20 years, urban soil temperatures have increased by 15 °C (1980-2000) and are, on average, up to 7° C warmer than nearby non-urbanised areas [2]. Industrialisation, extensive urbanisation, land use and the growth model adopted by cities, combined with factors such as macroclimate and geographic location, modify the climate in urban areas, giving rise to heat islands [3]. The morphology of the heat island is strongly controlled by the unique character of each city. The exact shape and size of this phenomenon varies in time and space as a result of meteorological, local and urban characteristics, such as [4] time of day, season, shape and function of the city [3]. More specifically, urban heat islands are caused by the thermal properties of materials, released anthropogenic heat, canyon radiative geometry, urban greenhouse effect, reduction of the evaporative surfaces, as well as reduced ventilation in the dense urban environment [5].

The warming of cities, enhanced by climate change, can pose serious risks to the health of their populations. As demonstrated by the IPCC Sixth Assessment Report, extreme heat events have resulted in higher human mortality and morbidity [6]. Research [7] related temperature to mortality in 384 locations in 13 different countries, showing that 7.7% of mortality rates are associated with suboptimal temperatures, with large differences between countries that ranged from 3.37% in Thailand to 11% in China. High and low temperatures have been correlated with increased risk of a wide range of cardiovascular and respiratory diseases, among others, suggesting the existence of multiple biological pathways, accounting for 4.62% of total mortality rates in São Paulo [7].

Extreme temperatures have a direct impact on all-cause mortality rates, with peaks occurring on the same day or shortly after exposure to intense heat. Peaks on the hottest days lead to a significant increase in mortality caused by myocardial infarctions and strokes [8]. High temperatures cause sweating, which can lead to dehydration.

Furthermore, in large cities, weather extremes can disrupt buildings operations, transport, waste management, water supply, drainage systems, together with the supply and consumption of electricity and fuel. These factors can lead to a wide range of adverse health effects, depending on the age, physical status, and financial resources of residents, interfering significantly in public health [9].

Climate risks and inequality in access to adequate living conditions are closely related, as low-income households living in large cities struggle to have healthy housing and quality health care. By making the infrastructure of residences more resilient to temperature changes, it is possible to obtain better conditions regarding comfort and health [9].

Urban climate-resilient development must be inclusive, considering adverse outcomes for distinct groups, in order to prevent increasing exposure to risks and exacerbating inequity. Adaptation will be more effective if it is responsive to regional and local land use development and addresses the fundamental drivers of vulnerability, thus reducing climate risk for low-income residents living in informal settlements, among others [6].

Therefore, the main purpose of this article is to evaluate the thermal sensation of two *favelas* located in the Maré complex - a grouping of several *favelas* – in order to understand the urban heat island intensity through the territory, as well as its risks, which, coupled with extreme weather events enhanced by climate change, can impact inhabitants' lives. Through this study, it was possible to analyse the temperature differences within the territory, discuss their causes and possible mitigation, and contribute with planning initiatives that target better quality of life and health for the inhabitants. This, in turn, can lead to greater resilience in relation to the climate emergency.

1.1 Context analysis

During industrialisation and rapid urban densification, lower-income population converged to the North Zone of Rio de Janeiro, concentrating along the railway and industrial zones, where urban heat islands are mainly clustered. Maré is a large complex of *favelas* located on the east border of the North Zone, and the Guanabara Bay (Fig 1).

Maré is formed by 16 communities with nearly 140,000 inhabitants in total [10]. It has been built on legal and illegal reclaimed lands since the 1940s, modifying the initial landscape outline. Nowadays, it has a high population density and a great absence of urban and infrastructure investments. There is a lack of collective services, mainly sanitation (clean water, waste collection, sewage, and drainage systems), rising the region's vulnerability to climate change, with frequent floods whenever it rains. In addition, it is located on a coastal area of low elevation, presenting susceptibility to sea rise [10].

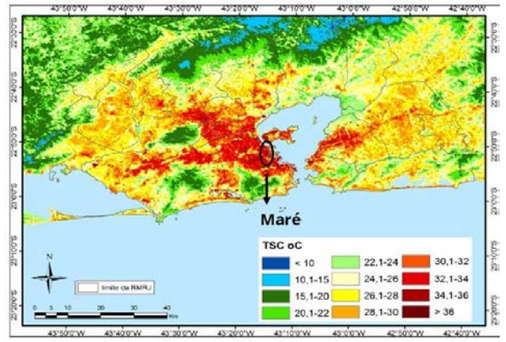

Figure 1: Maré location indicated on the Mean Continental Surface Temperature Map [2000-2010] of Rio de Janeiro Metropolitan Region.

Historically, different urban morphologies have developed and two of them were considered in this study: Nova Holanda and Baixa do Sapateiro (Fig.2).

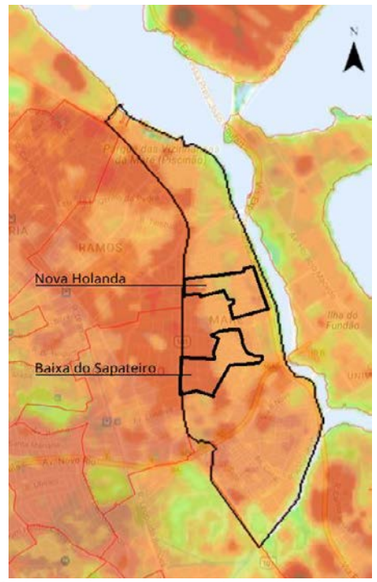

Figure 2: the *Maré complex extension and the* favelas *of Nova Holanda and Baixa do Sapateiro indicated on the overlapped Continental Surface Temperature Maps from years 2014, 2015, and 2016.*

Nova Holanda was planned and initially constructed as an area of temporary housing. Thus, streets are orthogonal, but narrow. The layout of blocks and regular-sized lots have remained the same until today, despite the modifications the buildings have undergone – wood houses were turned into self-built brick buildings as high as 5 storeys. The region has practically no green spaces. There is a high population density, with 920.7 inhabitants per hectare [11]. In Baixa do Sapateiro, growth was spontaneous from the beginning. Initially, there were self-built pile dwellings over the sea. Later, the land was reclaimed and the houses developed into self-constructed 4-5-storey buildings made of bricks, as Nova Holanda. It has narrow and winding streets, and density of 670.8 inhabitants per hectare [11].

2. METHODOLOGICAL APPROACH

This research was based on fieldwork and analytical work, where data collection took place through 2.1) identification of urban form characteristics; 2.2) air temperature and relative humidity measurements through mobile transect and calculation of thermal sensation from the recorded data, summarized as following.

2.1. Urban Form

The analysis of urban form includes figure-ground images, calculation of the Sky View Factor (SVF) of each point of Nova Holanda (Fig. 3) and Baixa do Sapateiro (Fig. 4) and infrared photographs of the surrounding surfaces.

To calculate SVF, two methodologies were used. Based on the analogue calculations by [4], the SVF data were simulated trough a "shading mask" tool (Ladybug/Grasshopper shading mask), and through a raster image and subsequent construction of the buildings in the SAGA-GIS model, where the vector image was rasterized, according to [12].

From left to right in the images (Fig. 3 and 4), one can see a large Avenue (Brasil Avenue) and an old industrial urban fabric between the avenue and the *favela*'s dwellings, which currently presents other uses such as deposits. It is an underused space through which the *favelas'* inhabitants access their homes.

The albedo analysis was carried out by observing the surfaces and infrared photographic images that indicate the temperature of the surfaces and show the amount of energy absorbed by them. The photographs were taken with a compact camera, model FLIR C3-X.

Figure 3: Urban fabric of Nova Holanda (NH), where the mensuration points can be seen in red from NH1 up to NH8; Sky View Factor (SVF) calculated as [4] with the sun position at mensuration time (AM and PM), and SVF calculated from raster image [12].

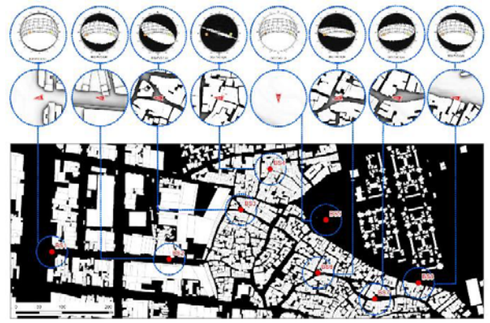

Figure 4: Urban fabric of Baixa do Sapateiro (BS), where the mensuration points can be seen in red from BS1 up to BS8; Sky View Factor (SVF) calculated as [4] with the sun position at mensuration time (AM and PM), and SVF calculated from raster image [12].

2.2 Measurements

Observing the Mean Continental Surface Temperature Maps of the Rio de Janeiro Metropolitan Region, it was possible to trace points of interest for the verification of intra-urban variations, in which the surface temperature differences were used as a starting point to be measured, in order to empirically verify this behaviour. Similarly, the measurement points (Fig. 3 and 4) were defined to contemplate the variations of different urban morphologies of the investigated *favelas*.

Urban climate was evaluated by collecting data on air temperature and air humidity through a mobile transect carried out by bicycle. A datalogger model TGP-4500 was placed inside a portable shelter, made with a white plastic bottle wrapped in aluminium foil – to reflect radiation – and cut on its edges, allowing cross ventilation inside it. Two measurements were taken per day during five days in each summer month of 2018 (January, February, March). The collected data were compared to that of a nearby meteorological station (Galeão International Airport) and related to the urban form characteristics.

The thermal sensation calculation used Heat Index methodology [13]. Its formula considers air temperature and relative humidity, and it is used by Rio's municipality to alert the population about climate and severe heat.

3. FINDINGS

The climate in Rio de Janeiro is characterized to be tropical hot and humid. At Galeão Airport (closest weather station from Maré), historical data (Test Reference Year) indicate that air temperature and solar radiation are normally higher from January until March, especially between 12am and 6pm. In summer, prevailing winds are from south and southeast, getting higher speeds up to 10.2 m/s during afternoon and evening. In the same period, when temperatures get above 29 °C, relative humidity gets as low as 70%.

In inhabited areas, SVF calculations range from 0.14 to 0.35 in Nova Holanda (NH, fig.3), and 0.06 to 0.44 in Baixa do Sapateiro (BS, fig.4). Better scenarios of SVF can be seen in the industrial areas when arriving at both *favelas* (NH1, NH2, BS1, BS2), streets junction (NH5), larger streets (NH8) or squares (BS5).

The streets, both in Nova Holanda and Baixa do Sapateiro, are generally made of asphalt or cobblestones, mostly grey and dark grey, with low reflectivity and high heat storage capacity. Buildings are built of ceramic bricks, mostly exposed, some plastered and painted in different colours, causing the albedo to vary between 20% (apparent brick) and 80% (white paint) of reflectivity. Roofs are made of exposed concrete slabs (albedo varies between 20% and 35%), asbestos, fibre cement or metallic tiles, varying their albedo. Hence, material colours have medium to high heat absorptance.

Air temperature collected data are 1-2 °C higher than the Galeão Weather Station (Fig. 5 and 6), which may be an indication of the difference in height between the measurement points (1 meter high in Maré and 9 meters high at the Galeão Weather Station). It is also noticed that the measured temperatures do not present a linear increase as the Galeão Station, thus suggesting the urban and anthropogenic influences in the different points.

Points NH1 and BS1, on Brasil Avenue, indicate lower temperatures than the others, although surface temperature maps and thermographic photographs suggest that these would be the hottest points. As SVF is high (NH1 = 0.78 and BS1=0.95), this difference could be explained by greater presence of ventilation. However, as thermal comfort also depends on exposure to radiation, experience at the site allows us to deduce that these points may have an increased thermal sensation due to lack of shading. When entering the the *favelas*, air temperature increases as the SVF decreases. However, the difference between the points was not greater than 3.5° C.

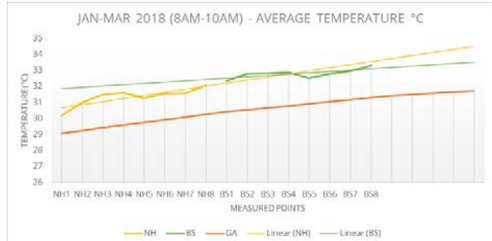

Figure 5: Graph of average temperatures, measured between January and March 2018, during the morning, in Nova Holanda (NH) and Baixa do Sapateiro (BS), compared to Galeão Weather Station (GA).

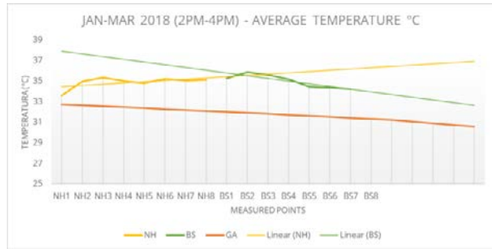

Figure 6: Graph of average temperatures, measured between January and March 2018, during the afternoon, in Nova Holanda (NH) and Baixa do Sapateiro (BS), compared to Galeão Weather Station (GA).

There were two points that stood out for lower temperatures, when comparing all measured points: NH5 and BS5. NH5 has a higher SVF, as it is located at a street junction, allowing greater ventilation at the pedestrian level. Also, it has, in its surroundings, some trees, non-existent in the other points measured in Nova Holanda. In Baixa do Sapateiro, BS5 is an open square where some vegetation and trees can be seen. This point also presented slightly higher relative humidity than the others. On the other hand, points measured in industrial areas (NH2, BS2) or close to them revealed higher temperatures (NH3, BS3), as seen in the Surface Temperature Map.

Nova Holanda shows a variation of approximately 5% of relative humidity in relation to Galeão Airport, which remained constantly higher (Fig. 7 and 8). Baixa do Sapateiro has greater variation in its different points, showing oscillations above and below the relative

humidity measured at Galeão (Fig. 7 and 8). The trend line of Nova Holanda is more constant when compared to the trend line of Baixa do Sapateiro, which maintains higher air humidity in the morning, dispersing it later in the afternoon, with lower averages than those of Galeão for this period.

The infrared photographic record demonstrated that surface materials, when exposed to the sun, such as asphalt, granite cobblestones, concrete blocks, and pink Portuguese stones, can reach 60 °C. The surfaces, in general, when in the shade, showed lower temperatures.

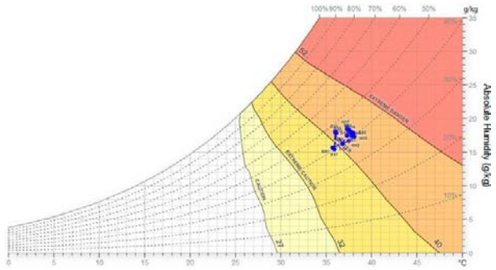

Figure 6: *Average thermal sensation during afternoons in January, in both Nova Holanda and Baixa do Sapateiro.*

The highest thermal sensations of the measured period occurred in January afternoons getting in the "danger" zone of the Heat Index (Fig 6). As the thermal sensation values through Heat Index are calculated for shady and low-wind conditions, they indicate that the "danger" can be even greater when one is exposed to solar radiation.

4. DISCUSSION

The surface Temperature Map of the Metropolitan region of Rio de Janeiro [Fig.1] indicates that heat islands cover the entire urban territory. It is noticed that urban heating is more intense in suburban areas than in central areas [2,14]. Also, higher surface temperatures can be found further away from forests, lakes and places where the sea breeze cannot easily reach.

In Maré, residents installed "public" showers on street corners, as well as plastic pools and water tanks for children on the streets to avoid thermal discomfort. However, besides recreation and hydration, it is important that citizens understand the causes of urban warming and its impacts when enhanced by global warming, in order to implement mitigation measures and avoid negative health impacts, morbidity and mortality.

Global warming if reaching 1.5 °C by 2040, would cause unavoidable climate hazards, as a severe increase in the frequency, intensity and duration of extreme heat events and precipitation presentmultiple risks to urban settings, especially to vulnerable communitieswith low socioeconomic development, causing impacts on human health and key infrastructure [6]. There are significant interdependent effects between regional and global climate change, intensifying urban heat islands during the period of heat waves [5]. Therefore, reducing the impacts of urban heat islands can relieve the consequences of heat waves, both in health and in the quality of life of citizens.

Analysing the results, points with higher SVF generally indicated lower temperatures and lower thermal sensations. In the *favelas*, vegetated areas showed lower temperatures. Nonetheless, points next to industrial areas revealed to be more intense.

The difference between the measured points in each *favela* was not greater than 3.5 °C, within one hour. This apparent small difference may have an important impact on indoor temperatures and heat waves in the near-term future.

Furthermore, January afternoons had the highest thermal sensation lying in the "danger" zone of the Heat Index Graph (Fig. 6), when "heat cramps or heat exhaustion are likely, and heat stroke is possible with prolonged exposure and/or physical activity" [13].

Anthropogenic heat production in urban canyons also influences their greater warming. Maré is not formed by wide streets, so there is no traffic generating high pollution and greenhouse gases inside the *favelas*. This is positive to thermal comfort. On the other hand, there is a lack of public transport, creating a mobility problem. Locals must walk up to Brasil Avenue across streets with no shading, depending on the time, increasing people's exposure to radiation.

Research on heat islands [2,15,16,17,22], thermal comfort [18,19,20] and health [7,8,21] report the importance of green spaces to lower temperatures and reduce the effects of air pollution. The use of reflective roofs and reflective and permeable pavements are also important strategies to mitigate heat islands [22]. Painting asphalt surfaces and grey floors with colours that absorb less heat, touching up tiles that are already aged and no longer reflecting, plastering and painting exposed bricks are some possible practices. These alternative solutions could be implemented and monitored in order to verify effectiveness.

5. FINAL CONSIDERATIONS

The observed phenomena reinforce what individuals face in their daily lives. Reports from those who have experienced the drastic changes in the landscape since houses were built on stilts, undergoing land reclamation, soil-sealing and urban densification, state that the thermal sensation in the territory has increased.

It is important that the population understands the causes of urban heating and climate emergency and how these are related to the thermal sensation, in order to reduce their effects and ensure their right to live in a healthy city. Therefore, this research sought to develop resourceshat can assist in the monitoring and understanding of the causes of heat islands in Maré.

The increase and frequency of rainfall can cause the depletion of the drainage and sanitary sewer systems, which leads to more frequent flooding. Nonetheless, floods can only be avoided through State intervention, by improving local sewage collection and treatment, and through worldwide efforts to prevent global warming heavier rainfalls and sea level rise.

To mitigate Urban Heat Islands, inhabitants and scientists can combine efforts to share knowledge and produce changes in local areas, such as plastering and painting surfaces, growing vegetation, creating shaded paths. Additionally, citizens will improve their understanding of both urban and global warming and feel empowered, through information, to defend themselves from the effects of local climate changes and fight for their right to a fairer city and a more resilient favela, as merely surviving is simply not enough.

ACKNOWLEDGEMENTS

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Housing for the poor
Analysis of community-led housing in Yangon

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ABSTRACT: Urbanization in Yangon brought about the rapid growth of informal settlements due to a lack of affordable housing. In recent years, community-led housing has emerged as an alternative housing practice for the urban poor, and there is a need to scale up its implementation as per the growing demand. Therefore, this study examines the strengths and weaknesses of the current community-led housing practice in Yangon through an analysis of the residents' perceptions. Community-led housing was found to have positive impacts on the poor not only by providing affordable house ownership but also by improving their capabilities and socio-economic conditions through ensuring their participation during the process. Based on the results of residential satisfaction, the current practice has a weakness in design development regarding space planning and indoor comfort. Although the community had the ability to bring ownership by themselves, the lack of government involvement hindered the quality of housing and land tenure security. This shows the need for assistance from different stakeholders, while prioritizing the community participation. This study contributes to the challenge of contemporary pro-poor housing practices by exploring the good practices and gaps in the approach through the residents' perceptions.
KEYWORDS: Community-led housing, Community participation, Housing quality, Residents' satisfaction, Yangon

1. INTRODUCTION

The recent economic growth in Yangon has brought about rapid population growth and placed a strain on affordable housing. This housing shortage resulted in many poor rural migrants living in informal settlements and resulting a population of half a million in 2018, which is expected to grow more in the future [1]. To address this issue, the local non-profit organization (NPO), Women for the World (WfW), initiated the community-led housing (CLH) program in 2009. WfW mobilized women in poor settlements and provided training for the women saving group (WSG) to improve the income of their households and address the challenges they faced. The housing project was started because having a house was the biggest aspiration of these women at the time, and the first pilot project was implemented with a group of 30 women from the saving groups. Together with the collective savings and the grant received from the Asian Coalition for Housing Rights (ACHR), the community surveyed the site, co-developed the design, and implemented simple single-unit thatched houses by themselves [2].

More project sites have been completed since then and by 2019, there are 11 settlement sites, providing permanent accommodation to more than 800 households from informal settlements [3]. This community-led approach showed an alternative grassroots housing practice for the poor through the collective actions of the community, and a network of practitioners. On the other hand, these 11 projects did not receive support from the government, and the CLH development experienced various trial-and-error processes to meet the diverse needs of different communities [4]. Therefore, on account of the lack of an institutional framework, those practices need to be documented and assessed for further development. However, no study has yet been conducted, particularly on the evaluation of current housing practices with its outcomes and impacts on the residents' community.

According to [5-7], studies on residential satisfaction provides various information regarding the present housing conditions, the needs and preferences of residents and the performances of the project. It also helps to improve the understanding of residential mobility and the internal and external factors that influence the satisfaction level. Therefore, the residential satisfaction is not only the descriptions of physical aspect of housing but also the quality of life that the residents determined based on their expectations. In this context, it is an ad-hoc evaluation measure to judge the performance of housing acquisition process that is important in informing housing policy and planning intervention [5]. Thus, this study evaluates the implementation of community-led housing through residents' perceptions to identify the practices that satisfy the requirements of residents, including the critical areas that need to be improved to address the housing inequality in the city.

2. METHODS

2.1 Study area

The community-led housing in Yangon was introduced by WfW after their post-disaster reconstruction and rehabilitation project from Cyclone Nagris in 2008. From the project, WfW continued their initiative of collective women group to improve the lives of poor households in urban area of Yangon, which was later developed into the CLH as the biggest aspiration of saving group members. The first CLH (Site 1) was implemented in North Okkarlar Township in 2009 and it was closely followed up with the second project (Site 2) in Hlaing Thar Yar Township, sub-urban area of Yangon city. Then, the project was semi-hiatus due to the political situation and the WfW's unavailability but restarted in 2017. Since then, nine project sites were completed between 2017-2019, making a total of 11 projects (836 houses) in altogether as shown in Figure 1.

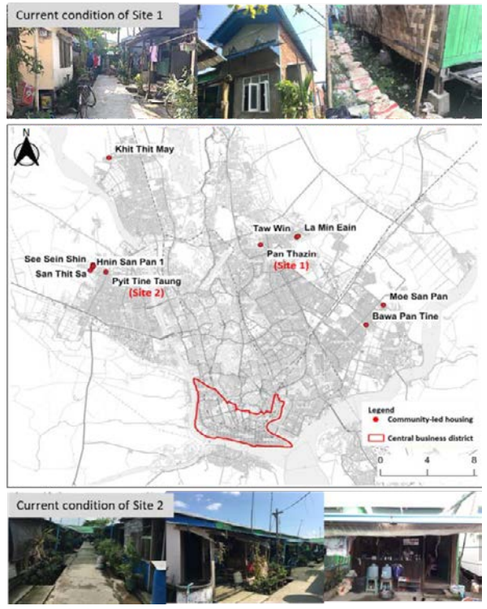

Figure 1. Locations of community-led housings and current situation of Sites 1 and 2.

2.2 Methodology

The methodological process of this study mainly consists of two parts: the identification of assessment criteria and the analysis of CLH based on user perceptions.

The assessment criteria for user satisfaction were identified through a systematic literature review. The articles were chosen based on their publication period '2010-2020' and the keywords such as 'users' satisfaction', 'assessment', 'social housing', and 'low-cost housing'. A total of 46 articles were selected and they were reviewed and analysed in MAXQDA software. The criteria were identified by coding based on the words found in the articles according to the following - parent code for main criteria categories, 1st level sub-code for assessment criteria, 2nd level sub-code for sub-criteria of 1st level sub-code.

Of the 11 sites (Figure 1), the household survey was conducted at Sites 1 and 2. They are the earliest projects that were completed in 2009-2010, and thus, have a longer post-occupancy period where the residents have a better understanding of needs and preferences, along with more cases of housing self-modifications. The survey initially aimed to include all households in both sites; however, some of the houses were temporarily unoccupied from the residents returning to their hometowns due to the pandemic and political situations in the city. Therefore, a total of 67 households were included in the survey; 24 of 30 households (80%) were from Site 1 and 43 of 64 households (72%) were from Site 2. The participants were asked about their perceptions on their houses based on the criteria identified in Table 1 where the satisfaction scale ranged from '1' for dissatisfied, '2' for neutral, and '3' for satisfied. Such data was then processed and analysed in Microsoft Excel, and the satisfaction score 'x' was calculated using the following Equation (1):

$$x = \{R_1(i) + R_2(i) + R_3(i)\} / (R - r) \qquad (1)$$

where R_1 = residents who responded satisfied, R_2 = residents who responded neutral, R_3 = residents who responded dissatisfied, r = residents who did not answer, R = total number of respondents, and i = satisfaction scale or scoring index. Based on the satisfaction results, the strengths and weaknesses of the current CLH approach were discussed on the key elements that are necessary for the successful implementation of CLH which were identified by [8-9]. The identified key elements are as follows - participatory designing and liveable design, localized financial mechanism, collective land ownership, community participation, networking, and post-occupancy management.

3. FINDINGS

3.1 Satisfaction criteria for community-led housing

Table 1 shows a list of satisfaction assessment criteria for CLH, which were identified from the systematic literature review. The criteria consisted of four main categories: (1) physical criteria that measure residents' perceptions of the site and housing quality; (2) financial criteria that evaluate affordability and the availability of alternative financial sources and their terms; (3) social criteria to measure the CLH process in terms of tenure security, safety, community participation and control over the process; and (4) the last criteria group to evaluate the

impacts of the housing practice to the development and livelihoods of the residential households.

Table 1: List of users' satisfaction assessment criteria. [5-7, 10-17]

Parent code: **Physical criteria**	
Site quality	P1. Housing layout and numbers of units P2. Plot area P3. Setback distance P4. Street width and accessibility P5. Accessibility to community centre P6. Green space P7. Recreation area P8. Site sanitation P9. Drainage system P10. Access to solid waste management P11. Access to public water supply P12. Access to public power supply P13. Location with non-disaster-prone area P14. Location with accessibility to basic services and facilities
Housing quality	P15. Quality of workmanship P16. Quality of materials P17. Aesthetics P18. Strength of housing P19. Ratio of beds and residents P20. Adequate living spaces P21. Barriers-free housing features P22. Culture compatible design P23. Indoor living quality (1) Noise (2) Natural lighting condition inside (3) Air quality (4) Ventilation
Parent code: **Financial criteria**	
Affordability	F1. Ratio of housing price to incomes
Availability	F2. Variability of financial models F3. Interest rates and mortgage F4. Adequate funding and provisions
Parent code: **Social criteria**	
Tenure	S1. Tenure security S2. House ownership
Safety	S3. Safety S4. Security S5. Privacy
Participation	S6. Community participation S7. Equality in housing distribution S8. Activities of social support
Parent code: **Well-being criteria**	
Well-being	I1. Household incomes I2. Economic security I3. Health and living condition I4. Education I5. Social cohesion I6. Local knowledge and life skills

3.2 Analysis of community-led housing based on residents' perceptions

Figure 2 shows the residents' perceptions of the community-led housings at Site 1 and Site 2. The evaluation was carried out based on the current conditions with 10 years of stay where the housing units have already made self-modifications. In this context, the modification patterns included spatial extension, material changes and renovation and addition of building elements such as interior partitions, windows, shade net, mezzanine, etc. Between two sites, Site 1 had more cases of modifications with both external and internal transformations while households from Site 2 mostly invested in interior altercations.

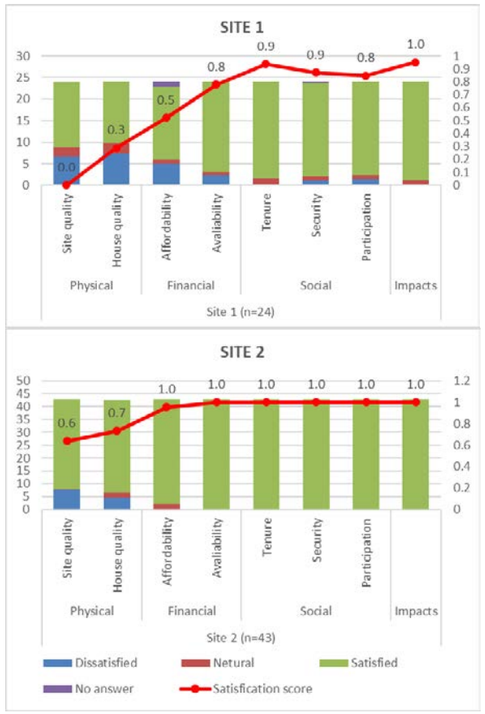

Figure 2: Residents' perception on current community-led housing. (Satisfied = '+1'; Neutral = '0'; Dissatisfied = '-1')

Based on Figure 2, both Sites 1 and 2 had generally similar results in the four main categories. It was found that both sites had lower satisfaction scores related to physical conditions compared to other three criteria group. Of the 24 households from Site 1, nearly 30% of the respondents were dissatisfied with site and housing qualities in the physical category, while 21% felt that the cost of housing was high compared to their household income. Nearly 90% of them were satisfied regarding the social factors relating to the housing acquisition process and positively agreed that the housing project improved their lives in terms of financial stability, life skills knowledge, health, education, and social cohesion conditions. Compared to Site 1, Site 2 had higher satisfaction scores, particularly in housing physical category. All the households from Site 2 who participated in the survey responded positively to the financial availability, social factors, and the housing impacts on their lives. Moreover, slightly more satisfaction answers were found relating the affordability even though the unit housing cost for Site 2 was higher than that for Site 1.

Figure 3. Residents' satisfaction scores on current housing physical situation.
(Satisfied = '+1'; Neutral = '0'; Dissatisfied = '-1')

Figure 3 reveals the residents' satisfaction on the current site and housing conditions at Sites 1 and 2. Regarding to the site quality, both sites complained about the lack of green and recreational spaces for children and residents. Due to the limited availability, both the communities could have a small open space which was served for the community center. Under this condition, the communities could create the green spaces in front or beside of their individual housing units but such individual spaces had also been decreased due to the extension from the limited indoor area. Other dissatisfactions were the residents from Site 1 complaining about the lack of drainage system which created wastewater logging under their houses as shown in the photograph from Figure 1, and Site 2 largely showing dissatisfaction regarding a narrow pathway which made the residents' concern over the accessibility to fire engine during the outbreak. In addition, the residents of Site 1 reported dissatisfactions with their location of site since it is far away from bus stop and other basic facilities.

For housing quality, most of the dissatisfactions of both sites came from the poor indoor environmental quality such as lighting, air quality and ventilation inside. This was possibly due to housing units close to each other, while the tarpaulin sheets they installed to protect external bamboo weaving walls from rainwater prevented the airflow from outside to inside. However, these issues were not found in the households which had changed the bamboo walls with modern materials and installed additional side windows. Aside from indoor environmental quality, it is found that though both sites had similar initial housing design with building materials, Site 1 had lower satisfaction scores even after the modifications. The reason may be related to the location of Site 1 which is close to inner urban area that influenced the residents' preference to better housing conditions and more modern buildings. In addition, as Site 1 had a smaller individual land plot compared to Site 2, it is possible that they had a low satisfaction score (0.5 (Site 1) < 1.0 (Site 2)) regarding the current living space, but it is noted that satisfaction with adequate living space had little relation to household size, but rather to residents' preferences, household organization types, and lifestyles.

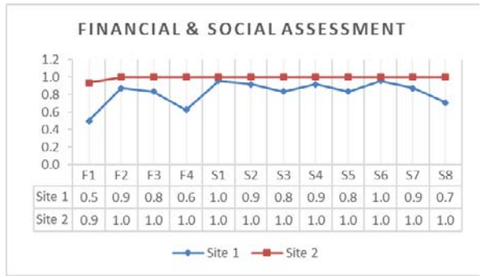

Figure 4. Residents' satisfaction scores on financial and social aspects.
(Satisfied = '+1'; Neutral = '0'; Dissatisfied = '-1')

Residents' perceptions of financial characteristics were evaluated in two ways – affordability and availability. First, 71% of the respondents from Site 1 (satisfaction score = 0.5) and 95% from Site 2 (satisfaction score = 0.9) said that house prices were affordable with relation to their household income. Regarding financial availability, Site 2 which had access to both WSG and microfinance loans was found with higher satisfaction score than Site 1 while, Site 1 firstly only had savings from WSG and took a long time to find additional financial source, due to the limited experience of WfW and community, which they later received the fundings from ACHR to continue the project.

Social characteristics evaluated the tenure security, safety, and inclusiveness of the project.

Based on Figure 4, only a small number of respondents (approximately 5%) from Site 1 showed dissatisfaction with social factors. The project has provided its residents with a sense of ownership and security. The high score on inclusiveness could come from WfW's encouragement of community participation in every step of housing development and decision-makings.

Similar to social assessment, the housing impacts of well-being assessment showed the CLH has positively contributed to the lives of the residents. After the loan repayment, the household could save the previous housing rental expenses and used it for other purposes such as business development, education, and healthcare, resulting in the improved livelihood conditions. Moreover, working and living together, the community had developed a strong bond between each other while the community-led actions and livelihood trainings from WfW improved the life skills of the women in financial and household management.

Based on the above findings, it can be seen that the residential satisfactions were varied not only on the physical conditions of the housing but also on their expectations and perceptions that could be different among each household. According to [5], the residents tend to evaluate their housing conditions based on the standards which they have already created in their mind or other aspirations from surrounding environment. This phenomenon was found when comparing the satisfaction scores on the physical criteria of Sites 1 and 2. Though the physical conditions of both sites are almost similar while Site 1 with better living conditions, Site 2 showed a higher satisfaction score possibly due to staying at the less-developed area, thus lowering down their expectations.

3.3 Strength and weakness of current CLH practice

Based on the analysis results of residents' satisfaction, a discussion on the strengths and weaknesses of current practice was conducted on the six key elements of community-led housing as follows.

A) Participatory designing and liveable design

Strength: Community has the full control over the design development of their houses.

Weakness: Though the community enjoyed full control over the design making, the residents were not satisfied with the quality of both site and house design. Limited technical awareness and experiences of both resident communities and WfW first resulted the lack of consideration of technical matters such as drainage system, indoor thermal comfort, outdoor green space. Even there was the participatory design workshop with technical group, the limited budget made the residents difficult to fully adopt the design co-developed by the architects and forced them to change and reduce the quality of floor plan, materials and structural system. Therefore, addressing the technical challenges of site and house design requires an integrated solution reflecting both current and future situation of the residents.

B) Localized financial mechanism

Strength: High satisfaction was shown on the combination of WSG and microfinance loans. Collective saving activities acted as the foundation for housing development and trust building while the integration with another financial sources made the development process more efficient. Other strengths are the community's full control over the savings and the flexible loan terms that allow the residents to negotiate with the bank, with WfW.

Weakness: Based on the responses from Site 1, the WSG alone cannot support the housing development but needs additional financial sources, while the capacity of saving groups depends on the saving ability of residents, which is uncertain.

C) Collective land ownership

Strength: Currently the land is owned by the resident community collectively and this practice not only provides them land ownership but also prevents the sale of the property without consent.

Weakness: Though the residents have showed satisfaction on tenure security, all the housing projects were constructed on the agricultural land due to the land affordability. Therefore, these project sites are actually vulnerable to removal by the local authority as housing construction is permitted only on the residential land.

D) Community participation and control

Strength: The evaluation results reveal that the current practice allowed a high level of participation in and control of communities during the implementation. This is possible due to the WfW's strategy of letting the community act by itself and by limiting the participation of other stakeholders who would control decision-making.

Weakness: Limiting the communication with the stakeholders such as technical experts sometimes could create the barrier during the design co-development workshop. Yet the communities were encouraged for full participation, the communities expressed their inability to provide feedback to the architects due to the knowledge gaps and social norms that have long been embedded in the society.

E) Networking

Strength: Networking among communities was done through the Women Saving and Development Network (WSDN,) which is the community-based organization established with all members from WSG and housing projects. For the external actors, WfW acts as intermediary and tried to include technicians and experts from both local and international organizations to support the technical issues of the housing.

Weakness: Though experts were getting involved, their participation was limited and there was a gap in relation with the community members. There is also a lack of government participation due to the limited interest in this kind of grass-root practice and a lack of the political commitment from the central government. This situation hinders the registration of land ownership and possible opportunities for subsidies, which could help the community reduce the financial burden and develop better housing.

F) Post-occupancy management

Strength: After moving in, the community is given full control to manage their houses and is supported by WfW and WSDN in enhancing their life skills management through skills training workshops.

Weakness: Both WfW and communities are not unaware of the need of post-occupancy management while the housing modifications are done by the households themselves without the supervision from either WfW or government or even technical experts. This creates the concerns over the safety and also the impacts to the community and its environment.

4. CONCLUSIONS

This study presents the residents' perceptions of their current housing practices and examines the strengths and weaknesses based on the satisfaction analysis. The results show that the current approach meets the expectations of residents in socioeconomic aspects which presents as the strengths. This includes financial diversity, collective land ownership, and the dweller-control of the process where community as the project's implementer and owner.

On the other hand, the weaknesses are found in the physical design of site and housing, relating to the lack of space for outdoor activities and indoor environmental discomfort. Thus, there are technical challenges in design development by the community, which indicates the need for assistance of technicians and NGOs. It is necessary to review housing designs and consider them as core houses that have the flexibility for residents to modify and improve them.

Moreover, the residents' satisfactions varies not only on the conditions of housings but also on the standards that the residents have already made up in their minds. Therefore, community participation is essential to meet the needs and preferences and this requires the integrated pro-poor policy that supports the communities' participation in housing development and public strategies for funding, land, and technology assistance so that the efficiency and effectiveness can be enhanced.

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Climatic recommendations for informal areas in Brazil

UCMaps and Brazilian technical standards

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ABSTRACT: In Latin America, more than 20% of the urban population lives in precarious urban settlements where the urban planning practices are often exceeded. The urban form and construction materials used in these areas frequently contribute to worse microclimatic conditions as well. Therefore, this paper aims to present urban planning and building recommendations, considering the climatic aspects, for informal areas of the cities of Belo Horizonte and João Pessoa, in Brazil. The method used consisted in carrying out an analysis of the results of the UCMaps, and of the Brazilian technical standard to produce a set of recommendations for the specific areas in each city. The results presented urban planning and building criteria such as shading strategies, wind corridors maintenance, materials for surfaces, sealing for external walls and coverage, and the need for cross ventilation in buildings. These recommendations may contribute to adapting the standard applied generally in urban planning and buildings to political and institutionally marginalized areas, considering the interaction between different climatic and action scales. Besides, the methodology applied could contribute to advance the discussions on climate action in informal settlements.
KEYWORDS: Informal areas, Urban climatic map, Brazilian technical standards, Climatic recommendations

1. INTRODUCTION

The urban population of the world and the extent of urban areas have increased in the last seven decades. In developing countries, much of this growth occurs in precarious urban settlements, as informal areas or slums, and often exceeds the urban planning practices. In Latin America and the Caribbean 21% of the urban population lives in these conditions, compared to 28% in Asia and 59% in sub-Saharan Africa (UN-Habitat, 2018).

People living in informal areas are particularly vulnerable to climate changes due to some factors: (i) sites that experience climate-related hazards; (ii) tenure security of the formal safeguards for their housing; (iii) lack of access to food and water; (iv) scarce social and financial services; (v) informal settlements are often left out of citywide development plans and strategies, and (vi) lack of understanding of the concrete climate changes forecasted for a specific location (UN-Habitat, 2018).

In addition, the urban form and building materials used in these areas frequently contribute to worse human comfort, especially in warm and humid climates (Baritu et al., 2019). In Brazil, few studies have demonstrated the bioclimatic characteristics of these regions. As examples of microclimate assessment in informal environments, Silva (2006) and Morais (2011) found temperatures above the maximum comfort limit in the region of Paraísópolis (São Paulo) and the Northeast of Amaralina (Salvador), respectively. Regarding housing conditions, these dwellings normally use construction materials that are inappropriate for the local microclimatic context (black plastic canvas, wood scraps, asbestos cement shingles, etc.). Some research showed that these precarious structures had a greater negative impact not only on thermal comfort but also on the respiratory health of residents (Utimura, 2010; Simões, 2021).

Despite the significant number of informal areas in Brazil (IBGE, 2019), there is no national climate policy that integrates the different scales of climate phenomena and suggests recommendations for improving the quality of life of these inhabitants in order to mitigate and adapt the effects of climate change at the local scale.

One method to help policymakers to identify areas that are more sensitive to climate change and with less adaptive capacity, guiding adaptation policies and building climate resilience is through climate change vulnerability assessments and climate action plans. (UN-Habitat, 2018).

Another method that can be used in addition to vulnerability studies is Urban Climatic Map (VDI-3787, 2015). This methodology develops an analysis of the impact of cities on the climate considering their effects on thermal aspects, ventilation, and air pollution. They generally recognize climatopes, which are homogeneous areas in terms of microclimatic characteristics, which are spatialized in the climatic analysis map – UC-AnMap. Then recommendations for action in urban planning and design are elaborated and represented in the recommendation map – UC-ReMap (Ren,Ng, Katzchner, 2011).

In Brazil, for the specific scale of buildings, the technical standard NBR 15.220 brings building recommendations in the context of thermal comfort, but they are not always applicable to the reality of informal areas. This Brazilian national standard is focused on formal housing and do not consider local climatic characteristics.

Considering the above, it is important to make specific recommendations for these informal areas that should be linked with aspects of regional climate, climatopes, climatic elements, available building materials, and socio-environmental vulnerability. Urban and building strategies provided by bioclimatism researchers (Lengen, 1980; Romero, 2000; Huigueras, 2006; Pizarro, 2012, Heywood, 2017) can contribute to the formulation of recommendations for these settlements.

In the coming decades, projections related to climate change are of higher and increasing average temperatures. In informal areas, the high density of buildings, little open/public space, and often, inadequate roof materials and poor ventilation lead to higher indoor temperatures. So, it is necessary to use strategies for adaptation. And the first step is to understand the physical conditions, the demographics, and the differentiated vulnerability to adequately plan feasible interventions. In addition, it is important to make possible a multi-level governance, which opens inclusive and accountable adaptation space across scales of decision making (IPCC, 2022).

Therefore, this paper aims to present recommendations for informal areas for the cities of Belo Horizonte and João Pessoa, in Brazil, based on the results of the UCMaps, national technical standard, and specialized literature. This may contribute proposing recommendations based on those established by standards that are applied generally in urban planning and buildings to political and institutionally marginalized areas, considering the interaction between different climatic and action scales.

2. METHOD

The method used in this study consists of six steps: 1. selection and characterization of informal areas for Belo Horizonte and João Pessoa; 2. identification of the study areas in the UCMaps, evaluation of recommendations, and their application to the microclimatic scale; 3. identification of recommendations of Brazilian technical standard for each city; 4. evaluation of urban and architectural guidelines; 5. production of a set of recommendations on urban planning and buildings for the specific areas in each city.

2.1 Study areas

In this study, two informal areas were considered, delimited according to the Brazilian Institute of Geography and Statistics, which defines them as areas predominantly residential and generally characterized by an irregular urban pattern, lack of essential public services, and land use restrictions (IBGE, 2019).

In Belo Horizonte, the district of Nossa Senhora da Conceição was selected (Fig. 1). It has an area of 0.2 km² and a population density of 31,329 inhabitants/km². The altitude varies between 949 to 1,049 meters. Belo Horizonte (19°55'20"S, 43° 55' 49"W) is in the Southeastern region of Brazil, has about 2,375,151 inhabitants and a population density of 7,167 inhabitants/km².

Figure 1:
Nossa Senhora da Conceição district (Belo Horizonte).

The second area is located in the city of João Pessoa called Timbó Community (Fig. 2). This informal settlement covers an area of 0.158 km² located on the eastern edge of the city. It has 900 housing units and an approximate population of 4,600 inhabitants, which leads to a high housing density of 29,113 inhabitants/km². João Pessoa city (7°09'28S, 34°47'30"W) is in the Northeastern region of Brazil, has about 830,000 inhabitants and a population density of 3,943 inhabitants/km².

Figure 2:
Timbó Community (João Pessoa).

Both informal settlements and cities are in the tropical zone, however according to the Köppen Climate Classification, Belo Horizonte and João Pessoa are classified as Cwa/Cwb and As,

respectively. Considering the Brazilian bioclimatic zoning (ABNT, 2005), Belo Horizonte is classified in Zone 3, while João Pessoa is classified in Zone 8. Table 1 presents the climatological data, showing that João Pessoa has higher mean temperature, relative humidity, and wind speed values than Belo Horizonte.

Table 1:
Climatological data (Annual data from 1981-2010)

Climatological data	Belo Horizonte	João Pessoa
Mean Air Temperature (ºC)	21.8	26.8
Mean Relative Humidity (%)	67.2	75.9
Mean Wind Speed (m/s)	1.7	3.3
Predominant wind direction	E	SE

Source: INMET. Normais Climatológicas do Brasil - 1981-2010. Available: https://portal.inmet.gov.br/normais [05 August 2021].

2.2 Analysis of UCMaps and Brazilian standard

The UCMaps from Belo Horizonte (Ferreira et. al, 2017) and João Pessoa (Souza & Katzschner, 2018) showed the climatopes for the specific areas of Nossa Senhora da Conceição district and Timbó Community (João Pessoa), respectively. Based on the german standard VDI 3787 (VDI, 2015), some recommendations were proposed for urban planning. For building design, the recommendations were proposed based on the Brazilian technical standard NBR 15.220 (ABNT, 2005), considering the building guidelines for zones 3 (Belo Horizonte) and 8 (João Pessoa).

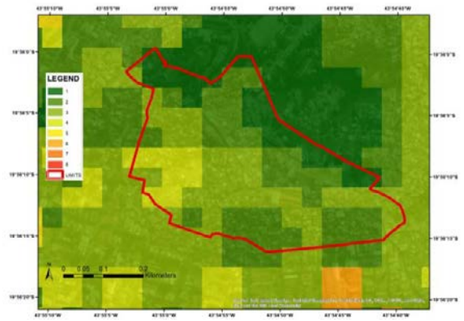
Information from the literature review complemented the analyses for both types of recommendations, urban and building scales, associated with the climatic parameters (temperature, humidity, wind and solar radiation) influenced by these recommendations. It added another layer of knowledge to propose strategies that incorporate physical conditions and differentiated vulnerability to plan feasible interventions adequately.

3. RESULTS

The UCMaps indicated different classes of climatopes for the informal areas in both cities.

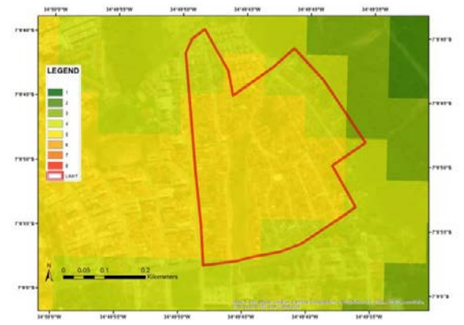
For Belo Horizonte, the UCMap is classified in 8 climatopes considering a combined data from building volume, vegetation, topography, land cover, and wind. Specifically in the district of Nossa Senhora da Conceição (Fig. 3), three climatopes are presented: climatope 2 (urban climatically valuable area, with some negative thermal load and good dynamic potential), climatope 3 (neutral climatically sensitive area, with low thermal load and good dynamic potential), and climatope 4 (neutral climatically sensitive area, with some thermal load and some dynamic potential).

Figure 3:
Climatopes of the Nossa Senhora da Conceição district



The UCM of João Pessoa contains 8 climatopes ordered according to a probable impact of physical aspects of the city (building volume, vegetation, topography, land cover, natural landscapes, and proximity to open spaces) on the thermal comfort of the population. The Timbó Community (Fig. 4) was classified with the class 3 (Low climatic activity) and class 4 (Relevant climatic activity).

Figure 4:
Climatopes of the Timbó Community



Despite the specific recommendations for each climatope class, it is understood that adaptation actions associated with ventilation and thermal load reduction are essential to improve the microclimate. Table 2 shows the recommendations based on climate and adjusted to local realities, integrating the scales - from urban planning to building design.

Because both cities are in the tropical zone, preserving the natural wind conditions and reducing heat storage are recommendations to reduce the thermal load in urban spaces. However, in Belo Horizonte, the wind speed is lower than in João Pessoa, so, for the first one, it is essential to maintain all wind corridors, while for the second one, the

Table 2:
Climatic Recommendations for Informal Areas

Strategies	Belo Horizonte		João Pessoa	
	Guidelines	Specific recommendations - climatic parameters	Guidelines	Specific recommendations - climatic parameters
Urban scale (Consider the characteristics and recommendations associated to climatopes)				
Shading	Ensure shading in summer, and allow the incidence of solar radiation in winter	All climatopes ☑ increase areas with deciduous trees ☑ install shading elements over streets, sideways and walkways (i.e.: tensioned structures, permeable to the wind)	Promote shading throughout the area during all the year to reduce thermal gains from direct solar radiation	All climatopes ☑ afforestation with species of vegetation suitable for the size of public spaces (non-deciduous trees) ☑ construct shelters with alternative materials (i.e., fabrics, plastics, wood, etc.)
Permeability to wind flow	Preserve natural wind conditions and corridors	Climatope 2: ⛔ do not allow increased densification of buildings ☑ preserve and encourage expansion of green areas, allowing permeability to winds	Preserve natural wind conditions and corridors	Not applicable
		Climatope 3: ☑ maintain or aim at low-density housing (to facilitate air exchange) ☑ preserve green spaces and wind corridors		Climatope 3: ☑ maintain or aim at low-density housing (to facilitate cold air exchange) ☑ preserve green spaces and wind corridors ☑ protect pedestrian areas from high-speed winds
		Climatope 4: ☑ increase the distance between buildings ☑ replace walls with grids or hollow elements		Climatope 4: ☑ increase urban permeability by removing elements that obstruct winds or walls ☑ encourage the creation of open public spaces (i.e.: open-air fairs, sports fields) to increase wind flow
Materials and surfaces	Promote control of the incidence of direct solar radiation and reduce heat storage	All climatopes ☑ use permeable paving and materials with low albedos ⛔ avoid further sealing	Promote control of the incidence of direct solar radiation and reduce heat storage	All climatopes ☑ use permeable paving and materials with low albedos ⛔ avoid further sealing

Strategies	Belo Horizonte		João Pessoa	
	Guidelines	Specific recommendations - climatic parameters	Guidelines	Specific recommendations - climatic parameters
Building scale				
Shading of openings	Enable shading in summer and allow sun during winter	☑ grow climbing plants on facades ☑ grow trees (deciduous vegetation) in the outside of buildings ☑ install shade elements on facades to protect openings and walls of solar radiation (brises, wide eaves)	Shading throughout the year to reduce direct solar radiation input.	☑ grow climbing plants on facades ☑ grow trees-in the outside of buildings ☑ install shade elements on facades to protect openings and walls of solar radiation (brises, wide eaves)
Openings for ventilation	Ensure openings with a size between 15% and 25% of the floor area	☑ use of brick or hollow elements (i.e., cobogó), structure that allows cross ventilation	Ensure large openings, with dimensions above 40% of the floor area, to ensure night cooling and cross ventilation during the day.	☑ use of brise-soleil, cobogós, solid bricks, perforated ceramic blocks in a creative way ☑ use elements in the roof that allows cross ventilation
Facet - external walls	Use of light and reflective materials for walls	☑ grow climbing plants on facades (vegetable gardens) ☑ use light materials to increase the reflection of the sunlight	Use of light and reflective materials for walls	☑ grow climbing plants on facades (vegetable gardens) ☑ use of coatings with reflective colours (light and pastel tones) to reduce the absorption of solar radiation by external openings ☑ build double walls with an air layer to reduce heat transfer from the outside to the inside
Facet - roof	Use of light and insulation materials for roofs	☑ grow climbing plants on roofs (vegetable gardens) ☑ use insulation materials to reduce heat transfer ☑ use of roof with elements that allows cross ventilation	Use of light and reflective materials for roofs	☑ ensure steeper slopes in order to air space in the high area of the roof to reduce the thermal load ☑ use insulation and reflective materials to reduce heat transfer

Legend: Recommendations: ☑ allowed, ⛔ not allowed; Climatic Parameters: Temperature, Humidity, Wind, Solar Radiation (the colours indicate INCREASE / REDUCE

recommendation is to protect areas of winds with high wind speed. Furthermore, Belo Horizonte has lower temperatures during the winter, so it is essential to preserve the incidence of direct solar radiation in urban spaces and buildings, avoiding shading during this season. However, for João Pessoa, this recommendation is not applicable

In summary, the recommendations show differences between the informal areas and within these sites that have to be considered for urban and building actions. For all interventions, the bioclimatic principles have to be taken into account to improve human thermal comfort and reduce the vulnerability to climate change impacts.

4. CONCLUSION

In informal areas, in order to adequately plan interventions associated with climate action, it is important to understand the physical conditions, and the differentiated vulnerability for each place. From the methodology applied here, we observed that the climatic maps show the intra-urban climatic differences of informal settlements. The accessible language of these maps enables presentation and discussion with local actors and planners for further refinement of recommendations. In addition, the Brazilian technical standard showed specific recommendations for buildings which could improve their downscale considering the climate of each city. In this way, it is understood that the principles that should be applied in considering and implementing climate change adaptation measures in informal settlements are reflected in the recommendations presented here. Besides, the methodology applied could contribute to advance the discussions on climate action in informal settlements.

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