The Book Of Proceedings

CATE|2023

COMFORT AT THE EXTREMES

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COMFORT AT THE EXTREMES

Conference on 13/14/15 December 2023

4TH INTERNATIONAL CATE CONFERENCE: THE BOOK OF PROCEEDINGS

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VENUE

Balwantrai N. Brambhatt Hall, CEPT University ,
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COMFORT AT THE EXTREMES - CATE 2023

13/14/15 December, 2023
CEPT University | Ahmedabad, India

Climate change has introduced extremity in weather events by increasing their intensity and frequency. The recent pandemic has further exacerbated the extremities and added new challenges in addressing climate change.

The current state of affairs demands immediate action in multiple dimensions ranging from climate adaptation and mitigation to climate resilience. Moreover, focusing on the regeneration of resources is equally critical at present. Climate change affects various geographical, social, cultural, economic, and climatic contexts differently. Additionally, its impacts are visible at extreme physical scales ranging from an individual human body and its physiology to the urban level. Therefore, we need diverse solutions for diverse scales and contexts. The plethora of probable solutions must also be interdisciplinary to demonstrate effectiveness in multiple domains that affect each other.

Building on the success of the international 'Windsor Conferences on Thermal Comfort (1994-2020)' and the 'Comfort at the Extremes Conferences' in Dubai (2019), Oman (2021), and Edinburgh (2022), CATE 2023 at CEPT University, Ahmedabad hopes to bring diverse groups together to deliberate interdisciplinary solutions and strategies oriented toward climate change and associated extreme events at several scales.

A rapidly developing country in the global south, India is a representative of cooling-dominated countries and the challenges they face due to climate change. At CATE 2023, the authors will attend the conference in person in Ahmedabad, India to present their papers. Moreover, live streaming will be available to bring the proceedings of the conference to a wider audience worldwide.

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ABOUT KEYNOTE ADDRESSES

Ardeshir Mahadavi
Institute of Building Physics, Services, and Construction, Faculty of Civil Engineering Sciences, TU Graz, Austria

Pondering the Performance of the Performance Paradigm.

University Professor Dr Ardeshir Mahdavi is an internationally recognized authority in Building Science. Prior to his current affiliation at the Institute of Building Physics, Services, and Construction at the Faculty of Civil Engineering Sciences, Graz University of Technology (TU Graz), Professor Mahdavi held positions at the Carnegie Mellon University (CMU), Technical University of Vienna (TU Wien), and National University of Singapore (NUS). Professor Mahdavi conducts research in building physics, building simulation, building ecology, and human ecology. Professor Mahdavi has published over 700 scientific papers and has supervised over 65 doctoral students. Professor Mahdavi is the recipient of the prestigious IBPSA Distinguished Achievements Awards.

Performance paradigm is a natural reflection of our interest in the quality and effectiveness of the artifacts we build, whether they are machines, buildings, or whole cities. To this end, performance domains are defined, performance variables are established and included, together with their mandated values in standards and legal documents. We develop methods and tools to predict the performance implications of our interventions and proclaim that performance-based standards liberate stakeholders from the straightjackets of prescriptive mandates. Instead of prescribing professionals how to design and maintain their artifacts in detail, we tell them what performance is expected from those artifacts. However,, looking at the consequences of our interventions across multiple scales we may need to consider if the performance paradigm has been implemented sufficiently and properly. We may even need to consider if the performance paradigm itself is indeed performant.

Wouter D. van Marken Lichtenbelt
Professor Ecological Energetics and Health School for Nutrition and Translational Research in Metabolism (NUTRIM) Maastricht University, Netherlands

Are we tropical animals?

Wouter van Marken Lichtenbelt is head of the research group Thermophysiology & Metabolism at Maastricht University. The fundamental aspect of the research line is the effect of environmental temperatures on physiology and behavior. This ranges from indoor environments in western populations to extreme conditions in Siberia. The study results show significant beneficial effects of excursions outside the thermoneutral zone; i.e. being exposed to heat and cold positively affects metabolic and cardiovascular health and increases resilience to extremes. The applied part of the research puts emphasis on how daily indoor environmental conditions relate to thermal comfort, behavior, health, and prevention of metabolic syndrome. His group searches for an optimal mix of different lifestyles and environmental factors to create a healthy sustainable indoor environment.

Are we better adapted to heat than cold? The presentation will include examples and new results from traditionally living humans and how they cope with extreme environmental conditions. This will be linked to current physiological knowledge about heat and cold acclimation. Finally, there will be food for thought on what extremes of heat and cold we can cope with.

Richard de Dear

Professor Emeritus, The University of Sydney School of Architecture, Design and Planning, The University of Sydney, Australia

Alliesthesia – the other kind of thermal comfort.

Richard de Dear has been continuously active in the domain of thermal comfort for over forty years in Australian, European, Asian, and North American universities. With over 250 peer-reviewed research outputs on the topic de Dear is currently the most highly cited researcher in thermal comfort (Scopus), and his work forms the basis for ASHRAE's Standard 55 Adaptive Thermal Comfort section (from 2004 till present). Among his current duties are editorships for Nature Scientific Reports, ASHRAE Science and Technology for the Built Environment, and Elsevier Energy and Buildings. He was co-chair of the International Energy Agency's (IEA) Energy in Buildings and Communities Programme Annex 69 Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings from 2016 through to its completion in 2022. He serves on the WHO-WMO Indoor Overheating Technical Advisory Group. His thermal comfort research papers have received numerous best paper awards, including Building and Environment (2022, 2018), Energy and Buildings (2018), and ASHRAE Transactions (1999, 1998). He received ASHRAE's Crosby-Field Award (1998) for best research paper across all of its outlets in 1998. In 1993 ASHRAE awarded him the Ralph G Nevins Physiology and Human Environment Award. In 1999 he received the Environmental Design and Research Association's (EDRA) "Places" Research Award, and in 2014 he was inducted into the International Society of Indoor Air Quality's Academy of Fellows.

An overwhelming majority of our knowledge of thermal comfort is confined to relatively simple situations of steady-state and iso-thermal exposures. In this talk de Dear will review thermal comfort, pleasure, and irritation in more complex and non-steady exposures. The talk will begin with the conceptual framework of alliesthesia and its empirical bases, and end with identifying where alliesthesia is most directly relevant including outdoor and semi-outdoor settings, personal comfort systems, vehicle cabins, transition spaces including rapid transit carriages, and station environments.

Jeeth Iype

Architect and Co-founder, Good Earth

Building Sustainable Community: Good Earth Experiment.

Jeeth Iype is an Architect and co-founder of GoodEarth. A person of ideas,, he is excited by innovation and translating ideas into architecture. He ispart of the team that conceptualizes the communities. Having gained experience creating vibrant communities that make one feel psychologically and socially secure, he trying to address larger issues like climate change and desertification through regenerative agriculture, and sustainable water and waste management, to add value to its core business of building sustainable communities.

Jeeth and his team at GoodEarth, are engaged in bringing together like-minded people with a common vision of building a sustainable future. They believe that such a community generates a strong sense of belonging while also enabling a collective sense of security and responsibility. They foresee a future where many such communities keep growing, each influencing its neighborhood and context. Their vision is to inspire change in the way people live through our efforts in development. The keynote will narrate Jeeth's journey in making Good Earth a successful experiment.

Susan Ubbelohde

Principal Architect of Loisos + Ubbelohde, Alameda, California, USA

The Siesta and the Wildfire: Designing Comfort in Times of "Anomalous Weather".

Susan Ubbelohde is a founding principal of Loisos + Ubbelohde, an office of unconventional practice based in Alameda, California and a Professor Emerita in the Department of Architecture at University of California, Berkeley. Her practice specializes in high-performance integrated design and is recognized for expertise in daylighting and lighting design, zero-energy/zero-carbon design, energy and thermal comfort simulations, natural ventilation, building monitoring, solar reflections and data visualization, as well as design and fabrication of light sculptures. L+U projects have won over 240 design, sustainability, and lighting awards, including AIA/COTE Top Ten Green Project awards, Platinum LEED Certifications and Zero-Net-Energy projects. Throughout her career, she has served on design and sustainability juries, lectured internationally and published on green design, simulation tools, daylighting, and lighting. An Indo-American Fellowship in Ahmedabad in 1989 supported a study of climate response in Le Corbusier's Sarabhai House and Millowners Building, as well as the classrooms and dormitories of Louis Kahn's IIM. Susan is a graduate of Oberlin College, the University of Michigan and the University of Oregon.

As architects practicing at the cutting edge of low-energy and resilient design, our office of Loisos + Ubbelohde believes buildings should "sail". This means operating with minimal mechanical systems, like sails when they are becalmed can be assisted with a small auxiliary engine. We work in a design process that begins with human comfort delivered primarily by the envelope. But we practice in interesting times. With 2023, the "anomalous weather" that we assumed was sold in the future arrived. Our buildings designed 10 years ago can no longer be counted on to provide comfort and fresh air to the occupants. Germany is looking at Spain's siesta that they previously ridiculed, while Hawaiians need their open houses to transform to spaceships when the fires arrive. Integrated architecture, systems and controls must couple with buildings that can sell open to the world when the breeze is up and the air is temperate. We will need to both survive and remain human in our architecture.

ABOUT INVITED SPEAKERS

Wolfgang Kessling

Institute of Building Physics, Services, and Construction, Faculty of Civil Engineering Sciences, TU Graz, Austria

From cooled to fresh conditions - Hybrid Cooling for the Dry and Humid Zones.

University Professor Dr Ardeshir Mahdavi is an internationally recognized authority in Building Science. Prior to his current affiliation at the Institute of Building Physics, Services, and Construction at the Faculty of Civil Engineering Sciences, Graz University of Technology (TU Graz), Professor Mahdavi held positions at the Carnegie Mellon University (CMU), Technical University of Vienna (TU Wien), and National University of Singapore (NUS). Professor Mahdavi conducts research in building physics, building simulation, building ecology, and human ecology. Professor Mahdavi has published over 700 scientific papers and has supervised over 65 doctoral students. Professor Mahdavi is the recipient of the prestigious IBPSA Distinguished Achievements Awards.

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Leena Thomas

Professor, Faculty of Design Architecture and Building, University of Technology Sydney, Australia

Living laboratory insights for low energy, healthy and resilient built environments - the case of Fairwater, Western Sydney Australia.

Professor Leena Thomas is a sustainable architecture academic and research expert with experience in Australia and India. Her research and teaching focus on transforming development and design practices in response to global concerns for climate change and sustainability. Leena's presentation will focus on her research into workplace and living environments where she has pioneered the use of detailed post-occupancy evaluation to investigate the role of the built environment in delivering energy efficiency, comfort, productivity, health and well-being, and sustainability. Through her research findings, Leena argues for the consideration of the social dimension of user experience alongside technical performance and the value of linking public health with planetary health.

Building on detailed post-occupancy evaluation and living laboratory approaches, this presentation will highlight opportunities and barriers for strengthening climate resilience at the scale of buildings and precincts. It provides insights from the Fairwater Living Laboratory that focused on an 850-home development in western Sydney that is home to Australia's largest-scale geothermal air-conditioning installation and achieved a 6-Star GreenStar Communities rating. Covering a three-year period to include one of Sydney's worst summers as well as the pandemic, the research draws on precinct-level data, community and household surveys, as well as the detailed monitoring of 40 homes. Research findings have shown energy savings and electrical demand reduction attributable to the geothermal air-conditioning and the added impact of house size in driving consumption. Other findings in relation to the rebound effect from installed air-conditioning and installed rooftop PV in some homes and adaptive practices in others point to the importance of designing sustainable practices amongst users. Precinct-based findings include the cooling effect of light-colored roofs and trees and vegetation as well as the health and well-being benefits for residents in spite of extreme weather and pandemic conditions. Through these findings, we argue for the consideration of the social dimension of user experience and community engagement alongside technical performance, the value of linking public health with planetary health, and the benefits of a precinct-based approach for the built environment.

Ashok B. Lall

Architect and Founder, Ashok B Lall Architects, India

Integrated Design for a Warming Future – Resilience and Well-being in Warm Climates.

Ashok Lall, graduated from the University of Cambridge U.K. in Architecture & Fine Arts and obtained the Architectural Association Diploma in 1970. His architectural firm (estd. 1981) is committed to an architectural practice based on the principles of environmental sustainability and social responsibility. Engaged in architectural education since 1990, he has developed curricula and teaching methods to address environmental issues. He has published many articles and presented papers on environmentally sustainable design and has been an active member of institutions and groups promoting awareness and building competence in the sustainable design of buildings.

Given the rapid rates of urbanisation, the challenge for the developing economies of the warm climate zones dealing with Climate Change is two-fold: to provide resilient shelter with improved quality of life for growing urban populations, and to mitigate climate change while doing so. The key lies in urban morphology. We seek a framework for urban growth and regeneration that is affordable, achieves basic comfort and well-being for poor citizens, and does so with limited embodied and operational carbon emissions while optimizing the potential for integrating renewables with the urban fabric. Parallel lines of research are presented that converge toward a high-density low-rise morphology as the optimum. This is accompanied by a menu of passive design principles that need to be mandated by regulation with standards for sufficiency of thermal comfort accounting for heat waves and UHI. Case studies of housing, institutional, and commercial buildings are presented. The level of comfort sought is a cultural phenomenon. Greater the expectation - greater the need for complex integration of building and cooling systems. We see a possibility of convergence around an expectation of sufficiency met with low carbon means.

Drury B. Crawley
Director of Building Performance Bentley Systems Inc, USA

Impact of Climate Change and Urbanization on Future Building Performance.

Dr. Drury B. Crawley, Ph.D., AIA, Fellow ASHRAE, BEMP, is a Bentley Fellow and Director of Building Performance with Bentley Systems Inc., focusing on building performance, decarbonization, zero-energy buildings, sustainability, and smart cities. With more than 45 years of experience in energy efficiency, renewable energy, and sustainability, Dr. Crawley has worked in engineering software development, government research, and standards development organizations, as well as building design and energy consulting companies.

With the increasing interest in climate change driven by human activity, recent research has focused on the impact of climate change or urban heat island on building operation and performance across the world. But this work usually aggregates the energy and peak demand impacts across a broad sector. In a recent study, impacts on the operating performance of an office building were estimated based on climate change and heat island scenarios in 25 locations (20 climate regions). This presentation presents the variation and differences among the 20 regions when climate change is introduced. The focus is on changes in comfort conditions, building equipment operation as well as daily patterns of energy performance using prototypical buildings that represent typical, good, and low-energy practices around the world. Other issues such as fuel swapping as heating and cooling ratios change, impacts on environmental emissions, and how low-energy building design incorporating renewables can significantly mitigate any potential climate variation are also presented.

Marcel Schweiker
Professor
Healthy Living Spaces, Institute for Occupational, Social, and Environmental Medicine, Germany

Ways forward in thermal comfort prediction for building design and operation.

Marcel Schweiker leads the Research and teaching area Healthy Living Spaces at the Institute for Occupational, Social and Environmental Medicine of RWTH Aachen since April 2020. Previously, he was working at the Institute of Building Design and Technology, Karlsruhe Institute of Technology. Marcel does research in Environmental Engineering, Architectural Engineering and Mechanical Engineering with a focus on thermal comfort and human adaptation. One of the current projects is 'International Energy Agency Energy in Buildings and Communities Programme, Annex 79: Occupant-Centric Building Design and Operation.

Thermal comfort predictions are essential during building design and operation to aim for high satisfaction rates. Standardization currently includes two approaches to such predictions: predicted mean vote (PMV) based on Fanger's heat balance model, and predicted acceptable ranges of operative temperature based on regression based adaptive thermal comfort models (ATCM). Both approaches have advantages and disadvantages such as poor predictive accuracy for individual comfort votes and neglect of certain adaptive components of PMV and the neglect of variations in influencing factors such as air speed or clothing levels of ATCM. At the same time, research includes a much larger variety of methods and models for thermal comfort prediction including combinations of heat balance and adaptive approaches like the adaptive thermal comfort models (ATCM). Both approaches have advantages and disadvantages such as poor predictive accuracy for individual comfort votes and neglect of certain adaptive components of PMV and the neglect of variations in influencing factors such as air speed or clothing levels of ATCM. At the same time, research includes a much larger variety of methods and models for thermal comfort prediction including combinations of heat balance and adaptive approaches like the adaptive thermal heat balance (ATHB) approach, detailed multi-node thermo-physiological models, and individualized predictions based on machine learning approaches. The objective of this talk is an overview of these approaches and their suitability for building design and operation. Based on a large field dataset from India, some of these approaches are assessed and ways forward in theory-based data-driven modelling approaches including individual adaptive mechanisms and design characteristics demonstrated. The talk ends with open points to be discussed among research community and standardization bodies.

Susan Roaf
Emeritus Professor
Heriot Watt
University, Edinburgh
UK

The Quantum Comfort Leap.

Sue Roaf (B.A.Hons, A.A. Dipl., PhD, ARB, FRIAS) is Emeritus Professor Heriot Watt and an award winning architect, teacher, author and activist she has written and edited 22 books on solar and sustainable design, thermal comfort and climate change adaptation and is currently looking at extreme design in hot dry deserts and Antarctica.

The notion of Quantum Evolution refers to an "all-or-none reaction" where the transitional forms of an evolving species are unstable, perishing rapidly so that is left with is what the species finally has morphed into. The term describes the comparatively rapid transition from one stable type of species adaptation to another distinctly different type under the influence of some strong selection pressure. This paper outlines the need for a Quantum Leap in what we considered to be 'comfort conditions' today to ensure we can adapt to survive in the coming decades of climate heating. As the temperatures soar populations will have to rapidly set against the rising pressures of energy scarcity and costs, globally flat-lining economies and rising levels of fuel and food poverty. Individuals can accommodate only so much in terms of personal thermal adaptation. It has to be buildings that become the first bastion of protection against extreme weather. To avoid wasting time, their intermediate unstable transitional forms will have to be side-lined as designers try and anticipate what the final form of buildings must evolve into to protect populations from extinction. Most current design tools are inadequate for this task. Designers will have to rely on their own intelligent intuition and foresight to create buildings in which people can remain comfortable in a very different future. This requires a Quantum Leap of both Faith and Comfort Thinking.

Adrain Chong
Assistant Professor
Department of the
Built Environment
College of Design
and Engineering
National University of
Singapore,
Singapore

Harnessing Mixed mode ventilation and Occupant-Centric Control for Energy savings in the Tropics.

Dr. Adrian Chong is an IBPSA Fellow and Assistant Professor in the Department of the Built Environment at the National University of Singapore (NUS). At NUS, he leads the IDEAS Lab (https://ideaslab.io), a multidisciplinary group that leverages building performance simulation, real-time data, and machine learning to improve building energy efficiency and occupant comfort. Adrian also serves as a subject editor for the journal Building Simulation and holds the role of Early Career Board Member for the journal Building and Environment.

According to the IEA, buildings account for 30% of global final energy consumption, with energy demand for space cooling tripling since 1990. This escalating demand and climate change necessitates we rethink how we currently cool our buildings. Mixed-mode ventilation emerges as a promising solution to significantly reduce energy consumption through the integrated use of natural ventilation and air-conditioning. However, the application of mixed-mode ventilation in tropical climates has been constrained by a prevailing preconception of its limited effectiveness. This skepticism stems from challenges posed by consistently hot and humid conditions, which are thought to limit the potential of operating in natural ventilation. In this talk, I will share ongoing work at my research group to achieve effective mixed-mode ventilation in the tropics. Our approach, focusing on systems integration and occupant-centric controls, aims to address the skepticism surrounding mixed-mode ventilation in such climates. Preliminary findings underscore the promise of a more sustainable way to cool our buildings in the tropics through mixed-mode ventilation.

Aun Abdullah
Vice Deputy
President
Lodha Group
India

Lodha's approach of delinking growth from emissions by transforming the built environment.

Aun Abdullah leads sustainability/esg at Lodha and has been instrumental in shaping the sustainability strategy at the group. He comes from a building services and infrastructure design/design management background, with experience on large/very large landmark projects in India and the Middle East (UAE and Qatar). Abdullah has led the formation of Lodha Net Zero Urban Accelerator, which focuses on embodied carbon, passive designs, equipment efficiency, renewable integration, green mobility, and green finance - with the intention of making net zero carbon the new normal for the built environment. Abdullah isam interested in cleantech and ideas that have the potential to become cost-effective (for the developer as well as the end-user) given the scale and growth opportunities in our operations.

This talk explores the pivotal role of the built environment in navigating India's impending growth while addressing climate risks. Emphasizing resilience and decarbonization, it delves into the critical business case for climate action within the built environment sector. By examining the challenges and opportunities in supply chain transformation, the presentation advocates for sustainable practices that not only mitigate environmental impact but also foster economic growth. The intricate relationship between India's development trajectory, climate resilience, and the imperative for transformative actions in the built environment will be addressed.

DETAILED CONFERENCE SCHEDULE

Comfort At The Extremes Conference 2023
Wednesday - Friday | December 13-15, 2023 CEPT University, Ahmedabad, India

CATE 2023

DAY 0 : Tuesday, December 12, 2023		
09:30 - 11:20	**Workshop 2:** Urban Energy Modelling in the Global South (UBEM) Workshop By: Dr. Paul Ruyssevelt	**CFP 101C** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
10:00-11:20	**Workshop 1:** Climate Resilient Energy Efficient Design in Architecture (CREEDA) Workshop By: Prof Sukumar Natarajan	**Seminar U01-201** Above New Canteen, CEPT University, K.L.Campus, Ahmedabad, Gujarat.
11:20 - 11:30	Break: Tea, Coffee, snacks	
11:30 - 12:20	**Workshop 1:** Climate Resilient Energy Efficient Design in Architecture (CREEDA) Workshop By: Prof Sukumar Natarajan	**Seminar U01-201** Above New Canteen, CEPT University, K.L.Campus, Ahmedabad, Gujarat.
	Workshop 2: Urban Energy Modelling in the Global South (UBEM) Workshop By: Dr. Paul Ruyssevelt	**CFP 101C** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
12:20 - 13:05	Lunch	**CFP 103** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
13:05 - 16:25	**Workshop 1:** Climate Resilient Energy Efficient Design in Architecture (CREEDA) Workshop By: Prof Sukumar Natarajan	**Seminar U01-201** Above New Canteen, CEPT University, K.L.Campus, Ahmedabad, Gujarat.
	Workshop 3: Grounded Energy Modelling Development (GEMDev) Workshop By: Dr. Pamela Fennell	**CFP 101C** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
16:25 - 16:35	Break	
16:35 - 17:00	**Workshop 1:** Climate Resilient Energy Efficient Design in Architecture (CREEDA) Workshop By: Prof Sukumar Natarajan	**Seminar U01-201** Above New Canteen, CEPT University, K.L.Campus, Ahmedabad, Gujarat.

DAY 1 : Wednesday, December 13, 2023		
15:25 - 16:25	**Technical Tour 1** : Net Zero Energy Building and CARBSE R&D Facilities	**Ground Floor, Net Zero Energy Building**, CEPT University, K.L.Campus, Ahmedabad, Gujarat
16:25 - 16:35	Break	
17:15 - 18:55	**Registration and Reception**	**Balwantrai N. Brahmbhatt Lecture Hall and Kund area**, CEPT University, K.L.Campus, Ahmedabad, Gujarat.
DAY 2 : Thursday, December 14, 2023		
08:30 - 09:30	**Technical Tour 2 :** Net Zero Energy Building and CARBSE R&D Facilities	**Ground Floor, Net Zero Energy Building,** CEPT University, K.L.Campus, Ahmedabad, Gujarat
10:00 - 10:30	**Session 1:** Inauguration of CATE 2023	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
10:30 - 11:20	**Session 2 Keynote 1: Alliesthesia – the other kind of thermal comfort.** Richard de Dear, Professor Emeritus, School of Architecture, Design and Planning, The University of Sydney, Australia	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
11:20 - 11:30	Break: Tea, Coffee, snacks	
11:30 - 12:20	**Session 3 Keynote 2: Are we tropical animals?** Wouter D. van Marken Lichtenbelt, Professor Ecological Energetics and Health School for Nutrition and Translational Research in Metabolism, Maastricht University, Netherlands	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
12:20 - 13:05	Lunch	**CFP 103** CEPT University, K.L.Campus, Ahmedabad, Gujarat.

Session 4 : Paper Presentations (13:05 - 14:25)

13:05 - 14:25	**Session 4A** : Health and Well-being in buildings	Paper ID: 1110 Occupant satisfaction: a measure of Green Building Performance **Presenting Author: Grover, Ashima C**	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1125 Enhancing Indoor Air Quality and Occupant Well-being in Split Air-Conditioned Bedrooms through Integrated Ventilation **Presenting Author: Mondal, Nilabhra**	
		Paper ID: 1170 The daylight almanac of Indian hoseholds: A case of Ahmedabad **Presenting Author: Agarwal Minu**	
		Paper ID: 1189 Field study on measuring indoor air quality in certified green-rated urban Indian residences **Presenting Author: Gupta, Rajat**	
	Session 4B: Design Intervention in Buildings for thermal comfort	Paper ID: 1114 Contemporary Vernacular Architecture in The Brazilian Tropical Savana: The Case-Study of the Children's Village in the Canuana Farm, in Tocantis. **Presenting Author: Soares Goncalves, Joana Carla**	**CFP 101A** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1117 Impact of Naturally Ventilated Residential Units on Heat Stress **Presenting Author: Ghosal, Sreeparna**	
		Paper ID: 1127 Designing dwellings to cope with extreme heat in low-income communities **Presenting Author: Roberts, Ben M.**	
		Paper ID: 1130 The Future of Responsive Facade for Multi-Storey Residential Buildings in Tropical Climates **Presenting Author: Goncalves, Joana**	

Session 4: Paper Presentations (13:05 - 14:25)

13:05 - 14:25	**Session 4C**: Nature-based Solutions	Paper ID: 1126 Influence of Hygroscopic Property of Lime and Cement Plaster on Building Energy Consumption for Different Climate Zones of India **Presenting Author: Mullick, Divya**	**CFP 101C** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1150 Learnings from the extreme thermal comfort adaptation of Jain ascetics during the summer and the monsoon months in India **Presenting Author: Dhariwal, Jay**	
		Paper ID: 1153 Perception of the impact of biophilia on the health and well-being of occupants in a hospital setting. **Presenting Author: Watwani, Unati Kumar**	
		Paper ID: 1160 The Green Side of Passive Cooling: Building Facades Inspired by Evapotranspiration in Trees **Presenting Author: Siripurapu, Monish**	
	Session 4D: Climate Resilience Buildings and Communities	Paper ID: 1134 Role of urban morphology in enhancing the outdoor thermal comfort: A case of Mumbai **Presenting Author: Rahigude, Srushti**	**FP 102 Auditorium** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1191 Onsite Thermal Energy Storage for Efficient and Resilient Air-conditioning in Indian Buildings **Presenting Author: Goyal, Anurag**	
		Paper ID: 1188 Assessing the Integration of Building Science in Higher Education Curricula: Implications for Climate Change Adaptation in the Built Environment **Presenting Author: Kotharkar, Rajashree Shashikant**	
		Paper ID: 1115 The energy saving potential of using adaptive setpoint temperatures: a case study for offices in India **Presenting Author: Rubio-Bellido, Carlos**	

Session 5: Talk by Invited Speakers (14:25 - 16:25)

14:25 - 16:25	**The Quantum Comfort Leap** Susan Roaf Emeritus Professor, Heriot Watt University	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
	Advancement in Urban Energy Modeling Drury Crawley Director of Building Performance with Bentley Systems Inc	
	Integrated Design for a Warming Future – Resilience and Well-being in Warm Climates Ashok B Lall Architect and Founder, Ashok B Lall Architects	
	Lodha's approach of delinking growth from emissions by transforming the built environment. Aun Abdullah Deputy Vice President, Lodha Group	
16:25 - 16:35	Break: Tea, Coffee, snacks	

Session 6: Paper Presentations (16:35 - 17:55)

	Session 6A: Circular Economy, building materials and methods	Paper ID: 1116 Pitch to Policy program in India and Indonesia - a co creation approach towards decarbonisation **Presenting Author: Burton, Craig Alexander**	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1118 Circular Economy, Building Materials and Methods **Presenting Author: Bhandari Arun**	
		Paper ID: 1148 An experimental investigation on the impact of lime and cement mortar/plaster material on the indoor hygrothermal environment of test spaces **Presenting Author: Singh, Ayushi**	
		Paper ID: 1161 Assessment of the thermal performance of alternative wall and roof assembly in buildings: A case in Vijayawada **Presenting Author: N, Yeswanth**	

Session 6: Paper Presentations (16:35 - 17:55)

16:35 - 17:55	**Session 6B** : Thermal Comfort Models and Metrices, and Resilience	Paper ID: 1119 Characteristics of thermal comfort in the warm and humid climate of North-East India **Presenting Author: Singh, Manoj Kumar**	**CFP 101A** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1120 Applicability of existing models for predicting thermal comfort in sports facilities through the analysis of a case study **Presenting Author: Lamberti, Giulia**	
		Paper ID: 1167 Thermal comfort and occupants' behavior in Japanese condominium **Presenting Author: Aqilah, Naja**	
	Session 6C: Low energy Cooling Technologies	paper ID: 1129 Development of simulation-based strategy for mixed-mode operation of buildings **Presenting Author: Singh, Harshal**	**CFP 101C** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1141 Thermal performance analysis of thermoelectric radiant panel system for indoor space heating **Presenting Author: Mishra, Gaurav**	
		Paper ID: 1157 Passive Cooling Strategies For A Better Comfort During Weather Extremes – Adapting the Existing Building Stock In German Cities To Future Climatic Conditions **Presenting Author: Kader, Alexander**	
		Paper ID: 1181 Experimental assessment of various control algorithms for direct evaporative cooling systems **Presenting Author: Nigam, Shreya**	

DAY 3 : Friday, December 15, 2023		
07:30 - 09:30	**Ahmedabad Heritage Walk**	**Starting Point**: The house of MG, Opp. Sidi Saiyyed mosque, Old City, Gheekanta, Lal Darwaja, Ahmedabad, Gujarat 380001 **Ending Point**: Jama Masjid
08:30 - 09:30	**Technical Tour 3** : Net Zero Energy Building and CARBSE R&D Facilities	**Ground Floor, Net Zero Energy Building,** CEPT University, K.L.Campus, Ahmedabad, Gujarat
10:30 - 11:20	**Session 9 Keynote 4: The Siesta and the Wildfire: Designing Comfort in Times of "Anomalous Weather** Susan Ubbelohde Principal Architect of Loisos + Ubbelohde, Alameda, California, USA	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
11:20 - 11:30	Break: Tea, Coffee, snacks	
11:30 - 12:20	**Session 10 Keynote 5: Building Sustainable Community: Good Earth Experiment** Jeeth Iype Architect and Founder of Good earth, India	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
12:20 - 13:05	**Lunch**	**CFP 103** CEPT University, K.L.Campus, Ahmedabad, Gujarat.

Session 11: Paper Presentations (13:05 - 14:25)

13:05 - 14:25	**Workshop 4:** Preparing for climate change – a perspective on humans and buildings By: Marcel Schweiker and Hannah Pallubinsky		**CFP 101A** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
	Session 11A : Health and Well-being in buildings	Paper ID: 1135 Analysing indoor thermal comfort in LIG housing with respect building materials and openings, a case of Trivandrum **Presenting Author: Sherin P M, Fahmida**	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1136 Perceptions of IEQ, well-being and work performance in work-from-home settings **Presenting Author: Manu, Sanyogita**	
		Paper ID: 1154 Evaluation of the occupant perception of air quality within the indoor setting in the composite climate of Delhi **Presenting Author: Agarwal, Pooja**	
		Paper ID: 1168 Study on WBGT for heat stroke evaluation during summer in Japanese living rooms **Presenting Author: Mizutani, Nokuto**	
	Session 11B: Urban Heat Island and Outdoor Comfort	Paper ID: 1142 The climate spatial variability and its impact on the thermal energy simulation of buildings: a case study of São Paulo, Brazil **Presenting Author: Geraldi, Matheus**	**CFP 101C** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1162 An assessment of the Universal Thermal Climate Index of Urban Outdoor Spaces- A case study of Central Business District (CBD), Ahmedabad **Presenting Author: Mehta, Jahnvi**	
		Paper ID: 1177 Study on the role of vegetation towards thermal comfort in outdoor urban areas **Presenting Author: Subedi, Rupendra**	
		Paper ID: 1155 Impact of extreme weather events on the thermal comfort of vulnerable populations in the city of Sao Paulo **Presenting Author: Dardin, Alessandro Augusto**	

Session 11: Paper Presentations (13:05 - 14:25)

13:05 - 14:25	**Session 11C:** Climate Resilience Buildings and Communities	Paper ID: 1121 Enhancing Contemporary Envelope Design for Hot and Arid Climates: Integrating Vernacular Strategies for Window-to-Wall Ratios and Shading Devices. **Presenting Author: Goncalves, Joana**	**FP Auditorium** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1149 Reducing extreme discomfort in the global South – Comparison of a calibrated model and locally measured data from informal housing in Peru **Presenting Author: Oraiopoulos, Argyris**	
		Paper ID: 1175 Urban Oasis for Adaptation to Climate Change: Analysis of Climate Adaptation Plans (CAP) around the world **Presenting Author: Duarte, Denise Helena Silva**	
		Paper ID: 1124 Energy Usage in Buildings for future climate: A case study of Concordia University Buildings in Montreal **Presenting Author: Sharma, Kartikay**	

Session 12: Invited Speakers (14:25 - 16:25)

14:25 - 16:25	**Ways forward in thermal comfort prediction for building design and operation** Marcel Schweiker Professor Healthy Living Spaces, Institute for Occupational, Social, and Environmental Medicine	**Balwantrai N. Brahmbhatt Lecture Hall,** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
	From cooled to fresh conditions - Hybrid Cooling for the Dry and Humid Zones Wolfgang Kessling Director, Transsolar, Germany	
	Living laboratory insights for low energy, healthy and resilient built environments - the case of Fairwater, Western Sydney Australia Leena Thomas Professor, Faculty of Design Architecture and Building, University of Technology, Sydney	
	Harnessing Mixed Mode Ventilation and Occupant-Centric Controls for Energy Savings in the Tropics Adrian Chong Assistant Professor, Department of the Built Environment College of Design and Engineering National University of Singapore	
16:25 - 16:35	Break: Tea, Coffee, snacks	

Session 13: Paper Presentations (16:35 - 17:55)

16:35 - 17:55		Paper ID: 1171 Balancing Carbon Emissions and Comfort: A Comparative Study of Envelope Materials in Affordable Housing Projects **Presenting Author: Tripathi, Awatans**	
	Session 13A: Climate Resilience Buildings and Communities	Paper ID: 1190 Improved burnt clay brick masonry: Lowering upfront embodied carbon, improving thermal comfort and climate resilience of new housing in the Indo-Gangetic Plains **Presenting Author: Maithel, Sameer**	**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1178 Integrated evaluation for energy and comfort quantification of windows in a residential apartment of Mumbai **Presenting Author: Soi, Vardan**	
		Paper ID: 1198 Slum redevelopment and its gendered implications on thermal comfort – the experiences of female residents in Ahmedabad **Presenting Author: Fuchs, Janina**	
	Session 13B: Thermal Comfort Models and Metrices and Resilience	Paper ID: 1152 Roadmap to implementation of thermal comfort policies in affordable housing **Presenting Author: Ramesh, Nithya**	**CFP 101A** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1169 Study on thermal comfort zone in MM and HVAC office buildings in Aichi prefecture based on daily survey **Presenting Author: Khadka, Supriya**	
		Paper ID: 1182 Study on comfort temperature in Autumn season of naturally ventilated office building in Kathmandu **Presenting Author: Lamsal, Prativa**	

Session 13: Paper Presentations (16:35 - 17:55)

16:35 - 17:55	**Session 13C:** Design Intervention in Buildings for thermal comfort	Paper ID: 1132 Field Studies of Thermal Comfort in Heritage Hotel Buildings in warm humid climate of India **Presenting Author: Dasgupta, Shalini**	**CFP 101C** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1146 Historic windows with passive heat loss reduction strategies and their effect on indoor thermal comfort **Presenting Author: Mathew, Dennis**	
		Paper ID: 1166 Optimising energy efficiency and thermal comfort measures for a low-income residential building in Ahmedabad, India **Presenting Author: Sharmin, Tania**	
		Paper ID: 1204 Enhancing Net-Zero Energy Buildings: A Comprehensive critical Review of Passivhaus Design in the UK **Presenting Author: Singhal, Harshul**	
16:35 - 17:55	**Session 13D**: Health and Wellbeing in Buildings	Paper ID: 1173 Comfort Rating Method for Potential Inclusion in Australia's Nationwide Energy Rating Scheme (NatHERS) – Darwin Climate Zone Case Study **Presenting Author: Sadeghi, Mahsan**	**FP Auditorium** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
		Paper ID: 1176 Furniture layout in residences- The role of thermal comfort **Presenting Author: T K, Jayasree**	
		Paper ID: 1203 An assessment of the thermal conditions and users' thermal adaptability in air-conditioned offices in a hot climate region **Presenting Author: Al-Khatri, Hanan**	
17:55 - 18:25	**Closing Ceremony**		**Balwantrai N. Brahmbhatt Lecture Hall** CEPT University, K.L.Campus, Ahmedabad, Gujarat.
DAY 4 : Saturday, December 16, 2023			
09:00 - 18:00	Full Day Trip: Adalaj, Patan, Modhera Sun temple		**Pickup Point:** CEPT University, North Gate **Drop-off Point**: CEPT University, North Gate

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Paper Presentation - Session 4

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Note: The Presenting Author has been marked with an asterisk (*)

Occupant satisfaction: a measure of Green Building Performance

Ashima Grover[1*], Tejwant Brar[1], Anshul Gujarathi[2]

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Abstract

Green building certification is standard practice for ensuring positive performing buildings during their construction and operational phase. Throughout the lifecycle of the building, the major consumption of resources occurs in the operational phase, when occupants interact with the building systems and spaces for their comfort and productivity. Building performance is largely a measure of the number of natural resources it consumes for its work and the quality of spaces it provides for its occupants. Occupant perception and satisfaction within an environment is an implicit parameter that has a huge impact on building performance. This parameter of performance is hardly attempted for comprehension or quantification by building operators, managers, and owners by conducting post-occupancy evaluation (POE) studies. This lacuna in building industry practice leads to a gap in anticipated building operational performance. Therefore, this paper is an attempt to highlight the significance of occupant satisfaction in achieving green building performance targets.

Keywords - Building operational energy Performance, Occupant Satisfaction, Post Occupancy Evaluation (POE).

1. Introduction

Buildings play a critical role in overall environmental sustainability. Throughout the building life cycle construction, occupancy, renovation, repurposing, and demolition, have a huge impact on land use, material use, waste generation, atmospheric emissions, water, and energy consumption (Gupta, Gregg, Manu, Vaidya, & Dixit, 2019). Other than these mentioned effects on the environment, buildings/spaces also have effects on their occupant's physical/mental health, productivity, and satisfaction. In response to these, Green Building certification systems provide building experts with a global standardized yard scale to measure a building's impact on the environment and occupants. At large, Green building certification systems are based on similar domains like site sustainability, energy efficiency, water efficiency, material use, indoor environmental quality (IEQ), and waste management (Honnekeri, Brager, Manu, & Rawal, 2014). Within these domains of green building certification systems, the environmental benefit is indisputably the prime benefit, but there are several unspoken benefits as well that are addressed to occupant well-being- comfort and satisfaction majorly under the IEQ section. The green buildings industry has a deeper impact on the social transformation of society. It is not only the building designers and owners but it propagates a larger role to its occupants like understanding of design philosophy, generation of green ideologies, and encouraging pro-environmental behaviors. The provision of awareness, education, and training to occupants, a minor feature within the green rating systems, helps to regulate their behavior in using systems and operating the buildings which later affects the building performance significantly (Elham, Song, Angela, & Ying, 2017).

Published literature highlights the fact that green building designs do not always operate ideally as anticipated (Al horr, et al., 2016). In such a scenario strategies adopted in a green building may not always facilitate occupant's desired comfort conditions, therefore, it is of great significance to ensure that energy-efficient systems, technologies, operations, and measures do not have an undesirable impact on occupants' health, productivity, comfort and perception of indoor space, which may incite undesired adaptive behaviors of occupants later leading to altered unpredicted building performance (Kim & Kim, 2020). In this context, it is important to investigate how occupants respond and interact with green building technologies and find measures to sustain high energy performance along with desired occupant satisfaction (Kim & Dear, 2012).

2. Impact of space environmental factors on Occupant Satisfaction

People spend almost 90% of their life in indoor environments (houses, schools, work environments, etc.) and the effects of indoor conditions on human health cannot be ignored (Fantozzi & Rocca, 2020). It is of prime importance for fulfilling a space's purpose and productivity that occupants are comfortable, healthy, and satisfied. It is imperative for occupants that their psychological comfort and assurance at work are fulfilled through quality designs and efficient operation of space (Asmara, Chokor, & Srour, 2014). Satisfaction or dissatisfaction within a working/living environment space can be a subjective perceived opinion of an occupant which is also influenced by personal and contextual characteristics (Abbaszadeh, Zagreus, Lehrer, & Huizenga, 2006).

Building occupants are exposed to numerous indoor environmental factors like thermal, visual, acoustic, and air quality factors (Schweiker, et al., 2020). Various research indicates that there exists a very complex relationship between space environmental factors and occupant perception of satisfaction (Delzendeh & Song, 2017). The overall interactive outcome of this determines occupants' indoor environmental perception, and satisfaction leading to adaptive behavior toward its environmental space factors. These factors can have both short and long- term impacts on the occupants (Al horr, et al., 2016). Out of all environmental space factors, IEQ factors determining occupants' comfort levels are of high significance. The building owners claim that the cost of the occupant to do the job is substantially higher than the cost of energy, which goes contradictory if workplace designers fail to provide workers with an environment healthy, comfortable, and productive through improved space environmental parameters (Asmara, Chokor, & Srour, 2014).

3. Studies on Occupant Perception and Satisfaction

Conducting a POE study and surveying occupants, to understand occupant interaction patterns and evaluate satisfaction levels within a space is the most used method throughout. There exists a varied range of published studies conducted in other countries, but hardly any on Indian green buildings (Gupta, Gregg, Manu, Vaidya, & Dixit, 2019). Most POE studies aiming to investigate occupant satisfaction in the context of IEQ factors of space have investigated specific aspects such as thermal comfort, visual comfort, ventilation, stuffiness, and sound privacy. Some studies indicate that along with IEQ factors other space elements such as exposure to nature and daylight, noise, and ergonomics as well as opportunities for social gathering, relaxation, and exercise also impact occupant satisfaction (Kamaruzzamana, Egbu, Zawawi, Ali, & Che-Ani, 2011).

Interdisciplinary studies on human perception, behavior, and building performance evaluation have highlighted a wide range of facts, emphasizing the influencing factors and their implications on occupant satisfaction scores (Frontczak, et al., 2012). The satisfaction levels of occupants to a very great extent are influenced by the perception or image they have of their working/ living space/ environment. In comparison to green versus conventional buildings, it is found that occupants are more appreciative of their environment, even in cases of discomfort (Berquista, M. Oufb, & O'Brien, 2019). The Image of enhanced performance i.e., the green building certification label, has a positive impact on the user's perception, studies have revealed that the occupant satisfaction score with their workspace is much higher for a green building compared to a conventional building (Max Paul & Dear, 2010).

It is also found that the occupant's awareness of its building performance and system efficiency influences his perception of space psychologically. Even in the cases where all IEQ parameters of spaces are equally performing, a green certification label on a building can have a positive impact, influencing occupant perception and leading to scoring higher on occupant satisfaction compared to a non-green building (Holmgren, Kabanshi, & Sorqvist, 2017). This positive image influencing occupant perception was also investigated in a study (Khoshbakht, Gou, Dupre, & Best, 2018), highlighting that occupants of a green building even if they are experiencing discomfort in certain IEQ parameter, tends to forgive the discomforting conditions due to the overall positive image of the building performance. However, an experimental study (Geng, Ji, & Zhu, 2017) conducted to find the relationship between various IEQ factors and their related impact on occupant perception highlights that in some scenarios the unsatisfactory performance in any one of the factors not only affected the associated comfort levels of that factor but also had a comparative and relative impact on the perception of other IEQ factors indirectly leading to lower satisfaction scores. This study also highlighted the fact that the occupant's expectations from the environment in terms of comfort and satisfaction is higher in better-performing spaces or green-labeled buildings.

An analytical study to investigate the impact of interior design space layout on occupant energy behavior where space was studied by dividing into destination, circulation, and energy consumption spots highlights the significance of space design and how it influences the choices of activities and potential behavior (Delzendeh & Song, 2017). A detailed literature review of the relation between IEQ and occupant satisfaction is published where experts imply that top-rated green buildings with high IEQ scores, that have implemented measures to achieve improved IEQ conditions within the spaces have a positive influence on the satisfaction and perceived productivity of occupants (Kim & Kim, 2020).

In contradiction with the above facts, in a study where 65 LEED-certified and 79 conventional buildings were surveyed in the US, to investigate the performance and occupant satisfaction levels, the outcomes revealed that green buildings and conventional buildings have equivalent occupant satisfaction scores with the IEQ factors, building, interior, and workspace design, highlighting the fact that there is no substantial influence of LEED certification on occupant satisfaction (Altomonte & Schiavon, Occupant satisfaction in LEED and non-LEED certified buildings, 2013). A similar study was conducted to investigate occupant satisfaction in UK BREEAM- certified office buildings and showed similar results that certification does not have a substantial effect on occupant satisfaction (Altomonte, Saadouni, & Schiavon, Occupant Satisfaction in LEED and BREEAM-Certified Office Buildings, 2016). The above studies highlight the fact that any building or space, that maintains a positive optimal balance with its efficient operations, human-centric space designs, and ethical working social norms, like encouraging positive/constructive interactions and reducing negative/ relegating distractions, could help in maintaining desirable effects on occupant's satisfaction and perceived productivity (Gocer, Candido, Thomas, & Göçer, 2019).

The results from the POE study on 77 Australian open-plan offices emphasize a strong link of space physical configuration /space design with occupants' perceived productivity and satisfaction levels. Evaluating several features of a building design and operations like aesthetic quality of space and building, comfort conditions from environmental parameters- visual, thermal, IEQ and acoustics, personal controls, outside views and connections to spaces, privacy, security, maintenance, and individual space configuration. This study highlights the same fact that a good space physical configuration /space design with maintained building operations, positive occupant working conditions/experience, and regular working hours have a high association with the overall image of a workspace building for users (Gocer, Candido, Thomas, & Göçer, 2019). However, it is difficult to directly determine what environmental factors of space have a major role in inducing satisfaction or dissatisfaction to a user.

4. Parameters affecting occupants' satisfaction

The Reviewed literature supports that the overall space can affect its users through its performance or its experience/ perception. A study to measure user satisfaction broadly classifies a method within two main clusters such as performance-based building user satisfaction measurements and perception-based building user satisfaction measurements (Shafaghat, et al., 2016).

- Performance-based IEQ parameters

Thermal comfort – Temperature & humidity Levels, Visual Comfort- daylight & artificial light levels, Acoustic comfort – Noise control, Indoor Air Quality, Odour, CO_2 levels, pollutants, Ventilation & Air Exchange rate.

- Perception-based -Space design parameters

Aesthetics value, outside visual connections, Furniture, and Partition layouts, Colour and Material, Privacy, Cleanliness/Maintenance, and Building/Space System Controls.

The satisfaction of building occupants is affected by the above all parameters of space. Space constitutes tangible and intangible factors that form a relationship with the occupant. The Performance based IEQ parameters are quantifiable and can be measured space-wise, whereas the Perception based – space design parameters are subjective and qualitative. These parameters need to be collected for each user of the space and results may differ for each enquiry.

To understand the overall process and linkages it is necessary to evaluate all the above-mentioned parameters of a space that interacts with the occupant and helps to develop perceived satisfaction. These Space environmental parameters should form the core of all inquiries aiming toward occupant satisfaction.

5. The relation between occupant satisfaction, adaptive behavior & Building Performance

The assessment of occupants' perceptions and satisfaction within a building can provide valuable information about building performance (Kamaruzzamana, Egbu, Zawawi, Ali, & Che-Ani, 2011). It is a fact that the performance of occupants should be aligned with the building's performance to achieve the desired results of sustainability. There should exist a fine balance between energy and resource efficiency in a green building to provide a satisfactory and productive space for the occupants. For this, it is imperative to understand the engagement of occupants in the buildings. Occupant interaction and adaptive behavior within the building are strongly influenced by occupant satisfaction and perception which influences the building operations involving energy use and cost of operations thus forming a closed-loop (LBNL & Tsinghua University, November 2017). Technology and occupant adaptive behavior together hold the potential to achieve high-performing buildings and spaces. Space operational cost and energy consumed are greatly affected when occupants perform various actions to satisfy their physical, environmental, psychological, or physiological to achieve suitable indoor comfort conditions like adjusting thermostat settings to be warmer or cooler, opening windows for ventilation, turning on lights, pull down the window blinds and move around, among many other actions that significantly affect building operations (Belafi, Hong, & Reith, 2018).

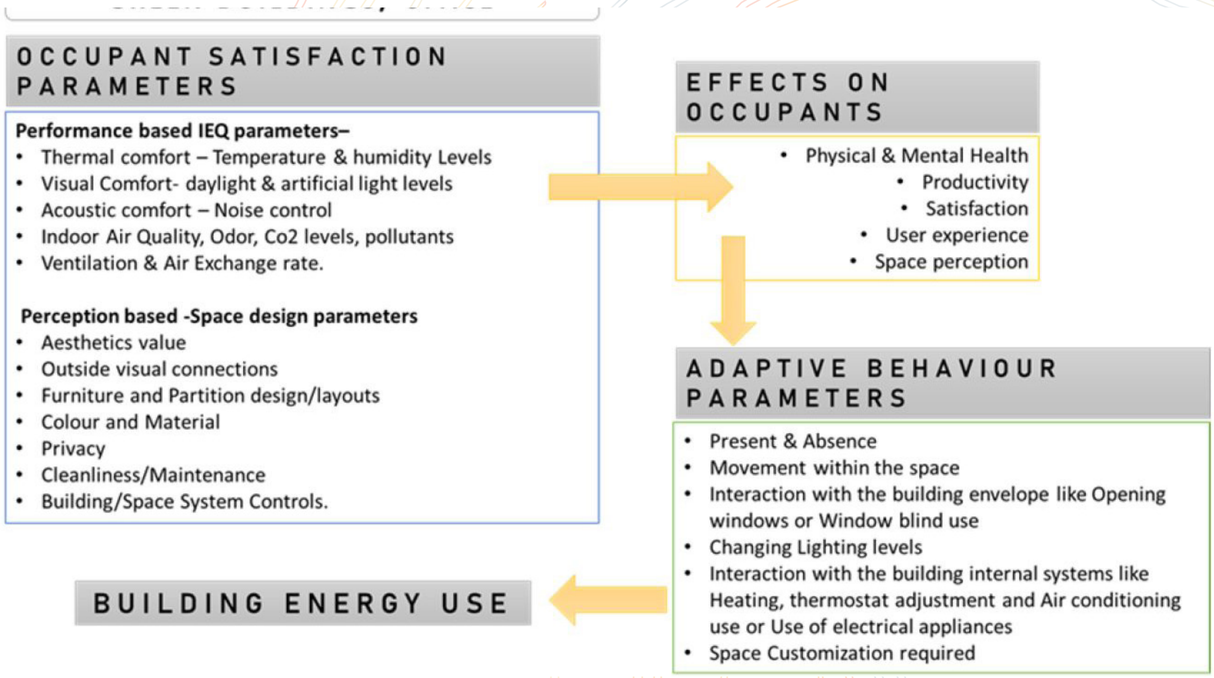

Figure 1: Illustrates the association between occupant satisfaction, adaptive behavior, and building performance

Experts claim that Occupant Adaptive behavior is the measure of user satisfaction and has the potential to improve building/space energy performance (Shafaghat, et al., 2016). However, Green building certification systems have not yet recognized a clear association between user satisfaction with adaptive behavior and energy efficiency. Within a green building code, the potential to enhance Indoor environmental quality (IEQ) is substantial. It is implied that a higher-ranked green building is high performing as well, with high-performance occupant comfort and comfort-related behavior is high performing as well, with high-performance occupant comfort and comfort-related behavior aligned (Brown & Cole, 2009). A study conducted with this theory (Keyvanfar, Shafaghat, Majid, Lamit, & Ali, 2014) provides evidence that the occupant's adaptive behavior formed due to discomfort or dissatisfaction, contributes highly to operations energy use, this implies building occupants when not satisfied with the building operational features or systems and they may adapt the building indoor environment design according to their satisfaction level with individual interventions, which causes higher energy consumption.

A review paper (Sujanova, Rychtarikova, Mayor, & Hyder, 2019) published based on an analysis of more than 300 scientific publications between 1960 and 2019, covering topics concerning IEQ, energy efficiency, occupant comfort, health, sustainability, and adaptability of the built environment, highlights the necessity of a human- centric design of the built environment, where the efficiency of technology can be measured only if it is successfully implemented and used by the building occupants.

6. Data Collection and Quantification Methods

All over the globe, experts are attempting to arrive at an accurate methodology to integrate occupant satisfaction and behavior modeling into pre-and post-construction building energy efficiency approaches. Methods like surveying, surveillance, and simulations have been used by experts in various studies to evaluate the same (Grover & Brar, 2019). For POE investigations Occupant Survey-electronic or handouts with walkthroughs, interviews, and field measurements are widely used.

- Survey-based approach

To evaluate occupants' perception and satisfaction levels, longitudinal surveys are the most used method due to their relatively low cost of implementation and ease of communication (Berquista, M. Oufb, & O'Brien, 2019). A literature review published by (Li, Froese, & Brager, 2018) shows that the occupant long-term survey helps quantify subjective opinions through a series of questions with scaled answers or responses and then benchmarks the outcomes. These types of longitudinal surveys are suitable for consistent building occupants who are exposed to the same space's conditions daily, over the long term (Berquista, M. Oufb, & O'Brien, 2019).

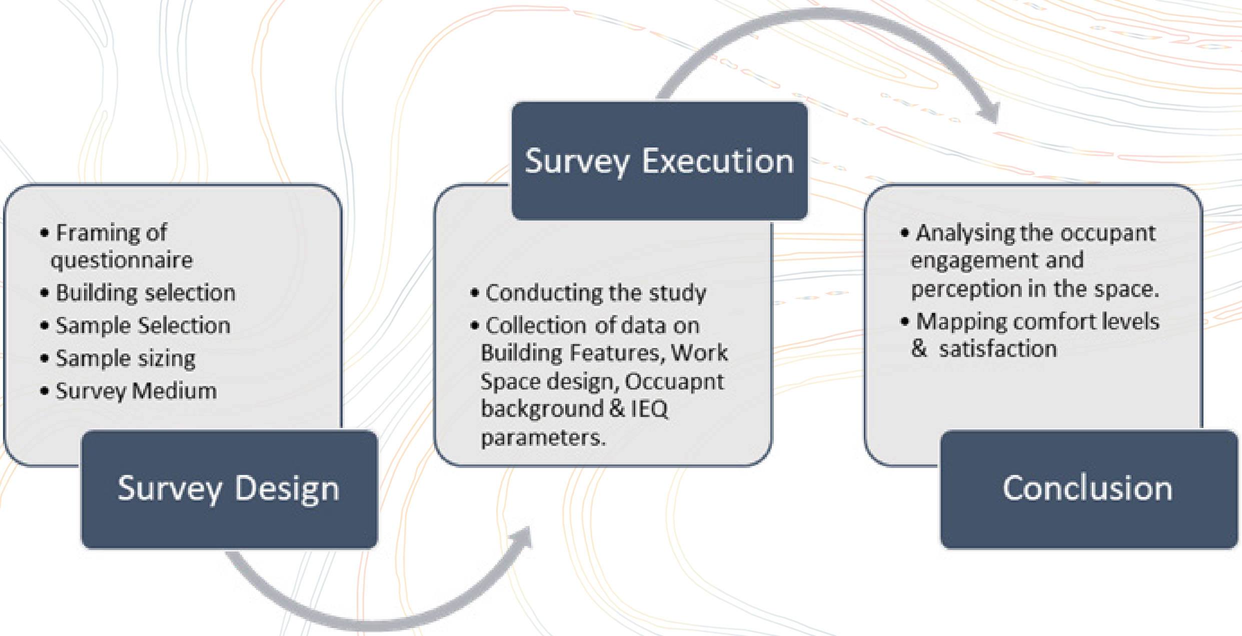

Figure 2: Illustrates the process of conducting a survey

UC Berkeley published a literature review on established survey methodologies and identified 10 surveys that evaluate occupant comfort, perception, and satisfaction on space IEQ parameters (Clara & Stefano, 2011). Seven of the ten surveys were used for specific research projects and fell into disuse. This review highlights that the two most extensively used survey methods for long-term assessments are the Center for the Built Environment (CBE) survey and the Building Use Studies Occupant Survey (BUS). Another Survey tool recently developed and widely in practice is BOSSA- The Building Occupants Survey System Australia. It is an Australian-developed POE instrument for office buildings (Candido, Dear, Thomas, Kim, & Parkinson, 2012). All these survey methods are based on a similar base ground of assessing the results from occupants and their engagement with the built environment. Although they differ in their approach, features, and structure of the questionnaire. All three survey methods are closed-ended with multiple-choice answers and require participants to choose each possible answer independent of the others, on the continuum of responses, provided by the Likert scale. They all have been established, verified, and kept consistent over many years thus enabling reliable benchmarking. The BUS questionnaire has been developed in the UK and used worldwide, the CBE questionnaire is developed and implemented in the USA, whereas BOSSA has most of its implementation in Australia.

The mentioned established survey methods are well designed to investigate occupant satisfaction scores, primarily dealing with IEQ factors and space design. They are widely implemented in various other countries but when tested for application in Indian office buildings, the questions and structure need modifications as per the climatic context, regional context, working pattern, and social norms followed in the Indian workspace. Also, the structure of these survey methods does not focus largely on adaptive behavior linked with discomfort experienced in the specific environmental or non-environmental space parameter. These lacunas accentuate the need for developing an advanced method tool structure specific to the Indian workspace context (Grover & Brar, 2022). To address these issues for Indian workplace post-occupancy evaluation of occupant satisfaction and energy adaptive behavior, an advanced survey framework - Workplace Survey on Occupant Perception, Satisfaction, and Adaptive Behavior (WSOPSAB) is developed and in the testing phase. The design of WSOPSAB aims to evaluate this complete loop of interaction system of occupants within the building space (Grover & Brar, 2022).

7. Discussion

The consumption of resources like energy, water, and daylight, are the prime focused parameters of efficiency in green buildings but there exists a strong relationship between occupant perception, satisfaction levels, adaptive behavior, and building performance levels, which is still overlooked in current green building practice. The occupant-centric discussion presented in the paper with the building systems and the space environment has large implications on building performance that need to be acknowledged by all stakeholders of the building industry and considered throughout the building life cycle.

The foreign existing established quantification-survey methods highlighted in the paper are well verified to comprehend the occupant perception and satisfaction levels of the space but this is still open-looped as this method does not close the connection of occupant dissatisfaction to the mapping of occupant adaptive behaviors and then methodically leading its connection to the building overall performance. To address this gap WSOPSAB is an advanced tool or method that can investigate the complete link between satisfaction, and adaptive behavior of occupants that can be adopted as a solution to test the performance of Indian workspace buildings.
In the current practice of green buildings, professionals have yet not acknowledged that occupant satisfaction can be a measure to test the building performance but it holds large potential for improving efficiency levels leading to the overall sustainability and mitigating adverse effects of building sectors on planetary problems like climate change.

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Enhancing indoor air quality and occupant well-being in Split Air-conditioned bedrooms through integrated ventilation

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Abstract

Maintaining Indoor Air Quality (IAQ) and ensuring the well-being of individuals in split air-conditioned indoor spaces such as bedrooms can be challenging, primarily due to the increased risk of airborne infection transmission and high CO2 concentration. To address these issues, pertinent guidelines recommend ensuring adequate ventilation with fresh air, as it effectively mitigates the spread of indoor pollutants. However, split air-conditioned spaces often lack a continuous supply of fresh air. The resulting indoor air quality deterioration can cause occupants to resort to opening doors and windows. This, in turn, can result in an unnecessary increase in heating or cooling energy use. The objective of this study is to address the limitations of existing air cleaning and airconditioning systems, which may include insufficient ventilation, excessive recirculation of indoor air, limited effectiveness, and the inability to dynamically respond to indoor pollutants in an energy-efficient manner. It has been observed that occupant's open doors and windows for fresh air ventilation in response to a feeling of stuffiness for a considerable fraction of the total operational hours of a split AC in a bedroom. The present study suggests that by integrating ventilation and air-conditioning in a coordinated manner, IAQ and hence occupants' well-being in bedrooms can be enhanced in an energy-efficient manner.

Keywords - Bedroom Ventilation, CoVID-19, Split AC, Energy Efficiency, Occupant Behaviour, IAQ

1. Introduction

The demand for energy consumption in India has surged due to urbanization and population growth. Buildings are significant energy consumers, especially for lighting, heating, cooling, and appliances. Efficient energy use is crucial to curb consumption. The rapid growth of the building sector in India is anticipated to lead to a substantial increase in energy use [1]. Moreover, urban densification has posed challenges to the liveability and well-being of urban populations. The recent Covid-19 pandemic has underscored the critical nature of health outbreaks in densely populated indoor spaces such as bedrooms in residences, dormitories, hostels, and apartments. The virus can spread via aerosols or airborne infections, leading to rapid clusters of infection. Furthermore, poor indoor air quality has additional adverse impacts on human health [2-7].

To address this, a novel Fan Filter Unit (FFU) technology proposed in a previous study can be utilized, as this technology can mitigate Covid-19 transmission in crowded indoor spaces by enhancing ventilation with clean outdoor air [8]. However, the key energy efficiency operational concept of Split AC is the airtightness of indoor spaces, and bringing hot air from outdoors to indoors can lead to reduced energy efficiency, as more energy is required for cooling. Additionally, numerous studies in the past have tried to address efficiency within existing systems through demand-controlled ventilation to occupancy-based AC system control [2]. However, air conditioning has operational constraints such as ventilation issues prevalent in both residential and commercial spaces, influencing indoor air quality by modulating temperature, humidity, and CO_2 concentration. Thus, even modern buildings, designed with energy efficiency in mind, can limit outdoor air exchange, resulting in the accumulation of pollutants, discomfort, and respiratory issues. However, achieving the best possible energy efficiency without compromising indoor air quality is always challenging. Therefore, there is a need to investigate the trade-off between energy performance and indoor air quality to optimally operate building systems such as Split AC in an airtight bedroom [2]. It has been hypothesized that occupant's open doors and windows for fresh air ventilation in response to a feeling of stuffiness for a considerable fraction of the total operational hours of a split AC in a bedroom.

The objective of this study is to identify the occupants' energy usage behaviour by analysing window/door operations and AC usage, using indoor and outdoor environmental data such as CO2 concentration and Dry Bulb Temperature (DBT) data. A rule-based method is employed to understand the window/door operation behaviour using collected data and to identify instances of energy wastage. Through behaviour modification, the potential for energy savings is also assessed. The outcome of this study can prove valuable for bedrooms or similar air-tight spaces where split AC units operate without proper ventilation provisions, aiming to enhance indoor air quality for the occupants' health and well-being.

2. Methods

A three-step methodology has been adopted in this study. In the first step, time series environmental data of indoor and outdoor CO_2 concentrations and air temperature (DBT) were collected for 2 months (15/02/2023-15/04/2023). This included time series occupant behavioural data for window and door opening and closing, along with time series data of the Split AC's on and off status, all obtained from the bedroom of a 1BHK residential apartment. Moving to the second step, the rule mentioned in Table 1 was utilized to identify window or door opening and Split AC's on and off behaviour.

Data status	Occupancy Status	Window/Door Status	Split AC Status
Indoor CO_2 > Outdoor CO_2 + Threshold (150 ppm based on sensor accuracy)	Yes	Closed	NA
Indoor CO_2 = Outdoor CO_2 + Threshold (150 ppm based on sensor accuracy)	Yes/No	Open/Closed	NA
Indoor DBT < Outdoor T + Threshold (3°C)	Yes/No	NA	AC ON

Table 1: Rule-based predictions for window opening and closing

This was done by computing the differences between indoor and outdoor CO_2 concentrations as well as indoor and outdoor temperatures. Proceeding to the third step, a comparison was made between the actual occupant behaviour and the rule-based occupant behaviour for window/door opening/closing and AC on/off activities. For the collection of indoor and outdoor environmental data, Testo 160 IAQ sensors were employed.

3. Results

- Overview of data:

The outdoor concentration values were mostly found stable, ranging between 400-450 ppm. In contrast, indoor concentrations in the bedroom were found varying from 400 ppm to 2800 ppm, depending on the presence of indoor CO_2 generation sources. Further, the outdoor DBT during the study period ranged between 22°C and 33°C. However, the indoor DBT was found mostly higher and ranging from 26°C to 32°C. However, instances where the indoor DBT pattern deviated from the outdoor trend were primarily observed when the split AC was in operation.

- Identification of No occupancy and AC usage hours:

Based on on-the-ground truth, the time-series data for CO_2 concentration and temperature profiles in Figure 3 have been annotated to indicate periods of no occupancy and usage of the split AC.

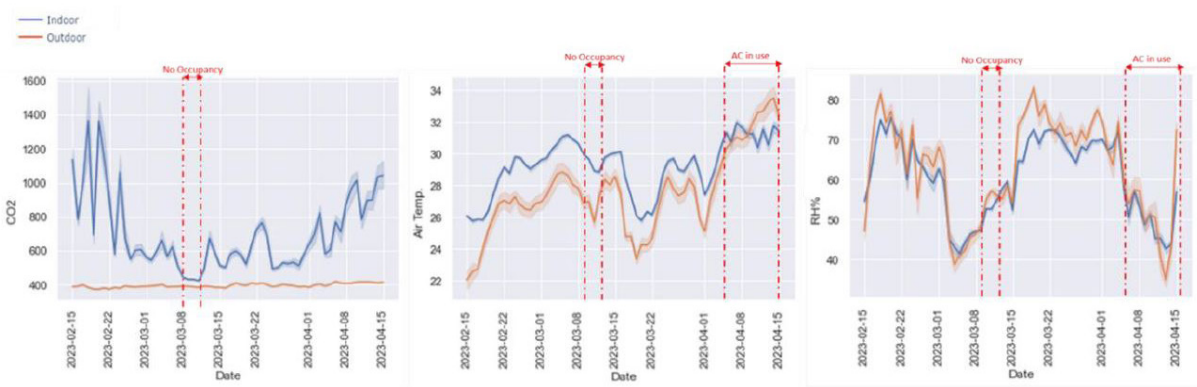

Figure 3: CO2 concentration and temperature profiles

- *Identification of AC usage during no occupancy and window open hours:*

Moving on to Figure 4 and 5, after excluding the ground truth data and relying solely on rule-based analysis, it was determined that out of the total instances occupancy status and window/door closed status was confirmed for 3391 instances, while for 2384 instances it was uncertain whether occupants were present or not and window/door was open or not. Furthermore, since the rate of CO_2 concentration decay is generally higher than the rate of generation [9], this method may estimate instances in a more conservative manner rather than leading to overestimation. The decrease in CO_2 concentration could be attributed to either the absence of occupants or the opening/closing of doors and windows. In both cases, whether occupants are absent or doors/windows are open, it is evident that energy is being wasted if the split AC is on. The main limitation with this method could be situations where occupants have left the room, but the delay in the decrease of concentration is solely due to the window/door being closed. However, based on ground truth, the likelihood of this scenario is negligible. To address this issue, a more detailed data assessment is needed. However, if this scenario exists, further assessment should involve analysing the slope of the time series difference between indoor and outdoor CO_2 concentration data to determine if there is occupancy or the status of windows/doors (open versus closed) is the key factor. If the slope of the difference between indoor and outdoor concentration is positive, it suggests that the window/door can be considered closed, indicating occupancy. Still, this interpretation depends on numerous factors, including the rate of infiltration/exfiltration and airtightness of the bedroom, which can be only confirmed through experiments such as the blower door test.

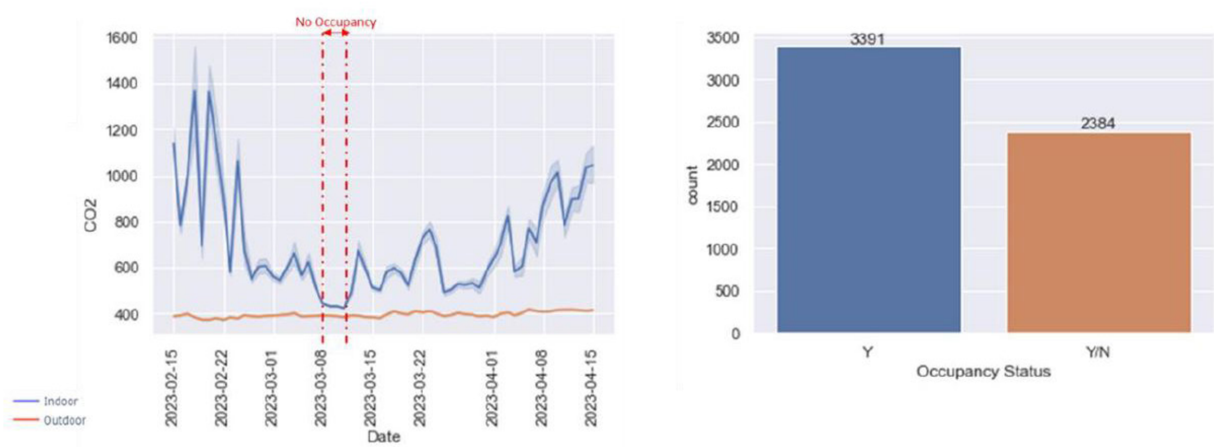

Figure 4: Occupancy presence/status identification

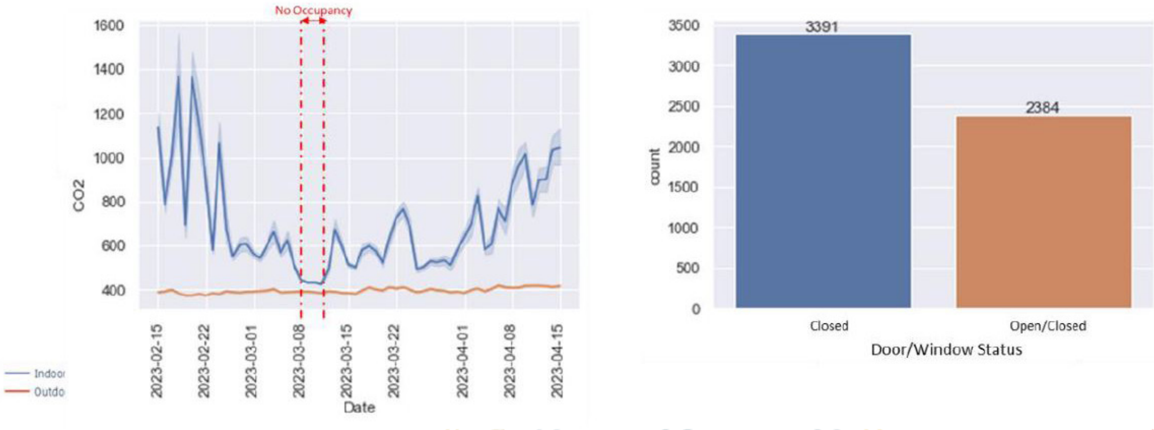

Figure 5: Window/Door Open/Close status identification

Furthermore, utilizing a rule-based approach to AC usage based on DBT, the on and off status of the AC is plotted against the air temperature profile in Figure 6. It was assumed that if the indoor temperature is consistently 3°C or lower than the outdoor temperature, the air conditioner (AC) is operational. This assumption is based on past observations, indicating that even when the AC is not running, the room maintains, primarily due to its thermal mass, a temperature that, as compared to outdoor temperature, is up to 3 K lower during summer and up to 3 K higher during winter. Among the total 227 instances when the AC was found to be on, in 64 instances, either doors or windows were open, or there was no evidence of occupancy. This indicates a potential for energy savings if the operation of doors and windows could be synchronized with the usage of the split AC.

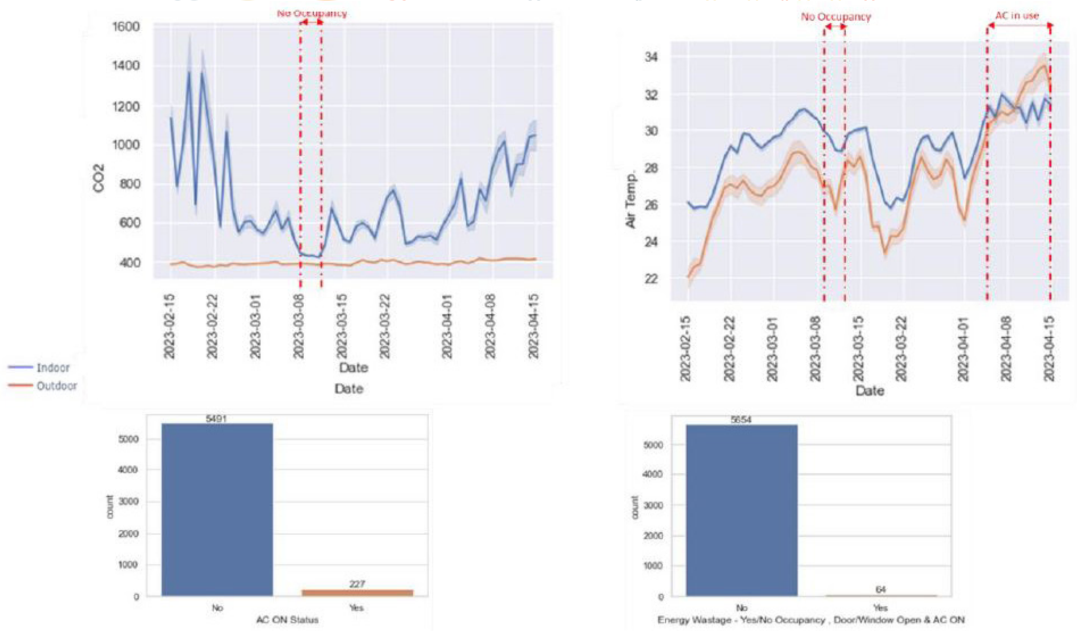

Figure 6: AC usage and corresponding window/door opening/closing behaviour

However, due to limitations in the collected data, accurately identifying energy wastage scenarios is challenging. For example, instances where windows and doors are open may be due to demand for fresh air ventilation as occupants might feel the space is stuffy. Therefore, a comprehensive investigation is needed to understand the reasons behind occupants' door/window opening and closing behaviour. Another limitation of this rule-based study is the consideration of CO2 concentration without accounting for time lags. There could be cases where occupants have left the room, but the delay in concentration decay is solely due to the room's door/window being closed. To address this issue, a more detailed data assessment is necessary. This should include the analysis of the slope of the time series difference between indoor and outdoor CO2 concentration data to infer the presence/absence of occupancy or the open/close status of windows/doors. Thereby, if the slope of the difference between indoor and outdoor concentration is positive, the window/door can be considered to be closed and occupants can be assumed to be present.

5. Conclusion

Maintaining good indoor air quality in split air-conditioned spaces such as bedrooms is crucial for people's health. However, these spaces often lack sufficient fresh air ventilation, leading to a decline in indoor air quality. Consequently, people frequently resort to opening doors and windows to introduce fresh outdoor air into the environment. This practice inadvertently results in the split air conditioner consuming more energy to maintain the room's cooling. Upon evaluating indoor and outdoor CO_2 levels, along with temperature data, it can be shown that individuals commonly open doors and windows while the split AC is operational. Although accurately quantifying the energy wastage is challenging due to data limitations, it is evident that significant energy savings can be achieved by influencing occupants' behaviour with regard to building systems operation. Nevertheless, this shift may potentially compromise indoor air quality (IAQ). This underscores the necessity for a smart ventilation system that collaborates with the split AC, automatically detecting deteriorating IAQ and supplying the minimal necessary ventilation to uphold occupants' health and well-being while optimizing energy usage. This insight thus suggests that orchestrating a coordinated relationship between the operation of the air conditioner and the provision of fresh air can not only improve indoor air quality in bedrooms and enhance occupants' well-being, but also reduce energy consumption.

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The Daylight almanac of Indian households: a case of Ahmedabad

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Abstract

Daylight access is a critical element for human health and well-being. Given the increasing density of urban built environments and large share of time spent indoors, daylight access in buildings has become a public health issue. At the same time, the need for visual privacy, controlling direct sun and glare may drive occupants to further curtail their daylight access at times. Cross modal research also shows that people in warm environments may prefer low light levels to enhance their overall comfort. This study tries to estimate to what extent occupants intervene to curtail daylight in their homes. A field study was conducted in the city of Ahmedabad from November, 2022 to March, 2023 to monitor light levels maintained by 10 households in their living room with daytime-active users present at home. At least one week worth of data (vertical illuminance on a window facing wall) was collected from each home. Depending on the home conditions, large variations were seen in the indoor light levels. For example, in the critical morning period (6:30 AM – 8:30 AM) daylight levels in the dimmest parts of the living room varied from 20 Lux to 100 lux in different homes. However, occupant interventions (lowering daylight access) were found to be most prevalent in the late morning (9:30 PM - 11:30 PM) and lunch period (12:30 PM to 2:30 PM).

Keywords - Daylight Access, Field study, Occupant behaviour

1. Introduction

Daylight access plays a critical role in human health and well-being. Given the large amount of time people spend indoors, daylight access in buildings has become a public health issue. Urban-scale studies show that buildings cannot support daylight needs at all times. At the same time, residents tend to assign a wide variety of roles to windows and view them as means to not only control daylight but also personal control over fresh and cool air, sound, sunlight, night-time street lighting, and privacy (Inkarojrit, 2005). Inkarojrit, (2005) organised several reasons due to which building occupants may modulate window openings (1) physical factors (e.g., regulating light and heat) (2) physiological factors (e.g., individual sensitivity to light), (3) psychological factors (e.g., access to view or privacy) and (4) social factors (e.g., norms). If we examine reasons due to which residential occupants may try to limit daylight access in homes, they could be categorized into two broad categories (1) Use of window openings to limit exposure to a nuisance (e.g., glare, excess heat) (2) to regulate their home environment (e.g., achieve preferred light levels).

One or multiple issues mentioned above could cause the occupants to curtain their daylight levels. For example, occupants have been found to modulate window openings (e.g., using blinds) based on global horizontal radiation (e.g., Tokel, 2006) or radiation incident on windows (e.g., Inkarojrit, 2008) suggesting under periods of high radiation occupants may curtail their daylight access. If we examine types of users or occupants, daylighting studies have identified two types of users 1) active users 2) passive users (Van Den Wymelenberg, 2012, Reinhart, 2004). Active users respond to environmental changes to modulate window openings and thus modulate the indoor environment. Passive users do not respond to environmental changes. The ratio of passive users in a multi-occupant space can be as high as 40 – 60% (Van Den Wymelenberg, 2012). Occupant interventions, and satisfaction with daylight in their space is also examined through use of artificial lighting. In the residential context, Bournas and Dubois, 2020 found that west-facing rooms use electric lighting less frequently compared to east-facing rooms indicating better daylight conditions in west-facing rooms. Room function did not affect use of artificial light during daytime suggesting that occupants are not neccessarily seeking different lighting conditions across their home. However, bedrooms were found to be the lowest reported priority of being daylit among residential users.

Residents using windows to limit exposure to nuisance

Movable shading devices enable the occupants to increase comfort levels and satisfaction from their home. Visual privacy is one of the ways in which occupant derives comfort from their homes (Amal et. Al., 2023) and is a rising concern in increasingly dense urban environments. For example, residents of a residential tower sued a neighbouring building with high footfall" that made the residents feel "like being on display in a zoo" in their own home (BBC 2023). Visual screens and curtains are often used by occupants to gain visual privacy. While screens and curtains can provide privacy, they can contribute to feelings of claustrophobia and also result in loss of daylight access. Among further reasons for curtailing daylight, cross modal research shows that people in warm environments may prefer low light levels to enhance their overall comfort. For example (Chinazzo, Wienold and Andersen, 2018). Glare and sun control are further well-known reasons for deployment of blinds that would result in curtailment of daylight (e.g., Gugliermetti 2016).

Residents using windows to balance comfort and needs

Curtailment of light extends beyond the use of blinds and curtains. Occupants may also try to control window openings to suit their specific needs. Thus, control of windows is not always to curtail a nuisance but to accommodate other preferences. For example, furniture, air-conditioning units, plants and other household items could be placed in front of or in the vicinity of the windows. Furniture placement in the room may further facilitate or inhibit daylight access. Comfort related factors that influence deployment of curtains etc. have been extensively studied, there is potential for endogeneity between indoor daylight availability and occupants' action (e.g., closing blinds/ curtains, daytime use of artificial lighting). For example, occupant may not only draw or close curtains under excess light (period of high radiation), in case of insufficient daylight availability also they may close the curtains as they do not derive the benefit of daylight access. This is an observational study that tries to examine how often and at which times of the day, occupants try to curtail their daylight access. The objectives of this study were as follows:

- What are the preferred and resultant daylight levels in homes in Ahmedabad as observed through an in-home survey.
- Do occupants tend to curtail their daylight access more at certain times of the day?
- Are the daylight access related controls more habitual in nature or tend to vary day-to-day?

2. Methods

We took a field study approach to assess 10 homes in Ahmedabad (hot and dry climate) where they were monitored for a week each (data logged at 15-minute intervals, October 2022- Jan 2023) for daylight levels received in the living room. Use of electric lighting and activities being carried out by occupants were also monitored. Weather data was also collected simultaneously from a local weather station. The frequency and duration of occupant interventions were estimated by running correlation tests between prevailing weather and indoor daylight levels.

2.1 Monitoring protocol for the indoor light environment

Onset hobo loggers were used to monitor daylight levels in each home for at least 7 days at 15-minute intervals round the clock. Since a limited number of photo sensors could be set up to measure the daylight levels in each home, the placement of the sensor was a critical issue. The intent was to measure the daylight contribution to the main activity area in the room and brightness of walls resulting from daylight (Nezamdoost and Van Den Wymelenberg, 2016).

The sensor was placed vertically on a wall in the living room at eye level (1.2 m) in all homes while trying to meet the following conditions depending on the home conditions:

- Access to direct daylight: The sensor was positioned on the wall such that it had direct line-of-sight to the sky through a window in the room while being placed on or near the darkest wall in the room. The sensor was thus placed so that light levels at the sensor location would be driven by daylight but also reveal the light levels in the darkest parts of the room.

- Proximity to the main activity area in the room: As far as possible, the sensor was placed within the activity area such as the main seating area in the living room (e.g., sensor placed above the sofa) or dining area.
- Alternate location: If both the above-mentioned conditions (direct daylight access and close to main activity area) could not be met at the same time in a given home, then the logger was placed facing a window (with direct sky access) next to the switchboard. Figure 1 shows two example cases of position of sensor.

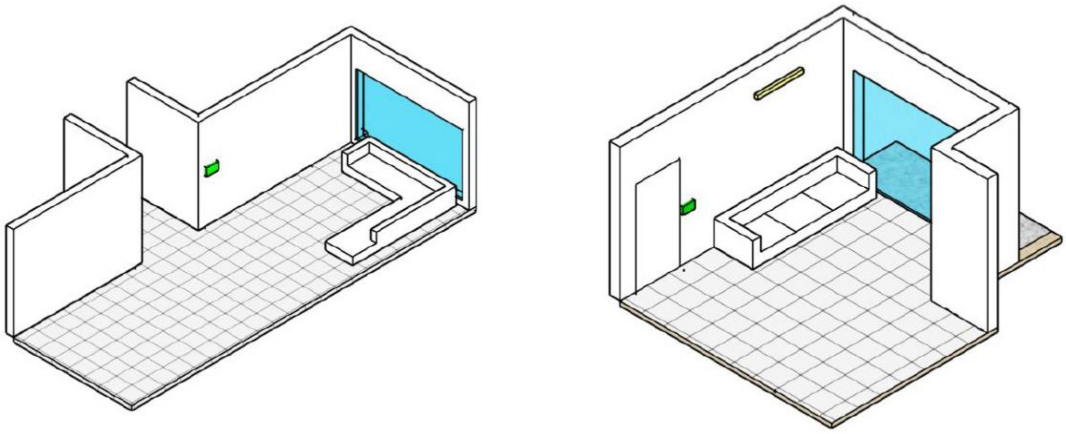


Figure 1: Schematic of two example houses prepared before monitoring to decide location of daylight sensor (shown in green rectangle on wall)

The location of the daylight sensor (with data logger) shall be referred to as the "sensor point" through the rest of the paper. Along with daylight access, the contribution of artificial light was also measured at the sensor point. Additional, secondary light sensors (with loggers) were all installed above the window head height and for the exclusive purpose of monitoring daytime and night-time use of artificial lights in the living room. Weather data for the duration of the field study was obtained from a local research facility.

2.2 Identification of homes, space description and duration of monitoring

A list of potential homes was created from known contacts and homes were shortlisted based on the following criteria:

- Size of household: Only households with two or more residents were approached for the study. It was also ensured that at least 2 or more people were present at home during daytime. Home with night-time shift workers were excluded.
- Household activities: The presence of residents was confirmed both before and after the study. Days of festivals and any special activities (weddings, large gatherings) were excluded from the data set. If the home occupants happened to leave, the duration of the monitoring exercise was extended.
- Physical context of the home: Size of the window openings, depth of space and sky view factor are the key determinants of daylight sufficiency.

2.3 Occupant survey through questionnaire

At the end of the monitoring period, when the loggers were removed from a home, the home occupants were also surveyed for their usage of the living room in the past week, use of curtains and presence at home.

3. Results

3.1 Data summary of home monitoring exercise

Table 1 shows the summary of homes that were included in the study. Total of 23 homes were approached for this study. Several home owners declined due to privacy related concerns or inconvenience the study may cause. An attempt was made to select a diverse set of homes with varying contexts (floor level) and design. It was also intended that at least two homes should be monitored simultaneously (e.g., RES 1 and 2 have the same monitoring period). This was also not feasible in the long term due to non-availability of home-owners. Data from one home survey was rejected as the homeowner was unavailable for the questionnaire-based survey afterwards and their presence at home during the study could not be confirmed. In all homes listed in Table 1, we were able to follow the protocol that was set forward in **Table 2.1.**

Table 1: Key descriptors of homes included in the study

	Study period per home and conditions in home						Descriptors of home and context				
	Period of Study	Average indoor temperature during period of study	Number of occupants at home during daytime	Location of sensor*	Living room used for sleeping in the afternoon?	Size of home	Floor	Number of window openings	WWR	AC present in room
RES1	9-11-22 to 16-11-22	30.7	3	2	Yes	4BHK	10th	1	70%	Yes
RES2	Same as RES1	30.4	4	2	Yes	6BHK	10th	2	65%	Yes
RES3	17-11-2022 to 24-11-22	27.1	2	1	Yes	3BHK	5th	1	60%	No
RES4	Same as RES3	27.1	2	1	No	3BHK	5th	1	60%	Yes
RES5	26-11-22 to 8-12-22	24.7	2	1	Yes	2BHK	Ground	3	35%	No
RES6	9-12-22 to 17-12-22	25.4	2	1	No	2BHK	Ground	3	35%	No
RES7	23-12-22 to 1-4-23	21.9	2	1	No	3BHK	Ground	3	35%	No
RES8	4-1-23 to 15-1-23	21.4	2	1	No	2BHK	Ground	3	40%	No
RES9	5-1-23 to 17-1-23	23.6	2	1	No	3BHK	Second	1	55%	No
RES 10	28-1-23 to 15-2-2023	24.4	2	2	Yes	2BHK	Second	1	40%	No

* 1 – Sensor location on a dark wall farthest from the window near the sofa
* 2 – Sensor location on a dark wall farthest from the window near the Light Switch

Table 2 shows the simple data summary of the data logging activity done in RES8 from 4th January to 15th January 2023. The dates on which the occupants were not at home were removed. The sensor logs the total light falling on it. The logged value is split into daylight and artificial light contributions using separate loggers that were used to track on/off status of artificial lighting in the room. RES 8 was found to rely on a fair amount of artificial light (indicated by orange area in Figure 2) during daytime as daylight availability was low.

Table 3 shows the comparison of illuminance data of RES 1 and RES2. The data logging activity in both these homes was carried out at the same time (9th November to 16th November 2022). The orientation of the two homes (RES1: east and west facing, RES 2 South facing) and number of windows in the living room (RES1: two windows, RES2: single window) was different. Occupant interventions towards reducing daylight access were seen in both homes. Figure 3(a) for example showed a sharp dip in light levels around 1:30 PM and daylight levels were kept low in RES until 12:30 PM. These initial observations were studied more formally and results are reported in the following section.

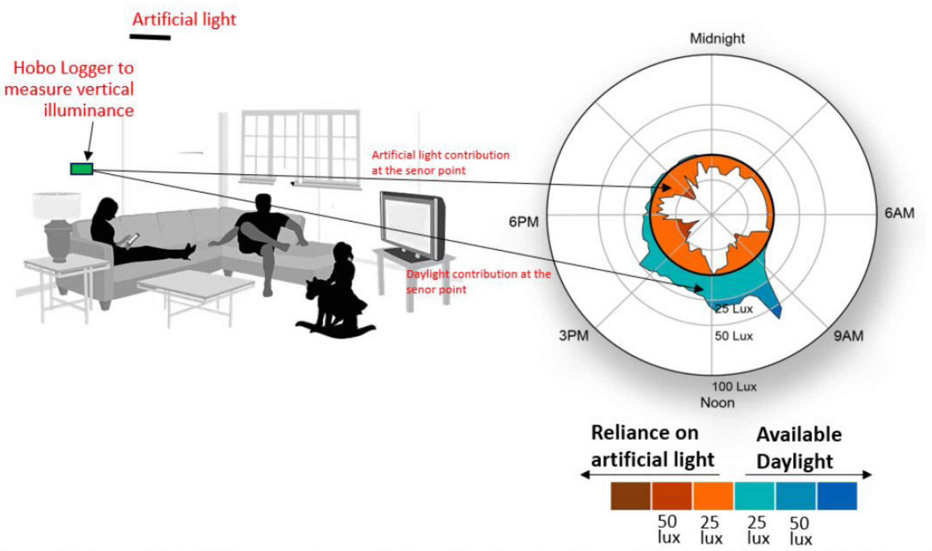


Figure 2: Example data summary showing average indoor illuminance (15-minute intervals) in example house (RES8) at the sensor point.

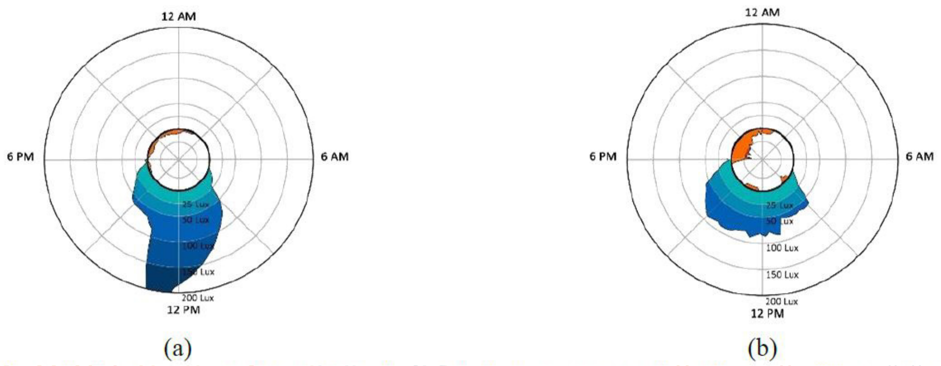


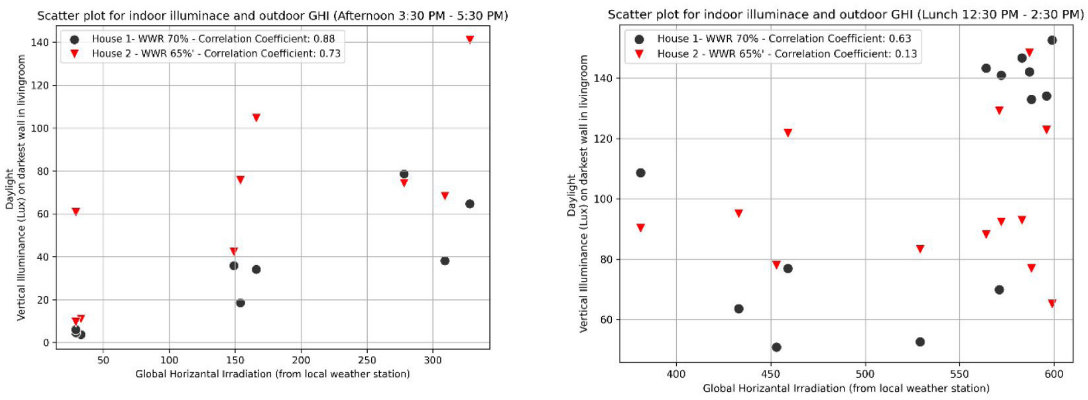
Figure 3: Example data summary for the whole study period showing average indoor illuminance (15-minute intervals) in (a) RES1 and (b) RES2 at the sensor point. Both homes were adjacent to each other and were monitored at the same time (identical weather conditions)

3.2 Tests for occupant interventions

In the monitoring exercise, we logged indoor illumination levels in each household for a week. Within a week, the solar declination angles change less than 1 degree. Thus, within a week, at a given time of day, the large changes in indoor light levels in a home will be brought about by change in weather conditions and occupant usage of blinds/curtains. Directly monitoring occupant activities such as use of blinds/curtains was not feasible. So, in order to estimate how often occupants may have felt the need to reduce the indoor light levels, we conducted two types of tests on the monitoring data:

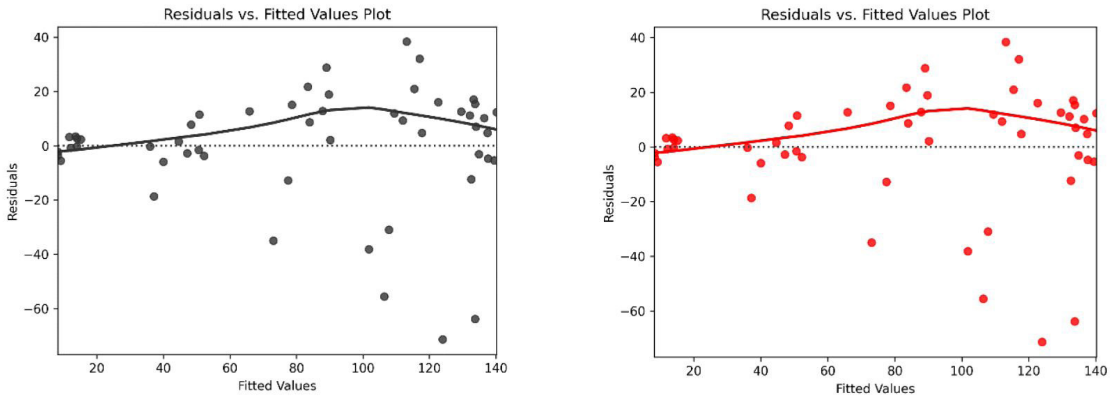
1. Spearman's rank correlation coefficient to assess monotonicity between indoor illuminance levels and outdoor radiation levels. We hypothesised that when the occupant intervenes, the monotonic relation between indoor illuminance and outdoor radiation levels would be disrupted. Spearman's rank correlations test was done for four different time periods of the day for each house to find the periods of low correlation (potential period of intervention by occupants). Other methods for testing correlation were rejected (e.g., Pearson's correlation) as they test linear relationships and rely on the magnitude of change in the variables. Low correlation on Pearson's test could also be the outcome of fairly steady radiations levels (e.g., during the lunch period)
2. Heteroscedasticity in linear regression was also looked at as a secondary means of testing the above hypothesis. If occupant do not intervene, a random distribution of residuals (on linear regression between indoor illuminance levels and outdoor radiation levels) would be expected.

Table 4 indicates better correlation between indoor illuminance and outdoor radiation levels (proxy for outdoor light levels) in the afternoon period. Figure 5 supports the notion that occupants are intervening in both homes from time to time to modulate indoor light levels. Figure 6 shows the summary of all homes included in this study. Low to negative correlation was found during 'late morning' and 'lunch' seen between indoor daylight levels and outdoor irradiation levels. While the low correlation could be attributed to the low rate of change in radiations levels (relative to early morning and afternoon), negative values suggest interventions by occupants.



(a) (b)

Figure 4: Scatter plot showing hourly values of indoor illuminance for RES1 and RES for the afternoon period (3:30 PM to 5:30 PM) (a) and Lunch period (12:30 PM -2:30 PM)(b)



(a) (b)

Figure 5: Q-Q plot of residuals of linear regression of RES1 (a) and RES 2(b) . "Fan" shape of residuals indicating heteroscedasticity. If the occupant interventions were absent then a more even distribution of residuals would be expected along the zero line.

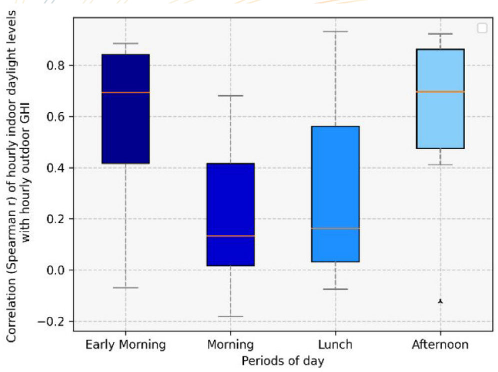


Figure 6: Spearman rank correlation to test monotonicity between indoor light levels and outdoor radiation levels for each home by time-of-day. Weak and negative correlation values (Morning and Lunch) indicate potential period of intervention by home occupants. (Early morning= 6:30 AM – 8:30 AM, morning = 9:30 AM – 11:30 AM, Lunch = 12:30 – 2:30 PM, Afternoon = 3:30 PM – 5:30 PM)

4. Discussion

Several studies classify users of blinds and active shading devices into two broad categories 1) active users 2) passive users. For active users, orientation of windows and incident irradiation levels have been found to be the strongest drivers of blind/curtain usage. Findings of this study appear largely consistent with the literature with regards to curtailment of daylight access (use of blinds/ curtains) during periods of day with high radiation. However, several other factors were found to influence occupant's behaviour. For example, RES1 occupants reported watching TV in the living room post lunch and closing blinds for this purpose. RES2 occupants reported that a small child in the house does not like bright light in the morning and so all curtains in the home are kept closed during morning hours. RES8 occupants reported that the daylight levels in their home were too low to serve much use and so they prefer to close the blinds and rely on electric lights throughout the day. Hence GHI values have been used in this study as a means to evaluate the timing of occupant interventions, but GHI was not considered to be an explanatory factor for curtailing daylight. Some homes were also revisited after a gap of 3 months and daylight access patterns were found to be similar indicating habitual nature of preferences.

5. Conclusion

This study aimed to survey indoor daylight levels being maintained by occupants in homes in the city of Ahmedabad. The data of indoor daylight levels was logged at 15-minute intervals for a period of at least a week (7 days) per home. We found that there is large variation in light variation in light levels. For example, the weekly average morning (6:30 AM – 8:30 AM) daylight levels in the dimmest parts of the living room varied from 20 Lux to 100 lux in different homes. These observed daylight levels were a combined result of the design of the home, its context and the occupant interventions. Irrespective of orientation of windows in the home, WWR, and time of year, afternoon light levels (after 12 noon) were found to be lower than morning in 9 out of 10 homes. This could indicate occupants lowering daylight access to support afternoon activities like sleeping, watching TV or lowering solar ingress. To further understand the degree of occupant interventions in modulating the indoor daylight access, we used correlation and linear regression-based tests. We found the occupant interventions (lowering daylight access) were most prevalent in the late morning (9:30 PM - 11:30 PM) and lunch period (12:30 PM to 2:30 PM).

6. Acknowledgements

We are thankful for support from families that supported our monitoring activity in their homes. We also sincerely thank Centre for Advanced Research in Building Science and Energy (CARBSE), CEPT University, India for generously providing us with weather data for the entire period of study.

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Field study on measuring Indoor Air quality in certified Green-rated urban Indian residences

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Abstract

India has the second largest registered green building footprint in the world, however, there is growing recognition that green building rating and certification systems do not always ensure better indoor air quality (IAQ) over conventional buildings. Moreover, residents spend a substantial fraction of their lives indoors, yet IAQ in homes has been studied far less than air quality outdoors, especially in urban India. To verify the actual IAQ performance of green-rated buildings built to sustainability standards, this study uses a socio-technical building performance evaluation (BPE) approach to empirically assess daily trends and variations in IAQ parameters measured across a sample of twelve green-rated urban Indian residences (high-income group) co-located in an apartment complex in Delhi. Using internet-enabled Airveda devices, time-series monitoring data at 30' intervals were gathered for indoor temperature, relative humidity, CO2, PM2.5 and PM10 for 7 days during the summer season when air conditioning was prevalent. Contextual data about the physical and social aspects of residences were gathered using household surveys. Results were compared against the recommended ISHRAE and WHO standards to observe any deviations. Given the paucity of empirical data, an online interactive dashboard (RIAQ) for visualising IAQ in green-rated homes was developed to enable further research.

Keywords - Indoor air quality, post-occupancy evaluation, green-rated residences, visualization

1. Introduction

The building sector in India is experiencing unprecedented growth, which is responsible for 47% of total energy consumption in India [1]. Catering to sustainable development, the Indian Green Building Council (IGBC) has launched 30 different IGBC GREEN building rating systems [2] to suit different types of buildings (residential, commercial, industrial, educational, etc.). To date, IGBC has over 10,698 registered projects with a footprint of over 10.26 billion square feet (as of March 2023), making India 2nd in the world in terms of green footprint [3]. Although many emerging smart technologies and building performance assessment systems have been developed to save energy and improve occupant-perceived comfort, many buildings do not perform as planned [4]. There is growing recognition that green building rating and certification systems do not always ensure better indoor air quality (IAQ) over conventional buildings. There is an unbalanced building evaluation development between the design and operation stages.

Building performance evaluation (BPE) in the green buildings sector is an emerging area of research in India, especially in the residential building field [5-7]. To address these concerns, Gupta, Gregg, Manu, et al., based on their experience in BPE work and the feedback from the expert survey, have developed one of the first BPE frameworks in India, namely the I-BPE framework (Building performance evaluation in an Indian context), to evaluate green building performance in the Indian context [8]. In the same year, Gupta, Gregg, & Joshi [9] and Gupta, Gregg, & Panchal [10] applied the I-BPE approach to a sample of 29 Platinum-certified green residential units located in the warm-humid climate and a green-certified office building in the hot-dry climate, respectively, to assess buildings' performance in actual energy consumption and indoor environmental conditions. These studies evidenced the applicability of the I-BPE framework and benchmarking data for green-rated buildings in India.

To better understand the green buildings' in-use performance, some studies have been conducted to develop an India-specific BPE method for green buildings in India, from both technical and occupants' perspectives. Table 1 summarises BPE-related studies in the Indian context related to

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energy consumption, indoor environment, and thermal comfort. These studies cover residential and non-residential buildings, such as office buildings, educational buildings, etc., as shown in Table 1. The table also indicates that there has been limited focus on monitoring the indoor environment as compared to energy consumption.

Table 1: BPE- related studies of green-rated buildings in India

Building type	Source	Energy	Indoor environment	Occupant Questionnaire
Domestic Building	Gupta, Gregg, & Joshi (2019) [9]	✓	✓	✓
	Verma et al. (2019) [11]			
	Basu et al. (2020) [5]	✓	×	✓
	IFC (2018) [12]	×	×	✓
	Batra et al. (2013)[13]	✓	✓	×
Non-Domestic Building	Gupta, Gregg, & Panchal (2019) [10]	✓	✓	✓
	Sonar & Nalawade (2019) [4]			
	Gupta, Gregg, Manu, et al. (2019) [8]			
	Sabapathy et al. (2010) [14]	✓	×	✓

Very limited resources and studies are available on building performance assessment of green-rated buildings in the Indian context [4]. Against this context, this study empirically investigates IAQ parameters' daily trends across a sample of twelve green-rated urban Indian residences located in Delhi, representing the composite climate. Contextual data about the physical and social aspects of residences were gathered using face-to-face household surveys. The results were compared against the recommended ISHRAE to observe any deviations. An online and interactive dashboard (RIAQ-Green Homes) for visualizing IAQ was developed for academics, policymakers and industry to enable further research.

2. Methods

2.1 Monitoring and survey data collection

The field study was carried out in a sample of twelve green-rated urban Indian residences located in Delhi during the summer season. The IAQ parameters of temperature, RH, CO2, PM2.5 and PM10 were monitored at 30' intervals by using the internet-enabled Airveda devices for 7 days (25th-31st May 2023) when air conditioning was prevalent. Airveda monitoring devices were installed in the most occupied space - the living room of the case study residences. Outdoor environmental data were gathered from the Central Pollution Control Board (CPCB) online portal [15]. A series of face-to-face interview-based surveys were conducted to collect data on dwelling and household characteristics of residences, such as the dwelling size, built-up area, the number of residents, annual income groups, the number and usage habits of different household appliances, as well as their received thermal comfort feedback information.

2.2 Overview of case study residences

The twelve sample residences are co-located in a 31-storey luxurious apartment complex in Delhi, which is certified as an 'IGBC Green Homes Pre-Certification' and was built 3-5 years ago. All sample residences were from the high-income group (HIG, income more than INR 18 lac per annum), with at least 6AC equipped in each home. Modern amenities, such as electric geysers, washing machines, TVs, music systems, computers, etc., are commonly equipped in every home, as detailed in Table 2. Except for DG-020 and DG-047, all the other residences are self-owned. Most of the sample residences were constantly occupied, except for dwelling DG-010, all others have 2 or more residents living in, with DG-012 having the highest number of occupants with 7. Across the overall sample, all residences owned 6 or more AC units, with DG-018 having the most, 9 AC.

Table 2: Residences' characteristics

Dwelling ID	Home tenure	Floor area (m²)	Dwelling size	No. of residents	No. of AC	No. of computer	No. of Electric geyser	AC usage
DG-008	Self-owned	277	3BHK	4	6AC	2	4	7-9 hours per day
DG-010	Self-owned	277	3BHK	1	6AC	2	2	7-9 hours per day
DG-012	Self-owned	337	4BHK	7	7AC	3	More than 5	4-6 hours per day
DG-017	Self-owned	277	3BHK	4	6AC	2	3	7-9 hours per day
DG-018	Self-owned	337	4BHK	6	9AC	2	More than 5	7-9 hours per day
DG-020	Rented	277	3BHK	3	7AC	1	4	10-12 hours per day
DG-024	Self-owned	277	3BHK	2	7AC	1	4	7-9 hours per day
DG-028	Self-owned	337	4BHK	3	7AC	1	3	7-9 hours per day
DG-032	Self-owned	337	4BHK	2	7AC	1	5	7-9 hours per day
DG-033	Self-owned	337	4BHK	3	6AC	2	5	10-12 hours per day
DG-040	Self-owned	277	3BHK	4	6AC	2	4	7-9 hours per day
DG-047	Rented	277	3BHK	3	6AC	2	4	7-9 hours per day

Statistical analysis was carried out to derive the descriptive statistics and perform significance tests for the IAQ data from measurements and household characteristics survey data. The daily mean IAQ values were compared against classification limits specified by the Indoor Environmental Quality Standard, ISHRAE Standard - 10001:2016 [16], which attributes three specific threshold levels for individual IEQ parameters under Class A (Aspirational), Class B (Acceptable) and Class C (Marginally acceptable). In this study, the maximum values (Class C) for indoor PM2.5 at 25µg/m3, PM10 at 100µg/m³, CO2 at 1100ppm, RH at 70% and temperature at 27°C, have been adopted.

3. Results

3.1 Temperature and Relative Humidity

Descriptive statistics were conducted to identify the variations between IAQ elements in each of the case study dwellings. During the monitoring period, external temperatures ranged from 10°C to 49°C, indoor temperature varied across 12 residences (with air conditioning), with daily mean temperatures ranging from 28.5°C in DG-008 to 33.4°C in DG-010, while the outdoor mean temperature was 26.4°C. The mean RH ranged from 37.7% in DG010 to 67.2% in DG-047, these values remained within the acceptable comfortable RH band of 30%-70% prescribed by the ISHRAE standard.

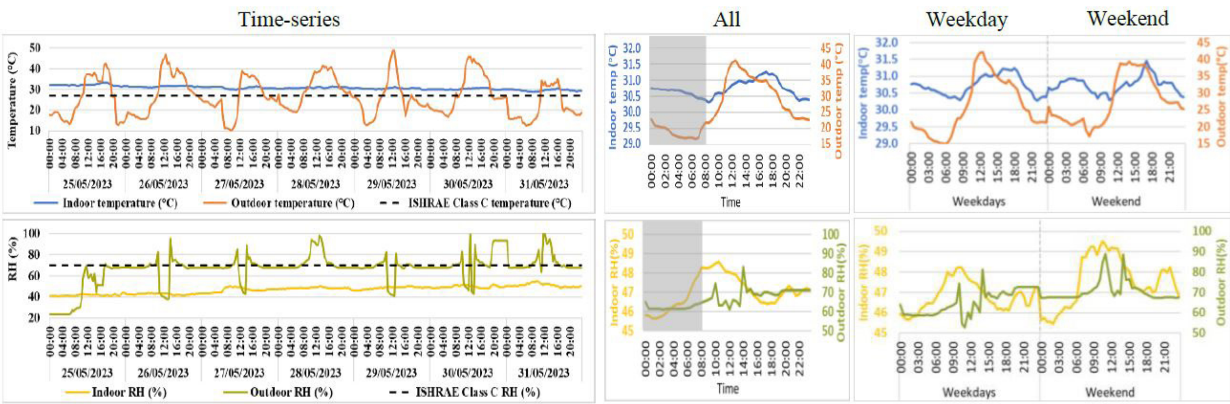

Figure 1: Line graphs of indoor and outdoor temperature & RH across the weekday and weekend

The daily profiles across all days, weekdays and weekends of indoor temperature and RH are given in Fig.1. The mean temperature of each case study dwelling during the monitoring period exceeded ISHRAE's recommended limit of 27°C for indoor temperature. At the sample level, the mean indoor temperature was 30.7°C, which is 3.7°C warmer than the recommended acceptable temperature prescribed by ISHRAE. More specifically, at the individual dwelling level, the temperature difference between the mean temperature of each dwelling and the maximum specified by the ISHRAE threshold varied from 1.5°C to 6.4°C, where DG-010 had the biggest temperature difference from the ISHRAE threshold, which was 6.4°C, and DG-008's mean temperature was 1.5°C higher than the ISHRAE threshold.

Profiles for weekdays and weekends in Fig.1 show that the mean indoor temperature on weekends was lower than on weekdays, but the relative humidity was slightly higher than on weekdays. The mean RH levels varied from 37.7% - 67.2%, with a sample mean of 47%, these RH values correspond with the ISHRAE required range of 30%–70%. Over the course of sleeping hours (00:00-08:00, the shaded area in figures), mean relative humidity levels were respectively consistent when compared to the waking hours. Indoor RH showed a weak correlation with external RH with Pearson correlation r= 0.195, but a moderate negative correlation with indoor temperature with Pearson correlation r= -0.435, both significant at the 0.01 level. Observe when the outdoor temp is high at which indoor RH drops. This indicates the use of a space-cooling appliance. In addition, the indoor temperature is also influenced by the occupancy pattern and appliance usage. Residence DG-010 which was occupied by one person experienced the lowest mean indoor humidity and highest mean indoor temperature, which might be because of the lower frequency of cooling appliances (ACs, fans) usage.

3.2 CO2 level

Indoor CO2 levels indicate the level of ventilation in buildings. It is also used as a proxy for IAQ [17]. Throughout the monitoring period, the mean CO2 levels varied from 451ppm in DG-024 to 714ppm in DG-012, much below the ISHRAE standard's maximum threshold of 1100ppm. In line with the window opening frequency leading to higher ventilation rates, all residences experienced low CO2 concentrations in rooms. The mean CO2 concentrations on weekdays and weekends was 548ppm and 615ppm, respectively. There were some significant variations of CO2 levels during waking hours observed in the daily mean CO2 profiles for all residences. Weekday daily profile of CO2 showed a similar trend with the overall CO2 profile - with CO2 concentrations increasing around 07:00 at 510ppm and peaking at 600ppm at 21:30. On weekends, CO2 levels started increasing at 09:00 (560ppm) and peaking at 21:30 (695ppm). Daily profiles of CO2 showed a direct relationship to room occupancy rates and household activities like cooking, children playing, watching TV, etc. In addition, weekend effects were also obvious, in which CO2 levels were higher on weekends and during the evening time when more residents were at home most of the time. Residence DG-012 which experienced the highest CO2 levels was occupied by seven residents majority of the time (Table 2). A moderate correlation between indoor CO2 levels and number of residents was found, with a Pearson correlation value of 0.456, significant at the 0.01 level.

3.3 Particulate matter (PM2.5 and PM10)

India has been ranked the 8th most polluted country in 2022, with PM2.5 levels 10 times the WHO limit. Exposure to PM2.5 can impair cognitive and immune functions and could cause cardiovascular, respiratory disease and cancers [18]. Indoor PM sources include indoor origins and outdoor infiltration [21]. The level of indoor air pollution in the majority of Indian households is far worse than ambient air pollution [19]. More specifically, sources of PMs are indoor activities like smoking, cooking, cleaning, burning candles or incense, and air fresheners usage, etc. In addition, high PM concentrations are caused by outdoor infiltration sources including industrial and vehicular emissions, dust from construction activities, emissions from local power plants and biomass burning from the surrounding rural areas [20]. Other factors like the design of the building, air exchange efficiency in the room and occupancy pattern rate also have an impact on indoor PM concentrations [21].

In this study, at the sample level, the mean concentrations of PM2.5 and PM10 were observed to be 35.5µg/m3 and 57.8µg/m3, respectively. PM2.5 levels in all residences were both double both double over the 24-hour recommended WHO limit of 15ug/m3 [22] and the recommended ISHRAE limit of 25ug/m3. Throughout the monitoring period, the daily mean PM2.5 levels in DG-010 was recorded with the lowest value at 25µg/m³, while DG-033 had the highest value at 48.3µg/m³. Overall, the daily profiles of PM2.5 varied significantly throughout the daytime with high concentrations between 08:00 and 12:00, the influence of traffic and house cleaning activities were noticeable here. The weekday profile of PM2.5 concentrations showed a similar trend with the overall profile but with generally higher concentrations. Weekend trend was lower than weekday trend throughout the daytime, unexpectedly, higher and variable concentrations of PM2.5 were observed during the sleep hours on weekends than on weekdays, which were mainly attributed to human activities.

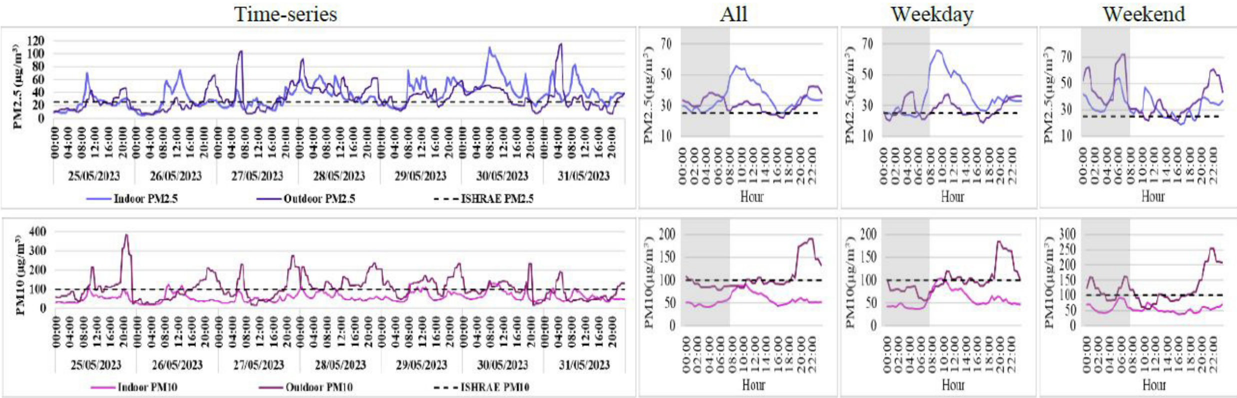

Figure 2: Line graphs of indoor and outdoor PM2.5 & PM10 across the weekday and weekend

At an individual residence level, the daily mean level of PM10 ranged from 42.2µg/m³ in DG-047 to 75µg/m³ in DG-033 and varied significantly throughout the daytime. Except for DG-047, the PM10 levels at the other 11 residences exceeded the 24-hour recommended WHO limit of 45µg/m³ but remained much below the ISHRAE limit of 100µg/m³ during a 24-hour period. Overall, PM10 had obvious diurnal variations with high concentrations between 08:00 to 10:00 but the lowest hourly concentrations often occurred around 03:00 and 16:00. The weekday profile of PM10 concentrations showed a similar trend with the overall profile. The weekend trend was higher than the weekday trend between 21:00 and 07:00. This might be associated with changes in the outdoor ambient PM10 concentrations, it can be seen from the daily profile in Fig. 2, that the outdoor PM10 concentrations at the weekend were higher than weekdays around the above-mentioned time frame. Higher concentrations of PM10 were observed between 08:00 to 16:00 on weekdays than on weekends, which might be associated with the traffic on weekdays. As evidenced by other studies, the average daily concentration of PM10 decreases as traffic flows decrease during late-night hours, and vice versa [23].

PM levels were related to household activities, with the highest PM concentrations observed between 20:00 to 22:00 wherein cooking and eating activities would have taken place. Cooking fuels are the main contributor to high PM concentrations in Indian households. In this study, all 12 households use gas as their primary cooking fuel, and 25% do not have exhaust fans in their homes, which explains why PM peaks occurred during cooking time in this study. Suggestions to reduce indoor PM levels include ensuring there is adequate ventilation, especially when doing activities that may generate PM.

3.4 Cross relating IAQ parameters and household characteristics

The strength of the relationship between indoor and outdoor parameters across dwellings has been calculated using Pearson's Correlation and presented in Table 3. Indoor CO2 levels were found to be weakly correlated with outdoor temperature and PM10, with the Pearson correlation value at 0.229 and 0.232, respectively. Weak negative correlation was found between indoor temperature and outdoor RH, with a Pearson correlation r= -0.201. Indoor and outdoor PM was weakly associated where Pearson correlation r=0.227 for PM2.5 and r=0.155 for PM10.

Table 3: Pearson's Correlation Coefficient between indoor and outdoor air quality parameters at the sample level.

	Outdoor Temp	Outdoor RH	Outdoor $PM_{2.5}$	Outdoor PM_{10}	Indoor Temp	Indoor RH	Indoor CO_2	Indoor $PM_{2.5}$	Indoor PM_{10}
Indoor Temp	.156**	**-.201****	-.078**	.065**	1	**-.435****	-.080**	-.174**	-.064**
Indoor RH	-0.012	.195**	.100**	-0.021	**-.435****	1	-0.024	.160**	.080**
Indoor CO_2	**.229****	.063**	.183**	**.232****	-.080**	-0.024	1	.150**	.106**
Indoor $PM_{2.5}$	.127**	.072**	**.227****	.113**	-.174**	.160**	.150**	1	**.928****
Indoor PM_{10}	.167**	0.020	**.203****	.155**	-.064**	.080**	.106**	**.928****	1

Unsurprisingly, a strong positive correlation was observed between PM2.5 and PM10, which had a correlation coefficient of 0.928. Moderate negative correlation with a Pearson correlation value of –0.435 was observed between indoor temperature and RH. Generally, as air temperature increases, air can hold more water molecules, and its relative humidity decreases. When temperatures drop, relative humidity increases, and vice versa. Weak correlation was observed between indoor PMs and CO2, implying that CO2 concentration on its own may not be an appropriate proxy for measuring IAQ in Indian residences since most of the PMs are generated due to household activities like cooking and cleaning. The relationship between CO2 and PMs is still under researched.

Using statistical analysis, the relationship between IAQ elements and household characteristics, such as the number of residents, and the number of appliances in terms of AC units, computers, and electric geysers, has been investigated. Indoor CO2 levels had a moderate correlation with number of residents, with a correlation coefficient value of 0.550, while weak negative correlation was observed between indoor CO2 and number of ACs, with a correlation coefficient value of -0.254. Interestingly indoor CO2 levels were observed to have a weak correlation with the number of exhaust fans with a correlation coefficient value of 0.358, showing that the exhaust fans were not used enough, while weak negative correlation has been found between indoor temperature and the number of electric geysers (correlation coefficient value = -0.184), both significant at the 0.01 level.

3.5 IAQ dashboard for green homes

To provide an overview of IAQ in green homes, a visualisation dashboard called RIAQ (RESIDE Indoor Air Quality Dashboard-Green Homes) has been developed. This is an online interactive platform that can be used to rapidly analyse and visualize the technical monitoring IAQ data along with the social data on physical dwelling properties and household characteristics. RIAQ dashboard consists of five main tabs, i.e. Characterising, Profiling, Distribution, Correlation, and Benchmarking. The outputs of each tab are varied by the selection of input variables, which can be filtered by different levels in terms of the Overall level (all residences), Typology level (by Home tenure, Occupation, Dwelling size and No. of AC units), and dwelling ID.

Figure 3: RIAQ green homes dashboard profile examples: Characterising (left) and Benchmarking (right)

The association between physical building properties and household characteristics can be reviewed on the Characterising page (Fig. 3. left). The Profiling page visualizes the indoor and outdoor ambient air quality monitoring data. Grouped by the number of AC units, the Distribution page presents the distributions of IAQ through the box plots by home tenure, occupation, dwelling size and the number of AC units. Grouped by dwelling size, the Correlation tab demonstrates the correlations between IAQ parameters data, the correlation strength between paired variables can be seen by positive and negative linear trend lines in each scatter plot. The Benchmarking tab (Fig. 3. right) presents the comparison between the IAQ data and the recommended acceptable range prescribed by the ISHRAE IEQ standard Class C [16], which attributes three specific threshold levels for individual IEQ parameters.

To our knowledge, there is no available interactive online dashboard that has been developed for green-rated urban Indian residences yet. It is free to access and easy to use for the public. The RIAQ dashboard developed in this study empowers users like academics, industry or building standards legislation authorities, to understand the changes happening in the indoor environment quality of green-rated homes in India, and also provides insights into the green building further development as well as the demand on IAQ legislation progress in India.

4. Discussion

A socio-technical BPE assessment of IAQ in a small sample of twelve certified green-rated urban Indian residences over seven days revealed IAQ conditions that exceeded recommended thresholds, particularly with regard to indoor temperatures and PM2.5. Indoor temperatures were found to vary across the 12 residences with daily mean temperatures ranging from 28.5°C to 33.4°C, all dwellings failed to meet the ISHRAE IEQ standard recommended minimum mean indoor temperature of 27°C, with an overall average of 3.7°C higher temperature than the ISHRAE threshold, where dwelling DG-010 having a 6.4°C higher temperature than the ISHRAE threshold, and DG-008's mean temperature was 1.5°C higher than the ISHRAE threshold. Mean indoor RH levels ranged from 37.7% to 67.2% and remained within the acceptable comfort range of 30%-70% prescribed by the ISHRAE standard. Despite all case study residences having 6 or more air conditioning units, indoor temperature and RH were found to have a moderate negative correlation.

All twelve residences experienced low levels of CO2 concentration ranging from 451ppm to 714ppm, much below the maximum benchmark of 1100ppm prescribed by ISHRAE. The mean CO2 concentrations on weekdays increased around 07:00 at 510ppm and peaked at 600ppm at 21:30. On weekends, the rise in CO2 levels started 2 hours later than on weekdays – with CO2 levels increasing from 09:00 at 560ppm and peaking at 695ppm at 21:30. Residents usually have a later start of the day during weekends. Weekend effects were also obvious, in which CO2 levels were higher on weekends and during the evening time when more residents were at home most of the time.
Although daily mean PM10 concentration ranged from 42μg/m^3 to 75μg/m^3, much below the ISHRAE prescribed upper limit of 100μg/m^3, daily mean PM2.5 levels (arising from cooking and cleaning activities) had a range of 25μg/m^3-48μg/m^3, much above the upper limit of 25μg/m^3 set by ISHRAE. PM levels were related to occupant activities, with high PM levels observed between 08:00 to 12:00, the influence of traffic and house cleaning activities was noticeable here. Weekend trend was lower than weekday trend throughout the daytime, unexpectedly, higher and variable concentrations of PM2.5 were observed during the sleep hours (00:00-08:00) on weekends than on weekdays, which were mainly attributed to human activities.

The RIAQ dashboard, an online interactive platform developed for the first time in this study, can be used to rapidly analyse and visualize the technical monitoring IAQ data along with the social data on physical dwelling properties and household characteristics. This allows academics, researchers, policymakers and building practitioners to better understand how IAQ varies daily in Indian residences with different numbers of residents. This can potentially enable further research related to improving IAQ in residences.

5. Conclusion

To verify the actual IAQ performance of green-rated buildings built to sustainability standards, this study used a socio-technical BPE approach to empirically assess the daily trends and variations in IAQ elements measured across a sample of twelve green-rated urban Indian residences co-located in an apartment complex in Delhi. The findings revealed that the green-rated homes had good levels of IAQ in terms of RH, CO2 levels and PM10 levels that remained within the acceptable thresholds prescribed by the ISHRAE standard. However exposure to PM2.5 levels was found to be high. Due to the lack of a comprehensive protocol for monitoring indoor PM2.5 levels in residences, such exposures go unnoticed.

Since the research presented is based on a small sample, there are limitations in drawing general conclusions on the link between IAQ and household characteristics in green-rated urban residences. Nevertheless, the proposed socio-technical POE method and valuable findings presented here can be rolled out more widely to provide more comprehensive coverage of green-rated urban Indian residences. The findings also reveal the urgent need for developing large-scale monitoring campaigns to measure different IAQ parameters in Indian residences and how these relate to occupant activities and behaviours. Starting this effort in green homes may have a rapid uptake.
The RIAQ dashboard, an online interactive platform developed for the first time in this study, can be used to rapidly analyse and visualize the technical monitoring IAQ data along with the social data on physical dwelling properties and household characteristics. This allows academics, researchers, policymakers and building practitioners to better understand how IAQ varies daily in Indian residences with different numbers of residents. This can potentially enable further research related to improving IAQ in residences.

6. Acknowledgement

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Contemporary Vernacular Architecture in The Brazilian Tropical Savana: The Case-Study of the Children's Village in the Canuana Farm, in Tocantis.

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Abstract

Completed in 2017, the building complex Moradias Infantis de Canuanã (Canuanã Children's Village) is located in the city of Formoso do Araguaia in Tocantins, in Brazil. Its architecture is strongly influenced by the local savanna climate which is characterised by distinct hot-dry and hot-mid seasons. In this study, the authors evaluated the buildings thermal conditions and the potential of natural ventilation using analytical procedures supported by computer simulations. Air movement in the transitional spaces was also simulated with CFD techniques. The findings reveal that, during the hottest periods of the year, the key habitable spaces (bedrooms) in the building have temperatures 10 oC below the outdoors. Primarily, this performance is attributed to the influence of thermal mass, combined with natural ventilation and shading. Additionally, a positive impact of natural ventilation on indoor conditions requires a combination of wind driven and buoyancy effects. In the courtyards, the distance between blocks is enough to allow perceivable air-speeds. Overall, this study has shown that the holistic design employed at the Children's Village building complex in Tocantins works well to maintain the indoor thermal environment at acceptable conditions.

Keywords -Vernacular Architecture, Tropical Savanna, Thermal Conditions, Natural Ventilation, Analytical Study.

1. Introduction

1.2 The Case Study Building: Architectural design and passive strategies

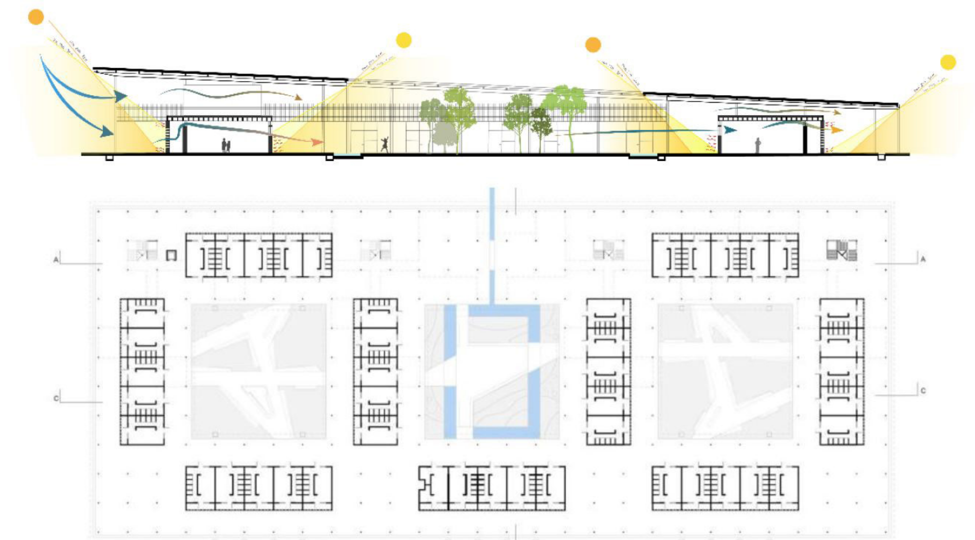
The building design of Canuanã Children's Village addresses the brief of reformulation of the spaces of the rural school of the Fazenda Canuanã, which houses 540 children (students from the Bradesco Foundation). The new building complex encompassed approximately 23,000 m² of built area [14]. Completed in 2016 in the city of Formoso do Araguaia, in the Brazilian state of Tocantins, the architectural design is strongly influenced by the local tropical savanna climate (tropical wet and dry - Aw), characterized by a dry and a rainy season, with peak air temperatures varying between 30°C and 40°C throughout the year and significant thermal amplitudes (mainly in dry periods), exceeding 10°C. The spaces are distributed in blocks around three rectangular patios, side by side (Figs 1 and 2), all shaded by a large roof structure made by glued laminated wood and external high-reflective metal sheets. The overarching structure acts as a second roof, shading the blocks and their roof terraces, with openings over the courtyards. The big second roof is slightly sloped to increase airflow at the roof tops. Dormitories are located at the ground floor, whilst classrooms, a library and other living spaces are on the upper level.

In the search for climatic responsive architectural solutions (the so-called passive solutions), for thermal comfort of the users throughout the year in the hot-dry and hot and humid climate of Tocantis, strategies were combined providing ample shading and natural ventilation, coupled with a high thermal capacity building fabric. The inspiration in examples from the regional construction and traditional building techniques, led to the choice of building components with low environmental impact, with emphasis on the use of raw adobe bricks, made from local soil, clay, sand and organic material for walls and floors, with the aim of adding thermal inertia to indoor environments, to deal with the high temperatures and thermal amplitudes. Precedents of analytical thermodynamic studies

Figure 1: Views of Canuanã Children's Village. One of the internal courtyards on the left and external view of the building complex, on the right [14, 5]. Architects: Aleph Zero & Rosenbaum.

for compact adobe construction environments in three hot climatic contexts showed that while the maximum external temperature occurs between 15:00 and 16:00 hrs, the temperature maximum internal temperature is registered between 19:00 and 20:00 hrs, pointing to a peak temperature delay of approximately 4 hours, accompanied by a damping between external and internal surface temperature around 12°C [8].

In Brazil, the assessment of the thermal response of brick constructions in housing was verified by measurements in loco at the Vila Butantã development in São Paulo (1998), showing that while the external temperature reaches 30°C, the internal temperature is around 24°C, given the thermal inertia combined with shading and opening control for ventilation, as applied in the Tocantins project [12]. Combined with the control of heat transfer from outdoor to indoor by means of thermal mass, perforated brick elements, known in Brazilian architecture as cobogós, are placed on the external and internal facades (in communication with the patios) of the dormitories, to induce constant air flow, which, at night, assists in the passive cooling of the internal spaces (in addition to cooling the envelope of buildings). In addition to the cobogós, dormitory windows for transitional spaces and movable wooden panels over doors and partitions have the potential to increase cross ventilation through the spaces (Fig. 2 and 3). The wooden components, including the rafters and roof slats, are made of glued laminated reforestation wood (the most local sustainable choice for the use of wood in construction). Looking at the arrangement of the building form, the courtyards facilitate cross ventilation and daylight to the internal environments, while the large double roof shades the buildings. In this way, open and transitional spaces on the ground and at roof level, where living and common areas are located, are protected against the direct impact of solar radiation throughout the year.



Figures 2a & 2b: Architectural drawings of the Canuanã Children's Village. At the top: Cross section highlighting the shading role of the double roof and the ventilation strategy through the perforated external walls. At the bottom: Ground plan of the building complex showing the three courtyards, with the bedrooms [5].

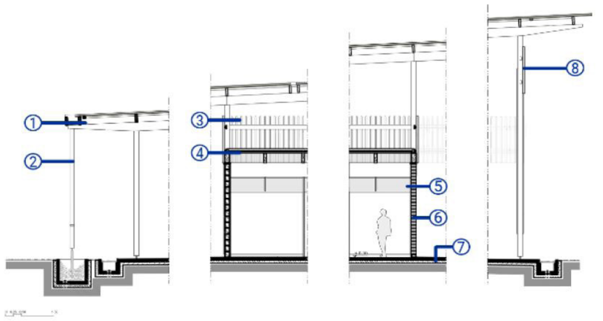


Figure 3: Detailed sections of different parts of the envelope, showing the building components and the different heights of the roof, as a result of its inclination [5].

The penetration of daylight in the dormitories occurs through the reflection of solar radiation through the external wall of the perforated elements, which shadows the area of the balcony, which, in turn, works as a transition zone for solar radiation, which is then reflected inwards. Previous analytical work showed that in addition to the meaningful reduction of solar gains, the roof worked also acts as a means to control excessive daylighting levels across the building, in locations close window openings, avoiding glare [7]. The same studies demonstrated that even without the big double roof, the occurrence of UDI in the "excessive" range is predominant in the balcony area, but does not go higher than 18%, approximately, in the worst case, being this the southwest.

In general, cross ventilation is possible by spatial communication between floors (stack effect), as well as by the continuity between same floor areas. In the dormitories, the design of the window frames allows for the complete opening of the window area. On the ground floor, open spaces in the interior and in the immediate surroundings of the buildings received a landscape treatment of native plants from the tropical savanna, qualifying the open spaces between buildings. Regarding the natural characteristics of the place, the water body close to the buildings, the Javaés River, contributes to the local microclimate, especially in the hot and dry season, increasing the relative humidity. The architectural synthesis achieved in the design Canuanã Children's Village, which explores the use of reforestation wood and earth architecture, made this design an international reference in contemporary vernacular architecture (and bioclimatic design) for hot and dry climates, awarded and published internationally. In this context, the main objective of this environmental assessment is to verify the thermal performance and the role of ventilation in the buildings complex of Canuanã Children's Village, in Tocantis, Brazil, through analytical evaluations carried out with the use of computer simulations. The analyses are focused on examining the impact of the thermal mass of the building fabric and of the large roof on the internal thermal conditions of the dormitories and their respective balconies, by quantifying the internal operative temperatures throughout the year. In addition, the resultant indoor air changes (ach) was estimated as a function of the design of the apertures and the proportions and orientations of the spaces. With respect to the outdoors, Air movement in the open and transitional spaces of the development were examined by means of simulations of computer fluid dynamics.

1.2 Climate

Located at latitude 11° 47'S, the city of Formoso do Araguaia is located in a tropical savanna region [12]. This climate is characterized by high temperatures throughout the year with a dry and a rainy season. Because of the low latitude, the northern and southern orientations receive significant amounts of solar radiation throughout the year, with the southern orientation mostly affected between January and April and from October to December (summer and spring seasons), while in the north, impinging solar radiation is significant from March to June and July to September (autumn and winter months). At this latitude, the solar path quickly reaches the most central area of the sky domo. As an example, at 12 o'clock the solar altitude reaches 77.5°on the equinoxes, 78° on the summer solstice and 55° on the winter solstice, making horizontal elements the most efficient strategy for shading. Climate data from the local meteorological station has shown that the global radiation on the horizontal surface is between 4,000Wh/m^3 and 6,000Wh/m^3, with August and October the months with the highest incidence and April the month with the lowest [12]. The dry-bulb temperature remains relatively constant throughout the year, with monthly averages ranging from 25°C to 30°C, with maximums exceeding 35°C and reaching close to 40°C in August and December, the hottest months. In general, the period between October and April comprises the most humid and hot months, with relative humidity rates around 80%, while the period between May and September is mostly hot and dry, with relative humidity around 40%. Because of the drop in humidity, the hottest and driest months are also those with the greatest daily temperature amplitude (ΔT), reaching 13°C in June and 18°C in September, while in the humid months this variation is about 6°C. Such values of ΔT, particularly in the hottest period of the year, point out to the advantages of thermal mass combined with night-time ventilation to moderate internal temperatures. The prevailing winds, important for wind-driven ventilation strategy, vary between the south and southeast throughout the year, with average speeds around 1.9 m/s and high speeds reaching 8.3 m/s.

2. Methods

The environmental assessment of this case-study is essentially analytical, focusing on dormitories and their respective balconies (space created between the external cobogó walls and internal facades), across three different orientations (Fig.5). For the thermal assessment, thermodynamic simulations were carried out, from which the percentages of annual hours of comfort and discomfort were calculated based on the ASHRAE adaptive thermal model [2]. In addition, aiming for a deeper understanding of the project's thermal response to the local climatic conditions, the profile of operative temperatures over two weeks of the hottest period of the year was extracted from the thermodynamic simulation, comprising the period between end of September and the beginning of October. The thermodynamic simulations were carried out with the Honeybee plugin of the Grasshopper simulation software, which makes use of the Energyplus computational calculation tools. The digital model was built with Rhinoceros 5. Tables 1 and 2 show the thermophysical properties of the building components and the internal gains and ventilation schedules used in the thermal model.

Table 1: Thermophysical specification of the construction components used in the thermal model [10, 5, 3].

Elemento	Materiais	thickness (cm)	Conductivity (W/m*K)	Density (kg/m³)	U Value (W/m²*K)
Floor	concrete	10	2,3	2500	2,79
	stone	40	1,3	2240	
	compact soil	10	1,28	1460	
External Wall	adobe block	14	0,37	1700	2,37
Slab	concrete	7	2,3	2500	1,60
	fibre wool	2,5	0,042	12	
Internal Wall	Concrete hollow block	15	0,48	880	1,35
	gypsum	2,5	0,22	800	
Windows	Single glass	0,3	1	2500	5,00

Table 2: Occupancy, internal thermal load and window opening regime for natural ventilation on weekdays.

Times	People	Artificial light (W/m²)	Equipament (W/m²)	Natural Ventilation Schedule (% of window opening)
00:00-7:00	6	0	0	100
7:00-8:00	3	5	1	50
8:00-9:00	0	5	0	50
9:00-18:00	0	0	0	0 (infiltration = 0,28 ach)
18:00-21:00	3	2,5	2	100
21:00-23:00	6	5	2	100

To examine the potential of natural ventilation, four room scenarios were simulated with the Optivent software, an analytical tool based on the fundamental equations of air flow [4]. The scenarios included two bedrooms, one from Block B, facing southwest (leeward side) and another one from Block A, facing southeast (windward side). In both cases cross ventilation was adopted, given the possibility of using the apertures on opposite sides of the room. For each room, two scenarios were tested, one for a mild day (in June) and another one for a hot day (in October). The results were extracted in air-changes per hour (ach/hour). In all four cases the results included the contribution of stack-effect (buoyancy) only and stack-effect plus wind-driven ventilation. In order to focus on the best possible outcomes, the results presented here refer exclusively to the combined effect of stack plus wind driven ventilation. The calculation of the required air-changes assumed an internal peak temperature 2oC above the outside. It is important to mention that the natural ventilation assessment did not consider the positive impact of the thermal mass, only the shading and insulation from the building fabric.

The computer fluid dynamics (CFD) simulation was executed using the open-source software OpenFOAM [10]. For the simulations of external airflow, the simpleFOAM solver was employed for the definition of the boundary condition. The equation proposed by Hargreaves and Wright was adopted to generate an Atmospheric Boundary Layer (ABL), which best emulates the characterization of natural ventilation in an urban environment. This process facilitates the creation of an urban gradient based on parameters like roughness values, porosity, and turbulence [6]. The input data for air velocity was set at 1.9 m/s, aligning with the characteristic direction for the city in question. The simulation was carried out using the SimpleFoam calculation method within a steady, adiabatic, incompressible, and turbulent regime. Air was treated as an ideal gas at a temperature of 25°C. The methodology for the CFD simulation was divided into four stages: 1. Pre-processing; 2. Setting boundary initial values; 3.

Solving equations; and 4. Post-processing. During the Pre-processing stage, the geometry was developed using solid modeling techniques within CAD software. Meshing stands as a pivotal phase in any CFD simulation. Mesh production involves subdividing the analyzed geometry into smaller segments for analysis. The mesh was generated in an unstructured manner, focusing on creating prism elements close to the ground and buildings to better capture the detachment of the boundary layer. Additionally, tetrahedral elements were constructed to form a non-linear polymesh. A mesh independence test was conducted using three distinct meshes (Table 3).

Table 3: Data from the three meshes used in the mesh independence test.

Mesh	Min size	Max size	Nodes	Elements	Skewness Average	Orthogonal Quality Average	wind speed at a specific point
M1	1,45E-01	29	62765	224135	0,2797604338	0,8382301043	0,18
M2	8,50E-02	17	73826	271314	0,2682210511	0,844354768	0,24
M3	4,25E-02	8,5	126342	474757	0,223688128	0,86130751	0,25

The equations were repeatedly solved, with each iteration aimed at minimizing the residuals. This iterative approach stems from the differential nature of the Navier-Stokes equation, striving to converge towards values approaching zero. Beyond addressing residuals, it is imperative to ensure the physical stability of the analyzed variables. For the analysis and validation of simulation results, only simulations with residuals smaller than 10e-4 and exhibiting a physical stability variation of less than 5% across simulations were considered [9]. In addition to the examination of the internal conditions, the outcome of the CFD simulation was use to inform a qualitative interpretation of the thermal outdoor conditions in the transitional and open spaces of the building complex.

3. Results

3.1 Thermal Performance

The results of the analytical studies showed that the rooms/dormitories facing the three orientations present a high percentage of comfort hours (above 85% of the time in the dormitories and above 69% in the respective balconies) for scenarios with and without the roof. The greater exposure of the balconies to the external environment (even if well protected) results in a slightly worse thermal performance. In the case of the scenario with the big double roof, the difference between the dormitory and the balcony is around 5%. This difference goes up to 20%, approximately, in the scenario without the roof. Looking exclusively at the dormitories, as shown in Table 4, while in the scenarios with roof the heat discomfort is practically zero in all orientations, without it, the heat discomfort is between 9.19% and 11.58%, depending on the room orientation. With respect to the balconies, the difference between orientation is much greater, staying at a little less than 1%, in the best case, with the roof, and reaching almost 30% in the worst case, without the roof. Comparatively, the percentages of discomfort due to cold were low, being 4% in the worst case of dormitories facing the northeast and 7% on their respective balconies, not being a problem, per se, as a small percentage of night-time thermal discomfort can be adjusted with blankets. The small difference of annual hours of discomfort between the scenarios with and without the double roof can be attributed to the high degree of shading inherent to the external walls of perforated elements, combined with the effects of thermal mass and controlled natural ventilation.

Regarding trends of operative temperatures during the two representative weeks, the thermodynamics simulations showed that the blocks have little difference among them. Therefore, for the purpose of objectivity, Figure 4 brings the data exclusively to the dormitory and the balcony of Block B, with and without the roof, during a period of two weeks of hot and dry conditions, between September 19 and October 3. The results point to a clear thermal stability of the simulated environments, even in the scenario without the roof. However, it is worth noting that in the scenario with the roof, the air temperatures in both the dormitory and the balcony are more in the center of the comfort zone (close to the neutral temperature line). In the case of September 23, one of the hottest days of the selected period, while the outside temperature is around 38°C, the indoor temperature in the scenario with the double roof is 25.8°C, whilst without it, the temperature reaches 29°C, both still within the comfort zone. Another point to note is that only in the balcony of the scenario without the roof the upper limit of the comfort zone is exceeded during the day, presenting daily amplitudes of 12.5°C and 9.3°C, respectively, which are significant for the effectiveness of night ventilation. The operative temperature profiles prove the relevant role of the roof for the thermal comfort of the dormitories and balconies. Due to its effect, the internal temperature in the dormitory is about 3.2°C below the scenario without it.

Table 4: Annual percentage of comfort and discomfort hours, in the simulated scenarios

ASHRAE (90% acceptance)	Block A External facade: SO				Block B External facade: NO				Block C External facade: SE			
% in relation to the comfort zone	with roof		without roof		with roof		without roof		with roof		without roof	
	D*	B**	D*	B**	D*	B**	D*	B**	D*	B**	D*	B**
% Below	4.01	7.01	0.61	0.58	2.59	5.23	0.47	0.55	1.86	4.46	0.56	0.43
% Above	0.00	0.89	9.19	29.68	0.00	1.96	11.76	23.39	0.01	1.88	11.58	24.55
% Comfort	95.99	92.01	90.21	69.55	97.41	92.81	87.77	76.06	98.13	93.65	87.87	75.01

*Dormitory **Balcony

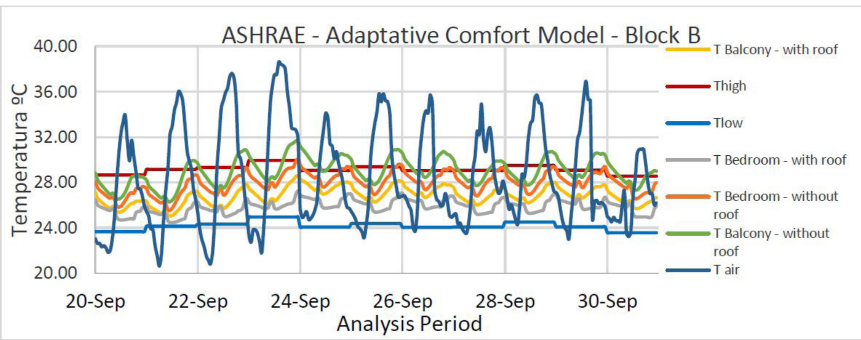


Figure 4: Profile of Operative Temperatures in the dormitory and balcony of Block B (main facade to the Southeast orientation - 2080), in the scenarios with and without the double roof, for the period between September 19 and October 3, showing the comfort zone according to the adaptive model of ASHRAE [2].

3.2. Indoor natural ventilation

Firstly, the Optivent results confirmed the need for cross ventilation if higher air change rates are required (results associated with stack effect only are not shown in this work, as they failed to provide the required air-changes in all cases). The room in the leeward direction (SW), scenarios 1 and 2, achieved more than half of the required air changes during the milder day, but stayed at less than half of the required performance on the hot day. The room on the windward orientation (SE), scenarios 3 and 4, showed a similar trend. It should be noted that, although on the leeward side, the air movement in the courtyard allows for enough wind speed to promote wind-driven cross ventilation. The insufficient air-changes found in scenarios 2 and 4 indicate the high probability of temperatures will be above the upper limit of the comfort zone during those hours.

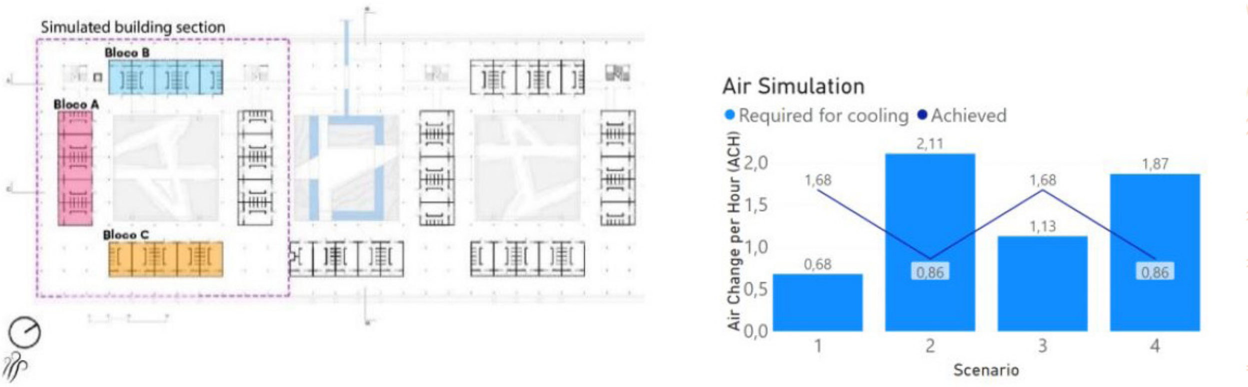


Figure 5: Comparison of air changes required and achieved in rooms A (SW) and B (SE), during the peak hour of a mild and a very hot day in Tocantis, Brazil.

3.3 Air Movement in the open and transitional

The study of air movement focused on the courtyards and respective external areas around the buildings, for the prevailing southeast wind of 1.90 m/s (Fig. 6). The result highlights a plane at 1.5m (pedestrian level), where it is possible to observe speeds of the order of 0 to 1.5m/s at some points in the open space between the buildings. Data acquisition was done for the central point of the external courtyards, where wind speeds vary between 0.24 and 0.28 m/s. It is possible to verify with this simulation that the air speed occurring inside the blocks is low, whilst natural ventilation driven by the wind should be a potential strategy to improve thermal conditions in outdoor and transition spaces. With the study of air movement, it was possible to extract the Pressure Coefficient on the facades of the buildings (Fig. 7). Figure 7 illustrates the predominantly positive pressure coefficient on facades 1 and 2, this positive Pressure Coefficient in conjunction with the predominantly negative Pressure Coefficient on facade 5 favors cross ventilation in the buildings located in row 3, however, the Pressure Coefficient predominantly Negative pressure on facades 4 and 6 adversely affects the pressure coefficient in buildings located on row 1.

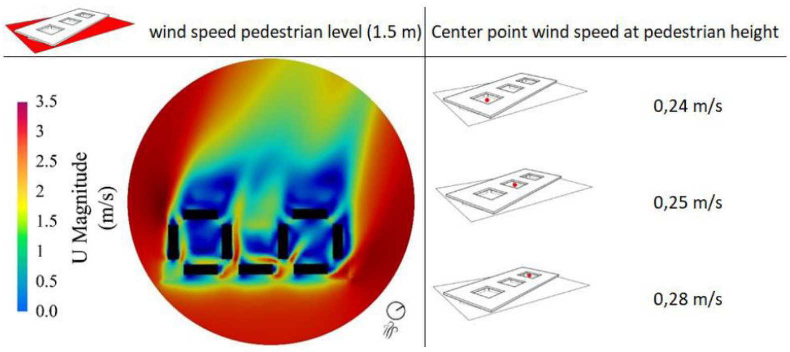


Figure 6: On the left, the ground floor plan of the buildings with the identification of the location of the simulated rooms. On the right, wind speed simulation in the open and transitional spaces, at ground level.

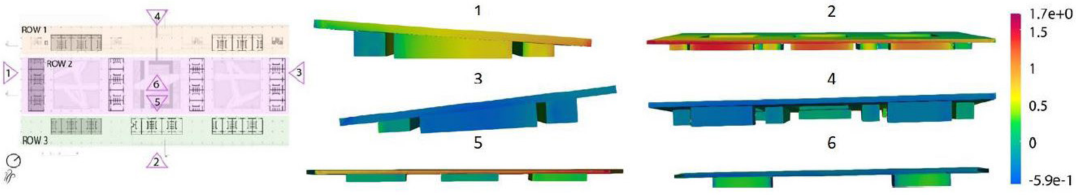


Figure 7: Pressure Coefficient on six facades that make up the Canuanã Children's Village.

4. Discussion

The thermal performance analysis of the design strategies of the Canuanã Children's Village, located in the Brazilian tropical savanna of the state of Tocantins, revealed the potential of satisfactory thermal conditions in the dormitories and their respective balconies throughout the year. As an example, for a typical week of hot and dry conditions, there were verified operative temperatures in the internal areas of the dormitories around 10oC below the outside temperatures, showing the influence of the thermal mass of the adobe walls, combined with shading. Furthermore, the overarching roof has proved to have a role in reducing solar gains, resulting in a difference of 3°C to 5°C in the dormitories, between the scenarios with and without the roof shading. Similar to the precedent studies on thermal mass [8, 11], in the Children's Village of Tocantins, internal temperatures are stable, around 25oC, while the external temperature oscillated to around 30°C. However, in general, in the dormitories operative temperatures vary within the comfort zone, even in the hypothetical scenario of the absence of the double roof, because of the shading created across all external walls by the perforated brick wall, alongside the thermal mass and the selective natural ventilation strategy, which is essential for the night-time cooling.

Commenting on the results from the indoor natural ventilation studies, the risk of thermal discomfort on the very hot day, due to the insufficient air-changes, can be dealt with by decoupling the interior spaces from the outside, but closing the ventilation openings and allowing the thermal mass to act moderating the internal peaks and the swings, as shown in thermodynamic simulations. What is also interesting to see is that, when outdoor temperatures are not so extreme, cross ventilation is sufficient to provide enough air-changes for thermal comfort. The air movement indoors and outdoors are particularly desirable during the milder period because of the higher humidity levels. Moving to the CFD simulations, reasonably low values of air speed were found in the courtyard at some positions. On this basis, the site planning of the building blocks does not always favour the air movement across the courtyards and, consequently, the cross ventilation of the internal spaces at ground level, in particular.

5. Conclusion

In conclusion, the design in question proved the possibility of achieving thermal comfort, even in extreme heat conditions (when external temperature values are around 40oC), from the joint application of passive solutions appropriate to the local climate and using techniques already known to reduce the thermal load of buildings, present in the local vernacular architecture, including shading, thermal mass, selective natural ventilation and transition zones, ultimately dismissing the use of air-conditioning. Regarding the use of passive strategies, it is particularly important to highlight the advantage of controlling (openings and closing) the apertures for cross ventilation coupled with stack effect, during the mild periods, when external air temperatures are acceptable. On the other hand, the courtyard shape blocks wind and therefore reduces the natural ventilation potential. Moreover, the refined detailed design of visually striking building components, such as the double roof structure and the cobogo walls, coupled with the flexibility of the movable wooden panels and operable windows, create a robust response to the harsh and variable conditions of the local climate, with a range of environmental adaptability to be explored by the occupants, defining the parameters of a high-quality designed of a new vernacular for the Brazilian tropical savanna.

The innovation presented here is not in the methodology of how the building was studied, but in the building itself, which opens up a new era for Brazilian locally inspired building design, featuring local (and ecological) materials and spatial quality, which can support social and environmental development.

6. Acknowledgements

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Impact of Naturally Ventilated Residential units on Heat Stress

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Abstract

In recent years, the adaptive model of thermal comfort has gained traction as a more robust alternative to fixed set-point-driven design, which considers various factors that impact human comfort, such as humidity, air velocity, mean radiant temperature, and ambient temperature. Nonetheless, it is crucial to recognize the limitations of such models and the potential for discomfort and stress. This research employs simulations to systematically evaluate WBGT as a parameter to measure heat stress in residential buildings in Bhubaneshwar, India, comparing ventilation scenarios. The study assesses three building envelope materials: Conventional (RCC and Brick) and Innovative (EPS Core). The ECBC-R[11] standard and a dynamic method derived from regression analysis predicts heat stress, analysing natural ventilation in residential units using the IMAC-R [7] and ISO 7243 [1] benchmark.

Heat stress profoundly affects well-being in hot climates. With the rise of energy-efficient, naturally ventilated buildings, understanding their impact on heat stress is crucial. This is particularly significant in countries like India, grappling with climate change-induced heat waves. The study focusses on the factor of heat stress in adaptive thermal comfort models, emphasizing the need for a more holistic approach to indoor comfort factors. Insights gained can lead to improved strategies for optimal thermal comfort and reduced heat stress risks, vital for occupant health. Indoor WBGT ranged from 16°C to 33°C for various envelopes, averaging 28°C (RCC), 24°C (Brick), and 22°C (EPS). Indoor air velocity of 0.9-1.8 m/s lowered WBGT by 0.15°C or 0.27°C annually. Discomfort hours were ~5,000 (RCC), 3,600 (Brick), and 3,200 (EPS), peaking in May-June at 40°C outdoor DBT. Proper insulation and ventilation are crucial for comfort and heat stress reduction. By considering diverse factors affecting indoor comfort, it offers insights to create safe and comfortable indoor environments, especially in regions prone to heat stress. The findings advocate a balanced approach that combines effective insulation and ventilation strategies for optimal occupant well-being.

Keywords -Heat Stress, Natural Ventilation, Thermal Comfort, Climate change, WBGT

1. Introduction

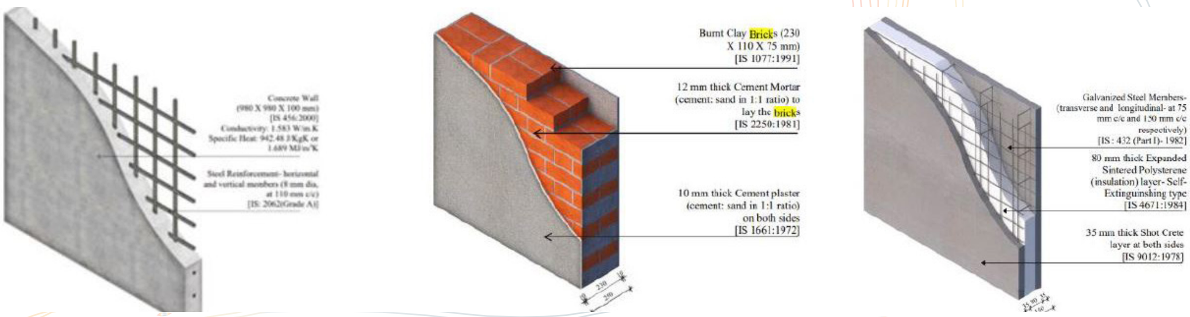
Thermal comfort and heat stress are two distinct concepts that are closely related to the indoor environment of residential buildings. Thermal comfort refers to the condition in which occupants feel comfortable and satisfied with the indoor temperature and humidity levels, and this can greatly impact their well-being and productivity. On the other hand, heat stress is a condition that occurs when the body is unable to regulate its temperature, leading to an increase in body temperature and potentially leading to serious health problems. To better understand thermal comfort, the adaptive comfort model was proposed by De Dear and Brager [8], which considers the subjective factors related to user habits and physiological and psychological adjustments in addition to objective quantitative variables. This model has been adopted in various standards, such as ASHRAE-55 and EN-16798, which use indices such as effective temperature (ET) and standard effective temperature (SET*) to derive thermal comfort. However, these indices do not consider other factors such as ambient temperature and mean radiant temperature (MRT). Maintaining thermal comfort in a building can be challenging due to the multiple environmental parameters that impact occupants' perceptions, such as air temperature, surface temperature, relative humidity, mean radiant temperature, wind speed, and direction. Additionally, geometrical and physical factors such as window location, orientation, and dimensions, occupants' clothing, user activity, position, and mood can also affect thermal comfort perception. Therefore, it is essential to consider various factors when designing buildings to ensure occupants feel thermally comfortable. Several studies have explored and evaluated various heat stress indices to estimate thermal stress accurately. One such index that is effective in assessing the climatic conditions of working environments is the Wet Bulb Globe Temperature (WBGT) index. The WBGT index is a comprehensive index that takes into account the effects of heat exposure over time for a specific activity. It is considered one of the most suitable and easiest heat assessment indices. The index was proposed to overcome the complexity of determining the effective temperature, which was derived from laboratory studies in the 1920s and was the established method for calculating heat stress. The WBGT index provides a better estimation of the thermal stress experienced by individuals working or performing physical activities in a hot environment. It considers various factors such as air temperature, humidity, wind speed, and radiant heat. The index is based on the measurement of three temperature parameters: the wet-bulb temperature, the dry-bulb temperature, and the blackglobe temperature. The WBGT index has gained significant popularity due to its simplicity and ease of use. It has been incorporated into several occupational health and safety standards, including the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values for Heat Stress and the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit for Heat Stress. Understanding and utilizing appropriate heat stress indices such as the WBGT index is crucial for managing the risks of heat stress and ensuring the health and safety of individuals working or performing physical activities in hot environments. Heat stress is a critical issue affecting people's health and well-being in hot and humid climates. In recent years, there has been a growing demand for energy-efficient buildings, leading to the widespread use of naturally ventilated buildings, which rely on natural ventilation instead of air conditioning to maintain a comfortable indoor environment. However, the impact of such buildings on heat stress and human comfort is not well understood, and there is a need to investigate the efficacy of these buildings in mitigating heat stress.

In countries like India, where climate change has triggered more frequent heat waves and extreme heat events, understanding both heat stress and thermal comfort is crucial for designing buildings that mitigate their impact on occupants' health. Unlike visible natural disasters, heat stress is silent, lacking public awareness, underscoring the need to grasp its implications. This study aims to comprehensively grasp how environmental factors affect heat stress in naturally ventilated residential buildings and devise effective strategies to mitigate it. The findings guide building design to enhance thermal comfort and minimize heat stress risks. Through dynamic heat stress prediction and benchmark utilization, we seek to comprehend environmental impacts on heat stress in naturally ventilated residential buildings using common materials like RCC, Brick, and EPS Core in Bhubaneswar. Ultimately, this research can optimize thermal comfort, reduce heat stress risks, and illuminate the nexus of environmental factors, human comfort, and stress. The study contributes to thermal comfort knowledge and potential policy-making regarding building materials and comfort standards. Focusing solely on Bhubaneshwar as a representative of the Indian climate, this study's findings can be extrapolated to other cities. For analytical simplicity, the entire unit is treated as a single zone due to the primary focus on material-induced heat stress changes. To deepen understanding of heat stress variations across areas, future work will introduce zoning and partitions.

2. Methods

2.1. Material Selection and RETV calculations

1. 1. Chosen envelopes included two common options in Bhubaneshwar: 100 mm RCC and 250 mm Brick with U values of 3.59 W/m^2K and 2.41 W/m^2K respectively, and 150 mm EPS Core (U value: 0.5W/m^2K) for a Demonstration Housing Project (DHP). The DHP was selected due to its participation in the Pradhan Mantri Awas Yojana (PMAY) and ongoing construction, ensuring reliability for assessing material impacts on comfort and stress.
2. The RETV values were calculated using the BEE (Bureau of Energy Efficiency) standard formula as described in Chapter 3 of ECO Niwas Samhita, 2018 [11]. The RETV values were calculated for all cardinal directions, taking into account the inputs specified in Eco Niwas. The values obtained for a warm and humid climate type of Bhubaneshwar were then averaged. The outcomes indicated RETV values of 17.4W/m^2 for 100mm RCC, 13.06 W/m^2 for 250mm Brick, and 6.02 W/m^2 for 150mm EPS Core technology. The values obtained through RETV calculations are effective in reducing indoor heat ingress, which is crucial in naturally ventilated spaces. These values can be used to understand



the heat stress limit for occupants within the building, as higher RETV values indicate better thermal insulation, leading to lower indoor temperatures. This will enable us to gauge the extent to which the materials currently in use, as well as those being utilized, affect the comfort levels and stress experienced within the space.

2.2. Development of simulation model

1. The simulation model was developed using a BEE standard unit of 48m² carpet area which was verified to ensure accuracy. The lumped parameter method was adopted, which treats the entire unit as one zone, without considering the spatial variability of temperature and air movement within the zone, and was considered for homogeneity of calculations. In future studies, buildings shall be divided into several horizontal and vertical sub-zones to obtain accurate information regarding the conditions of the occupied zone. To ensure uniformity, a constant clo value of 0.6, which is the standard for summer clothing, was used throughout the calculations. This value represents the thermal insulation provided by typical summer clothing worn by individuals within the zone. The 2BHK standard unit, which was analyzed for heat stress, is depicted in the following image.

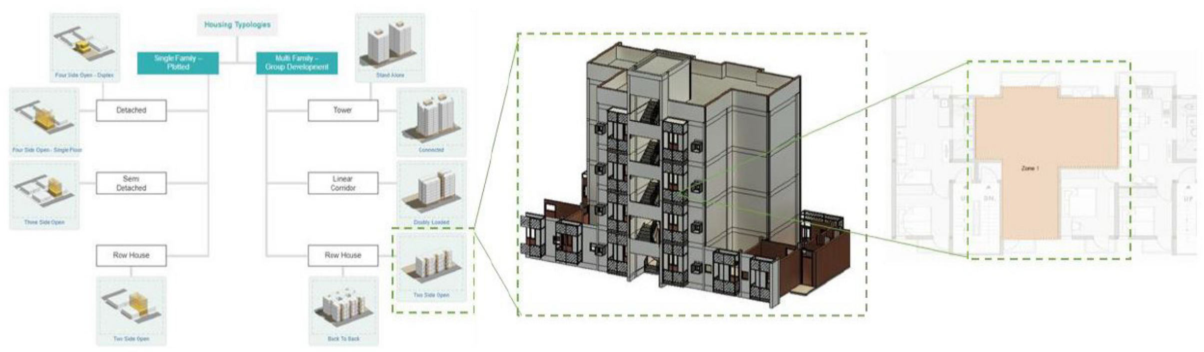


Figure 1: Image showing 2 BHK residence considered for analysis and zoning and lumped parameter method used for zoning [10]

2. The IMAC-R tool, developed by CARBSE, was utilized to derive weekly adaptive thermal comfort limits for 52 weeks. Energy Plus and Design Builder dynamic simulation software predicted the unit's thermal conditions.

3. Parameters for simulations included Bhubaneshwar's warm and humid climate (20.2961° N, 85.8245° E) (Source: ResearchGate) with an annual scope (January 1st to December 31st) for a typical year (Source: TMY). It is important to highlight that the simulation only takes into account air velocity that is not from external sources or mechanical ventilation (Free Running Building). This is to prevent any possible influence on the Mean Radiant Temperature (MRT) caused by the prevailing outdoor conditions. Consequently, the inclusion of air velocity is an assumption made solely to examine the impact of ventilation on heat stress and is not related to any external factors or sources. Changes in occupancy loads were omitted, and the exclusion of internal radiant heat sources (Fans, Lights, Computers etc.) and the focus on internal air velocity (Forced Ventilation) through the lumped zoning method are important considerations when evaluating the mean radiant temperature through simulation.

4. While certain factors may not be accounted for in the analysis, these assumptions allow for a more efficient and practical approach to understanding human comfort levels in the simulated space. Future plans involve introducing zoning and partitions for more varied heat stress analysis. The window-opening strategy revolves around opening windows when indoor temperatures surpass outdoor dry bulb temperature and the setpoint, enabling natural cooling.

2.3. Calculation of WBGT:

WBGT= 0.753Ta + 0.116Tr + 0.13RH - 0.232Va - 7.402------------------------------(1) (Indirect method of evaluation)
Ta= Air temperature (Source: Derived through simulations)
Tr= MRT (Source: Derived through simulations)
RH= Relative humidity (Source: Derived through simulations) Va= Air velocity (Source: ASHRAE 55).

2. Since the 1950s, WBGT predictions have evolved through various standards, beginning with ISO 7243, which assessed global suitability. However, it primarily relied on direct measurements, limiting its applicability. ISO 7726 and ISO 7243 lacked clarity on air velocity limits, prompting the need for enhanced specifications. To address this, models like Denedde and Bernard's [8] were developed, but only the former was validated under summer conditions. Further analysis of WBGT after 60 years [4]of it's use explored both theoretical and empirical approaches, emphasizing the need for consistent results across diverse conditions.

3. To provide a more comprehensive analysis, it would be beneficial to consider the variations in indoor and outdoor WBGT calculations, which were not taken into account in the ISO 7243 standard. By doing so, we can gain a deeper understanding of the impact of environmental factors on heat stress and develop more accurate strategies for mitigating its effects and thus various practitioners developed prediction models for the indirect evaluation of WBGT using air temperature, MRT, RH, and air velocity. Wang et al. [5] studied the influence of the indoor thermal environmental parameters on the WBGT and found that the WBGT changed linearly with indoor air temperature, mean radiant temperature, air velocity, and relative humidity, because of the limitations of indoor WBGT obtained via measurements [5]. Therefore, a simplified indoor WBGT equation using multiple linear regression was proposed based on environmental parameters. The parameters of indoor air temperature, mean radiant temperature, air velocity, and relative humidity ranged from 20 °C to 45°C, 20 °C – 50 °C, 0 m/s – 3 m/s, and 10% – 100%, respectively. In total, 20,000 data sets were randomly generated in the range of the parameters, and the WBGT was calculated using MATLAB [6] Thus, the simplified indoor WBGT equation using the regression analysis was developed which was extrapolated for residential calculations.

4. The dynamic values of the indoor air temperature and relative humidity can be obtained using the simulation described further in the paper. However, there is no way to predict the dynamic values of air velocity, which changes slightly in the summer as a result of natural ventilation. Therefore, during simulations, the air velocity was kept constant in the dynamic prediction. To explore the impact of air velocity on WBGT, which is an essential factor in enhancing the thermal environment, ventilation was varied from 0.3 m/s to 1.8 m/s (ASHRAE 55). Following the initial calculation of WBGT using equation (1), the results were post-processed and compared with the standards specified in ISO 7243.

5. ISO 7243 specifies reference values for the WBGT index based on different metabolic rates of occupants, ranging from resting metabolic rates to metabolic rates of 130 to 200 W/m^2. These reference values provide a benchmark against which calculated values can be compared to determine whether the heat stress levels are within safe limits.

6. For an acclimatized worker, the WBGT reference values range from 33°C for resting metabolic rates to 28°C for metabolic rates of 130 to 200 W/m^2, according to ISO 7243. This means that if the calculated WBGT index exceeds 33°C for a resting occupant, it indicates a need for corrective action to address the heat stress levels. Similarly, if the calculated WBGT index exceeds 28°C for occupants with higher metabolic rates, it indicates a need for intervention to prevent heat-related illnesses.

3. Results

Equation (1) was used to conduct preliminary WBGT calculations to examine the annual variation of heat stress for the aforementioned building envelopes. The calculations were performed with and without ventilation, using weekly adaptive thermal comfort limits derived from IMAC-R.

3.1. Outcome

1. The indoor air temperature of the unit ranged from 30°C to 35°C for more than 50% of the summer and ranged from 35°C to 41°C for approximately 130 hours. The mean radiant temperature was higher than the indoor air temperature by 0.9°C. The relative humidity was between 50% and 70% for approximately 90% of the summer, for the RCC Envelope (U value of 3.59 W/m²K). During the winter months, morning temperatures can surpass 28°C because of the substantial thermal mass and its capacity to retain heat and thus even with air velocities, occupants may feel heat stress at higher metabolic rates. (130 W/m2 to 200 W/m²), but shall be comfortable up to 130 W/m²

2. The indoor air temperature of the unit ranged from 28°C to 32°C for more than 50% of the summer and ranged from 33°C to 39°C for approximately 200 h. The mean radiant temperature was higher than the indoor air temperature by 1.3°C. The relative humidity was between 20% and 80% for approximately 90% of the summer, for the Brick Envelope. (U value of 2.41W/m²K)

3. The indoor air temperature of the unit ranged from 24°C to 30°C for more than 50% of the summer and ranged from 30°C to 37°C for approximately 165 h. The mean radiant temperature was higher than the indoor air temperature by 0.6°C. The relative humidity was between 30% and 90% for approximately 90% of the summer, for the EPS Core Envelope. (U value of 0.5W/m²K)

4. Buildings with the EPS building envelope have fewer discomfort hours (up to 3,200 hours) compared to those constructed with brick or RCC. This is because the thermal insulation properties of EPS can help to maintain a stable indoor temperature. Brick, on the other hand, has a higher thermal mass compared to EPS. It can absorb and store heat, which can lead to higher temperatures inside the building during the day. However, brick buildings can also have fewer discomfort hours (up to about 3,600) compared to RCC. This is because the thermal mass of brick can help to regulate temperature fluctuations and reduce the need for air conditioning. RCC has a higher thermal conductivity compared to EPS and brick, which means that it can transfer heat more easily between the inside and outside of the building. RCC buildings may have more discomfort hours (up to 5,000) compared to EPS and brick buildings, especially in hot and humid climates.

5. The indoor WBGT increased by 7.25°C with the variation in MRT from 30-35°C, suggesting MRT has a significant impact on WBGT.

6. The indoor WBGT decreased by 0.15°C or 0.27°C when the indoor air velocity ranged from 0.9 m/s to 1.8 m/s throughout the year.

7. The indoor WBGT increased by 1.8 °C or 3.1°C when the indoor air relative humidity ranged from 20% to 80% throughout the year, suggesting that the indoor air relative humidity has a very small impact on the indoor WBGT.

8. The indoor WBGT of the unit ranged from 16°C to 33°C, with an average of 28°C for RCC, 24°C for Brick, and 22°C for EPS Core Technology.

9. Overall, understanding the relationship between metabolic rates and thermal comfort is important in assessing and managing the thermal comfort and safety of individuals in different settings. By taking into account factors such as the acclimatization of occupants, their metabolic rates, and the ambient temperature and humidity levels, it is possible to optimize working conditions and reduce the risks of heat stress and related health issues.

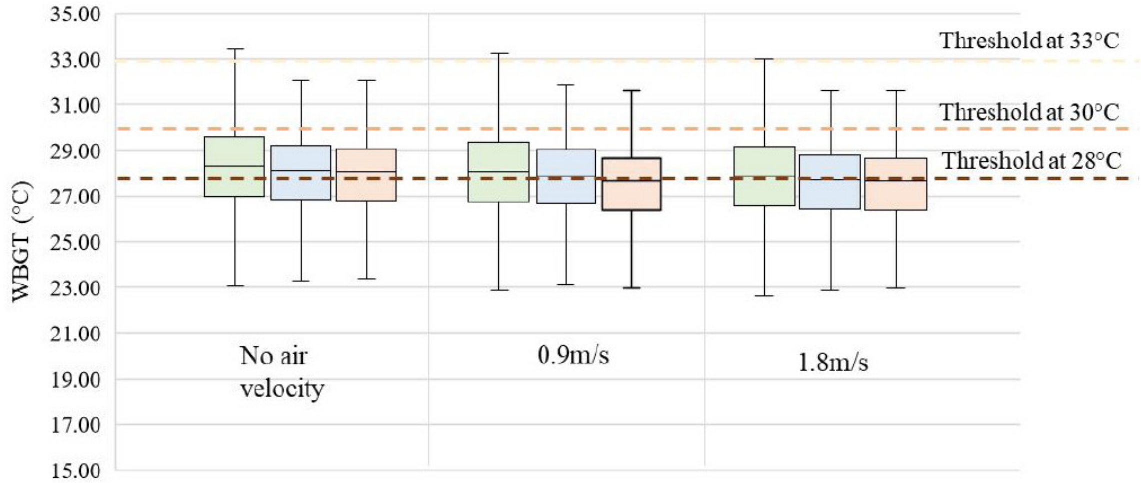


Figure 2: WBGT values for various building envelopes with changing air velocities for the summer months (March-June) (Source: Author)

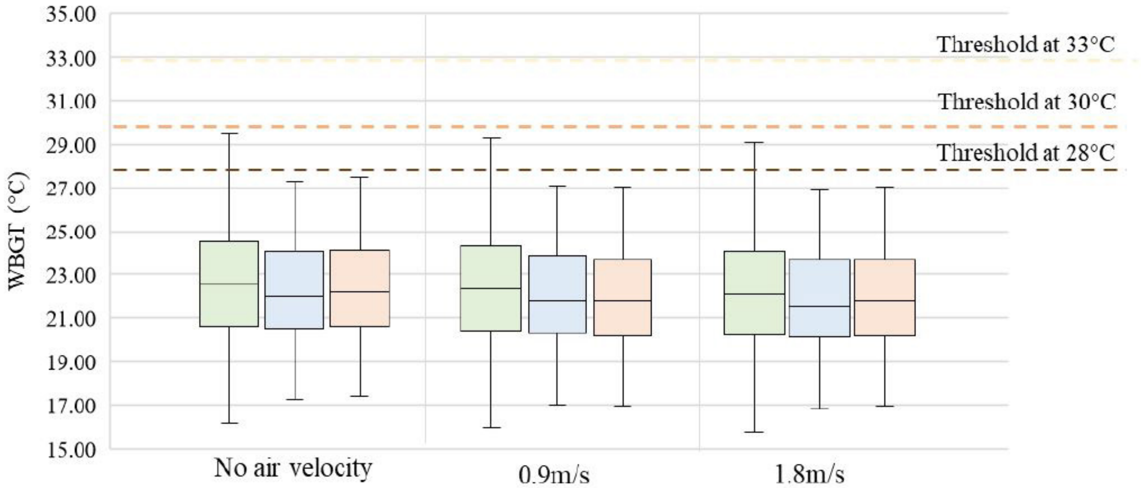


Figure 3: WBGT values for various building envelopes with changing air velocities for the winter months (November to February) (Source: Author)

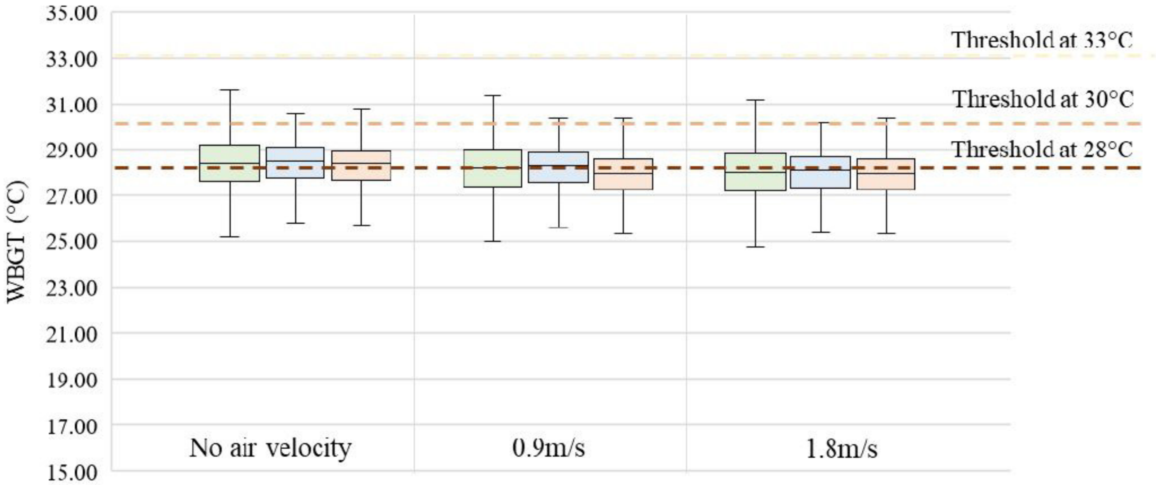


Figure 3: WBGT values for various building envelopes with changing air velocities for the winter months (November to February) (Source: Author)

4. Discussion

In this paper, the dynamic prediction of indoor WBGT in a BEE standard residential unit was investigated. A simplified indoor WBGT equation was developed based on indoor air temperature, mean radiant temperature, air velocity, and relative humidity. The main observations can be summarized as follows:

Table 1: Table showcases the range of operative temperatures and heat stress (WBGT) for various months throughout the year (Source: Author)

		RCC	Brick	EPS Core Tech.
Summer (March to June)	Operative temperature	23°C to 38°C	24°C to 31°C	24°C to 34°C
	WBGT	22°C to 33°C	21°C to 29°C	21°C to 29°C
Monsoon (July to October)	Operative temperature	25°C to 38°C	26°C to 33°C	26°C to 33°C
	WBGT	26°C to 32°C	26°C to 30°C	26°C to 31°C
Winter (November to February)	Operative temperature	19°C to 38°C	21°C to 27°C	21°C to 33°C
	WBGT	16°C to 29°C	16°C to 23°C	16°C to 27°C

1. The study presents a comprehensive analysis of indoor conditions under different building envelopes. It is observed that buildings with EPS core technology exhibit the most stable indoor temperature profile, with a range of 24°C to 30°C for over 50% of the summer. This can be attributed to the exceptional thermal insulation properties of EPS, which aid in maintaining a consistent indoor temperature. In contrast, RCC buildings experience higher temperature fluctuations, ranging from 30°C to 35°C, and even up to 41°C for approximately 130 hours. This is due to the higher thermal conductivity of RCC, allowing for easier heat transfer between the interior and exterior.

2. The study reveals that buildings with EPS envelopes demonstrate the fewest discomfort hours, totalling up to 3,200 hours. This finding aligns with the superior thermal insulation capabilities of EPS. Brick buildings, with their higher thermal mass, also show relatively fewer discomfort hours, approximately 3,600. RCC buildings, on the other hand, exhibit the highest number of discomfort hours, potentially reaching up to 5,000. This is primarily attributed to RCC's higher thermal conductivity and lower thermal mass compared to brick.

3. The research emphasizes the significant influence of Mean Radiant Temperature (MRT) on Wet Bulb Globe Temperature (WBGT). The observed increase of 7.25°C in WBGT with a variation in MRT from 30-35°C underscores the importance of MRT in assessing thermal comfort. This highlights the need for strategies that effectively manage MRT, such as utilizing materials and design elements that mitigate radiant heat exchange.

4. The study also examines the impact of indoor air velocity on WBGT. It is found that a range of 0.9 m/s to 1.8 m/s results in a decrease of 0.15°C to 0.27°C in WBGT. This suggests that optimizing airflow within indoor spaces can contribute to improved thermal comfort. Implementing strategies like natural ventilation or mechanical systems can aid in achieving and maintaining optimal air velocities.

5. The research explores the influence of indoor air relative humidity on WBGT. It is observed that a range from 20% to 80% has a relatively small impact, resulting in an increase of 1.8°C to 3.1°C in WBGT. While this effect is comparatively modest, it underscores the importance of considering humidity levels in conjunction with other environmental factors for comprehensive thermal comfort assessments.

6. The findings of this study have significant implications for occupational health and safety. Understanding the interplay between metabolic rates, environmental conditions, and building envelope characteristics is crucial for optimizing working conditions and mitigating the risks of heat-related health issues. This knowledge can inform design and operational strategies to create environments that promote occupant well-being.

7. Focusing on Bhubaneshwar as a representative city for Indian climate, this study's data holds extrapolative value for diverse urban settings. The simplification of analysing the entire unit as one zone aids in understanding the interplay between building envelope and indoor conditions. Overall, the research offers insights that reach beyond comfort, encompassing health and safety considerations and emphasizing the potential for designing environments that prioritize occupant well-being, notably through ventilation and enhanced air velocity for improved thermal comfort.

5. Conclusion

1. The calculation of WBGT provides valuable information on the heat stress imposed on the body, while discomfort hours give an indication of the degree of discomfort and potential health risks associated with the thermal environment.

2. Both concepts are crucial in assessing and managing the thermal comfort and safety of individuals in various settings. WBGT takes into account factors such as air temperature, humidity, and air velocity, and can help determine the risk of heat stress and related health issues. Discomfort hours, on the other hand, provide an estimate of the number of hours during which occupants may experience discomfort due to the thermal conditions in a given space. By considering both WBGT and discomfort hours, it is possible to optimize working conditions and reduce the risks of heat stress and related health issues.

3. Both the indoor air temperature and mean radiant temperature greatly impact the WBGT, and the indoor air velocity and relative humidity have a very small influence on the WBGT.

4. In warm and humid climate types, people tend to acclimatize to higher temperatures, which can affect their heat tolerance and comfort levels. As a result, the number of hours under heat stress may be relatively low even at high temperatures. However, when the metabolic rate of an occupant increases, the threshold temperature for heat stress decreases, and the person begins to feel uncomfortable even at lower temperatures.

5. In some cases, an occupant might feel uncomfortable according to the IMAC-R criteria at a certain operative temperature, but may not be experiencing heat stress due to their lower metabolic rates. This highlights the importance of considering the metabolic rate of occupants when evaluating the thermal comfort and heat stress risks of individuals in various environments.

6. Ventilation plays a crucial role in reducing heat stress. During warm and humid weather conditions, the body relies heavily on sweating to maintain a stable core temperature. When the air is stagnant and the humidity is high, sweat evaporation is reduced, and the body is unable to cool itself effectively, which can lead to heat stress.

7. Ventilation helps to reduce heat stress by increasing air movement and promoting the evaporation of sweat from the skin. This is particularly important in indoor spaces, where air conditioning may not be available or affordable. By introducing fresh air into the space and removing stale air, ventilation helps to maintain a comfortable and healthy environment for occupants.

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10. ECO Niwas replicable design

11.ECO Niwas Samhita 2018, pp. 6-50

Designing dwellings to cope with extreme heat in low-income communities

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1. Abstract

Designing effective passive cooling interventions for dwellings in low-income communities exposed to tropical climates is vital to ensure occupant health and comfort in a warming climate. More knowledge is needed, however, on which interventions would be culturally acceptable, affordable, and effective in reducing high indoor temperatures. Four experimental buildings were built in Ghana to evaluate such interventions. Their initial design was based on a typical home for low-income urban residents in northern Ghana. A multi-disciplinary team contributed to the design and the proposed cooling interventions. Using dynamic thermal simulation, engineers predicted indoor temperatures for different construction materials, shading, and ventilation strategies. Social scientists provided input on the cultural acceptability of the proposed designs. The study showed how simple interventions can achieve worthwhile reductions in indoor temperature. In future work, the dynamic thermal models will be calibrated using data collected inside the real experimental buildings.

Keywords - Extreme heat, overheating, tropical climate, thermal comfort, passive cooling.

2. Introduction

Extreme heat affects the health and wellbeing of millions of people worldwide (Zhao et al., 2021). High indoor temperatures that pose risks to human health have been recorded in informal settlements in the tropics (Wilby et al., 2021). Such communities in the tropical Global South are at particular risk because they are often overcrowded, have poor quality housing, a lack of cooling infrastructure, intermittent water and energy services, and high exposure to urban heat islands (Højgaard Borg et al., 2021; Kayaga et al., 2020; Matthews et al. 2019; Olotuah & Bobadoye, 2009; Scovronick et al., 2015; Wilby, 2007). The design of dwellings and cooling interventions to reduce indoor temperatures is, therefore, of vital importance. A proven cooling solution is air-conditioning. This technology is, however, costly to install, maintain, and operate. Furthermore, unreliable electricity supplies for 3.5 billion people globally means that reliance on air-conditioning for cooling puts people at risk when electricity supplies fail (Ayaburi et al., 2020; Darko et al., 2018). Therefore, passive cooling solutions, which require zero operational energy, and limited or no involvement of the occupants, should be implemented in the first instance.

The way new buildings are designed and the materials they are constructed from influences the indoor temperature. Similarly, retrofits to existing buildings also affect the indoor temperature. Wilby et al. (2021) have shown that roof type and the presence of ceiling insulation directly influence indoor temperature. High thermal mass walls have been shown to reduce peak daytime indoor temperature, although at the expense of higher nighttime temperatures (Amos-Abanyie et al., 2013; Hema et al., 2021; Roberts et al., 2023a; Wilby et al., 2021).

This study sought to develop passive, affordable, culturally acceptable, and locally available means of cooling dwellings and workplaces in Ghana. The work was organised in three phases: (1) dynamic thermal modelling of a common archetype building to allow for multiple cooling interventions to be rapidly and cost-effectively trialled in isolation and in combination; (2) construction of four experimental buildings with measurement of the indoor environment under different cooling retrofit strategies (Figure 1); (3) calibration of dynamic thermal models using measured data for prediction of indoor temperatures under climate change. This paper is a report of Phase 1 and the impact of alternative dwelling and intervention designs on indoor temperatures. This phase included] discussions with local communities to determine whether the proposed interventions would be culturally acceptable and affordable.

Figure 1: The four experimental buildings (test cells) in Tamale, Ghana. The nearest building has a ridge ventilator.

3. Methods

Indoor temperatures were simulated using the dynamic thermal modelling program EnergyPlus via the DesignBuilder graphical user interface. Dynamic thermal models allow for rapid and cost-effective exploration of the effect on indoor temperature when making multiple types and combinations of changes to the design of a new building prior to construction. They can also be used to evaluate retrofit design in existing buildings at an early stage of the process. This reduces the risk of implementing an ineffective retrofit design or construction of a new building which could otherwise harm occupant health and wellbeing. Dynamic thermal modelling also allows for direct comparison between different interventions under identical weather conditions and so the relative effect of each intervention on indoor temperatures can be assessed. A cautionary note to the use of dynamic thermal models is that they do not perfectly represent reality and the results may not be replicable if a different modeller attempts to model the same building due to various, necessary, assumptions and simplifications made during the model building process (Roberts et al., 2019). Models are therefore useful for investigating a large range of options at design stage and their relative effectiveness, but unless validated0F with measured temperatures, should not be relied upon to make accurate predictions of absolute temperature.

3.1 The base case model

The initial base case model design represented a typical urban dwelling in Tamale, Ghana and was given the code [R0]. This location was chosen as it was to be the site of the construction of the real experimental buildings. The base case model geometry was informed by a survey of 47 dwellings in Ghana to derive the mean average floor area and ceiling height (Wilby et al., 2021). The base case model1F had a single storey, with a mono-pitch flat steel

sheet metal roof, concrete block walls, concrete floor (Table 1), no windows, and no heat gains from occupants or appliances. The exterior east-west wall was 4 m in length and the exterior north-south wall was 3 m (i.e., the longest façades faced south/north). Accounting for wall thickness, the floor area was 10.6 m2. The wall height was 3.5 m with no overhang. There were no internal partitions. The infiltration rate was set to 1 ach as there is a lack of relevant measured data. It can be assumed, however, that temperature-driven air changes will be relatively low given that the indoor-outdoor temperature differential in Tamale is generally less than circa 10°C (Wilby et al., 2021) and it has been shown that under these conditions infiltration rates can be low (Roberts et al., 2023b).

Table 1: Base case model components

Component	Type	Material	Thickness (mm)	Conductivity (W/mK)	Specific heat capacity (J/kgK)	Density (kg/m^3)
Roof	Flat	Sheet metal	7	45	480	7800
Floor	Slab on grade	Cast concrete; screed	100; 70	1.13; 0.41	1000; 840	2000; 1200
Wall	Block	Concrete block (medium)	150	0.51	1000	1400

3.2 Weather data

Typical Meteorological Year (TMY) weather data for Tamale were sourced from "Climate.OneBuilding.Org" (Lawrie & Crawley, 2022). This comprised hourly data that covered a full year which allowed for annual simulations of indoor temperature. This was chosen over other sources which did not contain data for ground temperature.

3.3 Interventions

Forty-nine (49) different model variants were created using the base case model. Each were given a code, e.g., [R1], [R2], etc. Changes were made to the wall material, wall thickness, roof material, roof pitch, roof type (monopitch vs. dual-pitch), roof reflectivity, roof overhang, infiltration rate, ventilation schedule, ceiling height, ceiling type (and presence), ceiling material properties, roof ventilation rate, and roof structure. The 49 model variants comprised a single change to the base case model or a combination of changes. Most commonly one intervention at a time was tested, e.g., changing the wall thickness. However, sometimes this was combined with another intervention, e.g., changing wall material type and material thickness, which still allowed the effect of other individual interventions to be studied.

3.4 Data analysis

Comparison of the zone average hourly temperatures produced by the simulations for dry bulb, radiant, and operative temperature revealed negligible differences, and so only dry bulb temperature data were analysed (hereafter referred to as, simply, "temperature"). Temperature against time plots are presented for the day with the highest maximum outdoor temperature. Mean (Tm) and maximum (Tx) indoor temperatures were compared for each of the 49 model variants using the base case model as the benchmark. Thus, the potential cooling efficacy of each intervention was assessed relative to the base case comparator.

4. Results

4.1 Absolute temperatures and heat stress

The annual simulations of indoor temperature in the base case model [R0] predicted a mean indoor temperature of 30.4°C and a maximum temperature of 44.0°C. Some, but not all, model variants reduced the mean and/or maximum indoor temperature compared to the base case model (Figure 1 – where a negative number indicates cooler than the base case model and a positive number warmer than the base case model).

Amongst all the models, the highest annual mean temperature was recorded in a dwelling with sandcrete walls [R5] and was 31.0°C. The highest annual maximum temperature was recorded in a dwelling with wooden walls [R6] and was 52.4°C. The most effective intervention for cooling was a ventilated (open) roof with an insulated ceiling [R61] (Figure 51), which reduced the annual mean temperature to 28.3°C and the maximum temperature to 36.5°C. At the point in time when the predicted indoor temperature was 36.5°C, the outdoor relative humidity was 25%. Assuming the indoor relative humidity is also 25%, the wet bulb temperature would be 21.9°C, which falls below the threshold that threatens human survival (which is around 35.0°C (Lu and Romps, 2023)). This compares to a maximum wet bulb temperature of 28.6°C in the base case model [R0], which is 20% higher than in [R61], yet still below the lethal threshold.

4.2 Comparing model variants to the base case model

Walls constructed from a lower thermal mass material and at 10% of the thickness of the base case wall2F (wood [R6]) had a higher mean and maximum temperature than one with high thermal mass (concrete [R0]) (Figure 1 and Figure 3). The mean temperature, however, was very similar with the wooden and concrete wall because although the daytime temperature was higher in the wooden wall dwelling, the nighttime temperature was lower as the lower heat capacity of the 15 mm wooden walls [R6] allowed for more rapid cooling as the outdoor temperature fell at night (by up to 4.8°C cooler than the base case model).

Roofs made of straw thatch [R13] were effective at reducing mean and maximum temperatures compared to metal [R0] (Figure 1 and Figure 4), but these are increasingly being replaced with sheet metal roofs in Ghana. Insulated roof panels, e.g., polyisocyanate foam adhered to corrugated steel ([R15]: 0.05 m of foam and [R16]: 0.1 m foam) similarly reduced both mean and maximum indoor temperatures respectively ([R15], -1.7 and -7.1°C and [R16], -1.8 and -7.2°C). Alongside being lower, the time of the maximum (peak) temperature was shifted to later in the day with the other roofs tested, compared to metal (Figure 4). Roofs that are lighter in colour may absorb less solar radiation (providing they are clean and well maintained). Changing the roof solar absorption at increments of 0.2 between 0.0 and 1.0 [R30-R35] showed that the mean temperature could range from 2°C less than the base case model (solar absorption 0.0, [R30]) to 0.1°C higher (the base case solar absorption being 0.6 on a flat roof). Similarly, the maximum temperature difference ranged from -4.3°C to 0.6°C from the lowest to highest solar absorption – a 4.9°C range (Figure 2).

Alongside the roof, ceiling presence and material properties were also influential. Installing a plywood ceiling with a thermal conductivity ranging from 1 W/mK [R52] to 0.001 W/mK [R55], reduced the maximum temperature by between 1 and 4°C, with the lowest conductivity ceiling [R55] yielding the greatest reduction. Overall, the most effective intervention of all those investigated to reduce maximum temperature (excluding the unrealistic measures of total solar shading [R22] and no solar radiation [R36]) was ventilating the roof structure with a 2.5 m overhang above an insulated ceiling [R61]. This reduced the maximum indoor temperature by 7.5°C compared to the base case model [R0], and mean indoor temperature by 1.8°C.

To investigate the theoretical limit for the possible effectiveness of shading, one model variant was constructed with an adiabatic material suspended above the building which blocked all solar radiation falling on the building and immediate surrounding area. This endeavour yielded a maximum indoor temperature reduction of 8.4°C [R22]. Removing solar radiation from the weather file reduced the maximum indoor temperature by 10.4°C [R36] – these are the upper bound temperature reductions in maximum temperature. Set against the theoretical limit of temperature reduction in model variants [R22] and [R36], the mean and maximum temperature reductions achieved by a ventilated (open) roof structure and insulated ceiling [R61] are worthy of further investigation in the real experimental buildings.

Figure 2: Comparing maximum (Tx) and mean (Tm) temperature difference relative to the base case model.

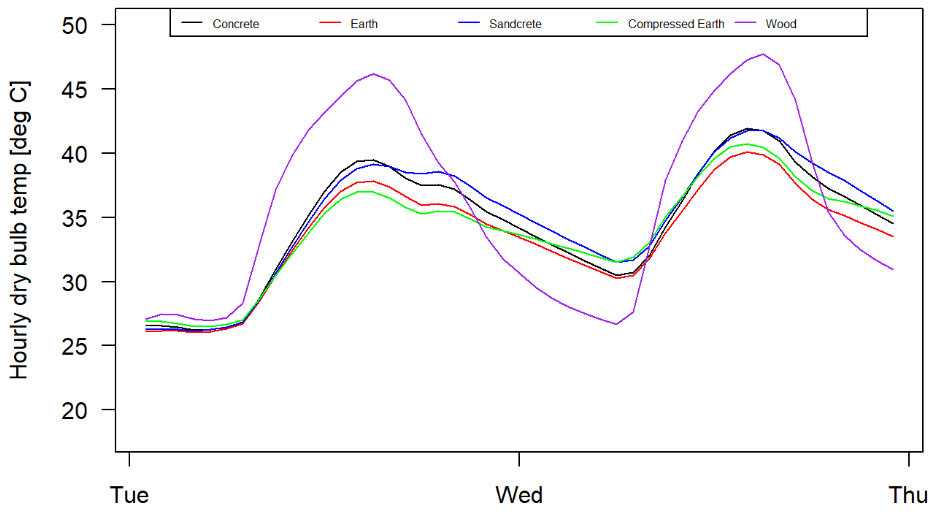

Figure 3: Diurnal indoor dry bulb temperature for model variants with different wall types on the day with the highest maximum outdoor temperature.

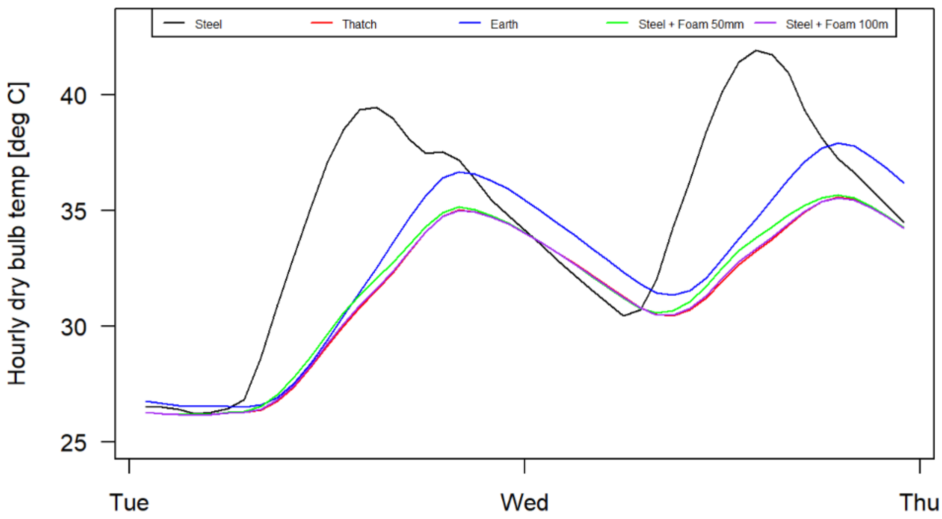

Figure 4: Diurnal indoor dry bulb temperature for model variants with different roof types on the day with the highest maximum outdoor temperature.

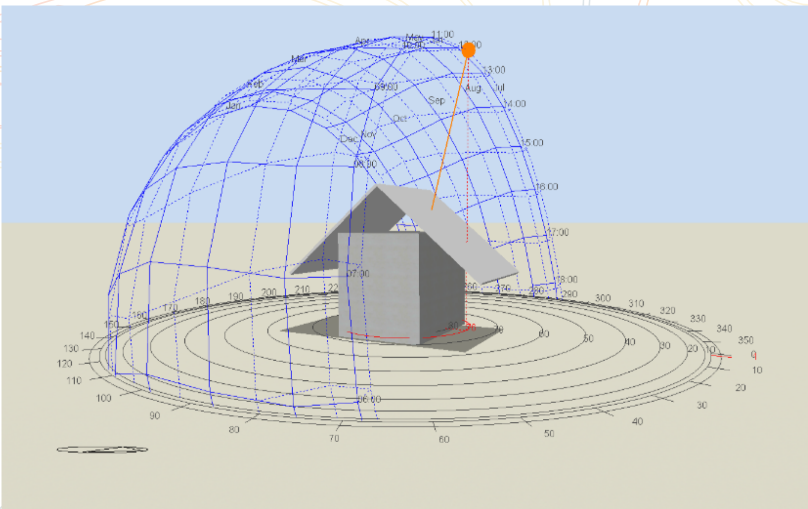

Figure 5: Variant R61 with a ventilated (open) roof structure with a large (2.5 m) overhang and an insulated ceiling.

5. Discussion

Dynamic thermal modelling of an archetype dwelling found in Tamale, Ghana revealed that to reduce the maximum indoor temperature – i.e., protect the building occupants from the most severe occurrence of extreme heat – the most effective passive cooling intervention was constructing a ventilated (open) roof structure with a large overhang, combined with an insulated ceiling below (annual maximum temperature 7.5°C lower). Walls of low thermal mass, e.g., wood, increased the maximum temperature by 8.5°C, but these dwellings are cooler at night (by up to 4.8°C compared to the base case model with concrete walls). A simple recommendation to reduce peak temperatures is to avoid a dwelling of low thermal mass construction. For a dwelling that is occupied only at night, however, dwellings with less thermal mass may cool more rapidly at night when the outdoor temperature decreases and so may be preferential. These findings are in general agreement with empirical studies (Hema et al., 2021; Roberts et al., 2023a; Wilby et al., 2021) and give confidence in the model results. In contrast with other research (e.g., Ali-Obaidi et al., 2014), decreasing the solar absorptance of the roof material was effective, but by no means the most effective cooling intervention. Overhangs to shade the walls, for example, were a more effective cooling intervention and these might be easier to maintain than light coloured roofs which require frequent cleaning and/or re-painting.

The fact that a passive cooling intervention based on ventilation3F was the single most effective option for reducing indoor temperature is important. Previous studies in the tropics have focused on the properties of building construction materials (Hashemi, 2017; Hema et al., 2021; Roberts et al., 2023a), whereas this research brings a renewed focus on the importance of ventilation for cooling. Incorporating higher rates of natural ventilation into dwellings in informal settlements might be one of the cheapest and simplest interventions to retrofit. For instance, opening roof spaces involves the removal of materials and will only require small amounts of mosquito mesh to be purchased and affixed. A ventilation intervention may, therefore, be more likely to be implemented in the communities. Although, there remains the issue of dust ingress which is a concern to those living in these communities and may be exacerbated by greater ventilation rates. Innovative ventilation solutions which reduce mosquito and dust ingress, whilst providing security from burglar entry must be sought.

Contrast ventilation with another effective cooling method: installing insulated roof panels [R15 and R16]. Foam adhered to corrugated steel may not be a locally available or affordable intervention. The longevity of foams exposed to extreme heat is also a concern as is their resistance to fire. Nonetheless, cost permitting, this may be more acceptable than thatched roofs [R13] which, whilst comparable to foam insulation in terms of the ability to reduce indoor temperature, is increasingly difficult to source in northern Ghana. Thatch is also disliked due to the risk of fire and harbouring insects and reptiles, and is viewed as being old-fashioned (Gough et al. 2019).
At present, the dynamic thermal model simulations described herein are unvalidated. This is a key limitation of the work and means that the predictions of indoor temperature should be taken with caution given the uncertainty present with dynamic thermal models and their operators (Judkoff et al., 2008; Roberts et al., 2019). To overcome this limitation, four experimental buildings have been constructed in Tamale, Ghana (Figure 1). Their design and choice of passive cooling interventions were informed by the simulations presented here. Future work will measure the indoor environment and use these data to validate the above dynamic thermal modelling results.
A second limitation of this work is the focus on dry bulb temperature which neglects air movement and relative humidity – both of which are important modifiers of thermal comfort. Future instrumentation and measurement in the experimental buildings should consider these factors alongside subjective human thermal comfort preferences.

6. Conclusion

The effectiveness of passive cooling interventions to reduce indoor temperatures were investigated using dynamic thermal modelling of a typical dwelling located in Tamale, Ghana. The key findings are:

1. A ventilated (open) roof structure with large overhang above an insulated ceiling [R61] was the most effective realistic intervention for cooling the dwellings when considering both mean and maximum temperature reduction. The mean and maximum temperatures were reduced by 1.8°C and 7.5°C respectively relative to the base case model [R0].

2. A thin (0.015 m) wooden wall [R6] resulted in the greatest increase in maximum (peak) temperature by 8.5°C compared to the 0.15 m medium density concrete block used in the base case model. But lower nighttime temperatures in rooms with less thermal mass make these suitable places to occupy at night. E.g., [R6] was up to 4.8°C cooler than [R0].

3. Reducing roof solar absorptance was effective at reducing indoor temperatures ([R30] Tx 4.3°C cooler than R0), but other interventions such as installing a plywood ceiling ([R53] Tx -1.8°C), earth roof ([R14] Tx -4.7°C), overhangs (even relatively short 0.2 m [R37] Tx -2.4°C), earth wall ([R3] Tx -2.2°C), thatch roof ([R13] Tx -7.2°C), insulated roof ([R16] Tx -7.2°C), and ventilated roof with overhang ([R60] Tx 6.2°C), and a ventilated roof with overhang and an insulated ceiling ([R61] Tx -7.5°C) were all more effective cooling interventions.

This work has informed the design of four experimental buildings (test cells) that were constructed in Tamale, Ghana. Future work will test cooling interventions, measure the indoor temperatures, and use these data to validate dynamic thermal models. In due course, these verified models can be used to investigate the efficacy of different interventions – whether in isolation or combination – under plausible climate change projections.

7. Acknowledgements

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The Future of Responsive Facade for Multi-Storey Residential Buildings in Tropical Climates

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1. Abstract

The design study seeks to comprehend the principles and elements of a Responsive Facade and how they affect user comfort and energy efficiency for space cooling in multi-story residential buildings in extreme hot conditions. The research is based on precedent studies, occupant behavior, and a critical analysis of challenges in existing building facades, having a tropical hot and dry city in Brazil as case study. It identifies the different factors that interfere in the internal thermal conditions and building performance to build passive strategies that will optimize facade design proposal and energy saving. As a result, a facade was proposed with ceramic being the main material to make perforated and opaque panels that function as a second layer of shade and permeable envelope that moves in response to the sun or under occupant's control. The impact on the internal conditions is seen in a reduction of 4°C of the internal resultant temperature , leading to a reduction of energy demand for space cooling of 44% .

Keywords - responsive facades, multi-storey residential building, tropical climate user comfort, energy efficiency.

2. Introduction

The facade is one of the main features of a building that promotes internal comfort and building performance, particularly in tropical regions. This has become an increasingly important feature to address as temperatures rise due to climate change. Attia, Shady (2016) describes adaptive facades as building envelopes that can adjust based on atmospheric conditions changes as hourly, daily, seasonal, or annual. The word "adaptive" means the ability to react or take advantage of outside weather conditions to fulfil productivity and, more essentially, to successfully meet the inhabitant's comfort. In addition to thermal comfort improvements, it also reduces energy consumption by lowering the demand for active systems to cope with the weather.
Therefore, the design study seeks to understand the principles and elements of a responsive façade for multi-storey residential buildings in tropical dry climates, as well as how they affect occupant thermal comfort and energy consumption. The research is based on a literature review, climate analysis and computational thermodynamic analysis using TAS software to incorporate potential passive strategies into the design concept, followed by an occupant's behaviour survey with families living in tropical climates and a façade analysis, with the city of Cuiaba, in Brazil, as the context of a typical middle-class case study building.

A great number of Brazilian cities have experienced in the last two decades a high demand for residential space, with multi-storey buildings dominating the construction market, but with little or no design attention paid to the climatic conditions, leading to inadequate treatment of the facades. The verticalization of buildings and densification of these cities are responses to the rise of land prices coupled with the cheapening of construction. The city selected for this analytical-design investigation is Cuiabá, Mato Grosso – Brazil, which is characterized as a Tropical Savanna Climate Aw (dry climate), according to Koppen classification. Temperatures can rise above 30°C all year, with temperatures reaching 35°C and greater during the drought season, which lasts from June to September. According to IPCC RCP, mean max temperatures in 2050 can reach up to 37°C if no action is taken to reduce overall ghg emissions in the country. In such climatic conditions there is a high demand for natural ventilation, shading, evaporative cooling, thermal mass and night ventilation, with air-conditioning maybe needed in the most extreme heating hours. In this context, the design study tackles the following research question: What passive strategies are required to achieve thermal comfort and energy savings in multi-story residential buildings, in a dry tropical climate, and what is the associated optimum responsive facade design guidelines?

3. Research Methods

In order to comprehend the principles required to attain comfort inside buildings, literature research and climate analysis was made to comprehend the best façade strategies for tropical climates, how the façade can impact the thermal comfort of the occupants and their energy consumption, and to highlight the challenges and potential solutions. Additionally, an analytical and thermodynamic analysis using TAS software of a base case building was also conducted as part of the background study to provide a reference for the development of the design guidelines and proposal. Prior to the design-analytical phase, a questionnaire was distributed to families in tropical climate cities in Brazil, to better understand occupant attitudes towards the use of passive and active systems and to develop a criteria to optimize active cooling operation based on realistic occupant behaviour. Second, the facade of an existing building in a tropical hot and dry climate in Brazil was analytically examined to see how a façade not designed for a tropical climate can compromise thermal comfort and energy performance.

As a result, outcomes and passive strategies for the design guidelines and proposal were established from the case study, and several façade scenarios were investigated as tested to find the best one for the climate that could promote better thermal comfort in the base-case building typology, for most of the day without the constant use of an active cooling system, thus reducing energy demand. As a final outcome, an optimized responsive façade was designed, which can be widely applied to new and existing buildings in tropical hot and dry conditions.

4. Occupants Survey

4.1 Questionnaire: Occupant's thermal preferences and behaviour towards the use of active cooling systems in Brazil

The questionnaire was made and sent online to one occupant of the family and answered by 26 middle-class families from 11 states of Brazil characterized for the high temperatures throughout the year. The survey questions were based on the paper from Ramos, Greici, et al. (2021) comprising a total of 16 questions. Based on the findings, a family profile could be developed to identify people's behaviour patterns toward the use of air conditioning and fans in hot climate regions of Brazil; most families interviewed consisted of three people, and all of them are usually at home in the evening, but 65% of the time there is only one person at home in the morning and afternoon, indicating a 24-hour occupancy.

When it comes to the ideal temperature, the average range of answers ranges from 20°C to 26°C. However, the results also showed a preference for naturally ventilated space at home, with 76.9% preferring it over air-conditioned space (23.1%). It also demonstrates a tolerance for high temperatures and a preference for passive strategies over fans and air conditioning. When asked what the maximum acceptable temperature was without the AC, the responses ranged from 26°C to 30°C. Furthermore, 38.5% of families do not use the air conditioner on a weekly basis, and when they do, it is 84.6% of the time at night. In this case, this behaviour is related to more than just human adaptive ability; it is also related to a general concern about energy consumption; 84,6% of responses stated avoiding the use of AC due to the cost. Keeping an AC on all day is expensive, making it unaffordable for middle-class families. In terms of air conditioning costs, the thermostat setting is critical for energy savings. When asked what AC setpoint they usually use, the responses range from 16°C to 22°C. According to the Brazilian Association of Refrigeration, Air-conditioning, Ventilation, and Heating (ABRAVA), the best air-conditioning setpoint for energy savings is between 22°C and 24°C. According to their research, every degree decrease in the setpoint results in a 3.5% increase in energy consumption. In terms of fan use, 65% of interviewed families say they use it daily, and 50% have at least one fan at home, compared to 15% who say they have 1 and 26% between 2 to 3 AC units. They were also asked what the maximum temperature acceptable for using only fans before introducing air conditioning; the answers ranged from 24°C to 35°C, indicating a high tolerance for heat before requiring the use of AC.

5. Analytical Studies

4.1 Case Study: Residential Tower Jardim Beira Rio, Cuiabá – Mt, Brazil.

The building chosen is the Residencial Jardim Beira Rio, located in Cuiabá – Mt, Brazil (-15.65 N/-56.1 E). The assessed flat is on the tenth floor and has two facades exposed to the outside, the main one facing north-east is exposed to the morning mid-day sun. The flat layout can provide cross ventilation between rooms and the color of internal and external finish are bright, however, the facade does not have any shading element, and the walls and windows do not have any insulating material/feature to decrease thermal conductivity.

Figure 1: Residential towers Jardim Beira Rio, Cuiabá – MT – Building external perspective, balcony and living room.

For the dynamic thermal simulation, only the living room and bedroom 01, which face northeast, were analyzed. According to the questionnaire results, most people are normally at home in the evening, but only one person is at home 65% of the time in the morning and afternoon; thus, a 24-hour occupancy was used to examine how the flat will behave in the worst-case scenario when people are working from home. In terms of energy consumption, the analysis was performed with the air conditioning thermostat set to 24°C, as recommended by the Brazilian Association of Refrigeration, Air-conditioning, Ventilation, and Heating (ABRAVA). The table below shows other inputs.

Table 1: Simulation Inputs

Constructive Materials: Ceramic block walls, single glazing windows, door facing outside (aluminum frames and glass 4mm)
WWR: Bedrooms: Between 17% to 19% and Living Room: 21%
Not air conditioning was applied on thermal comfort analysis
Windows open all day for the thermal comfort analysis
02 people per room
Bedroom Occupancy all day (24 hours)
Living Occupancy during daytime (12 hours)
The simulation was made in selected rooms on a typical day of the year with temperatures up to 35°C (mean maximum average temperature of the year), and a clear sky.

The thermal comfort simulation result graph below shows how the typical day acts during the hours without the usage of air conditioning, and how it influences the internal conditions of the flat. Peak hours of the day are between 1 and 3 p.m. when outdoor temperatures reach 35°C and the relative humidity drops to 20%. The hours with the lowest risk of overheating are early morning until 2 p.m., and late afternoon until 5 p.m., when radiation levels are lower. However, during peak hours, the temperature rises above comfortable levels.

Figure 2: Plan for thermal comfort analysis.

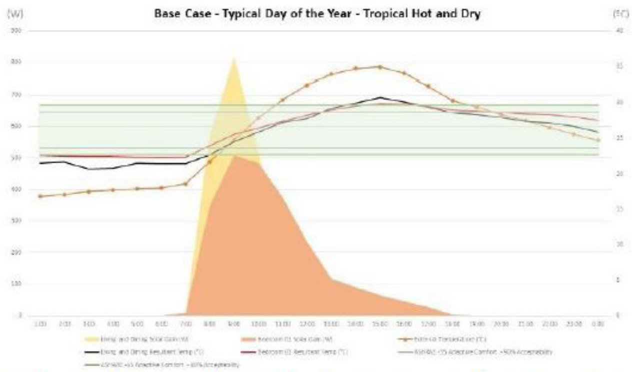

Figure 3: Thermal Simulation for the case. Chart derived from TAS

The annual cooling loads demonstrate a high energy demand, even using a reasonable thermostat setting, which can be assumed to be related to the poor envelope characteristics that doesn't provide any solar control strategy to cope the weather.

Table 2: Cooling Loads – Residencial Beira Rio

Setpoint	Annual Cooling Loads
24ºC	330,59 kWh/m²

5.1 Outcomes and Parameters for the design proposal

Based on studies results, limitations were identified that can interfere with the internal comfort inside the flat and which served as parameters to be optimized for the design proposal, for example, the absence of shading elements on the facades to control the solar gains, and the use of single glazed windows can result in an easy heat transfer between the external temperature and internal spaces. Furthermore, the external wall construction could also be improved to reduce thermal conductivity. Also, the small balcony has no adequate depth ratio to act as a shading feature on the facade and allows free solar gain into the internal space. About the apertures, the optimal Window-to-Wall Ratio (WWR) of the rooms was also lower than what has been suggested by ASHRAE-90.1-2013 to be between 0.30 and 0.45 for all sorts of climates and buildings. As a result, there is a high demand for active cooling systems like air conditioning, which, when paired with a poor envelope condition, can have a significant influence on energy usage. As a result, the strategies for a better façade design are as follows.

- External Wall

In terms of materiality, ceramic is the most used material due to its cultural significance in the Brazilian building environment and its high thermal mass properties, that decrease the time of the heat to travel through the wall to the inside space. Ceramic and concrete walls are the traditional building materials used in Brazil's tropical regions. Both materials have a high thermal mass, which is ideal for this climate because they can store heat during the day and reduce heat transfers. However, it is necessary to improve their ability to respond to climate change and perform better by employing it in more elaborate ways than just block, plaster, and finishing. A possible solution is to use insulation between the blocks, which increases the u-value and allows the wall to perform better, and for the design proposal, the following improved external walls were used for the simulation.

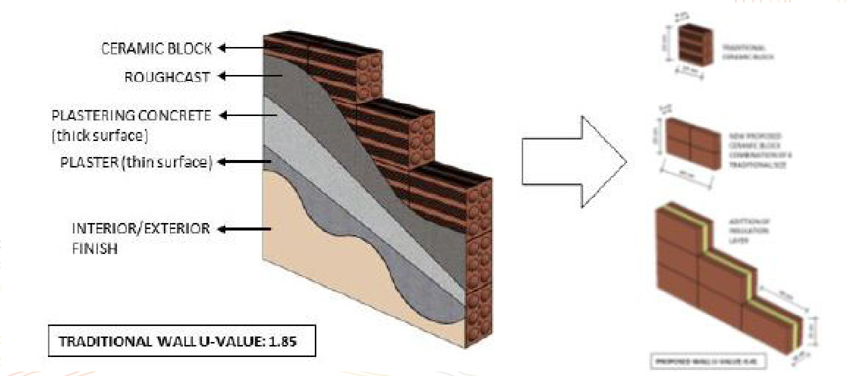

Figure 4: Ceramic block wall scheme.

As illustrated in the image, the scheme represents an arrangement of a ceramic block wall by adding an insulation layer. The U-value improves significantly from 1.85 W/m²K to 0.41 W/m²K with a 6 cm insulation of polyurethane foam layer and two ceramic blocks of 5 cm thickness each.

- Second Layer Envelope

To deal with hot, dry weather, the building's design is also essential. The shading mechanisms, which help regulate heat transfer between the internal and external temperatures, are one of the most popular facade features in those harsh climates. Therefore, the second layer envelope is proposed as a shading device, having the ceramic also used as a perforated screen panel as a reinterpretation of the "cobogó" blocks, an architectural element used as a perforated element for dividers and facades of buildings. It was introduced in Brazil in the 1920s, as a legacy of Arab culture, based on the mashrabiya (built-in wood). The reason for its introduction in Brazil was the need to create architectural solutions that allowed ventilation and lighting of the spaces, while also ensuring privacy. The cobogó has become an iconic and characteristic element of modern Brazilian architecture, being used in various architectural projects as a form of cultural expression and national identity.

Figure 5: Ceramic Panels for Shades and Double-Skin Façade. .

Moreover, ceramic can be reused and recycled. Its property can act as a heat mitigator for its dense material, a high capacity for storing heat during the day and radiate at night, and, when not highly treated, is porous enough to absorb moisture, ideal for the dry climate.

- Window Apertures

According to ASHRAE 90.1-2013, the optimal window-to-wall ratio (WWR) for all climates and buildings is between 0.30 and 0.45. A minimum of 35% of WWR was used for each room in the design studies. In terms of window aperture, the design proposal maximized the openable window aperture for improved airflow. The two sided slider pane is a common window design that obstructs 50% of the openable aperture. As previously discussed, natural ventilation can be critical to improving thermal comfort in a hot climate. Thus, for rooms where cross-ventilation is not commonly available, such as bedrooms, it is critical to provide as much airflow as possible; thus, more than the WWR, the openable value is also critical.

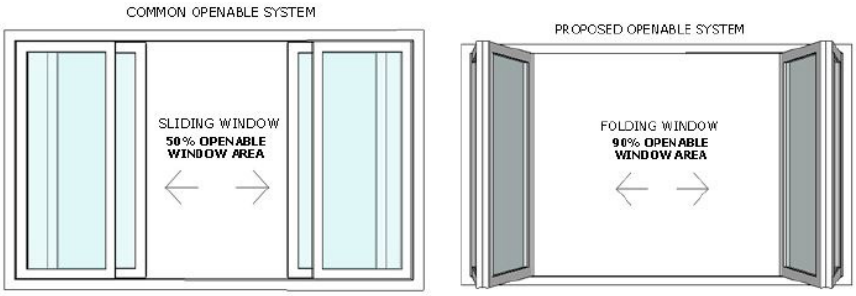

Figure 6: Openable window aperture scheme.

5.2 Façade Design and Simulation Results

Scenarios were created to simulate various levels of intervention to the facade for thermal comfort analysis. For the thermal simulations, a 2050 future weather file and the improved wall construction was used as a base case; from there, external facade features ranging from minor interventions that only used passive strategies to more complex interventions that included active systems were assessed. This way, the limits of passive strategies for maintaining indoor thermal comfort in the tropical hot and dry climate could be identified, as well as the best scenario strategy.

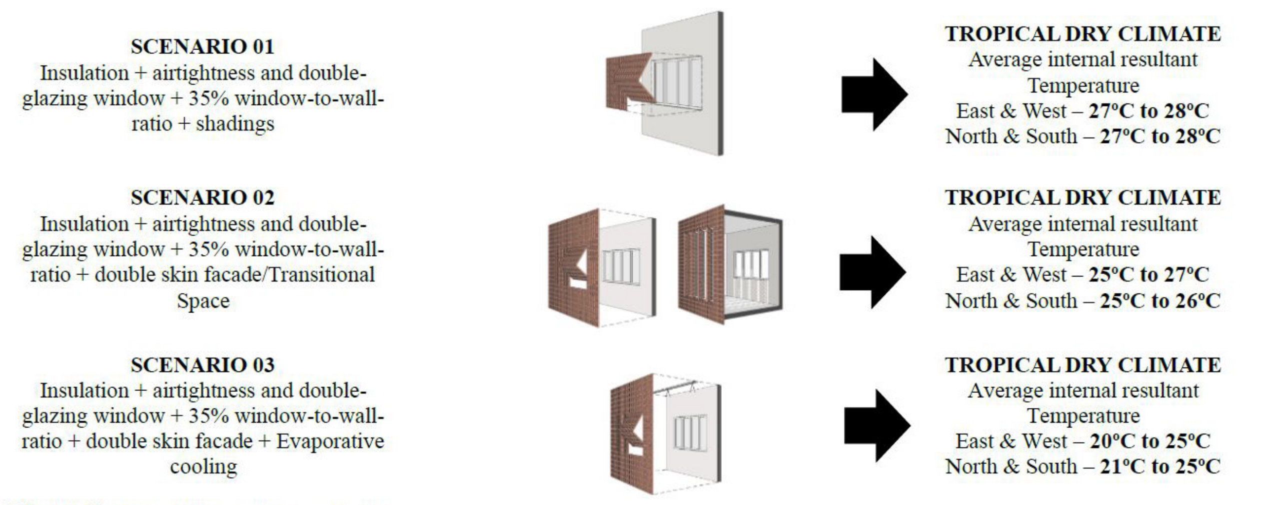

Figure 7: Facade intervention scenarios.

The double-skin façade, together with natural ventilation, reduces the internal temperature by 2°C from scenario 01 to 02, placing it into the comfort zone. In light of the dry climate and temperatures that can reach 35°C or more all year, a third scenario can be realised by installing evaporative cooling in the double-skin façade, which cools the air before it enters the flat and helps to improve air quality by providing moisture. Scenario 02, on the other hand, is the best scenario for the climate because it does not employ any active cooling equipment. When compared to the current building case study, the optimised design reduced 4°C, allowing the inside temperature to remain in the comfort zone for the most of the day.

Figure 8 also demonstrates that through envelope improvements and the implementation of passive strategies, it is possible to achieve and maintain thermal comfort for the majority of the day. This holds true even when considering future weather projections for 2050, which anticipate a rise in temperatures. Therefore, it is evident that with the appropriate measures in place, thermal comfort can be effectively managed and sustained in the face of changing climatic conditions.

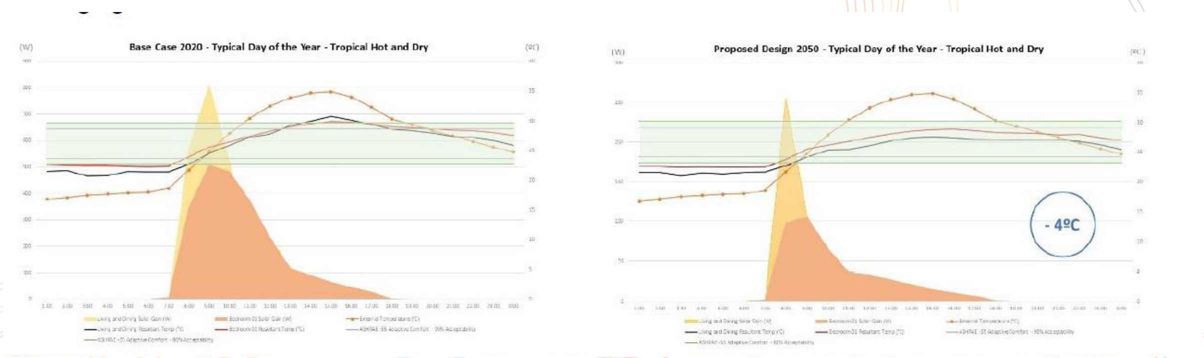

Figure 8: Thermal Simulation results comparison – left side, base case thermal result – right side, best scenario – double-skin façade, future climate projection (2050).. Residencial Jardim Beira Rio. Chart derived from TAS software.

The facade proposal is divided into three configurations, each of them includes a double-skin envelope consisting of a series of panels that are movable and perforated in front of windows and balconies and fixed and opaque when in front of walls. The proposed shadings' typology was based on the sun-path of city Cuiabá, Brazil (15°35′56″S/56°06′01″O), to optimize shading efficiency according to the orientation and can be both automated and controlled by the occupant. Based on the climate analysis and study results, the facade proposal adhered to the parameters described in the previous topic, which were deemed necessary for a better responsive facade design that can provide indoor comfort for users while also assisting in the reduction of energy consumption in daily life.

Figure 9: Design Facade Design

Horizontal shading was used on the east façade due to the high sun altitude from 51° to 77° when sun reaches 28°C.

The dynamic operation folds up and becomes a horizontal shade in front of the bedroom windows. However, shade was not required on the balcony; simply having the proper balcony depth ratio according to the sun's altitude can act as a shading device for the living room.

Vertical shades were required on the West facade due to the lower sun altitude from 1° to 4° when the temperature can get higher than 30°C. In this case, the shades in front of the bedroom windows fold horizontally, allowing for greater sun and daylight control. In contrast to the East, a proper balcony depth alone would not suffice; thus, vertical shades were also inserted in a different operating system; they can rotate on their axes and be completely moved to the sides, not obstructing the view.

During the day, the north and south facades are the most exposed to the sun. A different approach was required in this case. To control the amount of sunlight inside the flat, a combination of horizontal and vertical shades would be preferable for these orientations. As a result, a transitory space (either a corridor or a common balcony) was used to investigate the benefits of this larger space between the envelope and indoor.

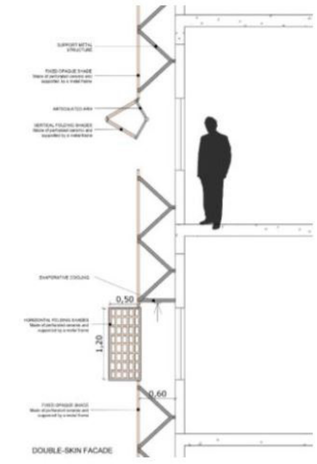

Figure 10: Double-Skin Facade section – Horizontal and vertical shade

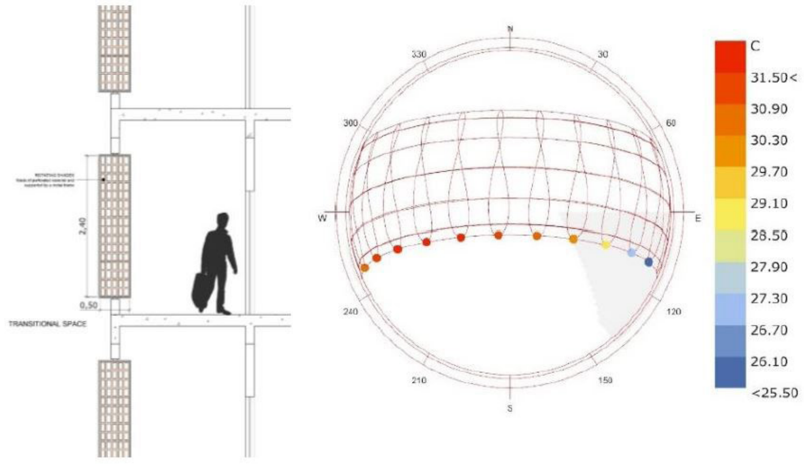

Figure 11: Sun-Path, Summer Solstice 21DEC. Cuiabá – detail and Transitional Space and rotating shade. MT.

5.2.2 Energy Performance of the proposal design

A comparison of results from the base case and the proposal facade was made to see the impact of the improvements made on the envelope. The same 24 hour occupancy was used, with a thermostat set of 24°C. The results clearly show the impact of the envelope towards energy consumption. When comparing the base case results with the proposed facade, the cooling loads reduced by 44%.

Table 3: Annual Cooling Loads for the proposal design and base case

Annual Cooling Loads – Proposal Façade Design	
North-East	184,76 kWh/m²
Annual Cooling Loads – Base Case	
North-East	330,59 kWh/m²

5.2.2 Energy Performance of the proposal design

The heat conduction of the exterior wall of both the living room and the bedroom was also investigated to demonstrate the effect of external shade and wall insulation. The graph below depicts an analysis of one external wall surface in each room, as well as a comparison of the basic case and the proposed façade design. The results show a significant reduction in conductive heat gains between the two scenarios, demonstrating the viability of the measures used to cope with the weather and offer better internal thermal comfort.

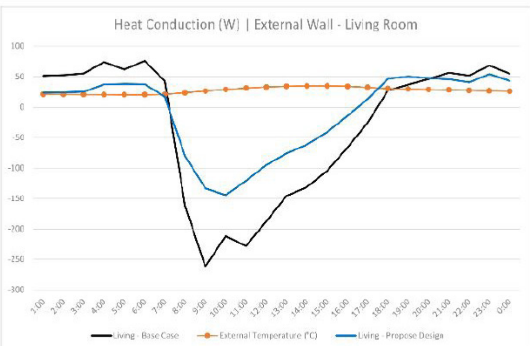

Figure 12: Heat Conduction – Living Room

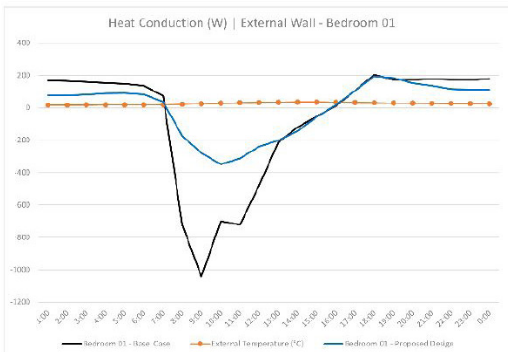

Figure 13: Heat Conduction – Bedroom 01

6. Discussion and Conclusion

As evidenced by the conducted studies, the implementation of a climate responsive building envelope plays a crucial role to improve user thermal comfort. In this research, this was achieved by reducing 4°C of the internal resultant temperature and contributing for energy savings of 44% by not demanding an extensive cooling load. The research findings underscore that the incorporation of shading elements, improvement of materiality and envelope construction, even when considering future climate projections (for 2050) is sufficient to maintain comfort with the same cooling demand. This emphasises the unquestionable importance of a well-designed envelope in achieving maximum occupants' thermal comfort. When contemplating its relevance in contemporary building construction in tropical and dry regions, the viability of this technique becomes clear.

By centering the architectural focus on creating a climate-responsive façade through passive strategies and harnessing the potential of locally available materials, such as ceramics with high thermal density, substantial improvements can be achieved. It is worth noting that these improvements can be attained without the need for drastic alterations to the original architectural layouts, but the integration of strategies that facilitate natural ventilation, such as cross ventilation, further enhances the overall effectiveness of these measures and keeping current market interests (due to no changes in the building form and plan layout).

In conclusion, the study emphasises the importance of the building envelope in improving user comfort and energy efficiency. The potential for enhanced building environments in tropical and dry climates becomes evident by proactively embracing passive design strategies and focusing on local materials. This method not only coincides with sustainability goals, but it also emphasises the balance of architectural creativity and environmental responsiveness.

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Influence of Hygroscopic Property of Lime and Cement Plaster on Building Energy Consumption for Five Climate Zones of India

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Abstract

Lime and cement are the commonly used walling materials in India. They are used as wall mortar and wall finish materials. Lime is a sustainable material with qualities such as breathability and better moisture transfer properties. Though it is a natural material, in contemporary construction practices, lime mortar or lime plaster has been replaced by cement mortar and cement plaster. To predict the impact of the moisture-buffering ability of building materials, hygrothermal simulations are carried out. It is a simulation-based study where the two numerical models of EnergyPlus are studied: Conduction Transfer Function (CTF) and Combined Heat and Moisture Transfer (HAMT). The study quantifies the annual energy consumption in a low-rise office building for five climate zones of India. Preliminary work shows that lime-plastered building has lower indoor relative humidity by 6 - 10% and the indoor conditions were 6% more comfortable. The results show that building having cement plaster is more energy consuming than lime. The moisture-buffering capacity of lime helped in reducing overall energy consumption by 12 – 23 kWh/m^2 for the five climate zones of India.

Keywords - Heat and Moisture Transfer, Lime Plaster, Cement Plaster, Energy Consumption.

1. Introduction

The building construction sector accounts for over one-third of global final energy consumption [1]. In India, 30% of the total electricity is used in space cooling [2]. The number of household air conditioners in the residential sector has increased by 50% in the last five years [3]. An increase of 10 - 45% in peak electricity load is expected by 2050 [2]. Therefore, to lower the environmental impact of buildings over their life cycle, energy efficiency has become a national and social imperative. The building envelope plays a key role in energy-efficient buildings. A well-designed building envelope responding to the external environment reduces the energy required for space conditioning. The construction materials and their hygrothermal characteristics affect both heat and moisture transfer across the building envelope. Additionally, the moisture-buffering capacity of internal finishes also affects the indoor relative humidity.

Several studies have established that the moderation of indoor humidity by interior finish materials results in energy savings. Qin et al. [4] found that potential savings in energy for heating and cooling were 4% and 7 - 30% respectively in 2009. In the case of a test building with an HVAC system to maintain indoor conditions, Zhang et al. observed a potential energy saving of 25 - 30% for temperate and semi-arid climates [5]. Few studies have emphasized designing the HVAC system based on the building envelope's moisture-buffering capacity [6]. Mendes et al. [7] predicts that ignoring the moisture effect may overestimate the conduction peak load by up to 210% and underestimate the yearly integrated heat flux by 59%. Boukhelf et al. [8] studied the hygrothermal behaviour of walls composed of eco-concrete made of glass powder to satisfy RE2020 requirements. Tran Le et al. [9] and Maalouf et al. [10] observed energy-saving potential with hemp concrete and hemp starch as interior finish, respectively. The overall impact of moisture-buffering depends on the hygroscopic property of the internal finishing material. In the long run, its contribution to the entire carbon footprint of the building would determine whether it is a sustainable material. In Germany and China, there is an increase in awareness of the need to maintain sustainable development using natural products [11]. Lime mortar or lime plaster is a natural organic material with a low carbon footprint in production and carbon absorption throughout its lifespan as a hardened material [12].

Lime plaster has been used as binding and finishing material since ancient times in India. The composition of lime deposits varies with the region due to different soil impurities [13]. There is a large variation in the preparation of lime mortar across India. Significant variation in lime plastering is also observed based on the addition of organic materials and application techniques mainly dependent on climate. Lime is a porous material that naturally absorbs ambient moisture and thus reduces dampness and pre-ageing of the building [14]. However, the decline in the use of lime was observed in the 18th century with the invention of Portland cement. Due to its ease of applicability and quick setting time, it replaced lime entirely in all aspects of the building. Cement also has low vapour permeability, which prevents the movement of penetrated water, causing the indoor environment prone to dampness. Unlike lime plaster, cement plaster is prone to cracking with varying outdoor conditions and is particularly not suitable for traditional and historic buildings.

Numerous simulations and experimentation-based studies have been reported on materials like hemp concrete, gypsum, spruce wood etc., and their moisture-buffering capacity [5,10]. However, studies of the hygrothermal behaviour of lime plaster or lime mortar have not received any attention in the literature. A lack of information on the hygroscopic properties of lime and cement plaster is also observed in the Indian context. Therefore, this research aims to bridge the gap, study the hygrothermal performance of lime and cement plaster, and quantify its impact on building energy consumption.

2. Objective

The primary objective of this work is to compare the hygrothermal performance of lime and cement plaster. The influence of both walling materials in building energy consumption for five climate zones of India is also studied.

3. Methodology

In this work, simulations are carried out with the EnergyPlus 9.4.0 version simulation tool to study the hygrothermal performance of lime and cement plaster. Preliminary simulations are carried out to re-establish the difference between an only thermal and thermal-hygrothermal model to ascertain the appropriateness of calculating the annual energy consumption in a building.

3.1. Properties of Lime and Cement Plaster

Measurements were carried out to determine hygrothermal properties of lime and cement plaster. Sorptionisotherm, vapour diffusion resistance, thermal conductivity, specific heat, and density were estimated as per the respective ASTM standards. These properties are not available for typical building materials employed in India. Table 1 shows the hygrothermal properties of lime and cement plaster determined for this research. Figure 1 shows the measured sorption-isotherm for lime and cement plaster.

Table 1: Hygrothermal properties of lime and cement plaster

Property	Lime	Cement
Thermal Conductivity (W/m-K)	0.16	1.58
Density (kg/m³)	1636	2252
Specific heat (J/kg K)	814.26	927.89
Porosity	0.276	0.164
Vapour Diffusion resistance	5.74	25.18

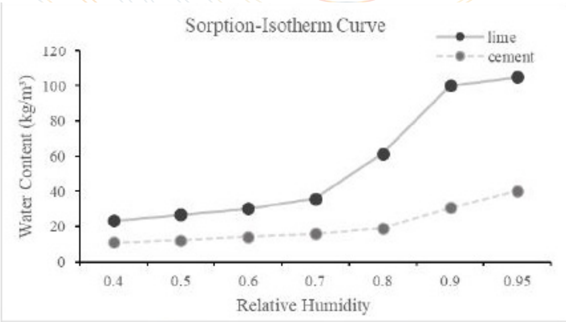

Figure 1: Sorption Isotherm Curve

3.2. Test case details for model applicability

A simulation-based study is carried out to observe the hygroscopic behaviour of lime and cement plaster. EnergyPlus has three different models for simulating heat and moisture transfer in buildings [5]. Conduction transfer function (CTF) model is the default model and provides quick results. Although it considers heat transfer of the building envelope with indoor and outdoor environments, it doesn't account for the moisture transfer across the wall surface. The indoor relative humidity is calculated by mass balance without considering the wall interactions. On the other hand, the combined heat and moisture transfer (HAMT) model considers detailed moisture interaction with the envelope. It considers the hygroscopic characteristics of the building materials, such as sorption/desorption curves, porosity, water absorption, and water vapour permeability. Qin & Yang [12] evaluated the building energy consumption for three different climate conditions to compare the accuracy of different models of EnergyPlus. They concluded that the HAMT model is the most accurate model for simulating heat and moisture transfer across the envelope. From the literature, it is understood that detailed and intensive simulation studies have been carried out worldwide. However, such hygrothermal studies are lacking in the Indian context with typical and new construction materials. One reason for fewer studies with the HAMT model is the lack of detailed hygrothermal properties. Lime and cement plaster are the commonly used finishing materials in India. Studies on moisture-buffering effects of lime and cement plaster, especially in Indian climatic zones are lacking. In this work, both CTF and HAMT models are employed to compare the performance of lime and cement plasters.

The CTF and HAMT models of EnergyPlus have been previously verified in the literature [12]. However, a primary verification of these models is carried out to check if physically realistic results are obtained in case of lime and cement plaster. The verification is carried out by simulating the BESTEST geometry [15] to avoid complex construction details and represent a test case to study the fundamental physical behaviour of lime and cement plaster. Several authors [11,16,17,18] have considered this model for hygrothermal analysis. The BESTEST geometry is 6m x 8m x 2.7m in dimension with no openings. The exterior wall assembly is of clay-brick with internal and external wall finishes such as lime plaster or cement plaster. The composition and configuration of the envelope chosen in this work are shown in Figure 2. A constant air change rate (ACH) of 0.5h-1 is maintained in the building throughout the day. The indoor condition (indoor air temperature and relative humidity) is not maintained in this case.

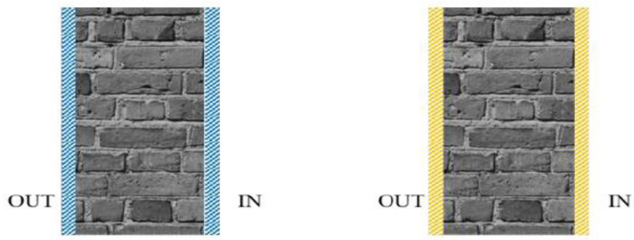

Figure 2: Typical sections of the envelope: lime plaster and cement plaster space

3.3. Test case details for parametric study

After verifying the model appropriateness, parametric studies are carried out in free-floating and air-conditioned modes to evaluate the impact of moisture-buffering on building energy consumption. The indoor air temperature range of 26 – 32°C and relative humidity range of 30 – 70% is considered for defining the comfort band. The commercial sector accounts for 8.6% of total electricity consumption in India and it is increasing rapidly due to urbanization [19]. Therefore, a test model of a low-rise commercial building model is considered for the parametric study. The low-rise office building model details and specifications are taken from the ASHRAE reference building [20]. The external envelope construction has clay-brick as masonry material but differs in the type of plaster. One case has lime plaster, while the other has cement plaster. However, this work does not consider the mortar, as EnergyPlus is incapable of modelling thermal bridging [21].

To study the indoor environment in free-floating mode, the comfort hours are compared with both the plaster materials. In the air-conditioning mode, variable refrigerant flow (VRF) with a coefficient of performance (COP) of 3.49 is used as the cooling system to maintain the indoor air temperature. An electrically heated steam humidifier with a fan is used to maintain indoor relative humidity. To observe the impact of five climate zones, five cities in India are selected based on NBC 2016. The same is:: Ahmedabad (23.02° N, 72.57° E): Hot-dry, Tiruchirappalli (10.79° N, 78.70° E): Warm-humid, Bangalore (12.97° N, 77.59° E): Temperate, Delhi (28.70° N, 77.10° E): Composite and Dehradun (30.31° N, 78.03° E): Cold [22].

4. Results

4.1. Model applicability

Annual simulations are carried out with the BESTEST case [15] as mentioned in Section 3.1. The cases considered are i) clay-brick wall with cement plaster in an only thermal model (C-CTF) ii) clay-brick wall with cement plaster in the hygrothermal model (C-HAMT) iii) clay-brick wall with lime plaster in the hygrothermal model (L-HAMT). These cases are simulated for cities in hot-dry (Ahmedabad) and warm-humid (Tiruchirappalli) climate zones. Figure 3 shows the results for these cases in the respective climate zones.

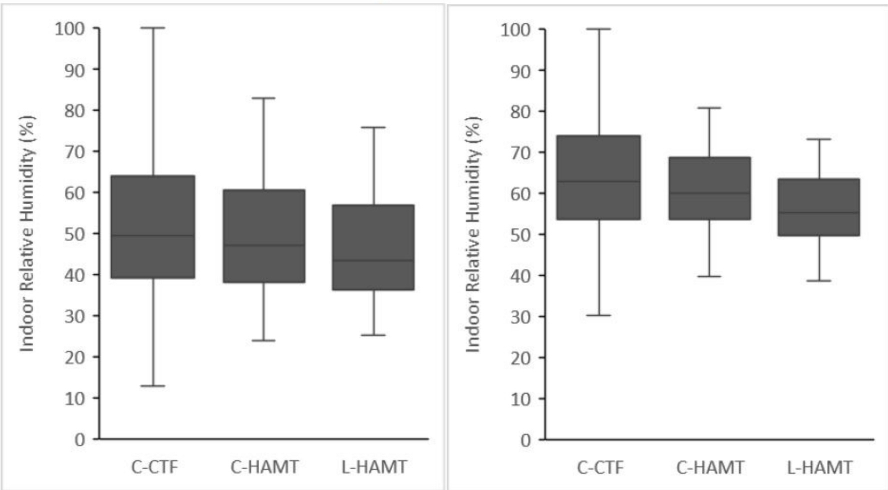

Figure 3: Indoor relative humidity comparing CTF and HAMT model (a) hot-dry (b) warm-humid

In hot-dry climate, 'C-CTF' predicts the highest indoor relative humidity of 96%. In 'C-HAMT', the highest predicted indoor relative humidity is 81%. Therefore, a reduction of 15% compared to the CTF model. While using lime plaster (L-HAMT), the maximum humidity is 78%. That is a difference of 3% more indoor humidity between cement and lime-plastered space. The difference between maximum and minimum values of indoor relative humidity for 'C-HAMT' is 10%, while 'L-HAMT' is 18% compared to 'C-CTF'. Thus, the overall range in the 'CCTF' case shows a wide distribution of data, whereas, in the other two cases (C-HAMT and L-HAMT), it is less dispersed and further reduced with lime (L-HAMT). While comparing the interquartile ranges, the difference in third and first quartile values of indoor relative humidity reduces from 25 in 'C-CTF' to 23 in 'C-HAMT' and 21 in 'L-HAMT'. In warm-humid climate, a reduction of 19% in indoor relative humidity is observed in 'C-HAMT' compared to 'C-CTF' model. Similar to hot-dry, the amplitude of lime plaster 'L-HAMT' is 7% less than cement plaster 'C-HAMT'. An absolute difference of 10% and 3% relative humidity between 'C-HAMT' and 'L-HAMT' in warm-humid and hot-dry climate. This is because, with a decrease in the vapour diffusion resistance factor of the finishing material, the moisture-buffering effect increases. Therefore, cement plaster has a high-water vapour diffusion resistance factor of

25.18 and that of lime is 5.74. The above results show that the HAMT model accounts moisture-buffering effect on the building walls compared to the CTF model. This reinforces the need for the HAMT model over CTF for evaluating the detailed analysis of energy consumption by walling systems. Also, it establishes that the moisture-buffering effect increases with the hygroscopic nature of lime plaster.

4.2. Parametric analysis

In the HAMT model, the effect of heat and moisture movement was prominently visible in the previous section. HAMT model is further applied to conduct parametric analysis. It is carried out in two modes: free-floating and air-conditioned mode. This study of heating and cooling energy demand has been carried out to ascertain the degree of influence of hygroscopic materials (lime and cement plaster) on energy demand for five climate zones of India. As mentioned in previous section 3.2, the low-rise office building has been carried forward for the parametric analysis [20].

4.2.1. Free-floating

Free-floating mode is considered with a constant air change rate and with no mechanical equipment. Air temperature and relative humidity are compared based on the aforementioned comfort band setpoints. Figure 4 shows the influence of porous and moisture-absorbing materials on annual comfort hours for warm and humid climates. A typical climate type is studied for analysing free-floating conditions in lime or cement-plastered buildings.

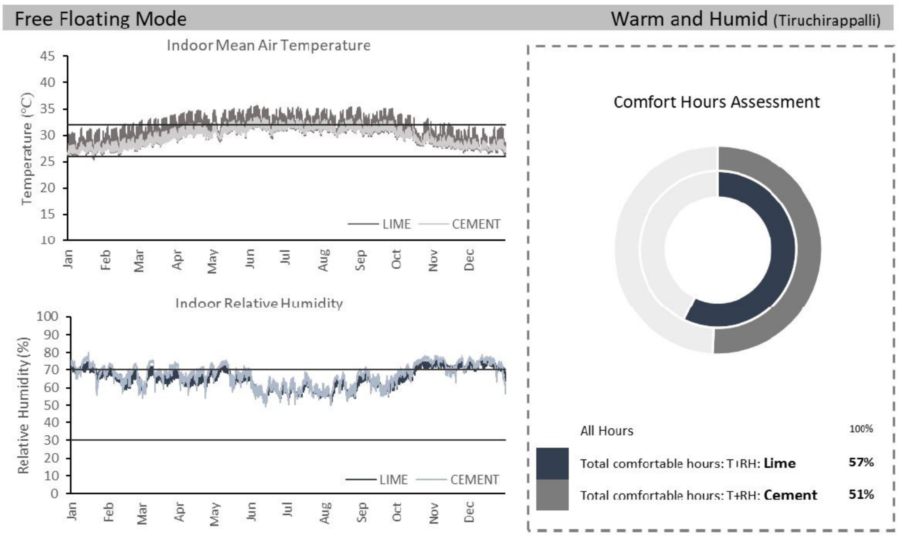

Figure 4: Free-floating Mode: Hourly analysis (L) and Comfort Assessment (R)

The summer indoor air temperature in both lime and cement-plastered spaces lies above the upper limit of the comfort band of 32°C. Whereas in winter, the temperatures lie within the comfort range for both materials. As lime-plastered space has higher peak temperatures during summer and monsoon season, cement-plastered space is 10% more hours in the comfortable range of temperature. For 73% of the hours, the lime-plastered space is in the comfortable range of indoor relative humidity of 30 – 70% while the cement-plastered space is comfortable only for 63% of the total hours (Figure 4(L)). Here with a constant air change rate and no mechanical air-conditioning system, 57% and 51% of 8760 hours are in the combined comfortable range of indoor air temperature and relative humidity for lime and cement respectively (Figure 4(R)). Overall, the hours with comfortable indoor air temperatures and relative humidity in lime are 6% higher than in cement-plastered space. The above observation confirms that lime has the potential to reduce energy requirements to make the space comfortable.

4.2.2. Air-conditioned

The impact of moisture-buffering through building walls was seen in the previous section (4.2.1.). A variation in indoor air temperature and relative humidity and the number of comfort hours was noted. This section assesses the impact of moisture transfer on annual energy consumption. The objective is to identify the magnitude of possible savings due to lime or cement plaster. The reduction in overall cooling load is shown in Figure 5 (L). With lime plaster, the reduction in cooling load is between 5% - 15% for all climate types. This is due to the lower thermal conductivity of lime plaster (0.16 W/m-K) than cement plaster (1.58 W/m-K). The reduction in overall heating load for all climates is shown in Figure 5 (R). For HD, WH, and TE climate, heating load savings are in cement-plastered space by upto 21%. Whereas, in CO and CD climates, lime-plastered space has higher heating energy savings.

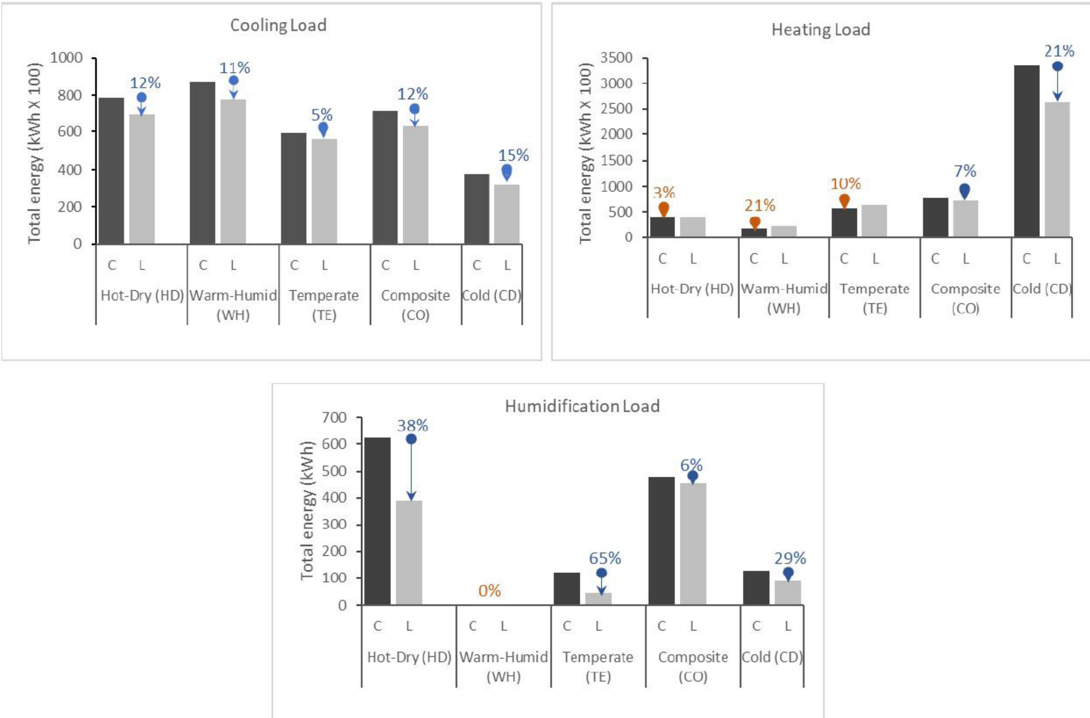

Figure 5: Comparison of energy requirement in lime and cement plaster

The humidification loads are 38% and 65% higher in cement-plastered space in HD and TE climates. Figure 5 (B) shows the reduction in humidification load in lime-plastered space to maintain indoor comfort. This is because heating and humidification loads are related to the moisture-buffering effect of the finishing material in the respective climates.

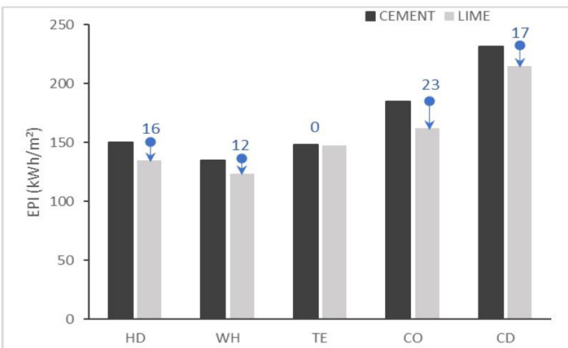

Figure 6: Energy Performance Index (EPI) reduction between cement and lime plastered buildings.

The potential for annual energy saving for the five climate zones is shown in Figure 6. An absolute difference of 12 – 23 kWh/m^2 is observed between lime and cement-plastered low-rise buildings around five climate zones of India. The maximum reduction is observed in composite, cold and hot-dry climates. Therefore, a substantial reduction in energy consumption due to lime plaster.

5. Discussion

In India, major parts of the country still rely on conventional finishing material, cement plaster. This study focuses on two plastering materials which are available in the Indian construction industry. Lime plaster was a heavily used material in the housing sector before industrialization [13]. The energy saving potential of lime plaster creates an opportunity to bring back lime to the market. This study is limited to wall finish, but the mortar is a prominent binding layer in the walling system. It is a thin layer between the bricks (usually 1-3 cm), therefore in a 1sq.ft. of wall construction almost 17 - 20% would be mortar. Due to the limitation of EnergyPlus in modelling thermal bridging, the energy consumption due to the mortar in the walling system is not considered in this study. Hence, the aspect of mortar needs to be studied to calculate its impact on energy savings due to lime plaster over cement. If there is an overall energy reduction, there would be a reduction in estimating peak load requirements in system design. Also, the conventional method of calculating the peak loads of a building is only through heat transfer calculation. The moisture-buffering phenomenon is not considered, which also contributes to the higher estimation of the peak load of an air-conditioning system. A more detailed study is required in calculating load requirements would help in reducing system sizes. Further research needs to be conducted to analyse the savings potential in annual energy consumption over ease of construction technology.

6. Conclusion

The conventional method of annual energy-used calculation is only dependent on one variable i.e., heat flux with the indoor and outdoor surface of the walling system. It does not calculate the moisture transfer with the surface of the walling system. It is observed that the CTF model, the conventional method predicts upto 15 - 26% higher absolute relative humidity than the HAMT model. This established the need to study both heat and moisture transfer for building energy assessment. Comparing the moisture-buffering factor between lime and cement-plastered space, a reduction of 6 - 10% in absolute relative humidity in lime-plastered space is observed. This is because lime plaster has a lower vapour diffusion resistance factor and higher porosity. Further, a low-rise office building with internal loads is studied for parametric analysis. In free-floating mode, the lime-plastered building shows the addition of 6% hours in annual comfort hours i.e., 536 hours out of 8760 hours. This implies that cement plaster is an energy consuming material. To quantify the energy savings for the five climate zones of India, the indoor condition is controlled with an air-conditioning system to maintain indoor air temperature and indoor relative humidity. It shows an overall energy reduction of 12 – 23 kWh/m^2 in the lime-plastered building while comparing five climate zones of India. Overall, lime as a wall finish material plays a substantial role in moderating indoor relative humidity. This helped in the reduction in energy requirement for space conditioning. The analysis proves to revive lime as a finishing and binding material for a sustainable future. It also evokes, along with focussing on ease of construction technology, a data-informed decision regarding the walling system for respective climate zones can help in making an informed decision.

7. Acknowledgements

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Learnings from the extreme thermal comfort adaptation of Jain ascetics during the summer and the monsoon months in India

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1. Abstract

Heat waves are rising in intensity and frequency. They could break the human survivability limit in India in the coming years. The goal of this paper is to understand the extreme thermal comfort adaptation of ascetics from Jain Svetambara sects in hot and dry as well as warm and humid weather in India to help the vulnerable populations beat the heat. A total of 65 subjects were interviewed in Delhi, Jodhpur, Siriyari and Ahmedabad between May and September 2023. Surveys were carried out with measurements of the indoor environment according to the adaptive thermal comfort methodology. Around 75% of the subjects had a neutral or a cooler thermal sensation while the thermal comfort index, UTCI, was in the strong to very strong heat stress range. Ninety percent of the subjects found these thermal environments to be acceptable. Two-third of the subjects preferred no change in the humid conditions when more than 50% of them acknowledged the presence of higher humidity in their indoor environment. An adaptive thermal comfort model proposed in this study suggests that it is possible to go beyond the IMAC-R model to further reduce the cooling needs of the warming world.

Keywords - adaptive thermal comfort, ascetics, UTCI, health and wellness, IMAC-R.

2. Introduction

Today, the world collectively emits over 50 billion tonnes of CO2 equivalent every year (Our World in Data, 2023). Many of the countries have pledged to bring down emissions to net zero levels by 2070 to keep the global temperature rise to less than the safe limit of 1.5 °C by the turn of this century (United Nations, 2023). Buildings are responsible for about half of the total electricity consumption in the world (International Energy Agency, 2022). Space heating and cooling accounts for nearly half of this consumption. The demand for space cooling is predicted to be more than three times by 2050 in the base case scenario due to the warming planet (International Energy Agency, 2018). While the cooling energy consumption can be brought down to a certain extent by passive solar architecture techniques and energy efficiency of cooling equipment, there is significant potential for increasing the adaptive thermal comfort range of people to reduce the need for cooling. Adaptive thermal comfort approach suggests that people in warmer climates can withstand higher indoor temperatures than the people from colder climatic zones. This approach suggests that people can undergo physiological (bodily responses to prevailing ambient thermal conditions or acclimatization), psychological (subjective preferences for a thermal sensation) and behavioural (occupant level changes such as clothing or envelope level interventions such as opening windows) thermal adaptation with their environment leading to reduced energy needs for heating and cooling (de Dear & Brager, 1997). India Model for Adaptive Comfort-Residential (IMAC-R) was developed with year long field surveys across all the Indian climates. It found 80% or more residential occupants expressing satisfaction with indoor temperature range of 16.3-35 °C for a 5.5-33 °C variation in the outdoor running mean temperature (Rawal et al., 2022). Jain ascetics have been experiencing comfort at the extreme, living without the use of any energy for hundreds of years (Muni Sheelgun Vijayji, 2023). In a study involving thermal comfort surveys of 20 Jain monks and nuns during the heatwave conditions in May 2023 with hot and dry weather in the composite climate of Delhi, 90% of the ascetics expressed acceptability of the thermal conditions with the indoor operative temperatures (Top) varying between 35 °C and 40 °C (Dhariwal & Gangrade, 2023). The work in this paper is being extended to understand their thermal comfort adaptation during the warm and humid weather conditions as well. To the best of the understanding of the authors, there is no other known work about people being able to withstand hotter temperatures beyond the adaptive thermal comfort range for the warm and humid conditions, which are increasing in intensity and lasting longer.

3. Methods

The research methodology, thermal comfort surveys and data analysis is inspired from the ASHRAE RP-884 document (de Dear & Brager, 1997). The thermal comfort right here right now surveys (Manu et al., 2016) were the basis for the surveys in this study. The responses were asked about the subjects' personal information, activity, building information, thermal sensation, air movement, humidity and overall comfort. They were also asked about their long term thermal comfort management strategies and concerns. Indoor environment measurements were recorded using sensor monitors near the occupants at the same time when the surveys were conducted. Testo 400 monitor was used with two wireless CO2 probes measuring air temperature and relative humidity, one wireless probe measuring air speed and another wired probe measuring globe temperature (Table 1). Testo 400 devices came with a calibration certificate during the purchase. They were also tested for accuracy before the experiments.

The indoor operative temperature (Top) calculations were based on ASHRAE Standard 55 methodology (ANSI/ASHRAE Standard 55-2017, 2017). The outdoor air temperature and relative humidity data was publicly available from the Central Pollution Control Board (CPCB) website (Central Pollution Control Board, 2023). The meteorological data was taken from the Air Quality Monitoring Station (AQMS) in Rohini, Delhi for the Delhi sites, AQMS in Collectorate, Jodhpur for the Jodhpur sites, AQMS in Indira Nagar, Pali for Siriyari and Kamlighat sites and Sardar Vallabhbhai Patel Stadium, Ahmedabad AQMS for the Ahmedabad sites. The air temperature data for the dates of the field survey was not available for the Pali AQMS so, this data was taken from the nearest AQMS at Jodhpur. There was a quality check for the data from the surveys and the sensors after which this data was merged to create a row of data per subject with a timestamp. ASHRAE Thermal Comfort Tool (Tartarini et al., 2020) was used to compute the PMV, PPD thermal comfort indices. The UTCI calculator was used to calculate the UTCI thermal comfort index (UTCI, 2023).

Table 1: Details of the instruments used

Device	Indoor parameters	Range	Accuracy	Resolution
Testo 400 CO_2 probes	Air Temperature (°C)	Air Temperature (°C)	±0.5 °C	0.1 °C
Testo 400 CO_2 probes	Relative Humidity (%)	5 to 95 %	±3 %RH (10 to 35 %RH) ±2 %RH (35 to 65 %RH) ±3 %RH (65 to 90 %RH) ±5 %RH (Remaining Range) ±0.06 %RH/K (0 to +50 °C)	0.10%
Testo 400 hot wire probes	Air velocity (m/s)	0 to 50 m/s	±(0.03 m/s + 4 % of mv) for (0 to 20 m/s) ±(0.5 m/s + 5 % of mv) for (20.01 to 30 m/s)	0.01 m/s
Testo 400 globe	Globe Temperature (°C)	0-120 °C	Type K thermocouple, class1. Approximately 30 minutes adjustment time	0.1 °C

4. Results

The surveyed subjects were monks and nuns from the Sthanakvasi, Terapanth and Murtipujaka sects of Svetambara Jainism (Jainism Global Resource Center, 2023b). A total of 65 subjects were interviewed with 37% of them being monks and the rest being nuns. We had 22 out of 65 subjects from the Sthanakvasi and Terapanth sects each and 21 out of 65 subjects from the Murtipujaka sect. The total number of surveys was 70 having 5 subjects interviewed twice with 40% of the surveys done for the monks and the rest for the nuns. The ascetics interviewed two times were surveyed once each in the hot and dry weather in May 2023 and warm and humid weather in September 2023 in Delhi. The subjects did not use any electricity from the time of their "Diksha" (monkshood or nunhood). Some of them would not allow the visitors to use fans or lights in their presence but others would allow them to do so. The fan at a low speed was on during the time of the survey only for 16/22 surveys from the Terapanth sect, 4/21 surveys from the Murtipujaka sect and for none of the 27 surveys from the Sthanakvasi sect. 3/20 of the surveys, where the fan was on, were old and had medical conditions. The average years of "Diksha" in the subjects was 26 years with a standard deviation of 18 years. The monks and nuns of Svetamabara Jainism wear white clothes (Figure 1). The clo values for the clothing for the monks was interpolated from the clo values for the existing garments from ASHRAE Standard 55-2017 and was assumed to be 0.54 clo. The clo values for nuns was assumed to be 0.62 based on the research done for finding clo values for an Indian sari (Indraganti et al., 2015). The nuns were in the age groups of 12 to 85 years with the average age of 46 years, while the age of the monks varied from 18 to 86 years with the average age of 47 years. The BMI of the subjects varied between 17.8 (5th percentile) and 32.5 (95th percentile) with an average of 25. The map in Figure 2 represents the five climatic zones of India (Nayak & Prajapati, 2006) having the details of the field survey locations and the dates of the surveys. The surveys were conducted in the composite climate region of Delhi during May and September 2023 and hot and dry climatic zones of Jodhpur, Siriyari and Kamlighat (a rural area near Siriyari) in June 2023 and Ahmedabad in July 2023 (Figure 2).

Figure 1: Photo of Svetambara sect nuns (Wikipedia, 2023)

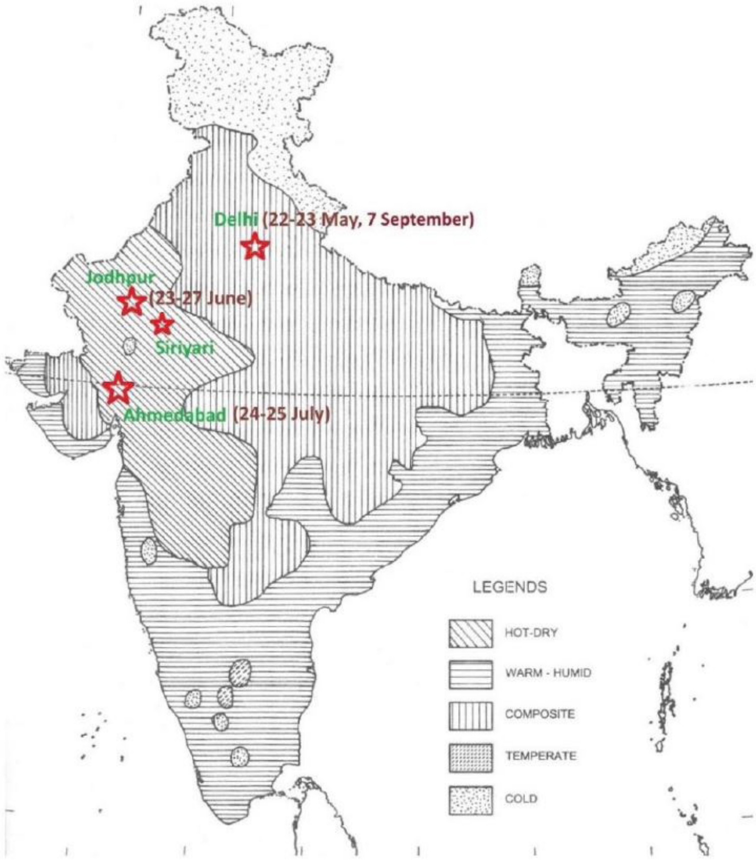

Figure 2: Field surveys in Delhi, Jodhpur, Siriyari and Ahmedabad during 2023

The surveys were administered in buildings using natural ventilation during the time of the survey. The subjects were interviewed in 22 buildings with six of them being multi-storied residential buildings, four being Dharamshalas and the rest twelve of them being Upashrays (Table 2). Dharamshalas were buildings where the ascetics stay but these buildings also have rooms for others to stay. Upashrays are buildings specially designed for the stay of Jain monks and nuns in between their travel from one place to another. The Jain Upashrays have been designed for natural ventilation and have higher window to wall ratios, typically over 50%. The building material for the Dharamshalas and the Upashrays appeared to be concrete based, which is similar to the other typical buildings of the area. The surveys were conducted from 8:45 am in the morning till 10:15 pm in the night with over 50% of the surveys in the afternoon. 26/70 surveys happened in Delhi, 21/70 subjects in Ahmedabad and 23/70 of them were from Jodhpur and Siriyari area in the state of Rajasthan.

Table 2: Description of the buildings where the surveys were conducted

Place	Building type	Floor	Surveyed Monks	Surveyed Nuns	Survey Time	Survey Date
Delhi	Residential	2	3	2	3:15 pm to 5:15 pm	22nd May 2023
Delhi	Upashray	2	0	3	7:15 pm to 7:45 pm	22nd May 2023
Delhi	Residential	2	1	2	10:30 am to 11:15 am	23rd May 2023
Delhi	Upashray	2	4	0	1 pm to 2 pm	23rd May 2023
Delhi	Upashray	1	3	0	3:30 pm to 4:45 pm	23rd May 2023
Delhi	Residential	1	0	2	6:15 pm to 6:35 pm	23rd May 2023
Jodhpur	Upashray	0	0	1	1:30 pm to 2:30 pm	23rd June 2023
Siriyari	Residential	0	2	0	10:30 am to 11:30 am	25th June 2023
Kamlighat	Residential	0	2	4	1:30 pm to 4 pm	25th June 2023
Jodhpur	Residential	0	0	3	1 pm to 2:30 pm	26th June 2023
Jodhpur	Residential	0	0	4	3:30 pm to 4:30 pm	26th June 2023
Jodhpur	Upashray	0	0	2	12:30 pm to 1:15 pm	27th June 2023
Jodhpur	Upashray	0	0	5	1:45 pm to 2: 45 pm	27th June 2023
Ahmedabad	Upashray	0	1	0	11:30 am to 11:40 am	24th July 2023
Ahmedabad	Upashray	0	2	0	12:05 pm to 12:30pm	24th July 2023
Ahmedabad	Upashray	0	0	2	1:00 pm to 1:30pm	24th July 2023
Ahmedabad	Upashray	0	3	0	1:40 pm to 2:30 pm	24th July 2023
Ahmedabad	Upashray	0	0	6	5:10 pm to 6:15 pm	24th July 2023
Ahmedabad	Residential	0	0	5	8:30 pm to 10:15 pm	24th July 2023
Ahmedabad	Residential	1	2	0	8:45 am to 9:30 am	25th July 2023
Delhi	Upashray	2	5	0	1:00 pm to 3:00 pm	7th Sept 2023
Delhi	Upashray	2	0	1	4:30 pm to 5:00 pm	7th Sept 2023

There were questions in the thermal comfort survey (TCS) form to document the subjects' activities in the hour preceding the survey. Most of the subjects were sitting before the interview. Some of them were standing, walking, and some had come back after getting food or Gochari (Jainism Global Resource Center, 2023a), doing yoga or washing utensils or clothes during or before the interview. ASHRAE Standard 55-2017 tables were used to translate the activities into metabolic rates. The surveys of the ascetics and the measurements of air temperature, relative humidity and air speed went hand in hand. The black globe thermometer used to compute the globe temperature takes time to reach equilibrium. So, the globe temperature was measured for the first case and it was found to be similar to the air temperature so it wasn't measured for the rest of the surveys. There is a possibility of the concrete based walls radiating heat during the time of the survey but the subjects had the choice of moving around in the buildings if they felt the radiant temperatures to be higher. The researchers seemed to feel a general absence of sources of radiation near the survey spaces so, the mean radiant temperature was assumed to be the same as the air temperature. Figure 3 shows the comparison between the air temperature and the relative humidity between the outdoor weather station and the indoor spaces for all the survey towns and cities. The weather in Delhi was hot and dry during the month of May but warm and humid in Rajasthan, Ahmedabad and Delhi in June, July and September respectively. The indoor temperature and humidity was close to the outdoor conditions in most of the cases owing to natural ventilation in the buildings. About 5 of the ascetics were sitting in the veranda during the survey. The Berkeley thermal comfort tool was used to compute the thermal comfort index, Predicted Mean Vote (PMV).

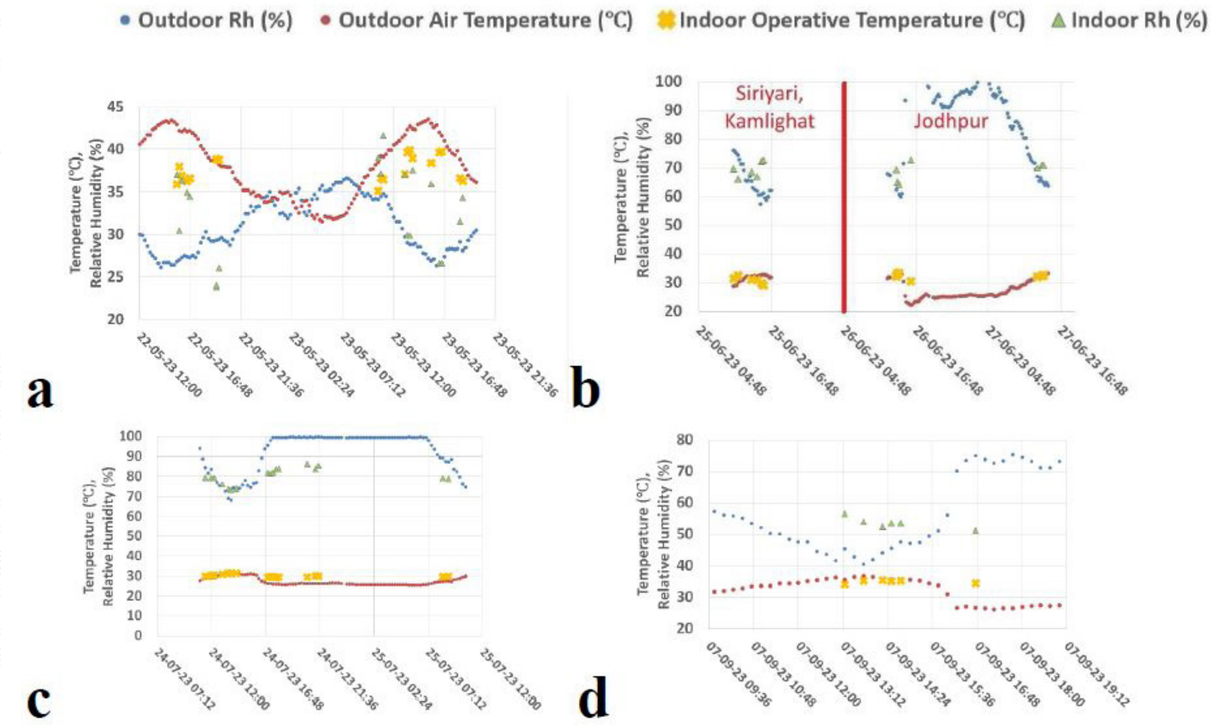

Figure 3: Outdoor, indoor air temperature and relative humidity vs. time at a) Delhi b) Rajasthan c) Ahmedabad d) Delhi

Figure 4 shows that the slope of the linear regression model of TSV with Top was non zero but much lower than the linear regression model based PMV slope with Top. The slope was lower for the TSV model owing to the neutral thermal sensation expressed by most of the subjects. PMV underpredicted the adaptability of the subjects significantly when compared to TSV. The percent people dissatisfied (PPD) calculated by the Berkeley thermal comfort tool was above 80% for over sixty percent of the subjects.

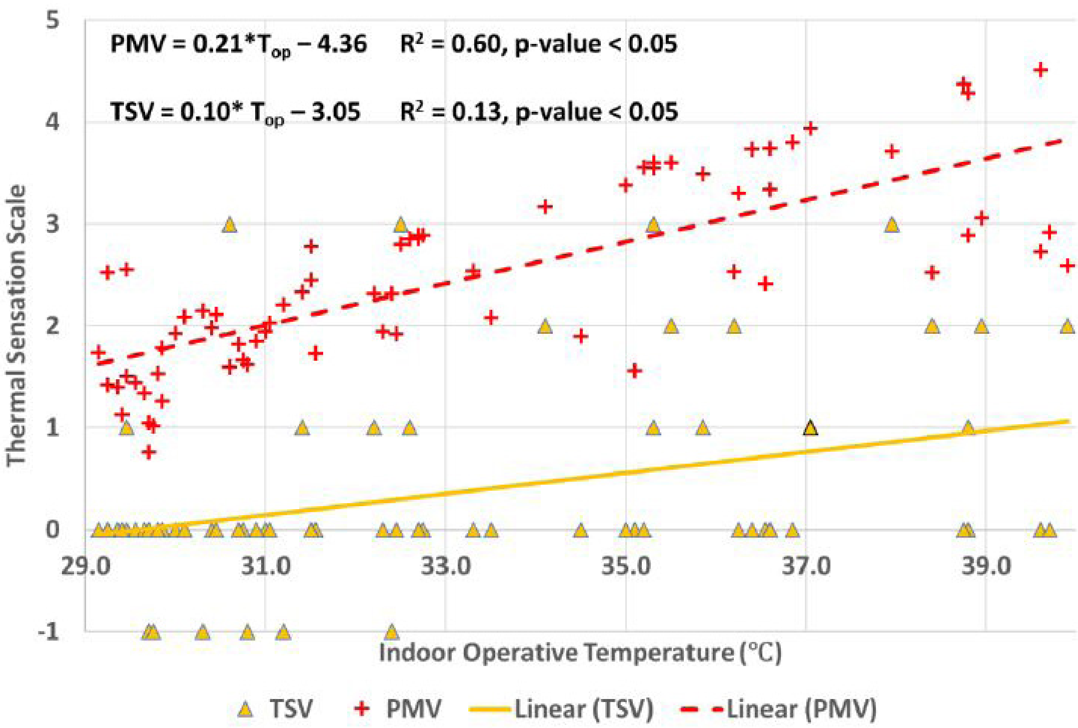

Figure 4: Observed TSV and calculated PMV vs. Indoor Operative Temperature

Figure 5 shows the points on the UTCI vs. TSV graph marked with "H" for the humid conditions from June to September 2023 and "D" for the dry conditions in May 2023. The relative humidity was greater than 50% for the humid conditions during the survey. About 75% of the subjects expressed a neutral or slightly cool thermal sensation even though the UTCI was in the strong to very strong heat stress range. All the surveys in the "Very Strong Heat Stress" UTCI conditions were for the dry conditions from Delhi and all the surveys in the humid conditions happened in the "Strong Heat Stress" UTCI conditions in Jodhpur, Siriyari, Ahmedabad and Delhi.

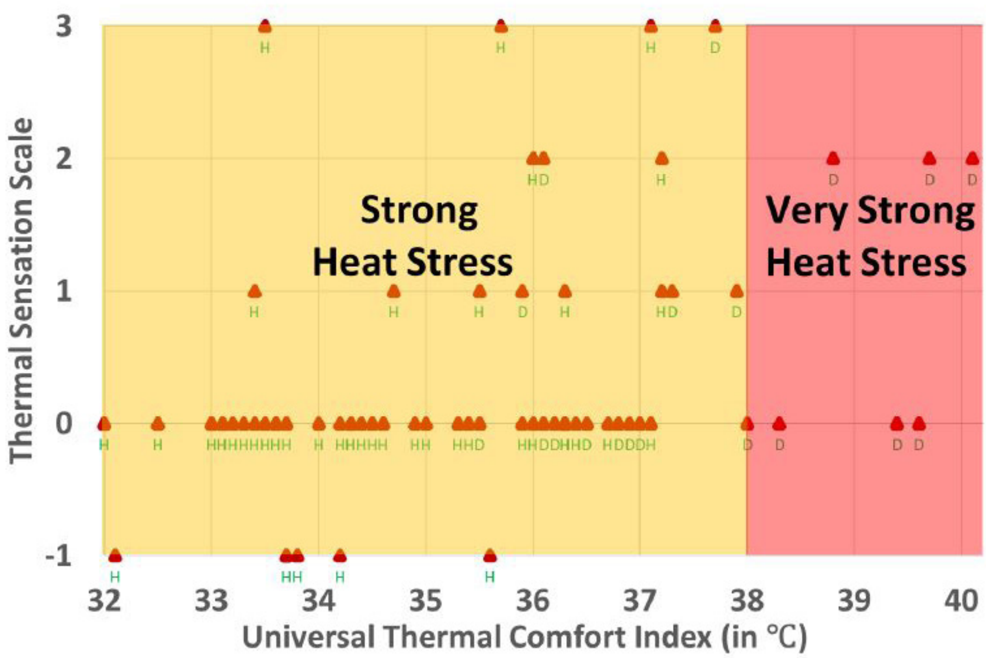

Figure 5: TSV vs. UTCI for the surveyed monks and nuns

90% of the subjects accepted the thermal conditions as per the Thermal Acceptability Vote (TAV) and less than 40% of the subjects preferred cooler thermal conditions as per the Thermal Preference Vote (TPV) in Figure 6. During the humid conditions from June to September during the surveys, less than half of the subjects experienced the weather conditions to be neither humid or dry as per the Humidity Sensation Vote (HSV). But about 64% of them were also accepting of the humid conditions and preferred no change in them as per the Humidity Preference Vote (HPV) in Figure 6. TAV and TPV results in Figure 6 are based on all the 70 surveys, whereas HSV and HPV in Figure 6 are based on the 50 surveys during the warm and humid survey conditions from June to September.

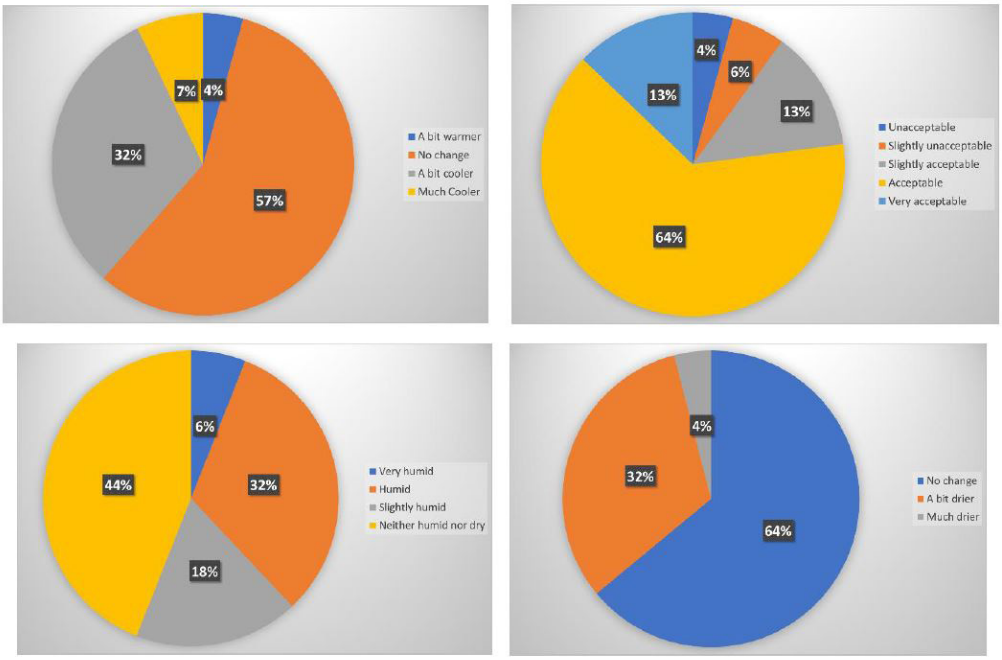

Figure 6: TPV in the top left figure, TAV in the top right figure, HSV in the bottom left figure, HPV in the bottom right figure

A 30 day outdoor running mean temperature (Tout-30DRM) was found using the outdoor weather data from the AQMS in the survey cities taking α = 0.8 (Rawal et al., 2022). The AQMS data from Rohini, Delhi AQMS was not available from 8th to 11th August 2023 so the outdoor running mean temperature was based on data for 26 days. A neutral temperature was found by performing a linear regression of Top (where TSV = 0) with Tout-30DRM. This model was called MACS (Model for Adaptive Thermal Comfort for a Sustainable world) and compared with IMAC-R (Figure 7). The slope of MACS is much higher than IMAC-R suggesting that the ascetics have a higher thermal adaptation than predicted by the IMAC-R model.

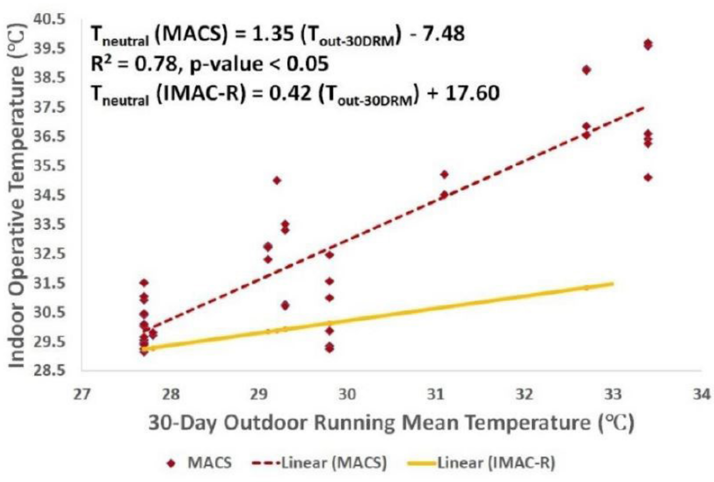

Figure 7: The adaptive thermal comfort model based on this study with neutral temperature = f(Tout-30DRM)

5. Discussion

The proposed MACS model shows that it is humanly possible for this "mindful" community to go beyond the IMAC-R model to have a neutral thermal sensation at a higher Top. This has implications for the possibility of reduction in cooling energy needs for the world. This community has vowed to live a life in sync with nature ever since they attained "Diksha". They have been practising this psychological adaptation from the day of their "Diksha" which was over 25 years on average for the surveyed subjects. It came to light during the survey that many of the ascetics had a lifestyle which included the use of air conditioners (ACs) in their homes and cars before their "Diksha". Committing to the lifestyle of a Jain monk or a nun is not an instantaneous act, instead they go through a phase of adaptation that can last for years in which they reduce their dependency on external means like the use of ACs incrementally for being comfortable. This suggests adoption of a lifestyle reducing the usage of ACs and increasing the thermal comfort range of individuals is possible over a certain time period. Some of them suggested that other living beings such as animals, birds and insects try to adapt to the changing climate without any external means of thermal comfort, so humans can also adapt to the natural environment if they mentally commit to it. One of them said that many of the villages in India didn't have access to electricity 50-60 years ago. We can also learn from people of the older generations about how they managed their lives in eco-friendly ways in earlier times.

One of the important questions to answer for the scientific community is about the temperatures that were safe decades ago, are they still safe now or the people in these communities are getting exposed to unhealthy conditions due to global warming? Apart from the planet warming up due to climate change, the cities are also heating up because of the densification of the built up area leading to an increased urban heat island effect. There are an increasing number of infrastructure projects and migration of people moving from rural to urban areas in search of better opportunities. The temperatures in Delhi have increased by 10°C in the past twenty years (Singh et al., 2022). Some of the ascetics are hopeful that most of the people in the world would be able to adapt themselves to the rising temperatures. One of them who doesn't use any electricity for him or his visitors said that they can bear up to 40°C temperatures but beyond that, they have to bear the hotter conditions until they last. While the focus of this study was on indoor thermal comfort, but many of them are used to much more extreme thermal conditions as a part of their daily routine. Many of them are used to going out in the scorching sun barefoot and an uncovered head every day to get "Gochari" or food for them. Their outdoor thermal comfort should be studied to get more insights about their thermal adaptations. The ascetics from some of the Jainism sects have recently let their visitors use fans for thermal comfort due to a warming planet. Some of the ascetics have also started wearing slippers when they go out in the scorching sun on the hot asphalt roads. But other ascetics argue that their foot sole skin becomes dead with their barefoot walking habits and it acts like slippers so they don't feel the need for slippers.

Since they have vowed to not use energy (psychological adaptation), so they remain equanimous irrespective of the thermal conditions which translates to a neutral thermal sensation. It must also be noted that they don't like to unnecessarily suffer from the uncomfortable weather conditions. Many of them would work on behavioural adaptation methods to keep themselves comfortable. They would move to a cooler room, a room which has breeze or use a wet cloth providing evaporative cooling. One of them was also observed cleaning his armpits with a wet cloth, may be to prevent body odours. This aspect should also be understood in the context of them using minimal water for their daily use. Another of the strategies used by the ascetics during the less bearable thermal conditions during the night was to distract oneself with reading of books or meditation until one was able to sleep. Another redeeming feature of their habitat is the architecture of the buildings called "Upashrays", especially built for their stay. These buildings have a high window to wall ratio (WWR) leading to good cross ventilation. These buildings are also largely empty since the ascetics have very minimal belongings. This might lead to a lower thermal mass of things in the building to heat up. We should study the spatio-temporal thermal characteristics of the buildings to understand whether the lack of thermal mass of things is helpful or not. Talking to some of them revealed that they sleep on a cardboard sheet on the floor. Having a bed made of something like a timber takht with string bases may help them to lose heat in all directions but they keep minimal belongings so they can't avail this option. Some of the ascetics also said that they prefer staying in these buildings than the building of a householder. The buildings made for air-conditioning would have much lower window to wall ratios and would be less comfortable to be used in natural ventilation mode. Another takeaway from this study is to consider the architecture of "Upashrays" for health and wellness. The naturally ventilated buildings with high WWR provide adequate amount of fresh air and need very less energy for thermal comfort (even if fans are used) with less capital cost and running cost for cooling needs. The air conditioned buildings would provide thermal comfort in a narrower range with lesser fresh air and much higher energy needs and costs.

The UTCI for warm and humid conditions was in the "Strong Heat Stress" range based on our measurements. There were more warm and humid conditions in the surveyed cities when the surveys couldn't be conducted. Surveys under these conditions could give better insights. It is difficult to predict weather and it rained during some of the surveys leading to more pleasant conditions. This study also suggests that thermal comfort indices such as PMV and UTCI developed with the subjects from the colder climates may not reflect the adaptive thermal comfort of the people from the hotter climates very well. It should also be brought out that monks from some of the sects, leading a more extreme life, requested not to participate in the surveys. Their reason was that they were principally not fine with us recording the weather measurements while we surveyed them. Their point was that this would make them indirectly responsible for energy consumption, which they have pledged not to use. They suggested for us to stay with them for a few days to observe their routine instead of recording the measurements for the point in time TCS. The researchers plan to stay with the ascetics for a few days continuously and share the findings in a future study. It should also be noted that the research scholars involved in the experiments were pleasantly surprised not to feel much discomfort during the interviews with the subjects. We would need to find out whether it was the presence of the ascetics being equanimous in those conditions, low metabolic rates of the research scholars, the architecture of the buildings or something else. This provides hope for the possibility of thermal adaptation of the normal people.

6. Conclusion

This paper helped in understanding the thermal comfort adaptation of 65 ascetics from Svetambara Jain sects in hot and dry as well as warm and humid weather conditions in Delhi, Jodhpur, Siriyari and Ahmedabad. 90% of them found the thermal conditions to be acceptable when the UTCI was in the strong to very strong heat stress range. The MACS model of adaptive thermal comfort suggests that it is possible to have a neutral thermal sensation at a higher indoor operative temperature than IMAC-R to further reduce cooling needs. Future work should involve having a higher sample size for thermal comfort surveys in hotter weather conditions, exploring their thermal comfort in winter conditions and finding out if these thermal comfort adaptations could become a part of normal householders. Learning from the thermal comfort at the extreme of these 'mindful' communities would open the doors for studying their low resource use lifestyles for other aspects such as minimal electrical energy use, water use, transport energy use, product use and so on. It is the need of the hour to make our planet cleaner and greener.

7. Acknowledgements

The authors would like to acknowledge the help of Ms Leela Mehta to connect them with the ascetics and also, share her valuable understanding about the lifestyle of the Jain ascetics during the course of this study.

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Investigating the Occupant's Perception of Biophilia on the Health and Well-Being in a Hospital Setting.

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Abstract

Individual perceptions are essential while evaluating the well-being benefits of nature. This study predicted biophilia's influences on the occupant's health and well-being in a building. The study was conducted in a healthcare building in the city of Pune- a case of a hospital designed on the principles of biophilia was taken such that a comparison of observation and perception of occupants was analyzed. A biophilic design framework developed by Kellert in 2008 was adopted and a questionnaire was prepared based on the elements and attributes present in the case building based on diligent on-site observation of the whole campus of the case hospital. The survey was conducted with the prepared questionnaire based on the elements and attributes present using a Likert scale of 1 to 5 based on dissatisfaction and satisfaction level where 1 stands for extremely dissatisfied and 5 is extremely satisfied. Perception of 100 occupants is taken by further dividing them into 3 main categories based on their nature and daily workflow, the inpatients; the outpatients and visitors; and the staff. Results reveal 57.7% of the staff,76 % of the outpatients, and 84.36% of the inpatients were satisfied with the presence of biophilic elements and attributes present in the campus and state having improved health and well-being, however, few attributes like connection to place, natural shapes, and form contain mixed reviews due to lack of understanding of the attribute. Also, the results state that each element and attribute are interlinked, and a group of attributes is such a form dividing them into 6 categories. Few recommendations have been suggested based on the elements and attributes for enhanced health benefits. Accordingly, the study recommends that with the successful implementation of biophilic design principles, hospital buildings can be transformed into healing places that will boost and bring many benefits to the occupant's health and well-being.

Keywords - Health and Well-being in the Buildings, Human Physiology and Adaptation, Nature Based Solutions, hospital building, Programmes and policies in health and well-being, biophilia, and Biophilic design.

1. Introduction

In 1950,67% of the world population lived in rural areas while the remaining 33% lived in urban areas. Netter job opportunities and higher living standards in the urban areas led to urbanization. Today 55% of the world's population lives in cities and it is projected that by 2050, 68% of the world population shall live in the cities by the UN [24]. Now, this population spends 90% of the time indoors causing negative effects on the body and the mind due to less exposure to natural light and fresh air leading to adversely affecting mental health, causing sleep troubles, stress, weak immune system, mood swings and anxiety in individuals. To overcome these negative effects of spending more time indoors incorporating nature in the buildings has proven beneficial. Humans and nature have an innate connection. Spending time in nature has proved multiple benefits to physical health and well-being, psychological health and well-being, social health and well-being, and spiritual health and well-being. As per the Nature Pyramid, a person should have exposure to nature on the below scales as per these frequencies and duration as shown in Fig 1. Incorporate health and well-being concepts like, U.S Green Building Council (USGBC)- Leadership in Energy and Environmental Design (LEED), Indian Green Building Council (IGBC), WELL Ratings, Green Building Initiative (GBI), Fitwell, Air Rated for air quality monitoring, the American National Standards Institute (ANSI), American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), General Service Administration (GSA), etc. Of which the International WELL Building Institute (IWBI) is engaged in a global movement to transform health and well-being with our people-first approach to buildings, organizations, and communities using the WELL Building Standard (WELL), a blueprint to design and create spaces to promote enhanced human health and well-being.[14]

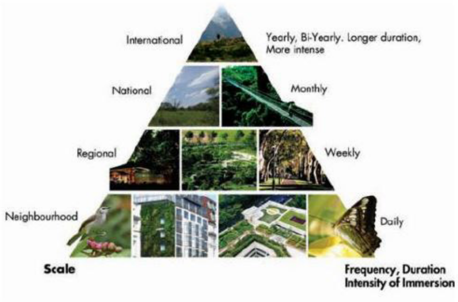


Figure 1: Conceptual diagram of the Nature Pyramid, 2012. (Concept by Tanya Denckla-Cobb and Timothy Beatley, University of Virginia,Illustration prepared by Singapore National Parks [19](Permission to use the figure was granted)

Figure 2: The 12 Impact Topics (Source: International WELL Building Institute) [19](Permission to use the figure was granted)

In 2019, WELL released the Global Research Agenda: Health, Well-Being and the Built Environment with 12 impact topics for research for the aim of achieving a healthy building concept as shown in Fig 2. Out of these 12 impact topics, Access to nature is one of the impact topics which states that there is an extensive body of research that demonstrates human contact with nature has a host of benefits like improved task performance, enhanced mood, stress reduction, increased focus, increased socialization, and boost in creativity. Various studies conducted on community scales- Parks and Gardens focus on how access to nature, both visual and physical, for building occupants, may have multiple health and performance outcomes. However, specific gaps and opportunities inside the building. [14] Connecting the benefits of access to nature to outcomes such as human performance and mental, physical, and social health may impact health and well-being and performance outcomes. This access to nature can be achieved through biophilia.

Biophilia, or the "philia" (love) of "bio" (life or living things), is understood by Wilson [26,27]as an emotional response that is "innate," "hereditary," and present in the genes. Most of human evolution has taken place in the natural world, where people have thrived. Our ancient dependence on nature for our survival persisted as we transitioned into the modern artificial environment, evolving into a quest for connections with nature that define our "personal identity" today. [15,16, 17].Biophilia's foundation is thus the "evolutionary dependence on nature" for "survival and personal fulfillment" [15,16,17]. Biophilic design has evolved over the years and has multiple benefits of incorporating nature as shown in the timeline of various biophilic interpretations by various researchers like Kelert, Browing, Heerwagen, Hildebrand, etc. as shown in Fig. 3.[2-4,7-12,15-17,27,28]

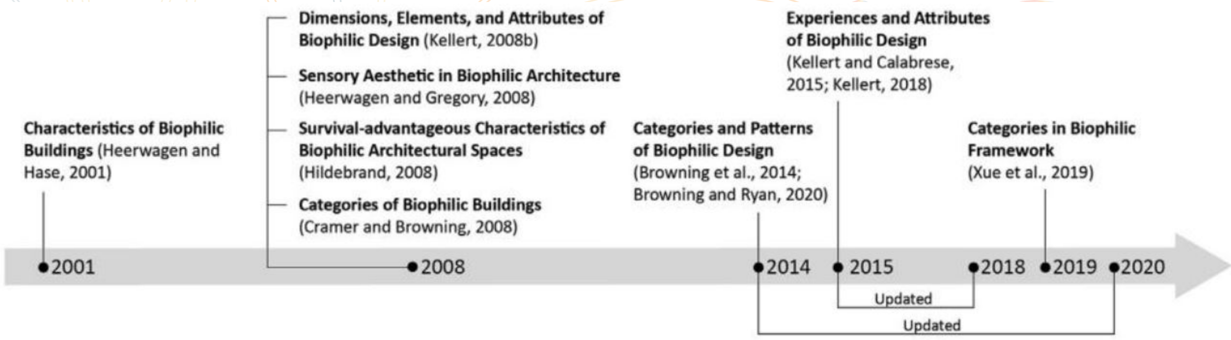


Figure. 3: Timeline of various biophilic design interpretations

The pioneers of biophilic architecture, Heerwagen, and Hase, established eight criteria encompassing habitability, natural elements, and design principles. The book "Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life" [16] further refined these ideas. Kellert's framework introduced two dimensions, six elements, and seventy attributes. Terrapin Bright Green identified fourteen design patterns [2,3,4], while Kellert and Calabrese [15]proposed twenty-four traits. The frameworks have evolved, emphasizing different connections between nature and human well-being.

They guide architectural certifications like LBC, WELL, and LEED. Browning and Ryan[2,3] focus on human-nature interactions, while Kellert's [16] extensive model contrasts with the recent concise approach. Challenges include overlaps and clarifications in categories.

Biophilia, or the "philia" (love) of "bio" (life or living things), is understood by Wilson [26,27]as an emotional response that is "innate," "hereditary," and present in the genes. Most of human evolution has taken place in the natural world, where people have thrived. Our ancient dependence on nature for our survival persisted as we transitioned into the modern artificial environment, evolving into a quest for connections with nature that define our "personal identity" today. [15,16, 17].Biophilia's foundation is thus the "evolutionary dependence on nature" for "survival and personal fulfillment" [15,16,17]. Biophilic design has evolved over the years and has multiple benefits of incorporating nature as shown in the timeline of various biophilic interpretations by various researchers like Kelert, Browing, Heerwagen, Hildebrand, etc. as shown in Fig. 3.[2-4,7-12,15-17,27,28]

2. Methods

2.1 Data Collection:

Primary Data:
A survey-based interview approach was utilized to gather insights from 100 occupants at the Symbiosis Hospital and Research Centre, Pune, focusing on their perceptions of the influence of biophilic elements on their health and well-being.
Secondary Data:

- Extensive examination of biophilic design standards.

- Review of biophilia and healthcare-related information from various sources, including journals, websites, books, magazines, and articles[1,5,6,20-23,25].

2.2 Study Design:

The study aimed to assess how occupants at the Symbiosis Hospital and Research Centre in Pune perceive biophilia's impact on their health and well-being. This was accomplished through a Google Forms survey that incorporated responses alongside biophilic design standards to evaluate the effects of biophilia.

The study comprised three main components:

1. Exploration of fundamental biophilic design concepts, definitions, historical context, and frameworks.

2. On-site observations to identify biophilic design attributes, followed by the creation of a questionnaire for the selected building.

3. Interviews with hospital occupants to gain insights into how biophilia affects their health and well-being.

2.3 Participants:

Based on similar environmental psychology studies with a crossover design, 100 participants were selected to ensure statistical significance. The sample included hospital staff (doctors, paramedical, and allied staff), inpatients, outpatients, and visitors. Two distinct questionnaires were designed—one for staff and inpatients, and another for outpatients and visitors- due to varying exposure levels to biophilic elements

Table 1: Socio-demographic profile of the sample (n=100)

	Type	% (n)
Gender	Female	**38**
	Male	**62**
Age Group	18-34	**25**
	35-64	**33**
	65=>	**42**
Type of occupant	**Category**	
Doctor	Staff (40)	**15**
Paramedical		**15**
Allied Staff		**10**
Inpatients	Inpatients (25)	**25**
Out-Patients	Out-Patients	**25**
Visitors	And Visitors (35)	**10**

(Note: Here n = number of samples collected. As it is 100 so the number of sample=the percentage of the Ntotal sample)

2.4 Environmental Exposure:

The survey was conducted in physical settings during the month of April between 9 am and 6 pm. Outpatients and visitors were the primary focus during OPD hours (9 am-1 pm), while staff interviews occurred during their lunch break (1-2 pm). Inpatient interviews were conducted later in the day. A Google Form tool was employed to allow participants to objectively rate biophilic elements according to the Kellert framework. The questionnaire was structured based on Kellert's comprehensive framework from his book "Biophilic Design" [16] and encompassed questions regarding participants' perceptions of elements such as plants, airflow, lighting, materials, biomorphic forms, and views. Details of some of the survey questionnaires can be found in Appendix 1. Responses were recorded and subsequently analyzed.

2.5 Framework Used:

The first framework in the fig by Kellert in 2008 is used and analyzed based on the elements present and correlated with the standards. The questionnaire and analysis of the data is done based on the highlighted attributes only, as and when the questionnaire is modified and a question for a combination of attributes is asked collectively. While some elements are not applicable are not considered. Only the highlighted attributes as shown in Table 2.
are considered as per Kellert's framework of 2008[16].

2.6 Perception Survey:

A perception survey was conducted for the onsite present biophilic elements and attributes. The occupants were interviewed in the form of a questionnaire such that they had to rate their perception and satisfaction level on a Likert scale of 5,
1– Extremely Dissatisfied 3-Neither dissatisfied nor 4- Satisfied
2-Dissatisfied Satisfied 5-Extremely Satisfied,
Thus, each participant's entry was recorded and compared with the onsite observation of that attribute further helped in analysing and recommending the necessary measures needed to be taken. Also based on the literature review of Bowings the health benefits were also mentioned for better understanding [2,3,4].

3. Questionnaire Results

A survey comprising 30 pertinent questions was undertaken, scrutinizing 24 distinct attributes. Some of these attributes necessitated multiple inquiries to ensure comprehensive comprehension. This survey meticulously adhered to the prescribed methodology and accounted for various occupant categories, as delineated in the methodology section. Table 3 provides an intricate overview, offering on-site observations of each attribute, coupled with a comprehensive analysis of occupant perceptions. Additionally, it furnishes indispensable recommendations for integrating these findings. Furthermore, Table 3 synthesizes the health advantages associated with each attribute, drawing from the existing literature [2,3,4].In Table 4, we present stacked graphs that dissect each attribute, revealing satisfaction levels across all three occupant types in meticulous detail. Strikingly, 20 out of the 24 attributes closely align with the on-site observations and the perception results. However, attributes such as natural materials, organic forms, and textures and patterns received a neutral response. This was primarily due to the occupants' limited awareness and knowledge of these elements, compounded by their relatively subdued presence within the environment. Notably, when assessing the attribute of water, the perception analysis focused solely on occupants with access to and visual engagement with this element. Nevertheless, Table 3 advocates for the incorporation of a water feature to ensure universal access across all occupant categories. Interestingly, while the ecological aspect of the connection to place attribute was evident in the building's design, occupants lacked a profound understanding of this element, leading to a collective perception that it was absent. This contrasted with the on-site observations. Elevating awareness and fostering an appreciation for this facet can effectively bridge this perceptual gap.

In the case of the building under scrutiny, it stands as an exemplary model of biophilic design. Post-survey analysis reveals that, when averaging all attributes, 57.7% of the staff expressed satisfaction, 76% of the outpatients reported satisfaction, and an impressive 84.36% of the inpatients were satisfied. These findings underscore a notable improvement in recovery rates and a multitude of health and well-being benefits attributed to the presence of biophilic elements within the building. As a result of this survey, it is evident that the staff areas and offices would benefit from additional biophilic features. Elements such as potted plants, organic forms, patterns, and natural materials can be seamlessly integrated into the interior design, yielding a profoundly positive impact on the health and well-being of all occupants. Also after analysis, it is seen that the attributes are interlinked and categorized into six groups as shown in Fig. 4.

Table 2: A list of elements and attributes of biophilia as per Kellart's framework of 2008[16]:

Environmental features	Natural Shapes and forms	Natural Patterns and Process
Colour	Botanical motifs	Sensory variability
Water	Tree and columnar supports	Information richness
Air	Animal motifs	Age, change and the patina of time
Sunlight	Shells and spirals	Growth and efflorescence
Plants	Egg, oval and tubular forms	Central focal point
Animals	Arches , vaults, domes	Patterned wholes
Natural materials	Shapes resisting straight lines and right angles	Bounded spaces
Views and vistas	Biomorphy	Transitional spaces
Façade greening	Geomorphology	Linked series and chains
Geology and landscape	Biomimicry	Integration of parts to whole
Habitats and ecosystems		Complementary contrasts
Fire		Dynamic balance and tension
		Fractals
		Hierarchically organized ratios and scales
Light and Space	Place -Based Relationships	Evolved Human Relationships
Natural Light	Geographic connection to place	Prospect and refuge
Filtered and Diffused Light	Historic connection to place	Order and complexity
Light and Shadow	Ecological connection to place	Curiosity and enticement
Reflected light	Cultural connection to place	Change and metamorphosis
Light pools	Indigenous materials	Security and protection
Warm lights	Landscape orientation	Mastery and control
Light as shape and form	Landscape features that can define building form	Affection and attachment
Spaciousness	Landscape ecology	Attraction and beauty
Spatial variability	Integration of culture and ecology	Exploration and cognition
Space as shape and form	Spirit of place	Fear and Awe
Spatial harmony	Avoiding placelessness	Reverence and spirituality
Inside-outside spaces		
(Note: The elements and attributes that are present on site in the case of this hospital are highlighted using this:)		

https://doi.org/10.62744/CATE.45273.1153-121-130

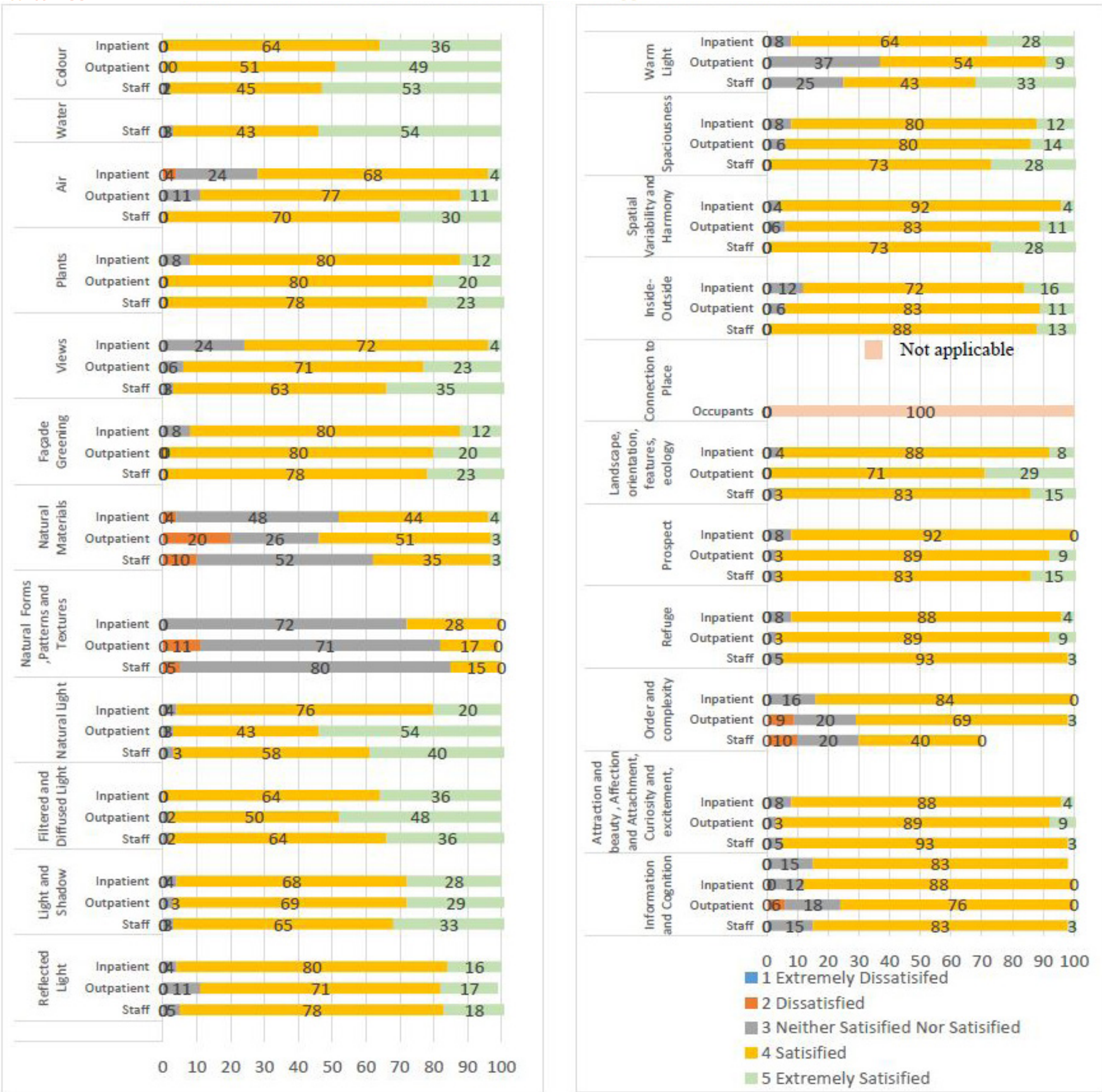
Table 3: A representative sample of Observation, Analysis, Recommendation, and Health Benefits of a few Attributes.

<table>
<tr><td>1</td><td>Colour</td><td>Observations</td><td>Analysis</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">
Fig. a. Image of the hospital wards showing the colour scheme (Source: Author)</td><td>The ward rooms are designed with warmer and subtle hues of colours that are complemented with teak laminates. Encouraging wayfinding, the nurse stations are highlighted with shades of warm yellow/orange to be identifiable from any side of the long corridor</td><td>The colour scheme is as per the colour psychology and the occupants are majorly satisfied with the colour scheme.
64% Inpatients are satisfied.
51% Outpatients and Visitors satisfied.
53% Staff are totally satisfied.</td></tr>
<tr><td>Recommendations</td><td>Health Benefits</td></tr>
<tr><td>---</td><td>Positively impacted perceptual and physiological stress responses and improved comfort.</td></tr>
<tr><td>2</td><td>Water</td><td>Observations</td><td>Analysis</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">
Fig. b. Image of the water fountain at the skill centre entrance. (Source: Author)</td><td>The use of water features of fountains creates a sense of tranquility, mask noise, provide a visual focus for outdoor spaces, and acts as a grandeur entry of the skill center.</td><td>The water feature is only accessible to the staff members; thus, the inpatients and outpatients do not get the benefits from the presence of the water feature.
54% of Staff are totally satisfied</td></tr>
<tr><td>Recommendations</td><td>Health Benefits</td></tr>
<tr><td>A water body or water feature can be incorporated into the central courtyard; thus, the presence of water can create a therapeutic experience that would be visually accessible to all.</td><td>Reduced stress, increased feelings of tranquility, lower heart rate and blood pressure. Enhanced perception, psychological responsiveness, and positive emotional responses</td></tr>
<tr><td>3</td><td>Connection to place</td><td>Observations</td><td>Analysis</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">
Fig. c. Image of the nature views around the campus seen from the cafeteria. (Source: Author)</td><td>Connection to place could be:
• Geographical connection
• Historical connection
• Ecological connection
• Cultural Connection
The building design incorporated courtyards and green landscape areas to develop an ecological connection</td><td>The building design incorporated courtyards and green landscape areas to develop an ecological connection, however, it is not perceived by the occupants.
0% of Occupants could perceive a connection to place.</td></tr>
<tr><td>Recommendations</td><td>Health Benefits</td></tr>
<tr><td>Awareness and connection with place should be made by marking and making display boards with relevant related information.</td><td>Positively impacted perceptual and physiological stress responses</td></tr>
</table>

4. Discussion

Thus, based on the study, Table 3., shows a few examples of the observations, analysis, recommendations, and health benefits of some of the attributes present on the site whose survey was done. For example, the color scheme is as per the IGBC Green Healthcare Facilities Rating System [13]. The hospital building has the colour scheme as per the color scheme and tones suggested in the standards. Also, the inpatients were perceived to be satisfied by 64%, the outpatients and visitors by 51% and the staff by 53%. As the colour scheme was apt as per the standards and the occupants were satisfied with it there were no recommendations suggested. However, based on the literature review[2,3,4], the health benefits specific to the attribute were noted for a better understanding of the benefits of the attribute, in the case of color as per Browings[2,3,4]. The colour scheme positively impacted perceptual and physiological stress responses and also improved comfort. For water as an attribute, the water feature was only accessible and visible to the staff so only their perception is noted, rest of the occupants did not answer the survey question related to water as only those questions whose elements and attributes were accessible and visible to the occupants were answered and noted and further analyzed. However, a recommendation of another water as an attribute was made in the recommendation table. The perception of all the occupants is mentioned in the stacked graphs shown in Table 4. For example, for Views, 72% of the inpatients were satisfied with the views, while 71% of outpatients and 63% of staff were satisfied with the views of nature and with the views, while 71% of outpatients and 63% of staff were satisfied with the views of nature and suggested that nature views available to them had a positive impact on their health and well-being. (Refer to table 4.) Similarly, all the 25 attributes were analyzed. One of the interesting attributes was a connection to the place where the occupants were asked if they felt any connection to the place, (refer to Appendix 1 Q.8), however, none of the occupants could perceive the ecological connection to the place so the suggestion of awareness of this attribute was recommended. The space-wise analysis is done stating that the building is designed as a part of access to nature however few areas such as the common lobbies, waiting areas, and corridors can incorporate biophilic elements like potted plants and natural décor and material treatments. So, the study recommends that with the successful implementation of biophilic design principles, hospital buildings can be transformed into healing places that will boost and bring many benefits to the occupant's health and well-being.

Table 4: Stacked graph with percentage responses of Perception of Occupants



5. Conclusion

In conclusion, the study at Symbiosis Hospital in Pune presents compelling evidence of the tangible benefits of biophilic design in healthcare settings. Notably, 57.7% of staff, 76% of outpatients, and an impressive 84.36% of inpatients expressed satisfaction with the biophilic elements, affirming their positive impact on well-being. The study aligns with Kellert's framework, revealing a nuanced understanding of how specific design attributes, such as colour schemes and water features, contribute to occupant satisfaction and have multiple health benefits. However, the research identifies a gap in occupant perception concerning certain biophilic elements, like connection to place, indicating a need for increased awareness. Biophilic elements can be used as a design strategy for improved health, faster recovery, relaxation, and stress relief measures. Incorporated natural as well as simulated, artificial representations of nature will have multiple health benefits. The findings conclusively assert that the successful implementation of biophilic design principles transforms hospitals into healing environments, fostering improved health outcomes.

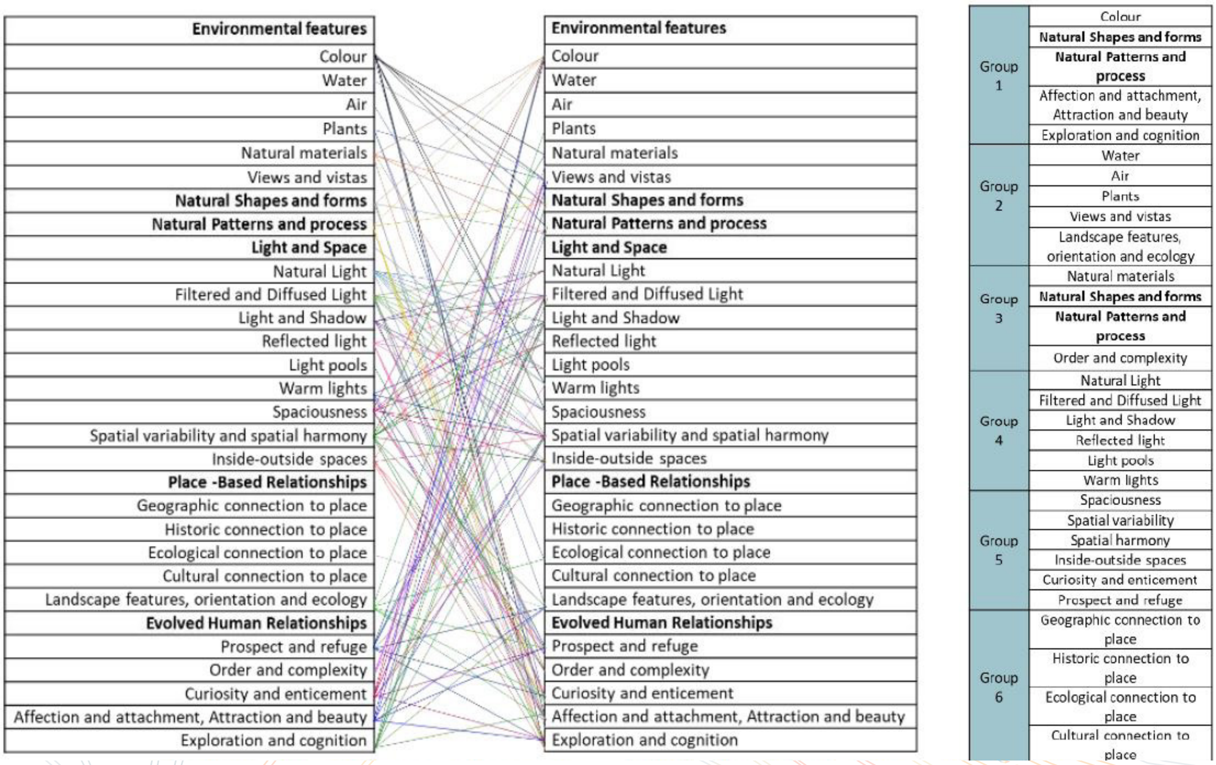


Figure 4. Inter-linkage and connection of all the biophilic features and categories

6. Future Research

The study conducted can be further explored in the hospital setting by actual measurement of occupants' blood pressure, heart rate, stress test, etc. And the benefits of improved health can be quantified accordingly. For well-being and health and safety, perception surveys are conducted, so the research can be a part of the ESG framework.

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8. Appendices

Appendix 1: Sample of a few Survey Questionnaires.

1. Type of Occupant:
o Inpatient
o Outpatient
o Staff

2.Gender
o Male
o Female

3.Age
o18-34
o35-64
o64=>

4.To what extent are you satisfied with the colour scheme of this hospital?
o 1– Extremely Dissatisfied
o 2-Dissatisfied
o 3-Neither dissatisfied nor satisfied
o 4- Satisfied
o 5-Extremely Satisfied

5. What is your satisfaction level with the presence of water feature creating a positive mood & reducing your stress levels? Rate on a scale of 1 to 5

6.What is your satisfaction level with the variety of spaces in the waiting areas, landscaped courtyards, green features in the cafeteria? Rate on a scale of 1 to 5.

7.What is your satisfaction level with the use of courtyards and large corridors to the wards contributing to connection to nature? Rate on a scale of 1 to 5.

8.Does the building have any of the below connections or relevance?
oGeographic
oHistoric
o Ecological
o Cultural
o Not applicable

9. What is your satisfaction level with design creating curiosity, exploration, and discovery of nature? Rate on a scale of 1 to 5.

10. What is your satisfaction level with the lighting layout in the corridors helping in wayfinding and easy movement? Rate on a scale of 1 to 5.

11. What is your satisfaction level with the use of cooler light in the morning and warmer light in the evening in creating a positive impact on your mood and well-being? Rate on a scale of 1 to 5.

The Green Side of Passive Cooling: Building Facades Inspired by Evapotranspiration in Trees

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Abstract

Buildings suffer from uncontrolled heat gain through their skin, which creates an urgent need for thermal comfort. In hot climates such as India, a growing economy with a rising per capita income is leading to an expected rise in cooling demand—by 11 times in the next two decades. The use of passive cooling strategies to reduce direct heat gain through building envelopes is an integral step in reducing the energy demand for cooling.
The system works as a shading device similar to adjustable louvres, moreover, the terracotta's porosity mimics cooling evapotranspiration. It adapts to sun angle, building orientation, and design. It combines terracotta and water to effectively cool, especially in multi-story buildings. The efficiency of the proposed passive cooling system was tested in the composite climatic regions of Raipur and Hyderabad, the nature-inspired passive cooling system reduced cooling energy needs by 30% and 47% respectively. The future of space cooling in buildings can benefit by using efficient passive cooling envelopes that can reduce the heat gain in the buildings. Climatically adaptive designs hold the potential to influence the shape of future buildings, landscapes, and cities, perhaps with earthy tones.

Keywords - Envelope Cooling, Passive Cooling, Building Façade, Climate Responsive, Biomimicry

1. Introduction

In India, a country experiencing hot climates, a growing economy with a rising per capita income is leading to an increased demand for cooling. Most of this demand is attributed to the construction industry as space cooling in buildings. According to the India Cooling Action Plan (ICAP), the cooling demand in the building sector is expected to rise by 11 times in the next two decades [9].
Using RACs for cooling our indoors is effectively heating up our outdoors. This leads to a further increase in demand for indoor cooling, what we can call the 'cooling paradox.' Navigating this demand effectively necessitates a well-balanced approach, involving adoption of energy-efficient cooling systems and integrating sustainable design practices that utilize passive cooling techniques for buildings.

Building Envelopes, made of roofs and facades, face high heat and solar radiation. This causes thermal transmission that affects indoor spaces negatively in tropical regions where temperatures are already too hot [8] (pp. 104-113). In Indian homes, ACs account for 20-40% of the electricity consumption [7]. Hence, it is important to lower the cooling energy consumption in buildings while maintaining thermal comfort.

1.1 Towards Alternative Cooling Techniques: Inspired by Nature, Guided by Tradition

Traditionally in India, buildings were designed in consideration of the environmental context, using passive strategies that channel air and sun into the building interiors in a way that reduced heat gain and increased thermal comfort [13] (p. (pp. 1901-1911). According to ICAP, using building envelopes that suit the climate can reduce the cooling energy demand by 20% by 2037-38 [9].
The temperature under a tree is often 10-12° C lower than the surroundings [1] (pp. 139-148). This difference in temperature is the combined result of the phenomenon of ventilation, shading, and evapotranspiration. Passive cooling systems based on the principle of evapotranspiration can be very effective for providing thermal comfort in building interiors, especially in hot-and-dry climatic regions such as India. Such cooling systems can be realized as an additional 'second skin' that can also be attached to the existing building facade to provide thermal comfort through passive means.

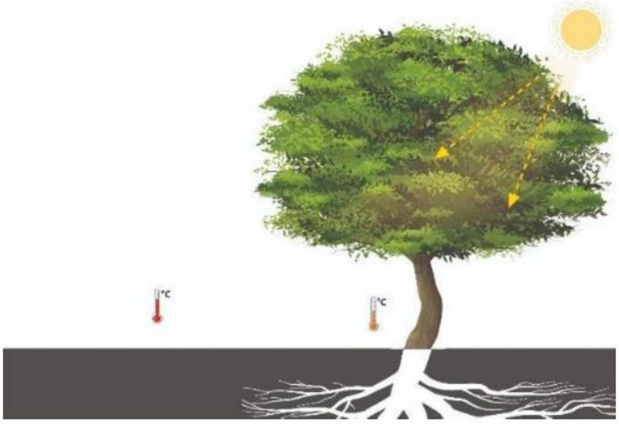


Figure 1: Lower Temperatures Below the Tree (source: Author)

1.2 Research Questions

1. Can building envelopes be inspired from the natural process of trees? What if buildings had a second skin that acts like the foliage of the tree?

2. What is the impact of such building envelopes on the Cooling Load of buildings?

3. What is the impact of such building envelopes on the Thermal Comfort of the occupants?

4. How can passive design strategies effectively reduce the energy demand for cooling in buildings in hot and dry regions like India?

5. How do these strategies and their performance differ as per different building typologies and project briefs?

2. Methods

2.1 Nature-Inspired Second Skin as Passive Cooling Systems

The proposed solution is realized as a second skin facade, called the 'Aerofoils' made with an assembly of porous material modules.Water is circulated through this system which cools the passing air through the principle of evaporative cooling.

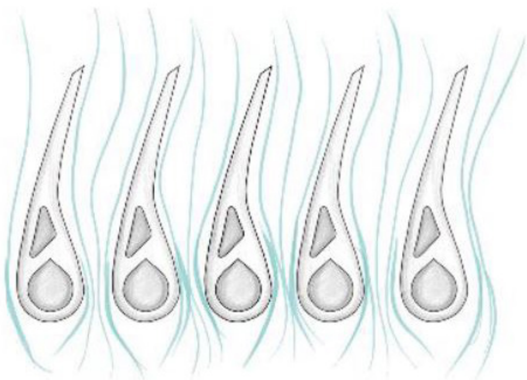


Figure 2: Part plan of the system (source: Author)

Each module in the system is designed in the shape of an aerofoil made of terracotta to imitate evapotranspiration of trees. It stores water which gradually evaporates through its surface to facilitate evaporative cooling as air flows between two modules. The aerofoil shape is assembled to create a nozzle effect that creates a pressure difference to allow better airflow.

For a comprehensive evaluation of the passive design strategies, we have considered different cases, pertaining to different building typologies and project briefs. Two of those cases are described in this paper: the first is a residential project in Hyderabad, and the second is a commercial complex at Raipur, both in composite climate. The selection of these cases is based on the fact that they belong to a similar climatic classification, but have differences in the project requirements and briefs, making them comparable. For Case 1 (Residence), the overall building envelope (facades) was adapted to the climatic context using shading devices, and optimising material specifications. In the second case, variations were introduced in the passive cooling facade as there was a lack of flexibility in specialising other envelope materials.

The evaluation parameters for both the cases considered overall temperature difference, energy consumption, and cost savings. Parameters specific to certain aspects of both cases were also evaluated: in the context of the Commercial Complex, performance in different scenarios- with ventilation, with evaporative cooling, with the shading only, etc. were considered to evaluate the monthly energy consumption and savings, carbon footprint and Energy Performance Index (EPI). Whereas, for the residential project, the paramount goal was to realise thermal comfort of the spaces throughout the year.

2.2. Evaluation

The studies are both located in regions where buildings predominantly receive maximum sun-exposure from the south and west facade; therefore the second skin is considered in these cardinal directions.

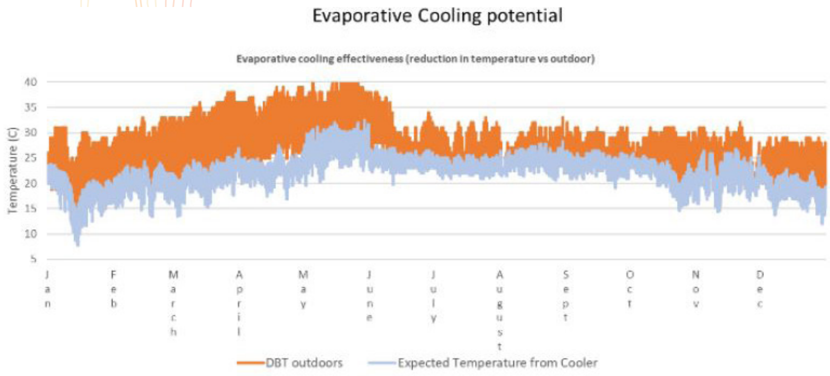
2.1.1. Case 1 | Residence in Hyderabad

Project Type: Residential
Location: Hyderabad,
Telangana Climate: Composite [10]
Built up Area: 2000 sqft.
Facade orientation: Aerofoils proposed on West and South Facades

Figure 3: Rendered View of the Hyderabad Residence

Plotting the average diurnal variations against wet bulb depression in the region gives us the potential of evaporative cooling in the region.

Upon close investigation, feasibility of evaporative cooling, as described in the image above, 33% of time of the year (approx. 2931 hours) passive cooling strategies such as Aerofoil facade have the potential to reduce the outdoor air by more than 5°C. The analysis is primarily to evaluate the potential of façade based evaporative cooling for providing comfort in Naturally ventilated or Hybrid Air-conditioned modes of operation. Three scenarios are evaluated:



Feasible hours showing more than 5C reduction in temperature

Feasible Hours	Jan	Feb	March	April	May	June	July	August	September	October	November	December
Daytime	260	249	346	342	271	153	83	1	14	178	85	207
Nightime	48	39	187	242	105	85	3	0	0	29	0	4

Figure 4: Evaporative Cooling Potential

1. AC mode to assess peak cooling load performance.

2. Naturally ventilated with Evaporative cooling,

3. Evaporative Cooling. To model the evaporative effect of the fins the model is to mimic through an Indirect Evaporative Cooler. Secondary air stream was kept the same as Primary air stream. Primary Air flow rate was calculated through Heat Load assessment assuming an AC building running on 24°C setpoint. Heat load calculations made using simulations- ASHRAE Heat balance method.

2.1.2. Case 2 | Commercial Complex in Raipur

Project Type: Commercial
Location: Raipur, Chhattisgarh
Climate : Composite [10]
Building Floor Area: 2145 sq m
Facade orientation: Aerofoils proposed on West and South Facades

Figure 5: Rendered view of Commercial Complex in Raipur

The performance of the aerofoil cooling facade system is assessed based on the following parameters:

1. Temperature Variation- between Indoors and Outdoors.

2. Cooling Load and Capital Cost savings- A lower temperature achieved through passive means translates to a reduced cooling demand. This reduces capital costs- an important factor considering the affordability of the system.

3. Building Energy Consumption- Reduced Cooling Load on buildings leads to a reduction in overall energy consumption in the building.

4. Energy Performance Index and Operational Savings.

5. Carbon Footprint- as annual and incremental savings in kgCO2e/kg

6. Water Consumption

2.3. Simulation

For both the cases, assessment of the applied strategies was carried out by simplifying the building design in Rhino 3D and analysed with the use of Energyplus on Openstudio and Honeybee (Ladybug tools).

3. Results

3.1 Case 1 | Residence in Hyderabad

The first set of assessments evaluated the impact of shading to reduce the Radiant and surface temperatures. "Fins Shading" indicates the effect using Aerofoil Cooling Facade. 3.1

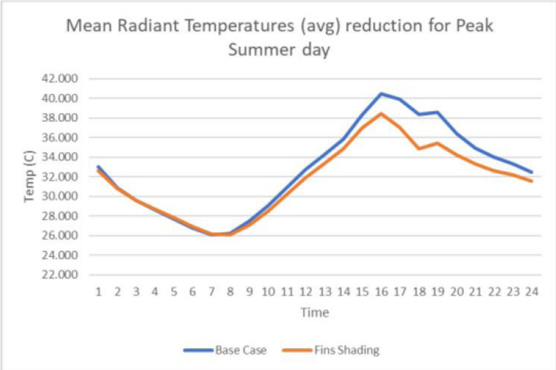


Figure 6: Average Reduction of Mean Radiant Temperatures for Peak Summer Day

The next set of iterations was performed to improve the envelope specification further to reduce the Peak Cooling loads and Average Mean Radiant Temperature. The iterations are summarized as follows:

Table 1: Reduction in Peak Cooling Loads by optimising various Building Materials

Case	Baseline	With Passive Cooling Building Façade (Shading Only)	With Glass specs (U value 3.8 W/m2k, SHGC 0.29)	With Roof Insulation (50mm XPS insulation- U value of 0.55 W/m2K)	With Wall insulation (AAC blocks 200mm- U value 0.8 W/m2K)
Peak Cooling Load (Building Level) kW	61.21	55.5085	50.99	44.69	40.59
% Reduction	0%	9.31%	16.70%	26.99%	33.69%

3.1.1. Thermal Comfort Analysis: Natural Ventilation, Passive Cooling Building Façade, and Optimized Fan Speed

A further reduction in temperatures were assessed by ceiling fan operation at 1.2 m/s fan speed. The Elevated Air speed method of ASHRAE 55 2016 [2] was used to calculate the Operative temperature. Upon Fan speed adjustment the hot hours diminished with the use of Ceiling fans at 0.9-1.2m/s. Adding and optimising operative schedules of ceiling and exhaust fans, along with Aerofoil Cooling facade and optimized construction materials, the comfort is achieved for 40.2% hours of the year. About 32.1% of the year is 'humid', 7.6% is dry, 15.4 % is 'cold', while 4.6 % of it is 'hot'.

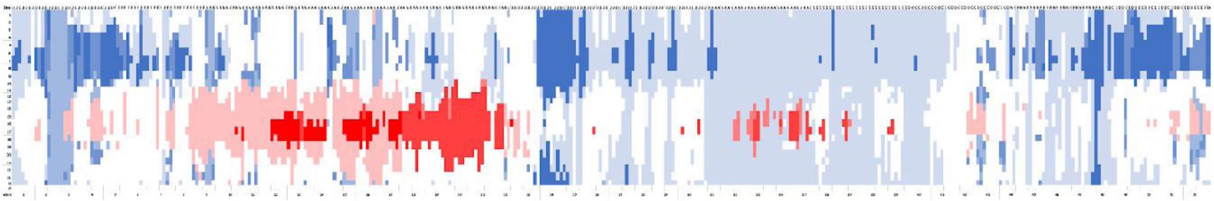


Figure 7: Final Comfort Conditions with Evaporative Cooling and Natural Ventilation

A comparison is also made on the Mixed mode band where all bedrooms are considered as Air conditioned. The perception of comfort in the evaporative cooled and natural ventilation is kept equating with the Naturally ventilated comfort band of IMAC.

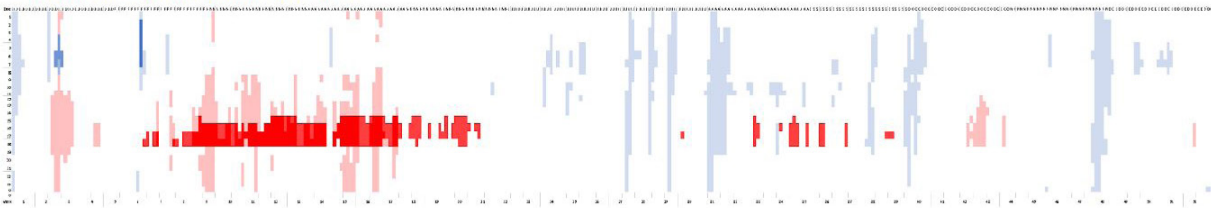


Figure 8: Comfort Analysis in the case of Mized Mode (Passive Cooling with AC)

The result of combining the mixed-mode operations (Passive Cooling with occasional use of Mechanical AirConditioning) was achieved of 85.5% of comfort hours.

Table 9: The Comfort, Energy and Cost assessment comparison for both the Air-Conditioned and Mixed Mode (AC+NV) and Evaporative Cooling with Natural ventilation mode.

		Evaporative Cooling + Fans + Natural Ventilation	Hybrid Mode (EVAP + AC + NV)	Air-Conditioned Mode
Comfort Assessment	Comfort Band	Natural Ventilation	Mixed Mode	Mixed Mode
	% reduction in comfort hours	29.51%	3.81%	0%
Capital Cost Assessment		Rs. 97, 472	Rs. 4,42,472	Rs. 4, 22, 472
Energy Consumption	EPI (kWh/m@)	52.61	86.79	98.44
	% of Reduction	46.55%	11.84%	
Water Consumption	Water (L)	93, 636	58,739	0
Operational Cost Assessment	Annual Running Cost* (at Rs 8 per unit energy and Rs 30 per Kl of water)	Rs. 82, 423.08	Rs. 1, 33, 096.07	Rs. 1, 48, 963. 84

3.2 Case 2 | Commercial Complex in Raipur

3.2.1 Average Monthly Temperature of the Interior

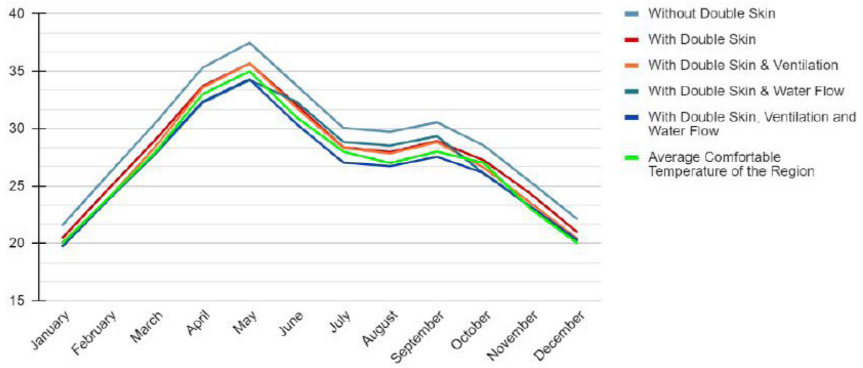


Figure 9: Average Monthly Temperature Variation

The temperatures throughout the year in the case of the building without any double skin is constantly 2-5°C higher. For the month of May the temperature rises to 37.5°C without double skin, in contrast to the building when treated with double skin, ventilation and waterflow experiences a temperature of 33°C.

Table 2: Cooling Load, Cost Savings and Energy Savings for Case 2: Commercial Complex in Raipur

	Without Double Skin (Base Case)	With Double Skin	With Double Skin & Ventilation	With Double Skin & Water Flow	With Double Skin, Ventilation and Water Flow
Total AC Tonnage	34.5	30.8	28.1	28.8	26.8
Capital Cost Savings	-	11%	18%	16%	22%
Operational Savings	-	15%	20%	26%	30%

3.2.2 Energy Performance Index (EPI) & Carbon Footprint

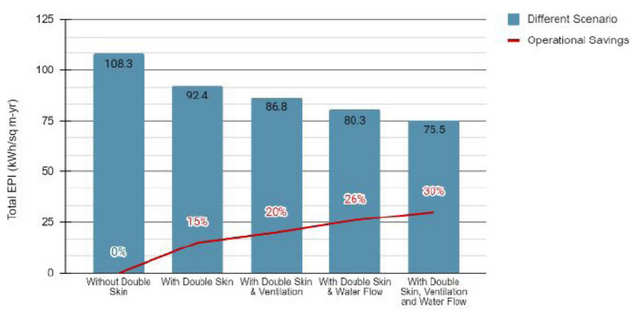


Figure 10: EPI in different Scenarios (source: author)

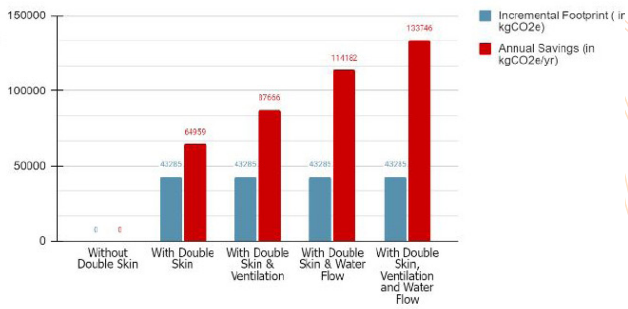


Figure 11: Annual Saving for Scenarios in kgCO2e/yr (source: Author)

The EPI further drops to 86.8 kWh/m²-yr and 80.3 kWh/m²-yr for facade with double skin with ventilation and double skin with waterflow, respectively. For scenario, with double skin, ventilation and water flow the EPI is the lowest at 75.5 kWh/m²-yr. Annual savings in carbon emissions observed is 133746 kgCO_2e/yr

4. Discussion

The resultant cooling system along with passive design strategies, has been shown to have a considerable effect on the building systems. For Case 1 (Residence in Hyderabad), it reduced the operational energy consumption by as much as 46.55% while delivering 80.49% comfortable hours. The Passive Cooling Skin is designed to also be effective as a shading device, thus being useful in humid conditions as well (making it better when compared to general evaporative cooling solutions which rely solely on hot and dry conditions). This feature also increases the adaptability of the system in areas with a shortage of water.

In Case 2 (Commercial Complex, Raipur) it resulted in an operational cost savings of up to 30% (table 3). The second skin also reduced the cooling load on the air conditioning system installed in the building by as much as 22% (table 3). It is notable that these results were obtained when the part of the south and west facades was not covered with the second skin, this was a deliberate decision on the part of the designers to leave some room for balancing the aesthetic needs of the project. The performance of the system is likely to enhance if the facades are fully covered.

4.3 Future Explorations

Further explorations for such strategies and passive cooling façade systems are being carried out, ranging from material specifics in terms of properties or possible additives, treatment of water and enhancement of its circulation system. Further explorations for terracotta products in specific, such as its symbiosis with moss and other organic growth and their subsequent impact on air quality are also being explored.

5. Conclusion

Building facades can be as much of a science as art. By integrating passive design strategies with thoughtful building practices, the research proves that it is possible to achieve comfortable living conditions without (or through minimal) use of mechanical cooling methods such as RACs. With conscious material choices with less embodied energy, proper orientation, and ventilation strategies, significant reduction in the building cooling loads, and the operational carbon footprint is observed.

Owing to practical constraints like site configuration, efficiency in utilization of space, design decisions etc., it might not be possible to always manage the best orientation in most of the buildings. With vertical fins, it is possible to design the best orientation at a micro level in building envelopes.

The future of space cooling in buildings will benefit by using efficient passive cooling envelopes that can reduce the heat gain into the buildings. Use of evaporative cooling integrated into building skins further enhances the performance of the buildings as seen in the results. Huge forest covers are lost in urbanization. Is it wishful thinking to imagine a future where buildings can perform the functions of a tree in a forest? Building Envelopes combined with biophilic solutions have tremendous potential to make up for these losses and creating sustainable and resilient habitats in our cities, focus on responsible and sustainable use of resources and energy. Such solutions can help mitigate climate change by reducing the dependency on energy intensive and refrigerant based cooling solutions.

6. Acknowledgements

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Role of urban morphology in enhancing outdoor thermal comfort: A case of Mumbai

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Abstract

In recent years, the city of Mumbai has been experiencing the pressing challenge of urban heat islands, affecting the thermal comfort of its high-density urban environment, impacting both air and surface temperatures. The Intergovernmental Panel on Climate Change (IPCC) projected that climate change would adversely affect 27 million people in Mumbai. Understanding the intricate relationship between the built environment and its influence on microclimates and thermal comfort was imperative for creating climate-sensitive designs. This paper investigated the role of urban morphology in improving the thermal comfort of a typical neighborhood in Mumbai. The analysis was based on simulations conducted using ENVI-met, a 3D urban climate modeling tool.

The research aimed to comprehend how open spaces, aspect ratio, setbacks, and plot boundary conditions within the neighborhood affected outdoor thermal comfort. The objective was to underscore the significance of urban designers and planners in assessing the impact of built environments on microclimates and leveraging microclimatic insights for the design of public spaces. Air temperature, relative humidity, wind speed, and mean radiant temperature were measured at 15 locations within the neighborhood, Matunga east, and its primary street in February 2023. The recorded data were used to validate the Envi-Met model . Two distinct scales were analyzed: neighborhood-level and plot-level iterations. Neighborhood-level iterations focused on block-level modifications, while plot-level iterations examined street and boundary conditions. Each iteration was evaluated using EnviMet to assess changes in thermal conditions relative to the current site conditions (Base case). The analyses were conducted for the critical summer month (May). The study ultimately revealed that the introduction of road networks in prevailing wind directions and the incorporation of green open spaces within the urban fabric could reduce overall heat stress duration from 12 hours to 6 hours. Smaller-scale interventions, such as 50% porous pavements and strategically placed trees, also yielded positive outcomes. This research aspired to provide urban planners with a comprehensive framework that integrated outdoor thermal comfort as a pivotal aspect in the design of future urban landscapes.

Keywords - Outdoor thermal comfort, Climate resilience, Urban morphology,

1. Introduction

In the realm of urban design and planning, the intricate relationship between built environments and their impact on microclimate plays a pivotal role in shaping the quality of life within cities. The configuration of urban neighborhoods, with their diverse geometries and spatial arrangements, exhibit a profound influence on the local thermal environment. Densely packed urban fabrics can induce heat islands by obstructing solar radiation and diminishing wind speeds. These urban geometries, characterized by parameters like the sky view factor and height-to-width ratio, dictate the openness of street canyons and define the heat exchange dynamics in open spaces. (Dayi Lai). The implications of built geometry on air temperature are starkly evident in studies conducted in various cities worldwide. In Fez, Morocco, a deep canyon with a high aspect ratio of 9.7 was found to have 6 K lower daytime air temperatures than a shallow canyon with an aspect ratio of 0.6 (Johansson, 2006). Similarly, in Dhaka, Bangladesh, a study demonstrated a maximum temperature difference of 6.6 K when comparing shallow and deep canyons with sky view factors (SVF) of 0.51 and 0.13, respectively (Kakon et al.,2009). This underscores the intricate correlation between urban geometry and microclimates. Wind patterns, a vital aspect of urban microclimates, are also linked to the built environment. The configuration of buildings exerts a significant decelerating effect on wind speed in urban areas. This can be seen in the case of Shanghai, with a 10% increase in SVF, the pedestrian-level wind speed increased by 8% (Yang et al.,2013). The direction of wind flow also affects the ventilation of urban canyons, with perpendicular flow creating vortices that limit wind speed. In contrast, oblique flow generates a helical vortex that funnels the wind along the street. To optimize ventilation in high-density cities Ng (2009) recommends keeping the angle between the street and flow orientation below 30°.

Transitioning to the role of green spaces in urban planning, which hold equal significance in enhancing urban microclimates and the overall well-being of residents. Open spaces, parks, and natural features provide essential relief from the built environment and play a crucial role in creating a sustainable and livable urban ecosystem. Parameters like size, location, and vegetation abundance define the functionality and environmental benefits of these spaces. The positive impact of vegetation on air temperature is well-documented. Trees, through transpiration and shading, effectively lower air temperatures. Studies show that increasing tree coverage by 33% can lower air temperature by 1 K in Hong Kong (Ng et al.,2012). In Athens, a "green atrium" with high tree cover and porous surfaces had a Tmrt approximately 8 K lower than a building atrium, according to Charalampopoulos et al. (2013). Planting trees at 6-9m intervals on 50% of building setbacks can result in a 12°C reduction in PET and a 18°C reduction in Tmrt values, with a 3-hour decrease in extreme heat stress duration. This strategy improves thermal comfort and reduces building heat gain (Rajan and Amirtham 2021). Green roofs can also lower air temperature by 0.3 to 3 K on a city scale. However, the pedestrian-level cooling effect varies with building height (Santamouris, 2014).

Oke et al. (2017) conducted studies that showed how trees in urban areas affect airflow by increasing surface roughness and creating drag. Trees, being porous, cause minor pressure differences and create smooth changes in wind speed, unlike solid buildings. Multiple studies showcase that trees can reduce wind speed in urban areas. For instance, four sidewalk trees were found to decrease wind speed by 51%, according to measurements conducted by Park et al.,(2012) at a scale model site. Heisler, (1990) analyzed the wind speed in urban areas with and without green cover and found that 77% tree coverage increased the wind-speed reduction from 22% to 70%. The Chicago Urban Forest Climate Project, (Heisler et al.,1994) reported that trees could reduce wind speed by 90%. Vegetation improves the microclimate by reducing radiation and lowering the air temperature, despite decreasing wind speed. Trees, which can provide shading, are more impactful than grass. Dense trees and grass can reduce MRT by 7°C and PET by 4°C in Dar es Salaam, Tanzania. Additionally, (Qin et al.,2013) the study in Shanghai Botanical Garden found that people consider the color of street greenery to be an essential aspect of their overall satisfaction with the surrounding vegetation.

As the global population continues to urbanize, the importance of sustainable and adaptable urban environments becomes increasingly evident. Urban designers and planners are tasked with the critical responsibility of harmonizing built and unbuilt spaces to create resilient and livable cities. The effects of microclimates on thermal comfort and outdoor activities cannot be underestimated. In the context of climate change and evolving urban landscapes, designing for enhanced public spaces is not just a luxury but a necessity to ensure the well-being of urban dwellers. The interplay between urban geometries, green spaces, and microclimates shapes the fabric of our cities. Understanding these dynamics and leveraging them through urban design and planning strategies is essential in creating vibrant, comfortable, and sustainable urban environments. As the global population continues to surge and cities become hubs of growth. Addressing the challenges posed by climate change and ensuring the well-being of residents through thoughtful design will be central to shaping the future of urban living. The same can be seen in Mumbai, the rapid urbanization has resulted in increased temperatures.

The study conducted in Mumbai (Bhanage, 2022), indicates that the temperature would increase by 1.41°C due to future urbanization. And by 2050, the total number of hyperthermal hours will increase by 3–5 hours per day over the newly urbanized area. However, if we adopt a mitigation strategy, then this rise would be restricted to 0.90°C. In the study conducted for the urban heat island effect in Delhi and Mumbai, higher urban heat islands were measured in Mumbai. (Grover, 2015) In Mumbai, the absence of tree cover along with other factors has led to increased land surface temperatures. With urbanization , the difference between maximum and minimum land surface temperature (LST) declined in Mumbai city from 30.04°C in 1991 to 20.07°C in 2018. During the last three decades, Rahaman et al. (2020) observed a threefold increase in areas with a higher magnitude of LST in Mumbai because of persistent growth in urban areas.Therefore the present study aims to explore the role of urban parameters in enhancing the comfort conditions outdoors thus improving the standard of urban living.

2. Methodology

The present study analyzes the relationship between various urban parameters and outdoor thermal comfort. Through the literature review, urban parameters such as open spaces, aspect ratio, setbacks, and boundary conditions were identified which significantly influenced the outdoor thermal comfort. Previous research had validated the methodology employed by EnviMet, particularly in a study by Ayyad and Sharples (2019) that demonstrated a high correlation between wind speed and air temperatures.

The methodology adopted in this study comprises five steps.

1. Mapping of urban built form: The built environment characteristics of the chosen neighborhood were mapped in detail to analyze the impact of the four identified urban parameters.

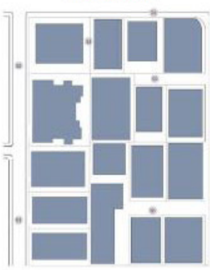
2. Field measurements: Field data on air temperature, relative humidity, and wind speed were recorded at 12 locations in the chosen neighborhood on a typical winter day (2nd February,2023).

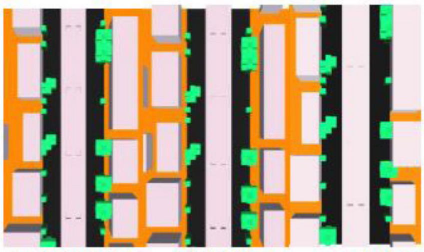
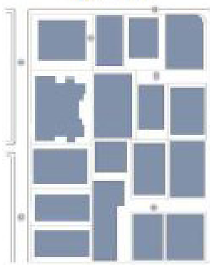
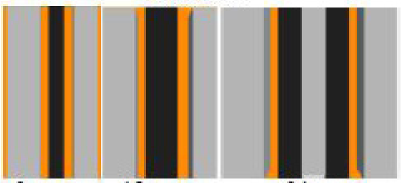
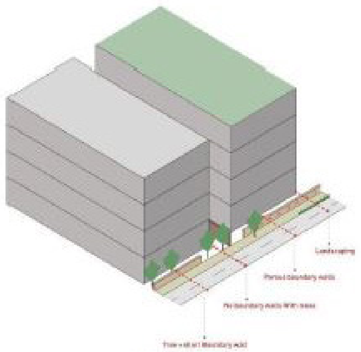
3. Envi-met simulation & Validation: Built environments around each location were mapped with a plan and section for a 100m x 100m site. The built environment characteristics around each measurement location were modeled in a 50 x 50 x 40 grid in Envi-met-lite (version 5) with each grid representing 2m. The model was then simulated using the field measurements and wind data from Matunga station located closer to the neighborhood. The simulation outputs were compared with the onsite field measurements for validation. The study revealed a higher correlation (R2 value of 0.75) hence taken forward for further iterations.

4. Urban parameters and thermal comfort analysis: After validation, simulations were done for a typical summer day (20th May 2022) and the median meteorological and comfort parameters were analyzed for three time periods in a day. Further, different proposed iterations of the identified parameters (open spaces, aspect ratio, setbacks, and boundary conditions) were modeled from macro to micro scale and simulated . Based on the analysis, the best-case iterations of open space were further analyzed for varying aspect ratio iterations until noticeable improvements in comfort conditions were observed. Table 1 shows the iterations considered for the study. Similarly, other parameters were also analyzed. The analysis focussed on five output parameters: wind speed, air temperature, relative humidity, mean radiant temperature, and PET. Rayman Pro was used to analyze PET with personal parameters of a 1.75m tall individual with 75kg weight, and 80W metabolic rate. A CLO value of 0.6 was considered for the study.

5. Recommendation: Based on the analysis of results, Urban design guidelines were recommended and a structure to incorporate the research in implementable ways was suggested.

Table 1: Neighborhood and plot level iteration considered for analysis

Scales	Iteration	
Base case 	-	-

Neighborhood Level 	**S1 Size and location of green open spaces**	S1.1 A central open space S1.2 Fragmented greens on the edges S1.3 Fragmented greens within the neighborhood
 Existing FOS 4.5 FOS 0 FOS	**S2 Aspect ratio 34 meter wide street**	S2.1 Aspect ratio 0.9 with existing Front Open Space (FOS) S2.2 Aspect ratio 0.6 with 4.5m FOS S2.3 Aspect ratio 0.8 with 0m FOS All scenarios have flyover running centrally in the street and have fragmented building blocks.
Base case 	-	-
Neighborhood Level 	**S1 Size and location of green open spaces**	S1.1 A central open space S1.2 Fragmented greens on the edges S1.3 Fragmented greens within the neighborhood
Plot Level  9 meter 18 meter 34 meter	**S3 Side Setbacks and road widths**	S3.1 road width 9 meter continuous built S3.2 road width 18 meter continuous built S3.3 road width 34 meter continuous built The 34 meter wide street scenario has a flyover running centrally.
 Plot Level	**S4 Boundary conditions :** (The interface between the built and street which includes, margins , footpath, materiality etc) The pavement material assigned was granite single-stone pavement along with low LAD deciduous trees, and this iteration was simulated only for peak hours from 12-4 pm.	S4.1 had compound walls as per the DCR and street design guides to bifurcate the street into different parts with vegetation on the footpaths. S4.2 replaced the compound wall with trees to create barriers S4.3 had a porous compound wall along with trees in the setback area.

3. Results

The relationship of various urban parameters from the neighborhood level to the plot level was analyzed to identify its significance in modifying the microclimatic and comfort parameters of each iteration.

3.1 Size and location of green open spaces

Micro climatic parameters: Fig.1 shows the microclimatic variation of three iterations (S1.1, S1.2 & S1.3). The analysis revealed that introducing new greenery in the neighborhood (S1.1) resulted in a 1°C decrease in air temperature compared to the base case. The reduction may be attributed to an increase in average wind speed of 1.2m/s throughout the day, which helps in maintaining a comfortable environment, especially in humid conditions. The maximum temperature was recorded at 16:00 hrs, with 33.6°C, while the minimum temperature was recorded at 10:00 hrs with 28.7°C. It was also seen that except for air temperature and wind speed, variation in other parameters was minimal. The surrounding built forms created a tunnel effect from all four edges, which channeled the wind into the central space. It was observed that even though open spaces were placed at the periphery of the neighborhood (S1.2), as they were shaded and parallel to the wind direction, the variation in air temperature was minimal. **Comfort parameters:** The study revealed that the mean radiant temperature (MRT) values varied significantly during the peak hour of 14:00, with a drop from 59°C (base case) to 55.8°C, 57°C, and 58°C in iterations S1.1, S.1.2, and S1.3, respectively, indicating that green open spaces have a positive impact in reducing the urban heat island effect and improving human comfort in urban areas. PET values revealed a maximum reduction of 7°C in S1., maintaining moderate heat stress levels for six out of the twelve hours, ranging from 29-35°C. S1.1 resulted in an overall reduction of 3.2°C in MRT. The highest MRT recorded was 58.6°C at 15:00 hrs, while the lowest was 23.6°C at 21:00 hrs.

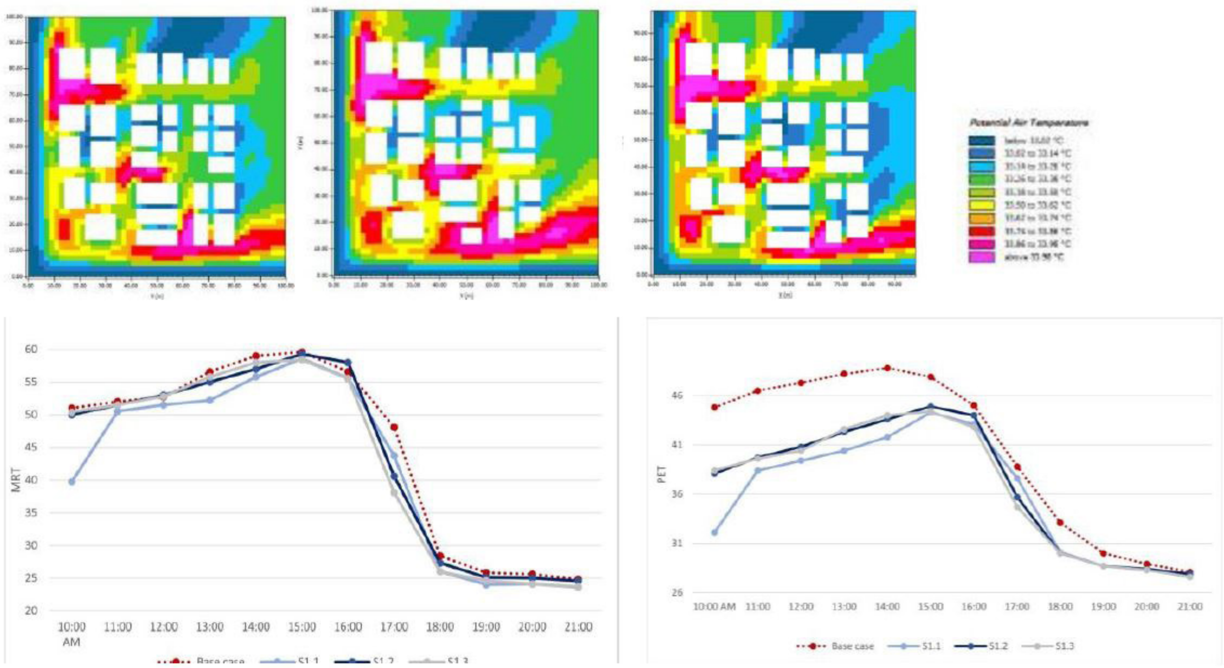


Figure 1: Air Temperature variation in S1 during peak hours (14:00) along with PET and MRT graphs comparing S1 to base case

3.2 Aspect ratio

Micro climatic parameters: S2.1 showed 0.3°C increase in air temperature compared to base case whereas S2.2 and S2.3 saw 0.1°C decrease than base case. In all three cases, there was a decrease in wind speed compared to the base case. The wind speed varied in all three cases from 1.15 m/s to 1.05 m/s. The humidity increased in all three iterations compared to the base case. Overall, 0.6 (S2.2) and 0.8 (S2.3) aspect ratio in the 34-meter-wide street iteration showed improved microclimatic parameters. **Comfort parameters:** MRT reduced considerably during the peak hours from 61.9°C in the base case to 48.4°C, and 49°C in S2.2 and S2.3. PET ranges for iterations S2.2 and S2.3 were decreased from extreme heat stress to strong heat stress. The decrease in MRT and PET values can be because of the change in the aspect ratio. Decreased MRT values were recorded in S2.2 with an aspect ratio of 0.6.

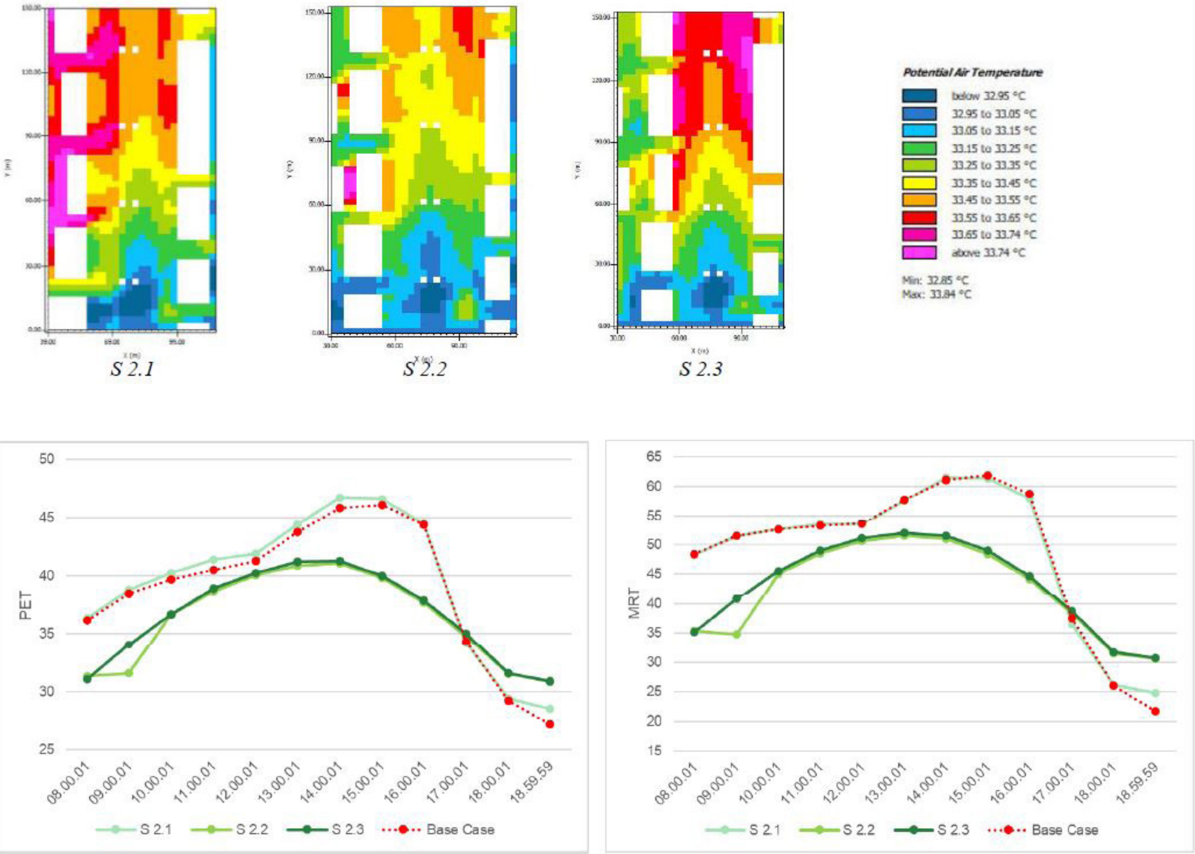


Figure 2: Air Temperature variation in S2 during peak hours (14:00) along with PET and MRT graphs comparing S2 to base case

3.3 Setbacks and road widths

Micro climatic parameters: Fig.3 shows the microclimatic changes in the different street widths with continuous building blocks. The analysis revealed that S3.2, S3.3 have recorded 1.6 m/s wind speeds which is slightly higher than the base case. The average air temperatures of S3.1, S3.2 and S3.3 were 32.4°C, 32.1°C, and 32.4°C respectively. When compared to the fragmented building blocks, S3.3 recorded slightly reduced air temperatures. Overall, changes in road widths and setbacks affect the microclimatic parameters. In the wider streets (S3.2, S3.3) with continuous building blocks, the wind speed increased while in the narrower streets, with fragmented building blocks (S2.2, S2.3) resulted in better wind speeds. This also showed that the air temperature in narrower street canyons was not reduced by side margins or by increasing pervious surfaces. The MRT values of S3.1, S3.2, S3.3 at peak time 14:00 were 54.4°C, 53.4°C, 53.2°C and PET values were 43.4°C, 41.4°C, 41.8°C respectively . The MRT in continuous building blocks(S3.2, S3.3) has significantly reduced, as compared to the fragmented building blocks(S2.2, S2.3) in both 9-meter and 18-meter streets. In

S3.1 and S3.2 (continuous building block) the peak temperature recorded was 5°C and 10°C lower than that of S3.1 and S3.2 (fragmented building block) respectively, ultimately reducing 5 hours of extreme heat stress to strong heat stress conditions. This reveals that the narrower streets work better when side setbacks are kept minimum.

The analysis of wider streets i.e. the 34-meter width (fragmented building block) iteration was more successful than the base case. The MRT and PET results of 34-meter width streets at peak time were recorded at 52.1°C and 41.6°C respectively suggesting that wider streets might act better in thermal comfort if more building frontage, side margins, and pervious surfaces were introduced. PET values of S3.3 both fragmented and continuously built have now changed from extreme to strong heat stress. The changes in material and vegetation may help lower the physiologically equivalent temperature further.

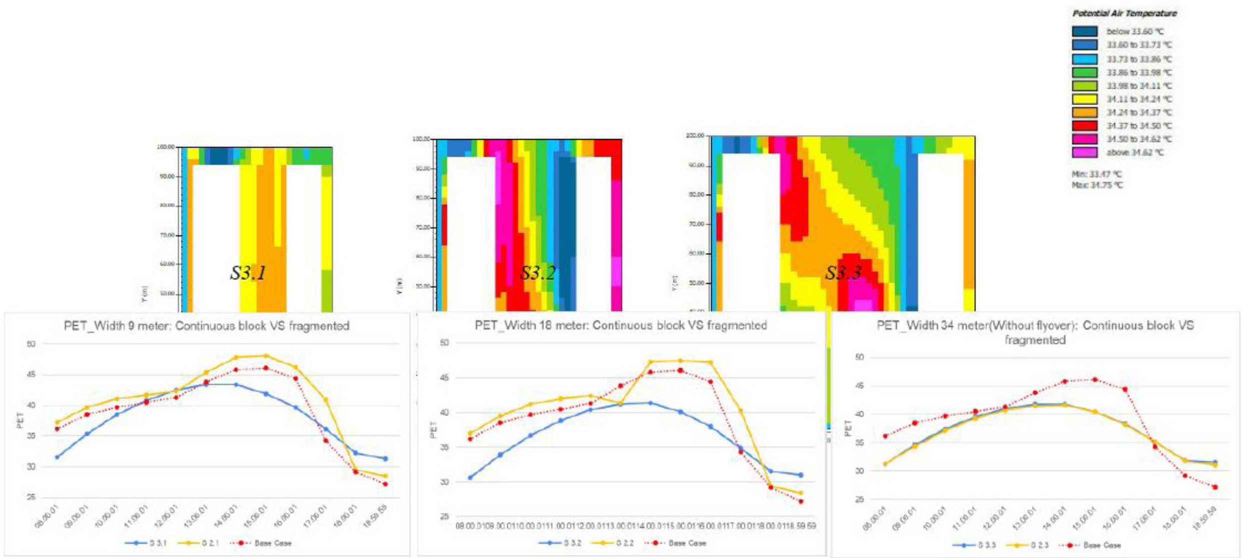
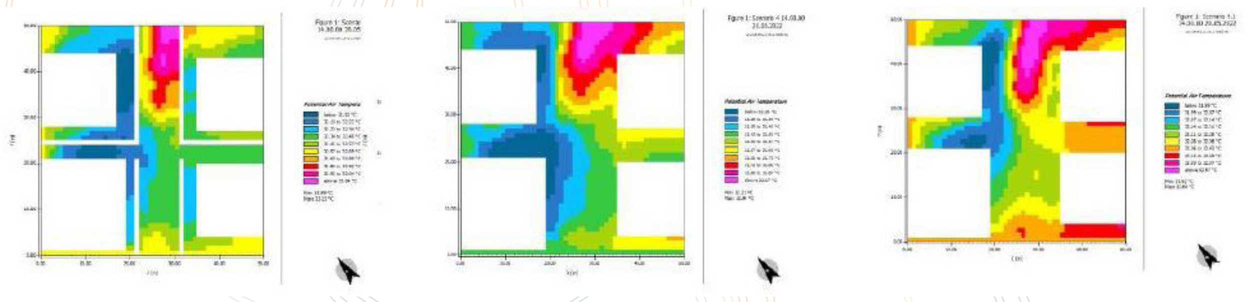


Figure 3: Air Temperature variation in S3 during peak hours (14:00) along with PET graphs comparing S3 (fragmented and continuous building blocks) to base case

3.4 Boundary conditions

Micro climatic parameters: Fig 4 reveals a substantial variation among the three iterations. As per the DCR guidelines, the air temperature values during the peak hour (14:00 hrs) were recorded as 41°C, which decreased to 36°C after the introduction of additional trees and porous compound walls in S4.2 and S4.3. An increase in relative humidity from 58% in S4.1 to 59% in both S4.2 and S4.3 was observed due to increased trees creating shade on the pedestrian walkway. However, the wind speed decreased from 1.4m/s in S4.1 to 1.2m/s in S4.3, as the trees obstructed the wind flow. MRT analysis showed a significant reduction of 10°C in iterations S4.2 and S4.3 compared to S4.1, despite having higher relative humidity values. This was attributed to increased shading by trees and an increase in pervious surface and albedo of pavement in the streetscape. PET results indicated that strategies S4.2 and S4.3 resulted in a transition from extreme heat stress to moderate heat stress during peak hours. These findings suggest that higher tree coverage can improve the pedestrian experience and contribute to the enhanced thermal comfort of users in the neighborhood.



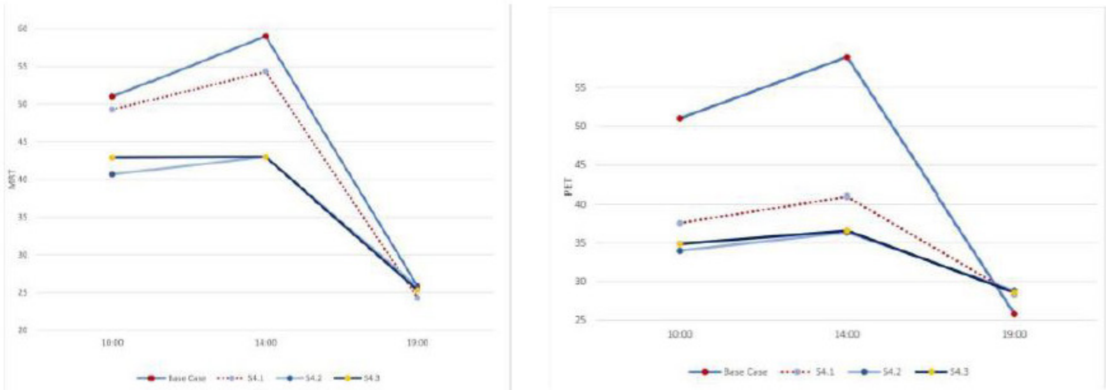


Figure 4: Air Temperature maps for S4 during peak hours (14:00) along with PET and MRT graphs comparing S4 to base case

4. Discussion :-

Impact of open space: Open spaces have been found to promote relaxation and social interaction among residents, making them an essential element of high-quality urban living. However, the literature review revealed that open spaces reduced wind speed and increased relative humidity levels within the surrounding area. Despite these challenges, introducing a large central open space comprising 10.5% of the total site area brought the neighborhood's microclimate within the moderate heat stress range for four hours out of the 12 hours analyzed. Similar results were observed when smaller, fragmented open spaces were introduced within the built fabric of the neighborhood. A study in Iran also indicated that "the changes in the geometry and morphology of the neighborhood in a constant ratio of greenspaces, water bodies, and buildings could affect the neighborhood's climate and subsequently affect their thermal comfort and satisfaction." (Ahmadi et al., 2022). Unlike the study in Iran, this study considered other parameters constant and did not introduce a water body as it would increase the humidity, especially in coastal cities like Mumbai. This suggests that multiple parameters within the open space can add to the thermal comfort of space, but what can be found through this study is that green open spaces are more effective when incorporated within the urban fabric rather than at the periphery, abutting primary or secondary roads. The study highlights the importance of providing relief points within the built environment to counteract the urban heat island effect. The introduction of new road networks within large parcels of land and open spaces can facilitate the movement of air and mitigate heat within the built environment, creating a more comfortable microclimate for residents.

Impact of aspect ratio: The study shows that the width of the street and the abutting built play a vital role in thermal comfort. The iterations with narrower streets have high shading possibilities with higher aspect ratios. The scenarios where H/W>0.6 worked better in terms of PET values. While in the wider street canyons, the smaller aspect ratio gave better results. The scenario with H/W<0.4 has worked efficiently. These findings also follow a similar trend found in other research stating that the higher the aspect ratio the lesser the PET values in the summer. (Muniz-G¨ aal et al., 2020) This finding thus concludes that the narrower streets such as pedestrian pathways, local streets, corridors, and avenues behave differently than the wider streets and need alternative recommendations for the building abutting the street.

Impact of setbacks and road widths:
The study clearly shows a strong relationship between thermal comfort with the front, side margins, and pervious surfaces of the building abutting the street canyon. The narrow streets, 9 and 18 meters revealed similar results with a drastic reduction in PET values when changes in side open spaces were made. This suggests that narrower streets work better with minimum side open spaces. A substantial drop from extreme heat street to strong heat stress for 6 hours at the peak time of the day was observed in the simulations with narrower streets and minimal side margins. The wider streets worked better in both larger side open spaces and front open spaces. The reduction of values is for 5 hours at the peak time of the day in iterations S3.2 and S3.3. This indicates that wider streets must have more pervious surfaces to reduce overall PET values. Wind speed was directly affected

by a change in the setbacks and pervious surfaces. The wind speed change was achieved in the final simulations when the side margins were altered. The 34 meter wide street recorded an increase in wind speed by 0.3-0.4 m/s and a 0.3 m/s increase was seen in the 18-meter street whereas the 9-meter street recorded reduced wind speed because of the wind shadow region created by the aspect ratio of the building. The increased wind speeds on 34 and 18 meter streets are largely because of the funneling effect that pushes the air out of the street canyon and results in overall cooling of the street. In narrower streets, the night temperatures might increase as the air will get trapped as seen in the scenario of a 9-meter street. Thus, for better wind speed with the optimum aspect ratio, the pervious surfaces need to be regulated as well to achieve thermal comfort. In wider streets, the larger setbacks will help increase the wind speed.

Impact of boundary condition: Looking at the microclimate conditions at the pedestrian level by zooming in from the macro-level iterations it was found that as per the current Mumbai DCR regulations, guidelines are related only to the height of permissible compound walls. No specific regulations are provided for a plot's street design and edge conditions. Hence, this study analyzed the impact of changing boundary conditions on the OTC of a neighborhood. Interestingly despite higher wind speeds, AT values remained constant throughout the iterations. The study observed that making 50% of the pavement porous, adding trees in setback areas, and using a porous compound wall resulted in a 10-degree drop in MRT values and a 5-degree drop in PET values, ultimately reducing heat stress in the neighborhood. Similar results were found in a study done in Chennai, which concluded that "50% of the setback area of each plot can be regulated towards a landscape with trees in the proposed new regulation, then the duration can substantially increase to moderate to no-thermal stress sensations in a given day" (Rajan & Amirtham, 2021). This suggests that simple changes to boundary walls, pavement choices, and adding trees can significantly improve the microclimate conditions of a neighborhood. Moreover, these are small but crucial decisions that are generally ignored in the regulations.

5. Conclusion

The paper underscores the significance of adopting an integrated approach to neighborhood development, wherein each successive step synergistically reinforces the previous one. Initially, the alteration of the neighborhood layout's subdivision was focused on enhancing wind speed. The outcomes demonstrated that reconfiguring the road networks to align with the prevailing wind direction generated a wind tunnel effect. This, in turn, facilitated the dissipation of accumulated heat within structures, effectively reducing the neighborhood's overall heat stress duration from 12 to 6 hours. Subsequently, an analysis of varying open spaces at the front and sides of the main street underscored that wider streets, measuring 34 meters, exhibited superior performance when complemented by such open spaces. Additionally, the study revealed that augmenting the proportion of pervious surfaces along the 34-meter street resulted in a transition from extreme to strong and moderate heat stress levels. The third phase of the research focused on investigating the impact of incorporating open green spaces within the urban fabric. Notably, the study demonstrated that integrating green open spaces within the neighborhood fabric led to a substantial 7-degree Celsius reduction in heat stress, particularly when compared to peripheral spaces adjacent to roads. This is similar to the findings drawn in research by Grover, (2015), wherein lesser green cover resulted in increased land surface temperatures in Mumbai.

Lastly, smaller-scale interventions, including implementing 50% porous pavements, strategically placing trees in setback areas, and employing porous compound walls, yielded impressive outcomes. These measures collectively contributed to a noteworthy decrease of 10 degrees Celsius in Mean Radiant Temperature (MRT) values and a 5-degree Celsius drop in Physiological Equivalent Temperature (PET) values. Consequently, these modifications effectively mitigated heat stress within the neighborhood. In summary, the comprehensive study revealed that the amalgamation of strategies on both at the neighbourhood level and the plot level resulted in a significant alleviation of heat stress at the site. This underscores the necessity of adopting a holistic approach to crafting comfortable urban neighborhoods. The study further presents the practical strategies and methodologies employed, forming a comprehensive framework that can serve as a step-by-step manual for developing thermally sensitive neighborhoods that prioritize pedestrian well-being.

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Onsite Thermal Energy Storage for Efficient and Resilient Air-conditioning in Indian Buildings

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Abstract

Thermal energy storage (TES) systems enable storing energy during off-peak hours (low demand) and release it in peak hours (high demand), improving the energy efficiency and resiliency of buildings. We present a simulation methodology to assess the performance of the TES system integrated with heating, ventilating and air-conditioning (HVAC) systems. We use a validated thermal load profile of the building in a detailed thermodynamic simulation framework to assess the feasibility of TES systems. TES coupled with HVAC systems can help improve the capabilities of building energy simulation platforms by enabling simulations of load shaving potential of TES systems and selecting the optimal material for storage. Our model can analyse the feasibility of TES for any residential or commercial building, which will help identify the most impactful categories for implementing energy storage. Our results show a load-shaving fraction of up to 38% can be achieved for a medium office building in Ahmedabad. It will help reduce the size of the vapor compression system, leading to a significant reduction in the initial capital investment and demand charges.

Keywords - thermal energy storage, building energy efficiency, load shaving, grid-interactive

1. Introduction

Rapid urbanization in India and many parts of the world will lead to a drastic increase in the demand for energy to provide comfortable residential and commercial spaces to the masses. Building energy consumption generates ~20% of the total greenhouse gas emissions. We must sustainably meet this energy demand to prevent further environmental damage while ensuring better access to clean energy and comfortable living conditions for the masses. About 50% of the total building energy consumption is due to cooling and heating (Fig. 1) [1]. Moreover, buildings cause peak demand periods that coincide with the need for cooling or heating. Peak demands strain the grid and can lead to catastrophic brownouts and blackouts. Therefore, thermal energy storage (TES) for buildings is an attractive idea to store energy in a form that can be readily used.

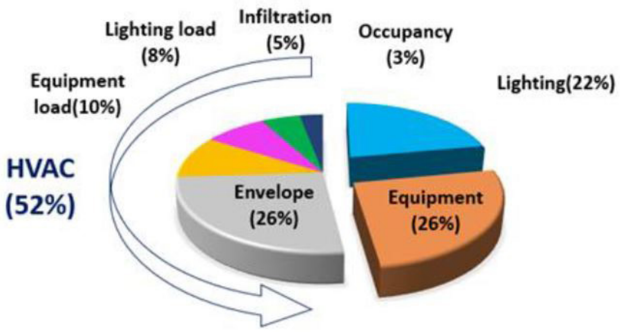


Figure 1: Components of energy consumption in buildings

Thermal energy storage (TES) systems enable storing energy during off-peak hours (low demand) and release it in peak hours (high demand), improving the energy efficiency and resiliency of buildings [2,3]. Before implementing energy storage technologies, estimating the impact on energy efficiency, resiliency, and demand response capabilities that the proposed solution can provide is essential. The available building energy simulation programs have limited capabilities to evaluate the potential of TES in buildings comprehensively [4]. The existing models have been developed using empirical models of commercial energy storage systems [5]. Therefore, the existing platforms do not allow changing the operating conditions or the storage materials. In this paper, we present a simulation methodology to assess the performance of the TES system integrated with the HVAC system. We use a validated thermal load profile of the building in a detailed thermodynamic simulation framework to assess the feasibility of TES systems. It can help improve the capabilities of building energy simulation platforms by selecting the optimum storage capacity and material.

2. Methods

2.1 System Description

We developed a detailed thermodynamic model of a vapor compression system (VCS) consisting of an air-cooled chiller coupled with a phase-change TES module based on the energy balances in each component using an overall conductance (UA) – log mean temperature difference (LMTD) method (Fig. 2). The chiller is selected to operate at a fixed cooling capacity. During the charging phase, the excess capacity of the chiller available after meeting the building cooling load is used to store energy in the TES module by freezing the material. During the discharge phase, the TES material is melted to provide balanced cooling to the building.

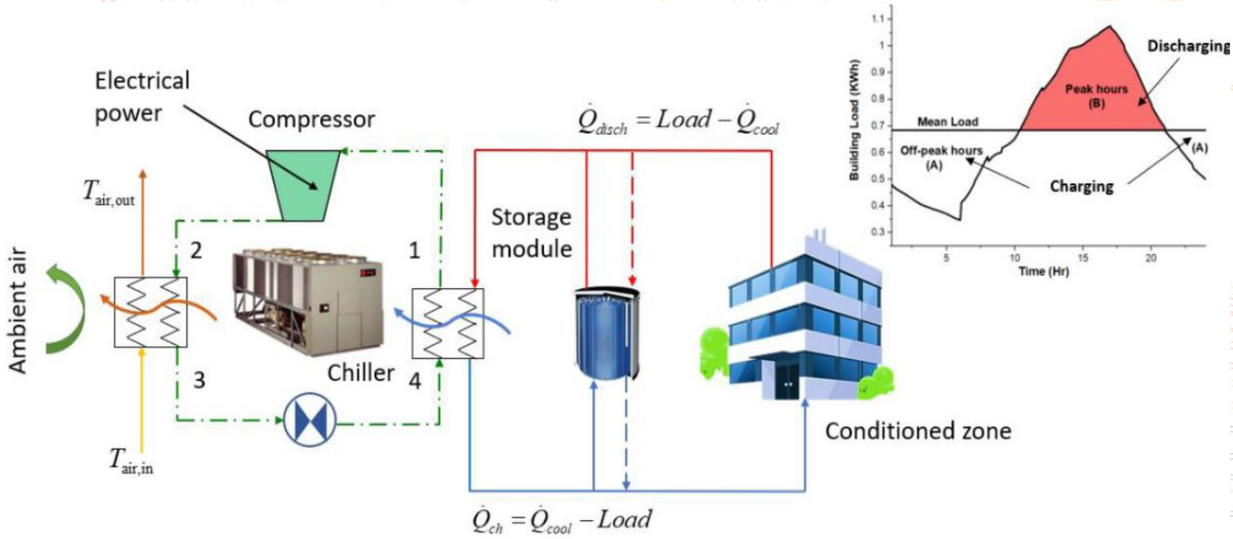


Figure 2: Schematic layout of the vapor compression cycle coupled with a TES module

2.2 Modeling Assumptions

TES is an inherently unsteady process. Therefore, for an overall system-level analysis, we simplified the dynamic heat transfer process occurring in the TES-integrated VCS by using the following assumptions:

- VCS is modeled as a quasi-steady system with all the transient effects limited to the TES module.
- Condensers and the evaporators operate under isobaric processes with negligible pressure drop.
- Storage material is always at its transition temperature, so there is no sensible heat gain or loss.
- Evaporator and condenser operate with a closest approach temperature (CAT) of 5°C.

2.3 Working Fluid and Storage Materials

We performed the analysis using R410A refrigerant in an air-cooled VCS. A propylene glycol (PG)-water mixture of 25% by weight PG is used on the evaporator coupling fluid side. We selected water/ice as the storage material with a transition temperature of 0°C and enthalpy of phase change of 336 kJ/kg. The model allows for using any phase-change material with a specified phase-change temperature and enthalpy.

2.4 Governing equations

We modeled the VCS cycle for an initial baseline condition (standard AHRI 210/240 rating condition [6]) with the above mentioned assumptions using a 10-coefficient compressor map for available compressors using Danfoss CoolSelector2® software [7]. We used Engineering Equation Solver (EES) to model the system [8]. The compressor model uses the saturated refrigerant temperature conditions in the condenser and evaporator to calculate the mass flow rate of the refrigerant and the compressor power. We selected separate compressor maps for the charging and discharging phases depending on the phase change temperature of the module and the standard cooling fluid supply conditions.

The baseline model helped determine the size (overall conductance, UA) of the condenser and evaporator for a design day. The compressor map dictates the system performance by providing the refrigerant mass flow rate and the compressor power output based on the operating conditions. Figure 2 shows the state points and components of the VCS-TES cycle. The energy balance equations for the condenser refrigerant and air stream are:

$$\dot{Q}_{cond} = \dot{m}_{ref}(h_{ref,2} - h_{ref,3}) \quad (1)$$

$$\dot{Q}_{cond} = \dot{m}_{air}C_{p,air}(T_{air,2} - T_{air,3}) \quad (2)$$

where,m_{ref} and m_{air} denote the mass flow rates of the refrigerant and the air, respectively, and href and Tair indicate the specific enthalpies of the refrigerant and air temperatures at different state points. The LMTD value is calculated across the condenser to determine the overall conductance, which is fixed for further analyses.

$$\dot{Q}_{cond} = UA_{cond}LMTD_{cond} \quad (3)$$

$$LMTD_{cond} = \frac{\Delta T_2 - \Delta T_3}{\ln \frac{\Delta T_2}{\Delta T_3}} \quad (4)$$

Here, ΔT2 and ΔT3 correspond to the temperature difference between the refrigerant and the air streams at the entry and exit of the condenser, respectively.

On the evaporator side, we calculated the volumetric flow rate of the coupling fluid (25% w/w PG-water) based on the cooling required as specified by AHRI 210/240 standard. We set the initial coupling fluid supply conditions with an approach temperature of 5°C with respect to the phase change temperature of the TES material during the charging phase. For the discharging phase, we implemented standard conditions. Using energy balance equations for the refrigerant and the coupling fluid, we calculated the overall conductance of the evaporator.

$$\dot{Q}_{eva} = \dot{m}_{ref}(h_{ref,1} - h_{ref,4}) \quad (5)$$

$$\dot{Q}_{eva} = \dot{m}_{CF}C_{p,CF}(T_{CF,1} - T_{CF,4}) \quad (6)$$

where m_{CF} denotes the mass flow rate of the coupling fluid, and TCF indicates the coupling fluid temperatures. The LMTD value is calculated across the evaporator to determine the overall conductance:

$$\dot{Q}_{eva} = UA_{eva} LMTD_{eva} \quad (7)$$

$$LMTD_{eva} = \frac{\Delta T_1 - \Delta T_4}{\ln \frac{\Delta T_1}{\Delta T_4}} \quad (8)$$

ΔT1 and ΔT4 correspond to the temperature difference between the refrigerant and the coupling fluid at the evaporator inlet and exit, respectively.

2.5 Thermal Energy Storage Module

For the TES, we formulated the charging and discharging phases based on the required cooling demand, the chiller cooling capacity, and the state of charge (SOC) of the system. The state of charge is the ratio of the quantity of storage material available at any given time to the total capacity of the module.

During the charging phase, the chiller operates at a capacity higher than required to meet the cooling demand of the building. The system performance is dictated by the outputs of the compressor map specifically designed for charging phases. We modeled the coupling fluid supply conditions from the evaporator to be at a constant temperature throughout the charging process. We considered a minimum approach temperature of 1°C for the glycol water leaving the storage module depending on the phase transition temperature of the module.
We modeled the transient heat transfer process in the TES module using a time-dependent overall conductance based on the peak charging rate, the exit setpoint temperature of the coupling fluid, and the time-varying SOC.

$$\dot{Q}_{ch,\max} = UA_{ch,\max} LMTD_{ch,design} \quad (9)$$

where $Q_{ch,max}$ denotes the peak charging rate considered for the design condition, $LMTD_{ch,design}$ corresponds to the LMTD value calculated using the coupling fluid supply and exit set point temperature and the phase transition temperature of the module, and $UA_{ch,max}$ is the maximum overall conductance of the module during charging. We calculated the actual charging rate at every time step of the simulation based on the SOC at the previous time instant and the design value of UA obtained from equation (9).

$$UA_{ch} = UA_{ch,\max}\{1 - SOC_{ch}[1 - \exp(-t_{ch} / \tau_{ch})]\} \quad (10)$$

$$\dot{Q}_{ch,actual} = UA_{ch} LMTD_{ch} \quad (11)$$

Where $Q_{ch\ actual}$, is the calculated value of the charging rate, tch is the time instant during charging, and τch is the time constant for the charging process calculated based on the total charging period. The time-dependent component of the UA function, i.e., the state of charge, denotes the increasing mass fraction of the solidified PCM in the storage module with a moving phase front. As the mass of the solid fraction increases, it offers increasing resistance to the heat extraction rate by increasing the distance of conductive heat transfer and, hence, reducing the charging rate. Assuming the storage material to remain at a constant phase-change temperature during melting or freezing, the $LMTD_{ch}$ is calculated at every time step with the PCM transition temperature as the constant high-side temperature and the coupling fluid supply and exit temperatures as the low-side temperature, respectively, as shown in the equation below.

$$LMTD_{ch} = \frac{\Delta T_{high} - \Delta T_{low}}{\ln \frac{\Delta T_{high}}{\Delta T_{low}}} \quad (12)$$

ΔT_{high} and ΔT_{low} correspond to the temperature difference between the PCM transition temperature and the coupling fluid supply temperature to the TES and the PCM transition temperature and the coupling fluid exit temperature from the TES, respectively.

The minimum value between $Q_{ch\ actual}$, and $Q_{ch\ avl}$, is considered for the charging rate in the module, where the charging rate available ($Q_{ch\ avl}$,) depends on the chiller capacity and cooling demand, and it is calculated by energy balance using the coupling fluid inlet and outlet temperatures.

$$\dot{Q}_{ch,avl} = \dot{m}_{CF} C_{p,CF} (T_{CF,out} - T_{CF,in}) \quad (13)$$

m_{CF} is the mass flow rate of the coupling fluid, $T_{CF,out}$, and $T_{CF,in}$ are the fluid exit and inlet conditions to the storage, and $C_{p,CF}$ is the specific heat of the fluid. We calculated the energy stored and the SOC of the TES as per the charging rate every time step. The SOC calculated at every time step is added to the value at the preceding time step to obtain the instantaneous SOC.

$$SOC_{ch}(t) = SOC_{ch}(t-1) + \frac{\dot{Q}_{ch,actual}(t)\Delta t_{ch}}{h_{ch} Cap} \quad (14)$$

$SOC_{ch}(t)$, $SOC_{ch}(t-1)$ are the SOC values at a given time step and its preceding instant, h_{ch} is the phase-change enthalpy of the material, and Cap is the total capacity of the storage module in terms of the mass of the material.

During the discharging phase, the chiller operates at a reduced capacity, with the storage module providing the cooling demand above the chiller capacity. We considered the return temperature of the coupling fluid to be constant throughout the discharging process. Similar to the charging process, we considered a minimum approach temperature of 1°C for the glycol-water mixture leaving the storage module.

We designed the TES module at a peak discharging rate and the exit setpoint temperature of the coupling fluid specified using the approach temperature. The overall conductance of the module is calculated using the peak discharging rate and LMTD values given below:

$$\dot{Q}_{disch,\max} = UA_{disch,\max} LMTD_{disch,design} \quad (15)$$

where $Q_{disch,max}$ denotes the peak discharging rate considered for design, $LMTD_{disch,design}$ corresponds to the LMTD value calculated using the coupling fluid supply and exit set point temperature and the phase change temperature of the module, and $UA_{disch,max}$ is the maximum overall conductance of the module during discharging. We calculated the actual discharging rate at every instant based on the SOC at the preceding time instant and the design value of UA obtained from equation (15).

$$UA_{disch} = UA_{disch,\max} SOC[\exp(-t_{dich} / \tau_{disch})] \quad (16)$$

$$\dot{Q}_{disch,actual} = UA_{disch} LMTD_{disch} \quad (17)$$

where $Q_{disch\ actual}$, is the calculated value of the discharging rate, t_{disch} is the time instant during discharging, and τ_{disch} is the time constant for the discharging process calculated based on the total discharging period. $LMTD_{disch}$ is calculated at every time step with the PCM transition temperature as the low-side temperature and the coupling fluid entry and exit temperatures as the high-side temperature, respectively, as shown in the equation below.

$$LMTD_{disch} = \frac{\Delta T_{high} - \Delta T_{low}}{\ln \frac{\Delta T_{high}}{\Delta T_{low}}} \quad (18)$$

ΔT_{high} and ΔT_{low} correspond to the temperature difference between the coupling fluid entry temperature (return from zone) and the PCM transition temperature and the coupling fluid exit temperature from the TES (supply to zone) and the PCM transition temperature, respectively.

The minimum value between $Q_{disch\ actual}$, and $Q_{disch\ req}$, is used for the discharging rate from the module at any time instant, where $Q_{disch\ req}$, is the discharging rate required to be supplied from the module depending on the chiller capacity and cooling demand, and calculated based on the energy balance using the coupling fluid entry and return temperature conditions.

$$\dot{Q}_{disch,req} = \dot{m}_{CF} C_{p,CF} (T_{CF,in} - T_{CF,out}) \quad (19)$$

where m_{CF} is the mass flow rate of the coupling fluid, $T_{CF,out}$, and $T_{CF,in}$ are the fluid exit and inlet conditions to the storage, and $C_{p,CF}$ is the specific heat of the fluid. We calculated the total discharged energy and SOC of the module using the actual discharging rate at every time instant. The SOC estimated at every time step is subtracted from the value at the preceding time step to obtain the instantaneous SOC.

$$SOC_{disch}(t) = SOC_{disch}(t-1) - \frac{\dot{Q}_{disch,actual}(t)\Delta t_{dich}}{h_{disch}Cap} \quad (20)$$

$SOC_{disch}(t)$, $SOC_{disch}(t-1)$ are the SOC values at a given time step and its preceding instant, h_{disch} is the enthalpy of phase change of the storage material, and Cap is the total capacity of the storage module measured in terms of the mass of the material.

3. Results

The model is first used to conduct design day simulations of TES-coupled HVAC systems in different climates of India [9]. The purpose of design day analysis of the TES-integrated HVAC system is to identify the extreme climatic conditions and the maximum thermal load to design and select various system components, including the compressor. It should be noted that the design day accounts for 0.4-1% of the total duration of a typical year, which means that the equipment selected under the design day operating conditions will almost always operate under relatively favorable conditions. To assess the performance in such a case, it becomes essential to study the performance and analyze the trend of different process parameters over a cooling/heating season where the temperature and the load conditions vary significantly.

We selected a medium-sized office building in Ahmedabad for a seasonal simulation with the same chiller data and compressor maps used in the design day for ice storage. We found 13 May to be the design day with the highest thermal load for a typical meteorological year. Based on that, we designed our chiller and storage module and used it to simulate the load profile for 90 days starting on 1 March. With the same thermodynamic model of storage integrated HVAC system, we incorporated a logic to reset the time steps to the initial value once a charging/discharging phase completes. We initiated our analysis on 1 March with a fully discharged TES module. We started charging it until the compressor switched from an ice-forming chiller to a standard discharge chiller, depending on the time of day and load conditions. After the end of every charging-discharging phase, the storage tank is set to charge to attain 100% SOC, following which the chiller either turns off completely or meets the building load profile. Fig. 3 shows the variation of the chiller capacities with the time-based thermal load profile for March to May. We found a peak load shaving of 38% in May(similar to the design day analysis), followed by 33% for April and 26% for March. Operating conditions in March under favorable ambient temperatures and a pattern of thermal load compared to the design day made the chiller oversized, thus reducing the peak-load shaving fraction. We also observed a reduction of 31% in peak compressor power.
Table 1 shows the utilization of the thermal storage module for all the days of a month throughout the simulation.

This result does not include the 26 weekends when the storage was fully charged and unused due to no occupancy.

Table 1: Utilization of thermal storage throughout the cooling season

TES utilization	March	April	May	Total
<10%	16	2	1	19
10-20%	3	9	3	15
20-30%	1	6	4	11
30-40%	0	2	8	10
40-50%	0	2	3	5
50-60%	0	0	1	1
60-70%	0	1	1	2
70-80%	0	0	2	2
Total (days)	**20**	**22**	**23**	**65**

To meet the building load during the off-design phases, mainly in March and early April, the system utilized up to 30% of the storage, accounting for 69% of the total duration (excluding weekends). As the weather conditions became close to the design day and the thermal loads continued to increase, storage consumption also increased.

Out of 22 working days in April, the storage capacity was utilized by up to 50% for four days, while in May, the storage was used by up to 80% for 10 days over 23 working days, equaling 43% of the total duration.

Fig 4 (left) shows the average compressor peak power variation in the three months of the cooling season for a conventional system and a system with integrated TES. As discussed above, we observed that the reduction in the compressor peak power was larger as the weather conditions and, consequently, the cooling load approached the

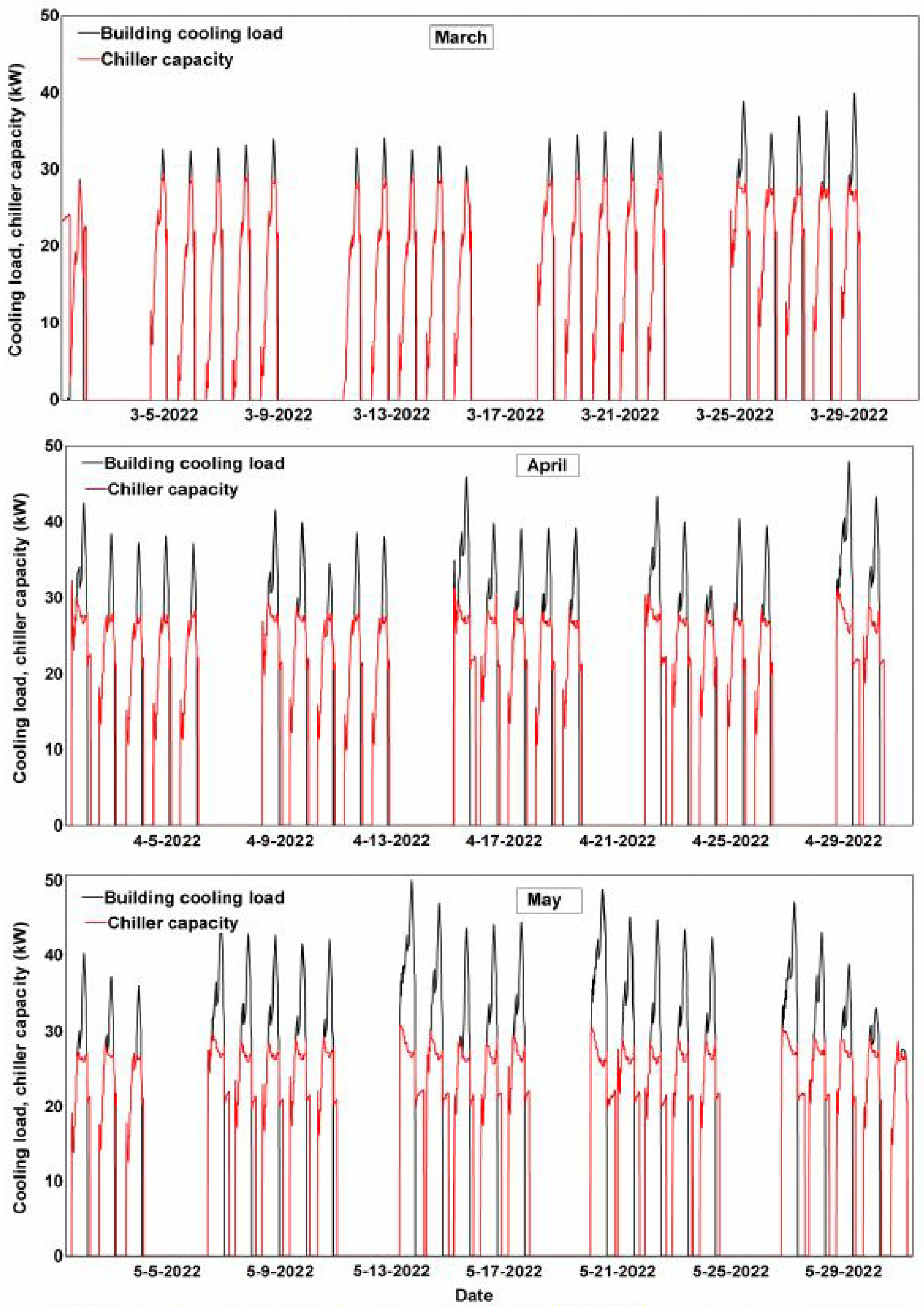


Figure 3: Variation of chiller capacity with load for the medium office building in Ahmedabad for the months of March-May

design day conditions. This is because the TES system is designed to meet the thermal load for the design day conditions. Figure 4 (right) shows the storage capacity utilization of the TES module in the cooling season. Because the TES and the compressor are designed for the maximum cooling load, the storage module capacity is not fully utilized most days. This has a significant implication on the levelized cost of storage (LCOS), which accounts for the percentage utilization of a storage asset over its lifetime. A lower utilization fraction increases the levelized cost and the cost of ownership. This is crucial to consider when designing a storage system. The costs can be significantly reduced if the storage system is sized to maximize utilization while taking a marginal penalty on peak load shaving fraction.

4. Discussion

While the proposed system could shave a significant portion of the thermal load, we also investigated the effect on the operating costs using the local electricity tariff charges (Table 2 and Fig. 5). We found that the ice storage-integrated system consumed 9075 kWh of energy, incurring a total cost of ₹44,840, while the existing system without any storage consumed 8247 kWh of energy, incurring an expenditure of ₹40,430 over three months. The excess energy was consumed to charge the storage module depending on the load profile and available state of charge after the end of the discharging phases, which, in many cases, occurred during the daytime when the ambient conditions were not favorable. The results showed that the total charging time over the entire period was 166.25 hours, with an average coefficient of performance (COP) of 2.19. The control strategy used to charge the tank leads to a low COP. Whenever the chiller switches back to the charging phase at the end of a discharging phase, it charges the tank to full capacity, regardless of weather conditions. There were instances when charging occurred at a comparatively higher ambient temperature than night conditions, yielding a low COP. We also analyzed the breakdown of the cost for each month for the office hours and the off-peak hours.investigated the effect on the operating costs using the local electricity tariff charges (Table 2 and Fig. 5). We found that the ice storage-integrated system consumed 9075 kWh of energy, incurring a total cost of ₹44,840, while the existing system without any storage consumed 8247 kWh of energy, incurring an expenditure of ₹40,430 over three months. The excess energy was consumed to charge the storage module depending on the load profile and available state of charge after charging time over the entire period was 166.25 hours, with an average coefficient of performance (COP) of 2.19. The control strategy used to charge the tank leads to a low COP. Whenever the chiller switches back to the charging phase at the end of a discharging phase, it charges the tank to full capacity, regardless of weather conditions. There were instances when charging occurred at a comparatively higher ambient temperature than night conditions, yielding a low COP. We also analyzed the breakdown of the cost for each month for the office hours and the off-peak hours.

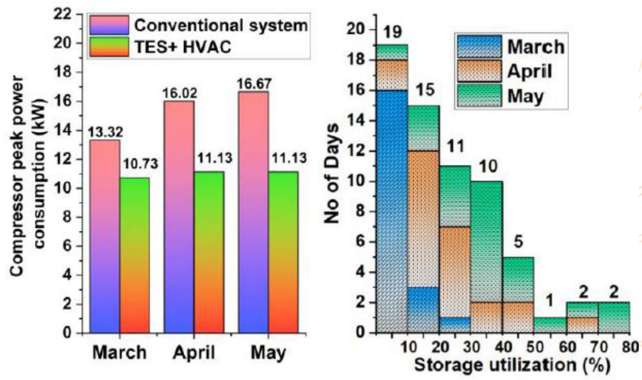
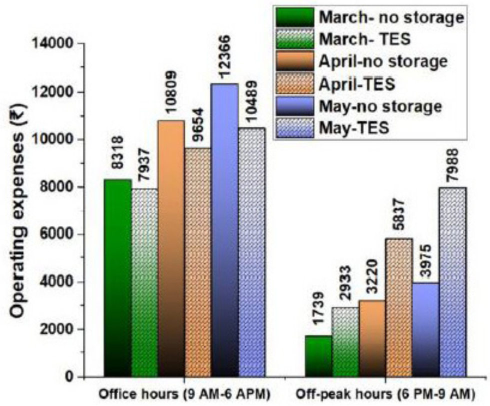


Figure 4: Variation of peak compressor power (left) for a conventional and proposed hybrid system and utilization of TES module over the three months of the cooling season (March-May) (right)

Table 2: Breakdown of operating cost based on occupancy

Time of day	March (₹)		April (₹)		May (₹)	
	Without TES	With TES	Without TES	With TES	Without TES	With TES
9 AM – 6 PM	8,318	7,937	10,809	9,654	12,366	10,489
6 PM – 9 AM	1,739	2,933	3,220	5,837	3,975	7,988
Total	10,057	10,870	14,029	15,491	16,341	18,477



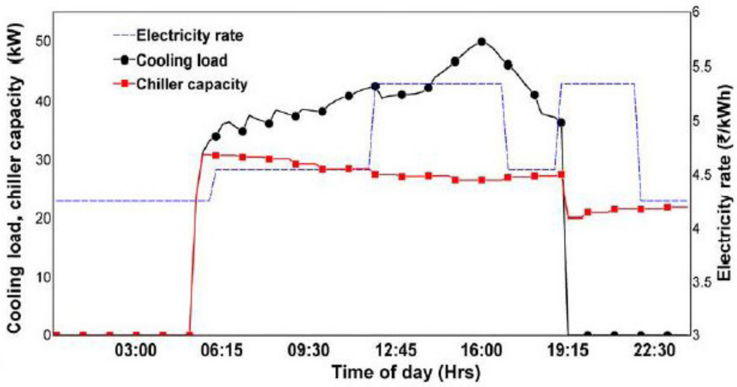


Figure 5: Variation of operating expenses during occupancy and evening hours (left) for a conventional and proposed hybrid system and a typical design day chiller capacity and load profile along with electricity tariff (right)

The tariff structure in Ahmedabad offers a base rate of ₹4.55/kWh, with a surcharge of ₹0.80/kWh during the peak period (12 PM – 5 PM, 7 PM – 10 PM), making it ₹5.35/kWh. The incentive for reduced power consumption during the off-peak period is also marginal at ₹0.30/kWh (10 PM – 6 AM) with a final off-peak rate of ₹ 4.25/kWh. Due to this unfavorable tariff structure, higher costs are incurred during the charging phase, which cannot be offset through savings obtained during the discharging phase. The techno-economic analysis of the seasonal performance of the TES-integrated system further emphasizes the revision in the electricity tariff.

5. Conclusion

This study analyzed the load-shaving potential of a phase-change TES system in a medium-sized office building in Ahmedabad for a typical cooling season. We developed a detailed thermodynamic model of a storage-integrated VCS using the first principles. While pre-defined templates based upon validated correlations are available in packaged software like EnergyPlus™, they cannot model different storage materials. It is also noteworthy that most packaged software that simulates the performance of an HVAC system use a constant COP, which is defined based on the rated capacity and the seasonal energy efficiency ratings (SEER) values, unlike our model, which calculates the COP of the system at every time instant based on the thermodynamics of the process. We simulated the performance of a TES-integrated HVAC system to determine the optimal load-shaving fraction in each case. Our analysis showed that upon integration with storage, an HVAC system could operate at a reduced capacity of ~ 38% of the rated capacity of a conventional system. The performance of the TES-integrated HVAC system showed a reduction in the compressor size by ~31%, which reduces the initial capital cost of investment. We found the existing flat tariff structure inadequate to provide significant operational cost savings, which may offset additional costs incurred for the TES system. This emphasizes implementing the time-of-day utility charges and an aggressive tariff structure to help with the broader adoption of clean energy sources.

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The authors gratefully acknowledge the financial support from Indian Institute of Technology (IIT) Delhi and University College London (UCL) for this research project through the Multi-Institutional Faculty Interdisciplinary Research Project (MFIRP) grant - MI02475. We also appreciate discussions with Prof. Rajan Rawal and Prof. Yash Shukla from CEPT Research and Development Foundation (CRDF) in Ahmedabad, India.

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Assessing the Integration of Building Science in Higher Education Curricula: Implications for Climate Change Adaptation in the Built Environment

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Abstract

This study critically examines the readiness of professionals in India to address the consequences of climate change. With a focus on architecture education, 15 institutes offering undergraduate courses were identified. The study solely assesses course syllabi on crucial building science topics related to climate change adaptation. The alignment of building science with the model curriculum guidelines provided by COA is also examined. The findings reveal certain building science topics are present in the syllabi only in a fundamental manner. However, there are gaps in in-depth coverage, integration with design studios, and practical skill development. The implications of these findings highlight the need for curriculum enhancements in architecture education, ensuring a comprehensive understanding of building science principles and their application in addressing climate change challenges. The study's application extends to guiding higher education institutions in revising their curricula to align with the urgent climate change impacts. Future research directions involve qualitative analyses and cross-country comparisons to enrich the discourse on integrating building science principles and climate adaptation into architecture education.

Keywords - Built Environment, Higher Education Institutes in India, Climate Change, Education of Building Science, COA.

1. Introduction

1.1. Background

Climate change poses a pervasive threat to our environment, economy, and societies, evident in rising temperatures, extreme weather events, and sea level rise. The year 2023 marked significant heatwaves worldwide, leading to the term "Global Boiling" [1]. Amid these changes, the built environment, where we live and work, is crucial [2]. Building science, encompassing physics, chemistry, engineering, and more, studies structures' impact on energy efficiency, durability, comfort, and air quality, guiding efficient design [3]. The reciprocal relationship between climate change and the built environment underscores their interdependence, necessitating cohesive approaches for mitigation and adaptation. As a COP 27 signatory, India faces pronounced climate risks, ranking nine states among the world's top 50 vulnerable regions [4]. This emphasizes the pressing need for India to actively address the implications of climate change on its built environment.

To effectively address the challenges of climate change, education plays a crucial role in enhancing our capabilities. By providing knowledge, promoting innovative thinking, and nurturing skilled professionals, it empowers individuals to understand and manage the consequences of the climate crisis [5]. In the context of architecture and the built environment, education has the potential to train professionals who can design and implement solutions that are both sustainable and climate resilient. Through these lenses, this research illustrates the critical role of the built environment and building science in shaping our response to the evolving global climate.

1.2. Literature Review

The literature review comprehensively explores climate change, the built environment, building science, and architecture education. Guzowski (2015) focuses on integrated luminous and thermal design for net-zero energy architecture [6]. Iyer-Raniga (2019) emphasizes sustainability education in the built environment curriculum for climate readiness [7]. Reid (2019) analyzes climate change education's potentials and issues Leal Filho et al. (2021) evaluates global climate change education approaches [8]. Iyer-Raniga and Andamon (2013) stress interdisciplinary sustainability education [9]. Manu et al. (2010) enhance architecture curriculum for clean energy economies [10]. Roy et al. (2022) examine disaster risk and climate change integration in urban planning curricula [11].

These studies reveal connections between climate change, the built environment, building science, and education, highlighting the need to bridge theory and practice to address climate challenges. However, there remains a lack of comprehensive studies examining the holistic integration of specific building science topics within architecture education, hindering a thorough understanding of how theory and practice are effectively interconnected to address climate change challenges. This study contributes to the scientific background by assessing the extent to which architecture institutes in India integrate subjects related to the built environment, building science and climate adaptation in their syllabi.

1.3. Aim and Approach

This study aims to examine and assess the capacity and readiness of higher education institutes in India to face future challenges in the context of climate change and the built environment. The study examined the syllabi of higher education institutes offering undergraduate courses in architecture. Based on NIRF ranking 2022 and institutes which have existed for more than 25 years, 15 institutes of National Importance have been identified for this study. For this study, the institutes are coded as Institute 1 (I1), I2, I3, and so forth.

1.4. Scope and Limitation of the Study

This research focuses on the assessment of syllabi accessible through the institute's websites. The scope of this study revolves exclusively around examining syllabi content and structure. It delves into the presence, coverage, and integration of specific subjects within the syllabi. It's important to note that this study is confined to the examination of syllabi alone, excluding discussions on pedagogical approaches, teaching methodologies, and classroom delivery. The study focuses solely on syllabi content limits insights into how the identified subjects are taught, discussed, or practically applied within the classroom environment.

2. Methods

2.1. Methodology of the study

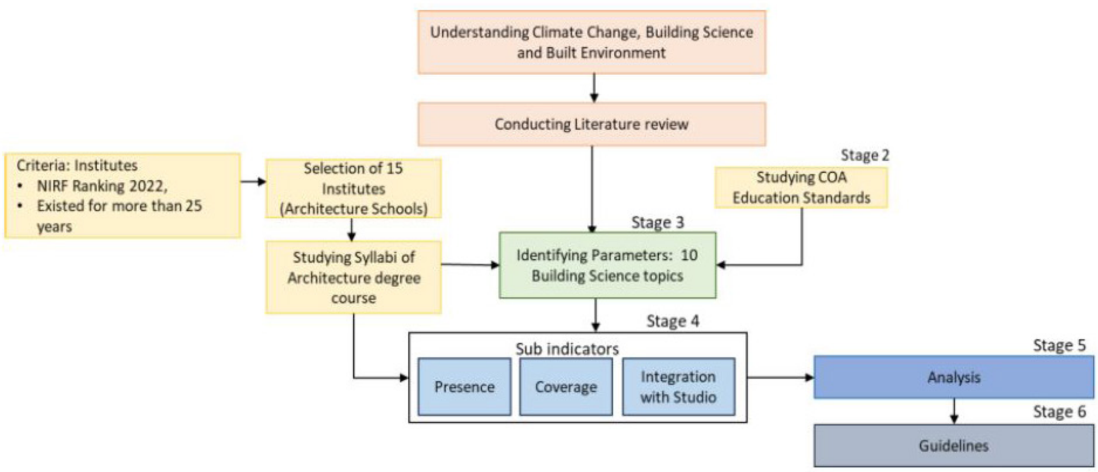

Figure 1: The diagram shows the methodology of the study.

The methodology (refer figure 1) consists of several stages. In Stage 1, the study reviewed climate change, building science, and the built environment, supplemented by a literature review. Stage 2 identifies 15 architecture institutes and examines and studies the model curriculum Council of

Architecture guidelines. Stage 3 selects 10 key building science topics for evaluation. Stage 4 assesses building science topics using sub-indicators as whether the topic is addressed or not, to what extent it has been covered, and its integration with the thrust area of the design studio. In Stage 5, the syllabi undergo comprehensive analysis using predefined benchmarks. Stage 6 integrates insights and study outcomes, leading to guidelines for enhancing subject integration. These guidelines aim to bridge theory-practice gaps, fostering comprehensive education that addresses climate change and building science implications within the built environment. This methodological framework offers a systematic means to investigate subject integration in architecture curricula, advancing educational practices aligned with evolving challenges.

2.2. Selection of Building Science Topics

Aligned with India's ambitious emission reduction targets of 33-35% by 2030 and net-zero emissions by 2070 [12], integrating these topics into architecture education gains vital significance. Equipping future architects with skills for designing in line with these goals contributes to sustainable, climate-resilient development. India's commitment to climate action is evident through international participation and the National Action Plan on Climate Change (NAPCC). This study identifies 10 key Building Science topics, carefully chosen based on Council of Architecture (COA) [13] criteria and global frameworks. These topics equip future architects to address climate complexities and create sustainable, resilient, energy-efficient architecture solutions.

2.2.1. Understanding the 10 Building Science Topics

The following 10 building science topics have been identified for examining syllabi, along with concise definitions:

1. Sustainable Design and Green Building Practices: Creating structures with a focus on minimizing resource consumption, maximizing resource reuse, optimizing site potential, and incorporating eco-conscious methods. Prioritizing energy efficiency, local and renewable energy sources, recycling, and minimizing emissions and waste throughout a building's lifecycle [14,15].

2. ECBC (Energy Conservation Building Code): A regulatory framework in India mandating energy-efficient design. Reduces energy consumption, and carbon emissions, and enhances sustainability by promoting insulation, efficient lighting, ventilation systems, and renewable energy integration [16].

3. Thermal Comfort: Ensuring indoor comfort by considering occupants' satisfaction with the thermal environment [17].

4. Green Landscape and Green Site Planning: Enhancing biodiversity, water efficiency, waste management, and quality of life through eco-friendly landscape and site planning [18].

5. Climate-Responsive Building Envelope Design: Designing building envelopes that align with specific climatic conditions, promoting occupant comfort and energy efficiency. Also, utilizes local materials and native technologies for minimal disruption to local microclimate [12].

6. Energy Efficiency in Services: Designing building systems for less energy consumption while ensuring occupant comfort. Focuses on energy-efficient equipment, smart controls, and system layout optimization [12].

7. Net-Zero Energy and Carbon-Neutral Building Concepts: Creating buildings that produce as much energy as they use, preferably from renewable sources. Balancing carbon emissions through energy-efficient technologies and strategies [12].

8. Integration of Renewable Energy Systems: Incorporating solar, wind, and geothermal power into building designs to reduce reliance on fossil fuels (Renewable energy sources) [12].

9. Energy Budgeting: Balancing energy needs and production throughout a building's life cycle by optimizing design elements and renewable energy sources [12].

10. Resilient Building Design for Extreme Weather Events: Designing structures to withstand extreme weather conditions and disasters, aligning with national policies and international frameworks [19].

By evaluating the integration of these Building Science topics into architecture curricula, this study aims to shed light on the preparedness of professionals undergoing training in Architecture Schools to effectively address the challenges posed by climate change.

2.3. Model Curriculum guidelines by the Council of Architecture (COA)

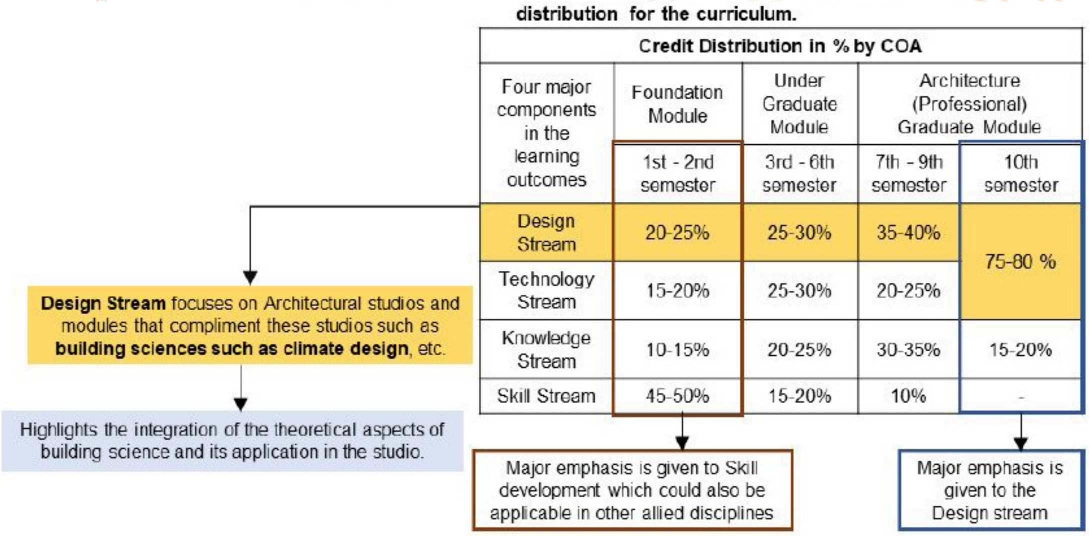

Figure 2: The diagram shows model curriculum guidelines by COA.

The Council of Architecture (COA) governs architecture education for both undergraduate and postgraduate courses. It sets minimum standards and guidelines for architecture education in India. According to the model curriculum, the five-year course is structured into three stages: a foundational module in the 1st year, an undergraduate module in the 2nd and 3rd years, and an architecture graduate module in the 4th and 5th years. Building science topics fall under the technology stream, which is part of the curriculum's technological aspect (refer figure 2) [13]. The curriculum highlights that the technology stream primarily revolves around the undergraduate module in terms of its distribution. This stream includes subjects like building services, construction, and structures. As a result, universities interpret the distribution and classification (Core/Elective) of building science subjects based on this framework.

Table 1: Alignment of Building science topics with the COA Curriculum guidelines.

Sr. no.	Building Science Topics	COA Suggested Building Sciences	Subject Title
1.	Sustainable design and Green building practices	No mention	-
2.	ECBC Codes (Building codes and regulations)	yes	Building Materials
		yes	Building Construction
		yes	Building Services
		yes	Environmental Lab (Non-Subject)
3.	Thermal Comfort	yes	Climatology
		yes	Environmental Lab (Non-Subject)
4.	Green Landscape/ Green site planning	No mention	-
5.	Energy Efficiency in services	yes	Building Services
6.	Climate-responsive building envelope design	No mention regarding building envelope design.	Climatology
7.	Energy Budgeting	No mention	-
8.	Net-zero energy and carbon-neutral building concepts	No mention	-
9.	Integration of renewable energy systems	yes	Building Materials
		yes	Climatology
		yes	Environmental Lab (Non Subject)
10.	Resilient building design for extreme weather events	No mention	-

Table 1. Alignment of Building science topics with the COA Curriculum guidelines.

Table 1 showcases the alignment between building science topics and the COA curriculum. Among the 10 building science topics identified for this study, four—ECBC, Thermal comfort, energy efficiency in services, and renewable energy systems—are addressed. However, topics like Net-zero energy concepts, energy budgeting, and resilient buildings are notably missing. These gaps could impact how institutes shape their syllabi.

3. Results

3.1. Overview of the Assessment

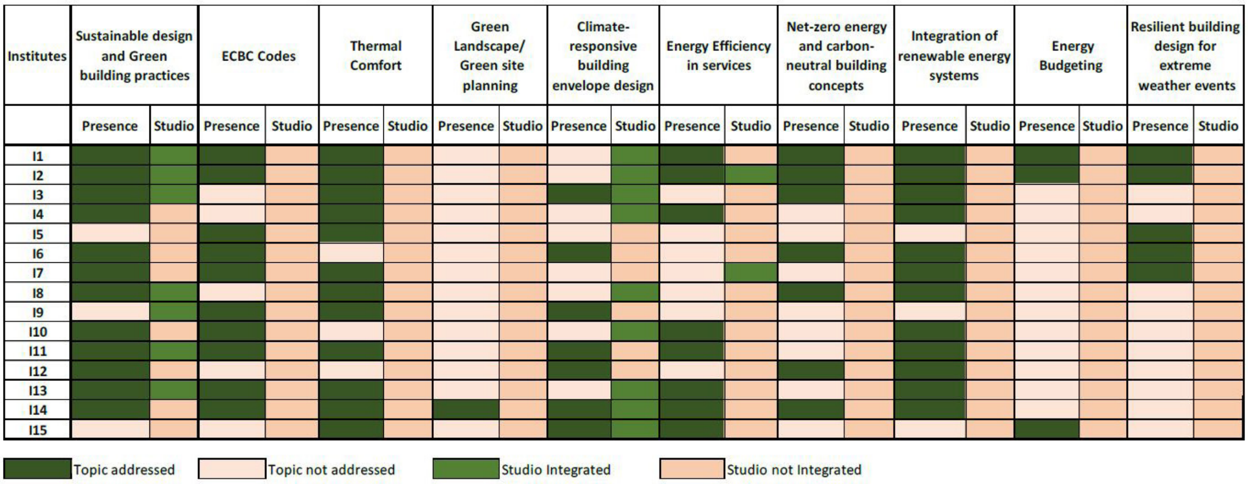

Figure 3: The matrix above shows the 10 building science topics covered by different institutes.

Figure 3 illustrates how various institutes incorporate 10 building science topics. The analysis reveals that several institutes prioritize subjects such as sustainable design, green building practices, ECBC codes, thermal comfort, and integration of renewable energy systems. In contrast, topics like net zero and carbon-neutral building concepts, energy budgeting, green landscape, and green site planning are less commonly addressed, often in a superficial theoretical manner without significant integration into design studios. The development of students' design skills through techniques and tools receives insufficient emphasis. Upon reviewing the building science topics, it becomes unclear whether students grasp the fundamental principles underlying these concepts.

Furthermore, the matrix depicting the integration of the 10 building science topics within design studios of different institutes indicates a distinct pattern. Sustainable design and climate-responsive design, albeit primarily limited to climatic considerations and energy efficiency, emerge as the predominant areas of focus. However, the incorporation of other building science topics within the studio environment is noticeably lacking. This matrix underscores the substantial disparity between theoretical knowledge and practical application within the context of design studios.

3.2. Inferences illustrating Coverage of the Subjects

This section focuses on the coverage of the 10 building science topics across different institutes.

The assessment of the integration of building science topics across different institutes reveals insightful patterns in their coverage and incorporation.

Sustainable Design and Green Building Practices (refer Figure 4a) are prominent in the curricula, with 12 out of 15 institutes including them. However, the treatment is mostly confined to basic theoretical exposure in early years. While a few institutions offer dedicated courses, these subjects generally lack integration with design and practical skill development. Similarly, ECBC (refer Figure 4b) finds coverage in 10 institutes, though primarily at a theoretical level, without significant application-based approaches or integration with design.

Figure 4: The diagram shows the theoretical topics covered under (a) Sustainable Design and Green building Practices, (b) ECBC, (c) Thermal Comfort, (d) Green landscape and Green Site Planning, (e) Climate-responsive building envelope design, (f) energy efficiency in services, (g) Net-zero energy and carbon-neutral building, (h) Integration of renewable energy systems,(i) Energy budgeting and (j) Resilient building design for extreme weather events covered by different institutes.

Thermal Comfort (refer Figure 4c) receives attention from 12 institutes, often addressed in foundational years through theoretical courses. Comprehensive integration with design is limited to a few institutions, underscoring a gap between theory and application. Conversely, Green Landscape and Green Site Planning (Figure 4d) suffer from limited representation, with only one institute offering an elective course, potentially hindering professionals' readiness to tackle climate change challenges.

Climate-responsive building envelope design (refer Figure 4e), covered by 7 institutes, imparts theoretical principles through core and elective courses. However, the focus remains predominantly theoretical. Energy Efficiency in services (refer Figure 4f) gets coverage in 8 institutes, providing a solid theoretical foundation, yet struggling to seamlessly merge with architecture design—an endeavour that requires interdisciplinary collaboration.

Net-zero energy and carbon-neutral building concepts (refer Figure 4g), while not explicitly covered, are touched upon in other subjects across the institutes. This rudimentary treatment underscores the necessity for in-depth understanding to create environmentally sustainable environments. Integration of renewable energy systems (refer Figure 4h) finds inclusion in 8 institutes, yet the syllabi emphasize basic theory and concepts over practical integration within architecture projects. Energy Budgeting (refer Figure 4i), despite its growing importance in the context of sustainability, remains largely absent from direct coverage within the curricula. Only a few institutes embed it within related subjects, revealing a potential gap in holistic energy management education. Lastly, Resilient building design for extreme weather events (refer Figure 4j) is considered by 5 institutes, with theoretical aspects explored in elective courses. While these courses provide foundational insights, they lack comprehensive in-depth coverage.

Collectively, these observations emphasize the need for bridging the gap between theoretical knowledge and practical design integration across a range of crucial building science topics. The study suggests opportunities for curricular enhancements to equip aspiring architects with comprehensive skills for creating sustainable, resilient, and energy-efficient built environments in the face of evolving challenges.

3.3. Integration with Design Studio

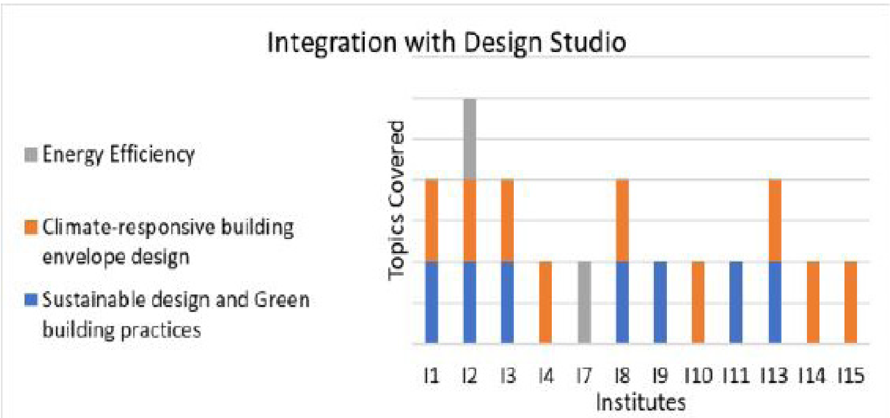

Figure 5: The diagram above shows the topics integrated into the design studio by different institutes.

Sustainable design and Green Practices, Climate-responsive building envelope design, and Energy Efficiency are integrated into Design Studios in just 12 institutes. The thrust area of the design studios primarily emphasizes site analysis, climatological factors (sun path, wind direction, orientation), and Sustainable design principles. Few institutes prioritize design studios centered on energy efficiency in services. Evident disparities between theory and design highlight a substantial gap in translating theoretical understanding into practical application.

4. Discussion

It's noteworthy that the results of the 15 institutes have implications for a broader educational landscape, as other institutions often look up to these top institutes. However, these findings reveal a concerning gap in incorporating the urgent needs of today's time.

4.1. Findings of this study

The outcomes reveal that certain subjects are included largely in theoretical manner, while others are visibly lacking from the syllabi. Several factors contribute to these results and offer explanations for the inferences drawn.

1. Emphasis on Theoretical Learnings: A significant reason for the outcomes is the syllabi's strong theoretical orientation. While some building science topics are covered, they often stay at a basic theoretical level with little focus on practical application or integration into design studios. This gap limits students' ability to apply theory to real-world situations, potentially leaving professionals ill-equipped to tackle climate change challenges practically.

2. Insufficient Focus on Key Issues: The assessment also highlights gaps in covering crucial building science topics. For instance, the absence of direct inclusion and integration of subjects like "Net-Zero Energy and Carbon-Neutral Building Concepts" and "Energy Budgeting" may hinder addressing India's sustainability goals.

3. Ambiguous Syllabus Guidelines: The ambiguity in Council of Architecture (COA) syllabus guidelines might contribute to the observed outcomes. Without clear directives that emphasize the integration of climate-related building science topics, educational institutions might struggle to design syllabi that adequately prepare students. This lack of a focused framework could result in fragmented teaching approaches, hindering a holistic understanding. The COA guidelines also miss out on providing a clear focus on the Technology stream, under which Building Science topics fall, further intensifying the issue.

4. Faculty Capacity and Expertise: Faculty expertise plays a vital role. Building science subjects require specific skills. Insufficient faculty knowledge might create a mismatch between curriculum intent and delivery. If faculties lack climate change training, academia might not meet evolving architecture needs.

5. Potential for Industry Marginalization: Limited education on climate-related building science could marginalize architects in broader design and construction fields. Engineers and sustainability experts might take a lead if architects aren't equipped to address these challenges. This shift could weaken architects' role in shaping holistic and integrated designs. \

6. Lack of Examination and Licensure: There is a need for a formal examination and licensure mechanism by the COA to evaluate architects' knowledge of climate change and building science, post degree completion. This examination would ensure that licensed professionals are well-prepared to address future challenges in their practice.

7. Scope and Limitation of the Study: It's essential to recognize study limits. Though the assessment focused on syllabi, it only scratched the surface of course and design studio structures. Pedagogy, teaching methods, and classroom effectiveness weren't explored. Thus, assessing actual knowledge transfer and skill development in classrooms falls outside this study's scope.

4.2. Recommendations

A set of recommendations and guidelines are proposed, aimed at enhancing the preparedness of future architects to address climate change challenges and contribute effectively to building a sustainable and resilient environment. The guidelines for Building Science Integration are as follows:

2. Fixed Percentage Allocation: Institutes should allocate a fixed percentage of their syllabi to building science topics related to climate change adaptation. This allocation ensures that these

crucial subjects are given due attention and prominence in the curriculum.

3. Compulsory Core Topics: Certain building science topics, such as Sustainable Design and Green Building Practices, Climate-Responsive Building Envelope Design, Energy Efficiency in Services, and Resilient building design for extreme weather events should be made compulsory core subjects in the curriculum. This ensures that all students gain a fundamental understanding of these critical areas. Practical lab-based activities and hands-on experiences should be integrated.

4. Application in Design Studio: Building science topics should be holistically integrated into design studios. This integration should focus on practical application, skill development, and real-world implementation. The orientation of the Design projects should be framed to challenge students to address climate change issues through innovative and sustainable design solutions.

5. Dynamic Syllabus Upgradation: The syllabi and course content should be regularly updated to reflect the evolving challenges and emerging issues such as climate change adaptation. A dynamic approach ensures that students are equipped with the most relevant and current knowledge in the field.
6. Skill Development for Climate Adaptation: The education system should emphasize skill development that equips students with the tools and techniques to design climate-adaptable and resilient structures. Practical exercises, case studies, site visits, and hands-on experiences should be integrated to enhance their ability to interpret theoretical knowledge into practical solutions.

The conceptual framework in Figure 6 shows the integration of 10 building science topics as theory subjects and design studio topics across different semesters, with some topics only being introduced.

Sr.no.	Building Science topics	Level 'A' (1 & 2 year)				Level 'B' (3 & 4 year)				Level 'C' (5 year)	
		I	II	III	IV	V	VI	VII	VIII	IX	X
1	Climate-responsive building envelope design										
2	Thermal Comfort										
3	Sustainable Design and Green Architecture										
4	ECBC										
5	Energy Efficiency in Services										
6	Green landscaping/Green Site planning										
7	Net-zero energy and carbon-neutral building concepts										
8	Integration of renewable energy systems										
9	Energy Budgeting										
10	Resilient building design for extreme weather events										

Theorical Input/ Theory Subject
Integration with design studio
Introduction to these subjects/concepts

Figure 6: The diagram above shows a conceptual framework for integrating building science topics with the curriculum.

4.3. Application of the Study

The findings and recommendations of this study have practical implications for architecture institutes and the architecture profession as a whole. Institutes can use the results as a guideline to revise and enhance their syllabi, ensuring that their students are well-prepared to tackle climate change challenges in their professional careers. COA, in partnership with industry experts, professionals, and educational institutions, should endorse the proposed framework aimed at integrating building science into the curriculum. To ensure the successful implementation of this framework, it is imperative to focus on faculty training. Additionally, there is a need to establish hands-on learning labs in various educational institutions through a collaborative effort with COA. Furthermore, the paper suggests the necessity of implementing a structured mechanism for continuous review and curriculum updates. This approach will help ensure that the curriculum remains aligned with current industry standards and evolving future challenges.

4.4. Future Scope

Looking ahead, there is a scope for qualitative analysis to complement this study's quantitative assessment. Surveys and interviews with students, faculties, and industry professionals can provide deeper insights into the effectiveness of teaching methods, the perception of students on the integration of building science topics, and the real-world impact of education. Such qualitative data can enrich the understanding of the challenges and opportunities within architecture education.

Additionally, the methodology employed in this study can serve as a reference for similar assessments in other thematic areas, such as sustainability, urban planning, or heritage conservation. By adapting the framework to different contexts, researchers can explore the integration of diverse subjects in higher education curricula, ultimately contributing to the advancement of various fields. The recommendations and insights provided by this study pave the way for a more holistic and practical approach to educating architects who will play a pivotal role in designing a sustainable and resilient future built environment.

5. Conclusion

Through a comprehensive analysis of syllabi from 15 selected institutes, the research provided insights into the current state of education in this critical domain. The findings revealed both trends and notable gaps, shedding light on the preparedness of future architects to tackle the challenges posed by climate change in the built environment. The study's findings underscore the urgency for reforms in architecture education. To address the limitations identified, a set of comprehensive recommendations and guidelines were proposed. These include the allocation of fixed percentages for building science topics, compulsory inclusion of certain core subjects, seamless integration with design studios to emphasize practical application, dynamic syllabus upgradation, and a heightened focus on skill development for climate adaptation.
In conclusion, this research brings to light the focal role that architecture education plays in shaping professionals who are capable of designing sustainable and resilient built environments. The findings advocate for an educational paradigm that bridges the gap between theoretical knowledge and practical implementation, ensuring that future architects are equipped to address climate change challenges with innovative, effective, and holistic solutions.

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The energy saving potential of using adaptive setpoint temperatures: a case study for offices in India

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Abstract

Adopting setpoint temperatures guided by adaptive thermal comfort models offers an efficient approach to conserving energy. Current research gives consideration to global models like ASHRAE Standard 55 and EN16798-1, which incorporate adaptive setpoint temperatures. However, this study follows a distinct path by incorporating a localized Indian adaptive comfort model, specifically the India Model for Adaptive Comfort for Commercial buildings (IMAC-C). This research delves into the energy-saving potential linked to the utilization of setpoint temperatures derived from IMAC-C. A comparative analysis is conducted, juxtaposing these temperatures with those based on the worldwide ASHRAE Standard 55 adaptive model and PMV-based setpoint temperatures aligned with the National Building Code for India. Comprehensive building energy simulations have been executed, encompassing all of India's climate zones and accommodating both naturally-ventilated and full air conditioning operational modes for buildings. The outcomes highlight that applying setpoint temperatures grounded in the IMAC-C adaptive comfort model in full air-conditioning mode could potentially lead to energy savings ranging between 9% and 26% in most of the climates. Consequently, it is conclusively determined that the integration of setpoint temperatures rooted in the Indian local adaptive comfort model represents a highly effective strategy for achieving energy conservation.

Keywords - Adaptive setpoint temperatures, adaptive thermal comfort, accim, computational approach.

1. Introduction

Approximately 30% of the global energy consumption is attributed to the construction sector [1]. This leads to the generation of about 40% of greenhouse gas emissions, prompting a targeted reduction of at least 80% in these emissions by 2050. Achieving this objective necessitates a substantial reduction (around 90%) in greenhouse gas emissions from the building industry [2]. These rigorous measures coincide with the backdrop of a pandemic crisis and escalating energy costs. The increased time spent at home due to intermittent lockdowns has fostered a more comprehensive understanding of energy regulation for ensuring healthy indoor conditions.

To incorporate customers' climate adaptation into reduced energy consumption, adaptive comfort models have been suggested. These models are incorporated into standards like EN 16798-1:2019 [3] and ASHRAE 55-2020 [4], which considers users' interaction with their environment. These standards stem from initiatives such as RP884 (conducted globally) and Smart Control and Thermal Comfort (SCATs, conducted in Europe). Test outcomes indicate a relationship between operational temperature, external temperature, and user comfort.

Numerous national standards, like China's GB/T 50785 [5] and the Netherlands' ISSO 74 [6,7], have been developed to account for regional distinctions. These standards devise unique models based on cold, warm, and mild climate zones. Additionally, China has tailored models for specific locations [8]. The Dutch standard's second edition from 2014 [9] focuses on defining acceptable interior conditions through global databases and local research within various boundaries.

Similarly, several adaptive local comfort models has been developed for India's climatic conditions and different building uses: the India Model for Adaptive Comfort - Commercial (IMAC-C) [10], specifically developed for commercial mixed-mode and naturally ventilated buildings, which has already been incorporated into the Indian Building Code [11]; and the India Model for Adaptive Comfort - Residential (IMAC-R) [12], specifically developed for residential buildings. There are also other models developed for India [13–17], however not all climate zones are considered in these, therefore these have not been considered for this research for coherency purposes.

Adaptive comfort models are specifically tailored for naturally ventilated spaces as outlined by the ASHRAE 55 and EN16798-1 specifications. However, recent research suggests that individuals seem capable of adjusting to a significantly broader spectrum of indoor temperatures, irrespective of the technologies implemented for indoor environments [18]. As a result, several studies have recently scrutinized the pros and cons of adaptive setpoint temperatures compared to models based on the Predicted Mean Vote (PMV), aiming to illustrate their impact on energy usage. The subsequent examples highlight such studies: (i) Sánchez-García et al. [19] explored the applicability of adaptive setpoint temperatures under changing climate conditions to reduce energy demand in office buildings. Depending on the climate scenarios studied, adjusting the daily setpoint temperatures led to reductions in demand and overall HVAC consumption, ranging from 63% to 52% and 61% to 51%, respectively; (ii) Holmes and Hacker [20] assessed the utilization of adaptive thermal comfort techniques across various government buildings in the United Kingdom, spanning both the present and future contexts; (iii) Kramer et al. [21] decreased the heating setpoint temperature of a museum to align with the lower boundary of the comfort zone established by Van der Linden et al. [22], thereby achieving a 74% reduction in energy consumption; and (iv) Dhaka et al. [23] investigated the effect of fixed and adaptive thermostat schedules on energy conservation within a university hostel situated in a hot, humid region of India. Their findings demonstrated the potential for a 40% decrease in energy usage.

The aim of this paper is to study the energy savings obtained from using adaptive setpoint temperatures based on the IMAC-C against the international ASHRAE 55 adaptive comfort model and static setpoint temperatures specified in the Indian regulations. The novelty of this paper resides in the use of a local adaptive comfort model for India instead of international thermal comfort standards. Building energy simulations have been performed across the country, for the 5 climate zones. In Section 2, the building case study is briefly described , the methodology for this study is explained, and a discussion of how 'accim' was used is also included. The energy results are presented and discussed in Sections 3 and 4, and the conclusions are then presented in Section 5.

2. Methods

2.1 Climate zones in India

The Indian Energy Conservation Building Code (IECBC) [24] and the National Building Code [11] consider 5 climate zones for the territory of India: hot and dry; warm and humid; composite; moderate (or temperate); and cold.

Therefore, in order to analyse the energy consumption as a result of using adaptive setpoint temperatures, a city has been respectively chosen for each climate zone consistently with the locations in which thermal comfort surveys have been carried out for the development of IMAC-C [10] and IMAC-R [12]: Ahmedabad, Chennai, Delhi, Bangalore and Shimla (Figure 1).

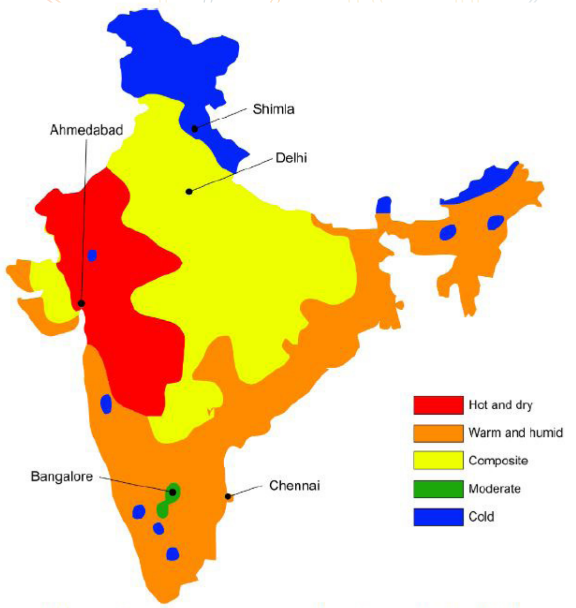


Figure 1: Climate zones and cities studied of India

2.2 Case study

The simulation engine used for this work has been EnergyPlus 23.1, and the building energy model corresponds to the Small Office Prototype 2018 IECC DOE Commercial Reference Building [25]. This model encompasses 6 distinct thermal zones. Among these, a central thermal zone referred to as CORE_ZN is flanked by four air-conditioned thermal zones denoted as PERIMETER_ZN_1 to PERIMETER_ZN_4. All these zones are situated on the building's ground floor. Additionally, an unconditioned attic area is also present (depicted in Figure 2).

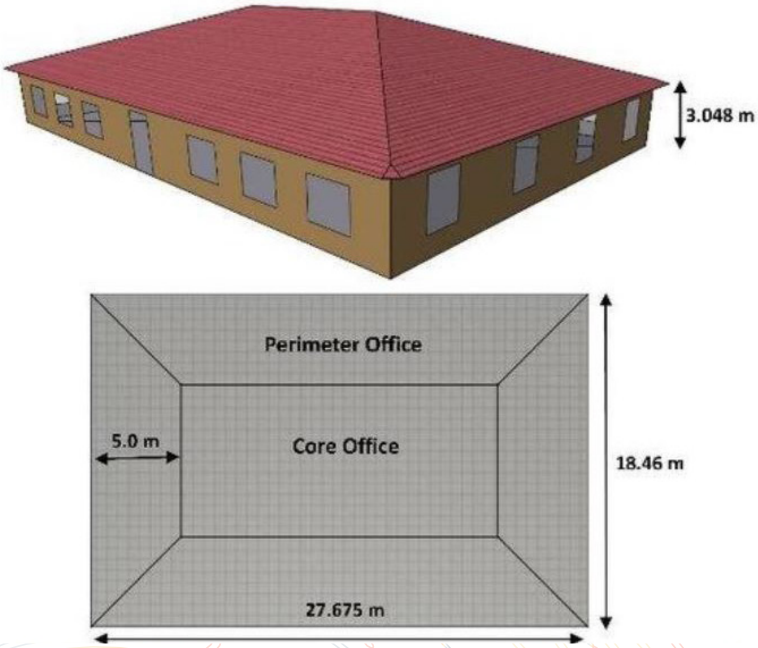


Figure 2: 2018 IECC DOE Commercial Reference Building Prototype Small Office

2.3 Inclusion of IMAC-C and IMAC-R local adaptive models in accim

Until recently, mainly international comfort standards were available in accim: EN 16798-1 and ASHRAE 55. However, multiple local comfort models have been added, being among those the different versions of IMAC-C (naturally ventilated and mixed mode). It has been chosen based on its high reliability, since IMAC-C draws on a total of 6630 thermal sensation votes gathered from 16 buildings from the five Indian climate zones.

$$RMOT = (T_{ext,d-1} + 0.8T_{ext,d-2} + 0.6T_{ext,d-3} + 0.5T_{ext,d-4} + 0.4T_{ext,d-5} + 0.3T_{ext,d-6} + 0.2T_{ext,d-7})/3.8 \quad [^{\circ}C] \tag{1}$$

$$Comfort\ temperature\ (IMAC-C-NV) = \mathrm{RMOT} * 0.54 + 12.83\ [°C] \tag{2}$$

$$Comfort\ temperature\ (IMAC-C-MM) = \mathrm{RMOT} * 0.28 + 17.87\ [°C] \tag{3}$$

Where $T_{ext,d-1}$ is the average temperature of the previous day to the day in question, $T_{ext,d-2}$ the average temperature of the day before, and so on.

The possibility of use of adaptive setpoint temperatures is based on the assumption that occupants in air-conditioned spaces are able to adapt to temperatures as if they were used to naturally-ventilated spaces. Therefore, the NV model from IMAC-C is used, whose upper and lower adaptive comfort limits are shown in Equations 4 and 5 for 80% acceptability levels.

$$Upper\ limit\ (80\%\ acceptability) = \mathrm{RMOT} * 0.54 + 12.83 + 4.1\ [°C] \quad (12.5°C \leq \mathrm{RMOT} \leq 31°C) \tag{4}$$

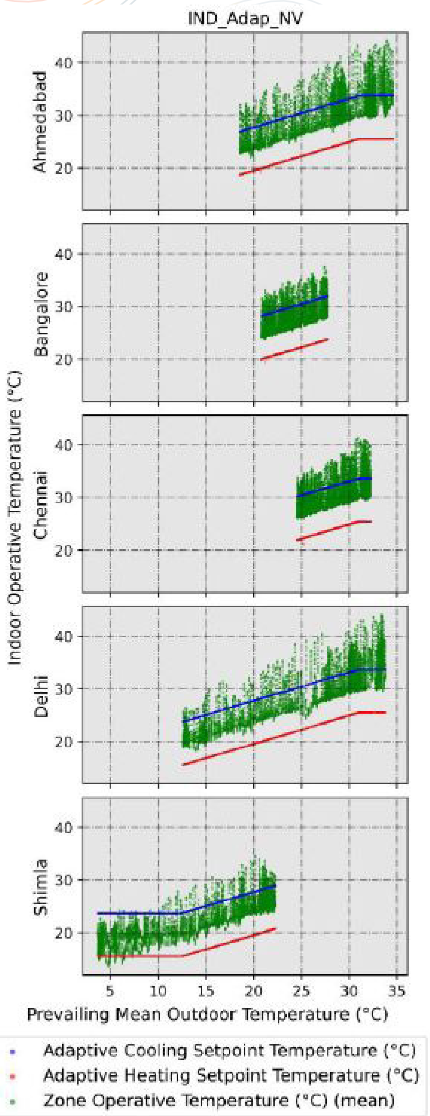
$$Lower\ limit\ (80\%\ acceptability) = \mathrm{RMOT} * 0.54 + 12.83 - 4.1\ [°C] \quad (12.5°C \leq \mathrm{RMOT} \leq 31°C) \tag{5}$$

3. Results

In the first subsection, the degrees of thermal comfort in all temperature zones and climate scenarios have been investigated in naturally ventilated mode, that is, without the use of any HVAC system. The second sub-section looks at the energy efficiency of setpoint temperatures based on the IMAC-C-NV model while taking air-conditioning mode into account.

3.1 Thermal comfort assessment in naturally-ventilated mode

Prior to the analysis of energy savings, the evaluation of the indoor temperature in naturally-ventilated mode must be carried out in order to understand the necessity of the use of air-conditioning, and particularly, adaptive setpoint temperatures. Figure 3 shows the operative temperature in free-running mode, which largely falls out of the adaptive thermal comfort zone. Figure 4 shows the percentage of comfortable hours, hours when operative temperature exceeded the upper or lower comfort limit, and hours when prevailing mean outdoor temperature fell out of the applicability limits. It reveals the comfortable hours range from 48% in Ahmedabad to 77% in Bangalore, while the hours exceeding the upper comfort limit range between 22 and 24% except for Shimla, where this value is 11%, and the hours exceeding the lower comfort limit are none. In case of the upper applicability limit, it is exceeded by 18 to 27% of hours, and only in case of Shimla, the lower applicability limit is exceeded by 35% of hours.



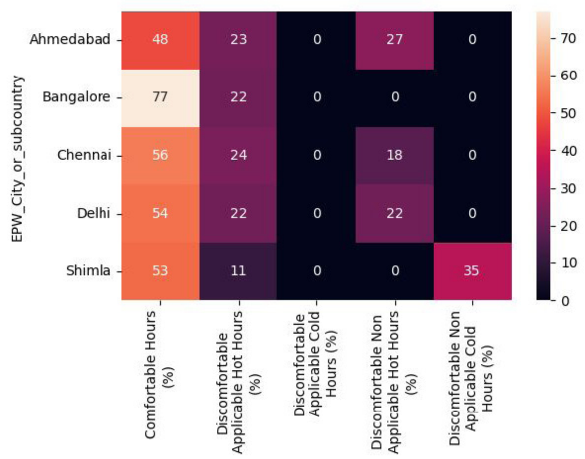


Figure 4: Heatmap of comfort hours

The aim of this research is assessing the energy saving potential of using setpoint temperatures based on the IMAC-C (named IND_Adap_AC in figures and tables) by means of its comparison with setpoint temperatures based on the adaptive ASHRAE 55 (ASH_Adap_AC) and static or PMV-based setpoint temperatures relevant for India (IND_Stat_AC), based on its National Building Code. Two main aspects have been evaluated: the indoor operative temperature and the energy demand. Figure 5 shows the operative temperatures resulting from the simulations considering the 3 aforementioned setpoint temperatures in full air-conditioning

Figure 3: Thermal comfort assessment in naturally-ventilated mode Considering air-conditioning mode, comfort
Figure 3: Thermal comfort assessment in naturally-ventilated mode Considering air-conditioning mode, comfort

mode. In this case, the aim was to calculate the energy demand considering as many hours of thermal comfort as possible, therefore, the comfort limits have been horizontally extended beyond applicability limits. Figure 3: Thermal comfort assessment in naturally-ventilated mode Considering air-conditioning mode, comfort hours range from 99.99 to 100% setpoints (i.e. unmet hours ranged from 0% to 0.01%). The related energy demand results are shown in Table 1, as well as the energy savings of IND_Adap_AC compared to ASH_Adap_AC and IND_Stat_AC in terms of relative (1 – (*1-IND_Adap_AC/Model for Comparison*) and absolute difference (*Model for Comparison IND_ Adap_AC)*. Cooling energy demand ranges between 213 and 306 kWh/m^2·year for the cities of Ahmedabad, Bangalore, Chennai and Delhi considering the different setpoint temperatures, while in case of Shimla, it ranges between 151 and 167 kWh/m^2·year. The energy savings in cooling demand compared to IND_Stat_AC ranges between 14 and 26 % decrease and 11% increase in case of Shimla, while compared to ASH_Adap_AC, it ranges between 9 and 16% decrease and 3% increase. Heating energy demand is null roughly in all cases, except for Shimla considering the IND_Stat_AC with 6.65 kWh/m^2·year. Therefore, total energy demand (heating + cooling) is exactly the same as cooling demand in all climates, except Shimla, where energy demand increases by 6% compared to IND_Stat_AC and by 2% compared to ASH_Adap_AC. To conclude, the IMAC-C-NV adaptive model provides energy savings in warm and hot climates, however the setpoint temperatures based on the National Building Code and ASHRAE 55 adaptive model are more suitable for cold climates similar to Shimla.

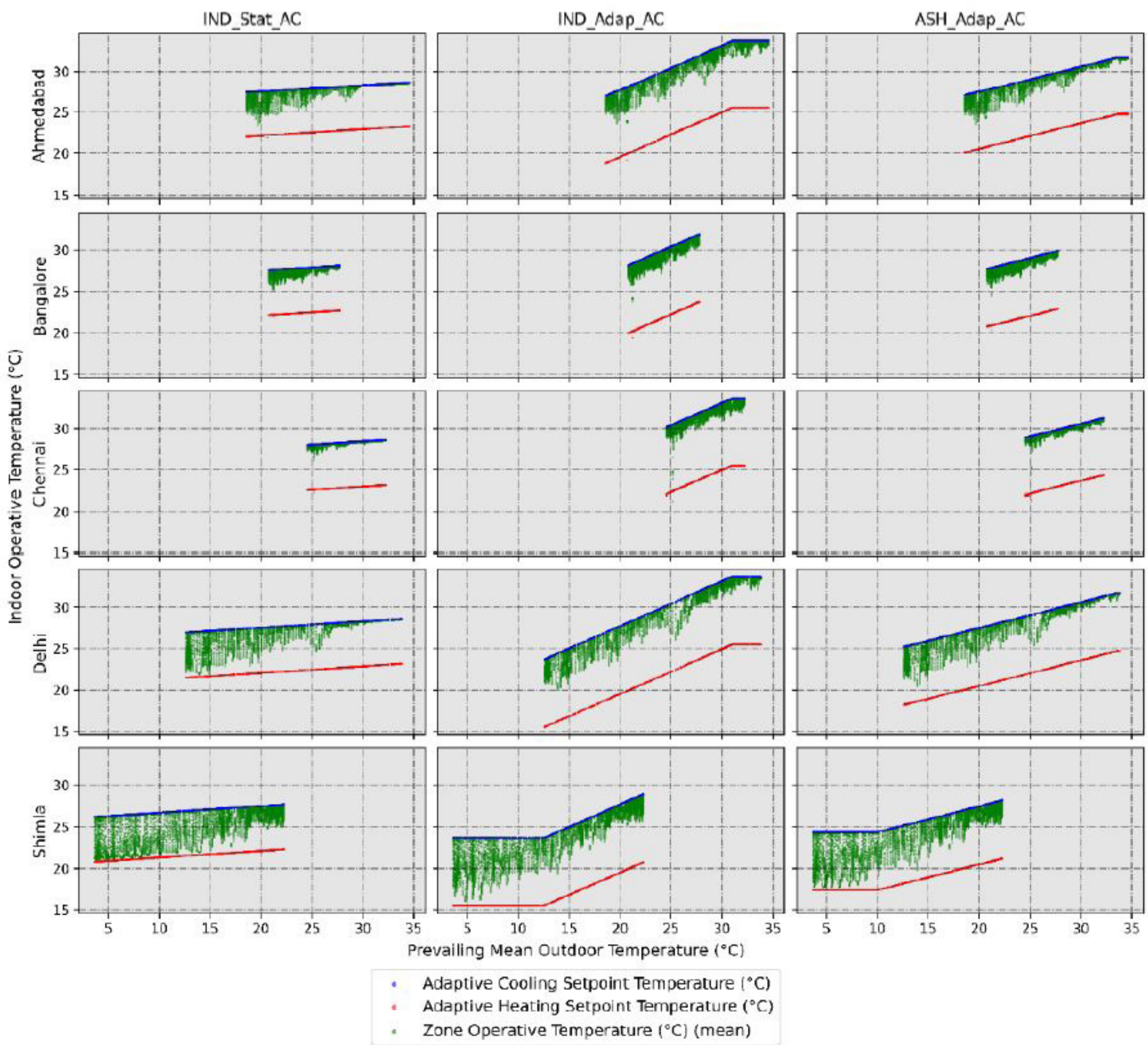


Figure 5: Operative temperature values considering setpoint temperatures based

Table 1: Energy demand values

HVAC system	Model	Ahmedabad	Bangalore	Chennai	Delhi	Shimla
Cooling Energy Demand (kWh/m²·year)	IND_Stat_AC	283.94	249.44	306.01	257.9	151.51
	IND_Adap_AC	217.14	213.8	226.09	213.02	167.59
	ASH_Adap_AC	250.81	234.32	268.41	236.3	163.12
	1-(IND_Adap_AC/IND_Stat_AC)	24%	14%	26%	17%	-11%
	IND_Stat_AC - IND_Adap_AC	66.8	35.64	79.93	44.88	-16.08
	1-(IND_Adap_AC/ASH_Adap_AC)	13%	9%	16%	10%	-3%
	ASH_Adap_AC - IND_Adap_AC	33.68	20.52	42.32	23.28	-4.47
Heating Energy Demand (kWh/m²·year)	IND_Stat_AC	0	0	0	0.17	6.65
	IND_Adap_AC	0	0	0	0	0.04
	ASH_Adap_AC	0	0	0	0	0.62
	1-(IND_Adap_AC/IND_Stat_AC)	-	-	-	100%	99%
	IND_Stat_AC - IND_Adap_AC	0	0	0	0.17	6.6
	1-(IND_Adap_AC/ASH_Adap_AC)	-	-	-	-	93%
	ASH_Adap_AC - IND_Adap_AC	0	0	0	0	0.58
Total Energy Demand (kWh/m²·year)	IND_Stat_AC	283.94	249.44	306.01	258.06	158.16
	IND_Adap_AC	217.14	213.8	226.09	213.02	167.64
	ASH_Adap_AC	250.81	234.32	268.41	236.3	163.74
	1-(IND_Adap_AC/IND_Stat_AC)	24%	14%	26%	17%	-6%
	IND_Stat_AC - IND_Adap_AC	66.8	35.64	79.93	45.05	-9.48
	1-(IND_Adap_AC/ASH_Adap_AC)	13%	9%	16%	10%	-2%
	ASH_Adap_AC - IND_Adap_AC	33.68	20.52	42.32	23.28	-3.89

4. Discussion

Given the energy saving values from Table 1, adaptive setpoint temperatures are identified as an efficient energy conservation measure. However, some arguments are needed at this point. According to current thermal comfort research, the human body adjusts to warm, cooled, and naturally ventilated environments differently, as seen by the slopes of the linear regressions. But according to a recent study, whether a space is naturally ventilated, heated, or cooled, individuals typically adapt to it [18]. Therefore, this is a subject that obviously need additional research, and it is noted as a weakness since this study takes the assumption that people would adapt to the air-conditioned environment in the same manner they would to one that is naturally ventilated.

Therefore, this energy saving strategy could have an important impact on building stock decarbonisation, since no retrofit is necessary, only the daily adjustment of setpoint temperatures. Nevertheless, a first step to take this approach from simulation to reality has already been taken by means of a Building Automation System, in which setpoint temperatures are set as per the comfort or neutral temperature of an adaptive comfort model developed for the climate of Seville [26–28]. Considering adaptive thermal comfort models have been initially developed for naturally-ventilated spaces, where the prediction has been found very accurate, these has a very close relationship with energy poverty. People who suffer from energy poverty usually cannot afford the extensive use of airconditioning or heating systems, therefore the conditions in those spaces are very similar to naturally-ventilated spaces, where the HVAC system is hardly activated. Therefore, considering no retrofit or equipment acquisition is necessary to use the adaptive setpoint temperatures, there are identified as an important energy saving measure in the context of energy poverty.

5. Conclusion

Adaptive setpoint temperatures, also known as setpoint temperatures based on adaptive comfort models, have lately gained recognition as a significant energy-saving technique because they practically require no installation costs to reduce energy demand. Up to now, investigations based on adaptive setpoint temperatures have provided the basis for the Adaptive-Comfort-Control-Implemented Model (ACCIM), taking into account the international models EN16798-1 and ASHRAE 55. This study examines, however, the energy implications of using regional or local comfort models, specifically the India Model for Adaptive Comfort in Commercial buildings (IMAC-C), by contrasting them with the effects of using the ASHRAE 55 adaptive model and static setpoint temperatures suitable for India, as suggested by national regulations. Furthermore, simulations of building energy were conducted in all five distinct climate zones, utilizing the climate data of Ahmedabad, Bangalore, Chennai, Delhi, and Shimla. This analysis took into account both naturally-ventilated and full air-conditioning operating modes.

The simulation results show energy savings ranging from 14 to 26% compared to the use of PMV-based setpoint temperatures according to the National Building Code, and ranging from 9 to 16% compared to the use of setpoint temperatures based on the ASHRAE 55 adaptive comfort model, for Ahmedabad, Bangalore, Chennai and Delhi. In the case of Shimla, energy demand increases by 6 and 2% respectively compared to PMV-based setpoints and the ASHRAE 55 adaptive model.
Thus, using setpoint temperatures determined from the Indian local adaptive comfort model appears as a highly successful strategy for energy conservation. However, it is significant to highlight that this study makes the assumption that people would adapt to air-conditioned environments in the same way they would to naturally ventilated rooms, therefore, this feature merits further investigation.

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Paper Presentation - Session 6

Session 6A - Circular Economy Building Materials and Methods

- Pitch to Policy program in India and Indonesia - a co creation approach towards decarbonisation
- Circular Economy, Building Materials and Methods
- An experimental investigation on the impact of lime and cement mortar/plaster material on the indoor hygrothermal environment of test spaces
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Note: The Presenting Author has been marked with an asterisk (*)

Pitch to Policy program in India and Indonesia A co creation approach towards decarbonization

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Abstract

Worldwide, the building and construction sector contributes 37% of energy use and 39% of energy and process related carbon emissions [1]. In order to keep global warming below 1.5oC the buildings sector must halve its emissions by 2030 and be net-zero by 2050 [2], yet emissions were their highest ever in 2021 [1] because rates of new construction and increases in energy demand were far greater than efficiency gains delivered by new building regulations and other policy reforms. Global Buildings Performance Network (GBPN) and Monash University Australia conceived and implemented the Pitch to Policy (P>P) programme as an innovative experiment aimed at validating crowdsourcing, co-creation and systems thinking approaches to promote inclusive policy making for climate action. The program brought relevant government departments, policy makers and entrepreneurs together to co-create innovative solutions for decarbonizing the buildings sector. The program was piloted in two growing economies - India and Indonesia - in partnership with local organisations. A total of 25 teams of professionals participated in the program and 6 finalist teams were awarded seed funding. Some teams have gone on to win contracts, initiate important industry efforts and trial their inventions. Future work will build on post-P>P government engagement for winning teams.

Keywords - Built environment, innovation competition, public policy, India, Indonesia

1. Background

In 2015 The Government of India inaugurated Pardhan Mantri Awas Yojna – Urban (PMAY-U), an initiative to largely address the housing shortages for economically weaker (EWS) populations in urban areas. The program aims to provide permanent housing to all eligible urban populations by 2024. Eco-Niwas Samitha (ENS) is another initiative by the Government of India to develop and implement the Energy Conservation Building Code for Residential Buildings (ECBC-R). India has made world leading progress in reducing poverty through housing [3], but more innovation in this sector is needed to also reach net zero for housing.

Like India, Indonesia is rapidly advancing and has its own goals for building sustainability. In 2016 Indonesia adopted the Urban Development Policy as part of the urban dimension of the SDGs. Among the 5 pillars of policy, pillar 2 calls for development of Green Building [6]. Following the introduction of the country's first regulation on green building in 2015 and the launch of a promising roadmap for decarbonising buildings, Indonesia is still continuing the process of strengthening and improving the coherence of the regulatory framework to support its implementation and enforcement. Indonesia too will benefit from more innovations both in technology but also policy implementations.

Climate Change – Indian Perspective

With a population of 1.38 billion, India is the most populous country in the world. India is currently the 3rd largest greenhouse gas emitting country with net GHG emission of 3619.8 tonnes of GHG emissions in 2018 [1]. The Indian climate is likely to warm by 0.5 degree centigrade between 2010 to 2030, (which is equivalent to the entire 20th century climate warming of India) and an overall warming of 2-4 degrees by the end of the 21st century [4]. India's per capita CO2 emissions have increased by 266% in the last two decades, from 0.6 metric tonnes in 1990 to 1.6 metric tonnes in 2019 [5]. Currently, the buildings sector is the 4th largest CO2 emitter in India with 164 Mt tonnes in 2019 [6]. In addition, the cement industry contributes 211 Mt tonnes of CO2 emissions to the national tally [6].

's urban population is growing at 2.3% per annum [7]. In 1990, 26% of the total population of India was living in Urban areas which increased to 35% by 2020 [8]. Urban areas often have higher temperatures than surrounding rural areas owing to the Urban Heat Island effect [9]. Some recent studies suggested that urbanisation contributes 30%-50% to heat stress index during summers [10]. According to the IEA, the buildings sector contributes 39% of global CO2 emissions and accounts for 36% of final energy use [1]. These climate impacts could reduce the country's GDP by 2.5 to 7% which could result in an increase in poverty.

Climate Change – Indonesian Perspective

With a population of 273 million Indonesia is the world's 4th most populated country. Indonesia is particularly exposed to global heating: from rising temperatures to irregular weather patterns that are causing wetter climate in one part of the nation to dry effects in other regions (World Bank, 2020). The total CO2 emission of Indonesia has increased from 665,929.63 Gt in 1990 to 1,593,163 Gt in 2019 [11] with a metric ton per capita increase from 0.8 in 1990 to 2.8 in 2019 (World Bank, 2022). The share of CO2 emissions of industry and energy sectors has increased from 19.3% in 1990 to 42.30% in 2019 [11]. This rapid industrialization has caused the equally rapid urbanisation in the country.

The country's urban population is growing at 4.1% per annum, the highest rate after China (World Bank 2021). Between 1980 to 2010, the country's urban population has grown 400% from 32.8 million to 118.3 million [12].

In the last two decades alone Indonesia's mean temperature has increased by almost half a centigrade from 25.85 in 2000 to 26.19 in 2020. (World Bank, 2020). Urban areas often have higher temperatures than surrounding rural areas owing to the Urban Heat Island effect [9]. Some recent studies suggested that urbanisation contributes 30%-50% to heat stress index during summers [10]. According to the IEA, the buildings sector contributes 39% of global CO2 emissions and accounts for 36% of final energy use [1]. These climate impacts could reduce the country's GDP by 2.5 to 7% which could result in an increase in poverty [13].

2. Methods

Given the climate imperatives in India and Indonesia and the opportunities to innovate with policy implementation, The Pitch to Policy (P>P) program was designed to bring government policy makers and entrepreneurs on to a single platform where they can collaborate and co-create entrepreneurial ideas into feasible solutions and policy ideas for governments to adopt and/or learn from to achieve greater policy ambition in built environment sustainability. The built environment is the main target for P>P due to the funding imperatives of the principal donor supporting the authors' organisation.

P>P inherits its approach from Knowledge and Innovation Community (KIC), an EU-funded open-source ecosystem for innovation [14]. KIC organises accelerators through its hubs internationally using business logic and results oriented approaches to cover entire innovation value chains in a specific field. P>P was adapted from KIC's ClimateLaunchpad and implemented as a policy bootcamp where applications/ideas are solicited from professionals, late-stage research, and startups. ClimateLaunchpad promotes as "the world's largest and most successful pre accelerator program for climate start-ups" and is market facing [15].

Governments and ministries at local, regional, and/or national level participate in P>P by workshopping a policy, regulation or programme that could be informed by "crowdsourced" (as in publicly solicited) proposals from professionals working close to the issue at hand. Since many technologies and new practices are needed to decarbonise the built environment, looking to emerging innovation with new or reformed public policy is a systems thinking approach [16] that benefits both from entrepreneurs, policymakers and many other contributors. This approach examines the built environment more like a biological system that includes features such as emergence, path dependency, established networks of actors, and various kinds of repeating cycles. This approach differs greatly from purely economic or engineering analyses. Most importantly, it helps identify the size and complexity of the changes which might be facilitated by technology; not just the utility of technology and its potential market value.

P>P is not, as such, part of the traditional government processes of public consultation, formation of research and development partnerships (R&DP's), public-private partnerships (PPPs) or government-run incubators. The programme has been designed with an intention and assumption that the climate emergency can motivate more rapid interactions across silos and that it can utilise more innovation. Trist [17] validated this approach in his research on "organisational ecology". Trist introduces that various actors and organisations in the economy have elaborate networks and influences on each other. Governance is rarely entirely "top down" and most often requires local adaptations to be implemented. Such a hierarchy is part of the overall organisational ecology.

The program was implemented to solicit policy and regulatory supporting technologies and practices from the innovation community. This included new ideas for reducing carbon footprint in the construction sector. Through a process of liaison, the theme of each P>P event was determined, usually from current government decarbonisation goals. This is then reframed as the callout to the innovation, sustainability and built environment ecosystem. The agreed callout also forms the basis of preselection of applicants.

Proposals meeting the criteria of the specific P>P callout were shortlisted to participate in the P>P programme. The callouts were via professional and academic networks. A team could include professionals, academics and researchers, but team members were explicitly limited by profession or interest. For teams to participate, one team member must be a country national located in the participating country. Teams consist of a minimum of two members. Applying for P>P required an online application.

The applicant ideas were evaluated by the judges and/or by the local country partner with this briefing from GBPN:

- Does the idea introduce and demonstrate the feasibility of a new policy or regulatory measures to improve the built environment or reduce policy implementation risk?

- Does the idea use building materials with a lower carbon footprint than conventional building materials?

- Does the idea introduce and use energy conservation techniques in building design?

- Does the idea use techniques for improving efficiency of alternative energy solutions such as solar power?

- Does the idea promote new teaching and learning programs for rapid accreditation or rapid upgrading of skills?

The India program was implemented in partnership with a research organisation, while the authors' institutions were the technical partners. In Indonesia, the national industry association partnered with the author's organisations and the callout was principally to the Indonesian membership who were given continuing professional development credits for participating.

The participating teams were developed by providing access to high quality information resources, expert insights, and specifically tailored education tools for each idea. The facilitator was an expert from KIC's ClimateLaunchpad. Mentors from industry, government and academia are recruited to interact individually with teams in a four week lead up after team selection.

The teams participated in 3-day intensive bootcamp where they were provided further coaching to polish their ideas to be ready to pitch. The boot camp also trained teams in the art of storytelling through a pitch, so they could develop and present a convincing pitch for their ideas and are ready to pitch it to relevant government and other relevant organisations and stakeholders.

Since this was a pilot program, the primary focus was to test and evaluate the program design and methodology assumptions. Post program evaluation surveys and focus group discussions were used as primary evaluation methodology. These are reported below.

A P>P workbook was developed to train professionals and startups on the art of storytelling through pitching. This toolkit was designed, based on an KIC creative commons workbook. It was amended and optimised to meet the requirements of the P>P program.

Whereas the KIC workbook pitching format includes content on cash flows, customer research and financial/funding projections (Figure 1, below) [18], while the P>P workbook was adapted to treat a government as the customer, with government needs as key to the pitch (Figure 2, below). As such, financial modelling was removed because the future profitability of innovations is less important than the potential for scale up via government adoption of innovation concepts in the pitch.

Figure 1: ClimateLaunchpad 2019 9-slide deck (layout changed by author) [18] (CC Attribution-ShareAlike 4.0

The workbook is a hands-on cookbook and in phase-1, uses systems thinking methodology for governance (for example: [19]) to train the professionals and startups to develop an eight slide comprehensive pitch deck. The slides and the narrative follow a very strict format which was also adopted from KIC. The deck and the intended narrative are:

1. Title Slide – Introduces the idea, the presenter, objective and intended outcome in one synthesised statement. Personal connection of the presenter.

2. Opportunity Slide – States the opportunity & possible benefit at scale. Not a statement of the problem.

3. Landscape Slide – History, actors, past efforts, path dependencies, ecologies, economics. This depends specifically on the approach the pitch takes to novelty.

4. Situation Slide – Presents the situational analysis and why the problem is a persistent problem. This should be a quite simple loop or loops showing some key actors, organisations or cycles.

5. The Change Slide – How the idea will influence the current situation and bring about change. This is often shown by the innovation breaking one or more of the cycles of slide 4.

6. The Ask Slide – States the resources required and reiterates benefits to the giver.

7. The Outcomes Slide – What the asked for resources will achieve in 1, 5, 10y if the asked for resources are provided. This may show what can be done with only some of the resources.

8. The Team and Dream Slide – Presents the team capacity, capability, and suitability for implementing the idea. Explains the dream - the very long term binding vision for the team.

In phase 2, the workbook was used as a guide to prepare for idea pitching. Using the workbook, the participants were mentored to practice and polish their pitch using a storytelling methodology provided from KIC. The focus of the training was to support the participants in building a strong

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narrative that complements the pitch deck and optimises their tone and tempo while practising under guidance of expert mentors. The storytelling asserts that the spoken part of the pitch is more important than the slides. It advises that the presenter personalise the narrative and align the goals of the project with personal events or desires.

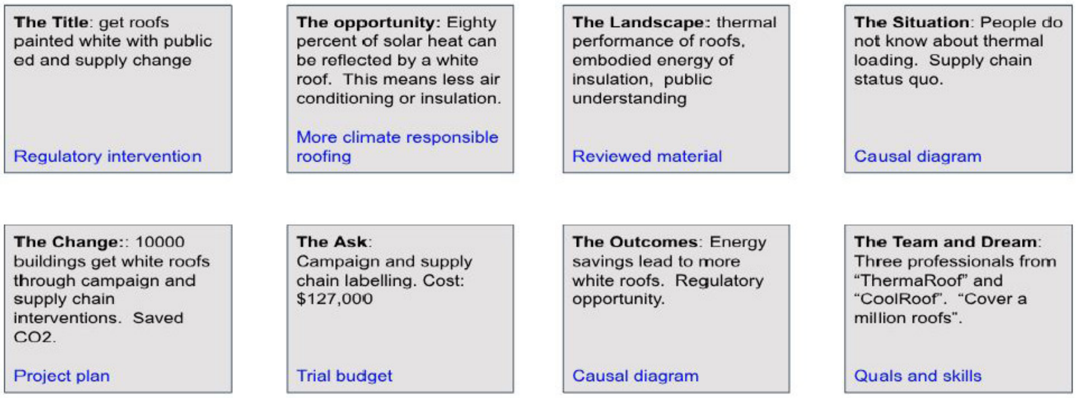

Figure 2: P>P Workbook 8-slide deck, with example content. (author's work).

The participating teams pitched their ideas in front of an invited jury consisting of building experts, engineers, policy makers and entrepreneurs. The jury developed a rubric for assessing teams objectively. The below is the default rubric which the jury are encouraged to collaboratively customise to fit the call out of the P>P run.

2. Title: What is this? Do you meet the presenter and know what he or she is going to do? Is it a market intervention, a new policy, a law change, a public campaign, etc.? This needs to be very clear immediately and through the whole pitch. For a call out concerning renewables penetration, the Jury may want to hear the Title introduce the renewable innovation - technical, finance, behavioural, energy system or such.

3. Opportunity: How big can this be? Is the opportunity or challenge they identified a worthwhile challenge? It might be a very big challenge, but it has to have very great potential.

4. Theory: Have they done their homework? How well do they know the theory, background, economics or history, law of their subject?

5. System and actors: Why has this not happened already? How well do they explain why their idea has not been done already or has not proliferated already? What are the current obstacles? Who are the current actors (organisations, persons) who control the current situation?

6. Intervention: What are they going to do? What is their intervention? What steps are they going to take, who will they reach out to? What will they demonstrate? Is this practical, realistic, can it start tomorrow?

7. Ask: What do they want from you? Is it clear who or what organisation they want to ask? Do you understand why they ask for what they do and is their request justified? They ask for something specific that lets them do what they want in slide 5.

8. Outcomes and multipliers: Will it grow and what are the larger benefits? Their idea has to cause larger change, if indirectly. There has to be some enabling aspect of their effort so that larger change is possible. They state a timeframe and the larger impact of their effort at that time.

9. Team and Dream: Who are they and are the right people to do this? Their roles as they introduce them need to make sense. They need to give a future goal that is large but plausible.

10. X-Factor: the pitch needs to leave you impressed with the idea, the potential and the people. This performance needs to look easy. Pitch team members speak slowly with confidence. Not too many words. It is evident they are prepared and have practised, but also they engage. X Factor is your personal feeling.

The rubric scores each slide at 10 points with "X-Factor" at 20 points, giving 100 possible points per team. The jury were given a fixed time after each pitch to ask only elaboration questions. The jury retired to compare notes and rank the teams.

Winners received feedback and input by experts to further optimise their ideas. The best three pitches in each boot camp were awarded USD2000 prize money. Teams are encouraged to report back to GBPN; using a LinkedIn group.

3. Results

At the time of writing three Indian teams have progressed after P>P. One team concerned with networking has organised an important supply chain charter in India and asserted ambitious sustainability goals for signatories. The signatories include large national builders and innovative materials suppliers. This team has reported that it benefited from P>P and it cites its inclusion in the programme at the inception of its successful business history:

"The fact that we got to run our idea by a lot of sustainability professionals, it was like the first litmus test. Everybody had so many great insights and so much great feedback for us that it gave us the confidence to take it forward and start strengthening our idea even further." [20]

An India team concerned with prototype housing won a contract to support the implementation of efficiency legislation for all of southern India. This team worked with Global Buildings Performance Network (GBPN) as a knowledge partner on an important advanced housing project. An India team performed successful low income housing community outreach in a subsequent project with GBPN. They were able to determine the expectations for better housing and energy services. Two judges from the India programme have gone on to cooperate with GBPN on projects and the P>P India LinkedIn page received more than a thousand followers.

A post program survey was conducted to evaluate the outcomes of the programme by seeking feedback of participants. The survey findings showed that 80% were happy with the team's choice of project. 50% chose projects like their work whereas 40% said their concept did not have any relation with their workplace. 50% of teams were satisfied with the pitch format; however, the consensus was that the pitch format should have been longer and flexible in terms of content. 90% of participants agreed on the efficacy of bootcamp in improving their pitch deck development and pitching techniques while 100% participants agreed that interacting with teams improved their pitches. 90% participants were satisfied with the facilitators and presenters of the bootcamp. While all participants agreed that interacting with mentors improved their pitch and pitching performance, and 60% believed they needed more mentorship support in further optimising their pitch. All participants showed strong commitment to continue working on their ideas and showed willingness to pitch their ideas at further avenues if any opportunity arrived. They further showed strong agreement that if they received the support they asked for in their call to action, they would be able to initiate their projects ideas quickly. 90% of participants agreed that the P>P programme improved their capacity to develop, present and pitch their ideas and 70% of participants were willing to again participate in the P>P program.

Focus group discussions

A focus group discussion was arranged with participants to seek their feedback as well as assess what they have learned and how the program could be improved. Participants joined in the bootcamp with a preconceived notion that the programme is about learning about government policies, however, they were pleasantly surprised to learn that it was a hands-on training and development program to help them market their ideas.

Most of the participants were of the view that the single most important thing they learned was the issue of sustainability and how to break it down and explain it in plain but convincing language to government policy makers through pitches. However, the participants were still confused about how they can align or integrate their ideas with government policies.

The participants were asked about whether the P>P program met their expectations, and the majority of the participants agreed. Though, a significant number of participants expressed that Systems Changing theory was difficult to understand and it would be better if it can be translated into the language of the participating country. Indonesia participants were very satisfied that they received CPD points through P>P which could practically help them in their career.

4. Discussion

The main objective of the programme was to introduce an idea of crowdsourcing innovation for policy support. Our approach is that a startup bootcamp designed for boosting the investment or commercialisation of a sustainable technology could be extended to the development of government outreach and policy focus. Overall, participants were pleased to get this opportunity to get exposure and training about pitch deck development and pitching. They were satisfied to have a chance to network with experts and professionals from industry and were eager to participate in such programs whenever opportunity came. However, the consensus of their views was that the ideas they presented have a good chance to succeed as private or development sector initiatives but for the work to be aligned and integrated with government policy, a more concentrated effort is needed. The bootcamp Workbook was successfully used according to the feedback. Adapting from the open source ClimateLaunchpad [15] workbook provided valuable materials that attendees were able to use to develop content appropriate for governance. It is clear from the feedback of participants, judges and experts engaged in the program that the programme helps participating teams in optimising their ideas into feasible products or services. The participants felt that they had improved their pitching techniques during the bootcamp and learned to use the art of storytelling as a methodology for pitching their ideas. The programme has provided networking opportunities and publicity for all involved.

Concerning policy potentials: the challenges for the upcoming and highly progressive Indian ENSBC may be regional localisation, implementation and enforcement. P>P can help ground-level enforcement in India, which has not yet seen substantial implementation of the building energy code: several P>P pitches supported these policy steps with innovative technology and practices. They included building carbon passport systems, free building energy modelling software, energy meters for “negawatts”, a clearinghouse for low carbon materials and more. Pitching these capabilities to state governments in India demonstrates that the market is ready and state implementers can look forward to coming technical capability and competition.

The similarities and differences between the two P>P programmes would provide material for a whole educational paper - but the main similarity was the raw ambition across teams regardless of whether they were younger, older, Muslim, women, academics or commercial providers, in both India and Indonesia equally. All overcame the challenges using English and heavily adapting their ideas to the fixed government-appropriate pitch format.

Some differences between India and Indonesia concerned how teams expected ongoing support and development. In Indonesia, since P>P was a closed event, participants treated it more as a membership design competition. In India P>P was treated more as an incubator. There was greater expectation in India to meet governments after P>P. This is an activity we will pursue much more actively next time.

5. Conclusion

It is clear that current policy progress for the built environment has not caused emissions to be reduced or in fact capped. This will require step changes in how buildings are designed, built and operated. Core to this will be innovative processes, products and practices. This work concluded a two-country pilot of Pitch To Policy (P>P), a special adaptation of Climate KIC’s ClimateLaunchpad from commercialisation of sustainable products and services to pitching sustainable built environment innovations direct to governments.

The programme ran in Indonesia and India, two countries with rapidly developing building sectors, and which are high energy and high carbon. Call-outs to commercial, academic and other sectors provided 25 teams of professionals for the two programmes. Each provided mentor support, educational materials, a bootcamp and a workbook introducing systems thinking and other concepts. A specialist facilitator from Climate KIC was engaged to deliver the modified programme.

From feedback received along with interviews and focus groups, the programme was popular and the material was felt to be relevant and valuable for polishing and pitching an innovation. How to directly connect innovations to live government policies was not fully solved, and follow-up after P>P did not connect teams to governments. To address this ongoing issue, we propose three changes:

1. Align each event with clear policy objectives/issues set by the participating governments;

2. Provide materials in local languages;

3. Follow-up and linking with incubator opportunities to further develop innovations with government support.

4. Judges/public servants should also participate in bootcamps to help keep ideation aligned with government priorities;

5. Revision of short-listing and judging criteria and rubrics to ensure more mature, implementable and scalable proposals are included in the pitching process.

India and Indonesia P>P could and should combine: many sustainability services are information and knowledge work that can be provided remotely. Also there is the great opportunity for exchange and cross-fertilization.

The P>P programme does not have set dates for its next event, however GBPN is presently pursuing a related programme in India which is establishing what would be the second part of the P>P ecosystem: living labs for testing policy and technology interventions in real homes. We also look forward to running P>P to explore the anticipated national carbon market in India. We hope to report on these in the future.

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Circular Economy, Building Materials and Methods

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Abstract

The concept of a circular economy is gaining prominence as a sustainable approach to resource management and environmental protection. According to the Ellen MacArthur Foundation, circular economy is "an economy that is restorative and regenerative by design, and which aims to keep products, components, and materials at their highest utility and value at all times" (Ellen MacArthur Foundation, 2013). The circular economy model emphasizes the efficient use of resources, reduction of waste, and promotion of closed-loop systems to create a sustainable and resilient economy. This research paper tries to understand the application of circular economy principles in the building design and construction methods in India. The study will analyse the existing manufacturing methods for brick, cement, and steel bars in India, identify market trends and innovative policy and regulatory practices related to circular economy principles. The paper argues the need for service level innovations and market transformation in the building material production process, Eco-labelling policy and whole building Embodied Carbon indicator and informed consumer behaviour as well as environmental product declaration recommendations as the long-term strategies for the circular economy in the building design and construction industry.

Keywords - Life Cycle Assessment, Circular Economy, Embodied Carbon, Eco-Labelling

1. Introduction

The aim of a research article on circular economy principles in building design, materials, and construction methods is to explore and analyse the potential for applying circular economy principles to reduce the environmental impact of the building sector. The article aims to provide insights into the integration of circular economy principles and life cycle assessment (LCA) in building design, selection of low-embodied energy materials, and construction methods. The research article aims to contribute to the growing body of knowledge on sustainable building design and to provide guidance to architects, designers, and builders.

The concept of a circular economy has gained considerable attention in recent years as a viable solution to the growing environmental and economic challenges faced by countries across the world. The circular economy is an economic system that aims to minimize waste and maximize the use of resources. It is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems. This research aims to explore how circular economy principles can be applied to the building materials and construction industry in India, which is one of the most resource intensive industries and contributes significantly to greenhouse gas emissions. This research will analyse the current manufacturing methods for Brick, Cement production and Steel Bars in India and explore the potential for circular economy principles to reduce carbon emissions and mitigate the impacts of climate change in India.

Importance of the Circular Economy

The importance of circular economy and life cycle assessment (LCA) in India's GDP economy and national growth plans stems from the need to address resource constraints, environmental challenges, and promote sustainable development. India has recognized the potential of circular economy principles and LCA to drive resource efficiency, reduce waste, and mitigate environmental impacts, leading to the development of policies and initiatives to support these approaches.

NITI Aayog (National Institution for Transforming India) is a policy think tank of the Indian government that plays a significant role in shaping India's national development strategies. NITI Aayog has recognized the importance of circular economy principles and has been actively promoting their implementation across sectors, including the building and construction sector. It has developed initiatives and policies to foster resource efficiency, waste reduction, and sustainable practices.

India's policy on circular economy and resource efficiency in the building and construction sector is guided by various regulations and initiatives. One such initiative is the National Resource Efficiency Policy (NREP) launched in 2019. The NREP aims to promote the efficient use of resources, including materials and energy, in various sectors, including the building sector. It provides a policy framework to enhance resource efficiency, minimize waste generation, and encourage recycling and reuse in construction activities.

In addition to the NREP, the Indian government has also implemented the Smart Cities Mission and Swachh Bharat Mission, which emphasize sustainable urban development and waste management. These initiatives provide a platform for integrating circular economy principles and LCA in the planning, design, and construction of buildings and infrastructure.

Implementing circular economy concepts, tools, and measures in LCA can bring several benefits to the building and construction sector in India:

▪ Resource Efficiency and Cost Savings: Circular economy principles promote the efficient use of resources, reducing the demand for virgin materials and minimizing waste generation.

▪ Environmental Sustainability and Climate Change Mitigation: The building sector contributes significantly to environmental degradation and carbon emissions. By employing LCA to assess the embodied energy and carbon emissions of building materials, India can identify opportunities to select low-embodied energy materials, reduce carbon footprint, and mitigate climate change impacts.

▪ Green Job Creation and Economic Growth: Circular economy practices in the building sector can stimulate economic growth and create employment opportunities.

▪ Regulatory Compliance and International Reputation: By implementing circular economy concepts and LCA, India can align with global sustainability standards and enhance its international reputation.

Scientific innovation in the context of circular economy principles and building materials involves the development of new technologies, processes, and materials that promote resource efficiency, waste reduction, and the closed-loop utilization of materials in the building industry. This innovation aims to address the environmental challenges associated with the traditional linear model of construction, where resources are extracted, used, and disposed of without considering their potential for reuse or recycling.

One significant area of scientific innovation is the development of advanced materials that have a lower environmental impact and can be easily recycled or repurposed. For example, researchers are exploring the use of bio-based materials, such as bamboo, mycelium, and bioplastics, as sustainable alternatives to traditional building materials. These materials offer advantages in terms of renewability, low embodied energy, and recyclability, contributing to a more recycle and reduce and reuse approaches to the construction.

2. Methods

Review existing literature on circular economy practices in the construction industry, both globally and in the Indian context. Identify key concepts, principles, and best practices related to circular construction. Highlight specific challenges and opportunities in the Indian construction sector.

Research objective helps us identify the circular principles in the building design and construction and draws literature and information analysis based on the recent market trends specific to Indian scenario and comparative global best practices.

Data collection methods include desk research, circular policy and regulatory data and internet and field based observations have been included in this paper.

Circular economy is a concept that has been studied extensively in academic literature. The concept was first introduced by Pearce and Turner in 1989, who suggested that the economy should be circular rather than linear. In a circular economy, waste is minimized, and resources are reused, recycled, and regenerated. (Pearce, 1989) Many researchers have explored the application of circular economy principles in different industries, including the construction industry. A study by Feng et al. (2019) explores the implementation of circular economy principles in the construction industry in China. The study suggests that circular economy principles can reduce the environmental impact of construction activities and contribute to sustainable development. (Feng et al., 2019)

In the Indian context, the construction industry is one of the most significant contributors to greenhouse gas emissions, and the use of natural resources is unsustainable. A study by Nidhi et al. (2021) explores the potential of circular economy principles in the Indian construction industry. The study suggests that circular economy principles can improve the efficiency of resource use, reduce waste, and lower carbon emissions. (Nidhi et al., 2021) Furthermore, the government of India has set a net-zero target by 2070, which requires a significant reduction in greenhouse gas emissions in all sectors, including the construction industry (Government of India, 2021).

This paper aims to study the most common building materials manufacturing methods for Brick, Cement production and Steel Bars in India and understand the material applications potential for circular economy principles to reduce carbon emissions and mitigate the impacts of climate change. The research will also explore how circular economy principles can be incorporated into the construction industry in India, including design, construction management, building material innovation, information management and material supply chains. The research explore following inquiries in the mainstream methods and practices:

- What are the existing manufacturing methods for Brick, Cement and Steel production in India?

- What is the potential for circular economy principles to reduce carbon emissions and mitigate the impacts of climate change in the construction industry in India?

- How can circular economy principles be incorporated into the construction industry in India, including architecture design, construction management, building material procurement system, and material supply chain, using modern information technologies?

- Can Indian consumers optimize on the cost to pay for circular economy products and services?

- What are the material research innovation and market challenges present in the building sector?

- What are the key indicators and tools in the LCA and circular economy implementation useful for the professionals and practitioners community?

- How are manufacturing companies and asset owners responsible for Carbon Accounting? What global technologies are available for carbon accounting and emission and environmental impact validations?

- What are the best practices and policy standards for adopting circular economy principles in the long term to improve the health of buildings, human thermal comfort, and affordability of building materials in the private and public sector?

In addition to the above, it is also important to consider the role of government policies in facilitating the transition to a circular economy in the building materials sector. The Indian government has set a target of achieving net zero emissions by 2070, which includes significant efforts towards decarbonizing the construction sector. In this regard, the government can play a crucial role in promoting the circular economy through policies that incentivize the use of sustainable building materials, and encourage the adoption of circular business models among industry players.

Why The Circular Economy principles

One of the key challenges that the construction sector in India faces is the consumer behaviour in the building material quality and quantitative pricing and impact in the construction process. It is essential to determine whether Indian building material consumers are willing to pay for circular economy products and services, given the cost implications. A study by McKinsey & Company found that cost is the biggest factor driving consumer behaviour in India, followed by product quality and brand reputation. However, the same study also found that consumers are willing to pay more for sustainable products if they perceive them as providing tangible benefits such as energy efficiency and durability. Therefore, there is potential for circular economy products and services to gain traction among Indian consumers, provided there are necessary support systems and implementation.

Another challenge in implementing the circular economy in the building sector is the service level innovations and market challenges present in the sector. The construction industry in India is highly fragmented, with a large number of small and medium-sized enterprises (SMEs) operating in the sector. This fragmentation can create barriers to the adoption of circular economy practices at Building product design and innovation level, as there may be limited awareness and resources available to SMEs to make the Indian market specific changes.

Despite the challenges, there are several global best practices that can be adapted to the Indian context to facilitate the adoption of circular economy principles in the building sector. For example, the Ellen MacArthur Foundation's "Circular Design Guide" provides a framework for designing buildings with circularity in mind. The guide emphasizes the use of modular construction, which enables buildings to be easily disassembled and components reused or recycled. Another example is the "BREEAM" certification system, which is used to measure the sustainability of buildings. BREEAM places a strong emphasis on circular economy principles, such as the use of recycled materials and waste reduction measures.

To promote the adoption of circular economy principles in the building sector, a hypothesis could be to establish a circular building materials hub that brings together industry players, government agencies, and academia to collaborate on research and development of circular building materials and methods. The hub could serve as a platform for sharing best practices, building awareness, and providing resources to SMEs to help them adopt circular business models. In addition, the hub could facilitate the procurement of circular building materials by connecting suppliers with buyers, and provide support in implementing circularity across the entire value chain.

The circular economy presents a significant opportunity for the building sector in India to decarbonize and improve resource efficiency. However, several challenges need to be overcome to facilitate the transition to a circular economy, including consumer behaviour, service level innovations, and public policy challenges. By adapting global best practices and establishing a circular building materials hub, the Indian building sector can overcome these challenges and realize the benefits of a circular economy.

The research paper emphasizes the potential benefits of incorporating circular economy principles in the building materials and construction industry in the Indian context. By reducing waste, reusing and recycling materials, and adopting more sustainable manufacturing and procurement methods, this industry can contribute to reducing carbon emissions and mitigating the effects of climate change. However, the adoption of circular economy practices in this industry requires a coordinated effort from various stakeholders, including the government, manufacturers, consumers, and other participants in the supply chain.

Circular economy principles have been applied to the manufacturing and use of building materials such as bricks, cement, and steel in various parts of the world. The use of these materials is widespread, and their production is resource-intensive, energy-intensive, and contributes significantly to carbon emissions. Hence, it is essential to adopt innovative methods, manufacturing processes, technology, and IT systems to reduce carbon emissions and impact on climate change. In this article, we will focus on the circular economy principles adopted for bricks, cement, and steel, and their application in building structures to minimize carbon emissions.

Bricks are one of the most widely used building materials in the world, and their production is a significant contributor to carbon emissions. The circular economy principles have been adopted to reduce carbon emissions in the manufacturing of bricks. The use of alternative materials such as fly ash, sludge, and waste materials from industries like steel and aluminium has been successfully incorporated in brick manufacturing. The adoption of cleaner production technologies such as vertical shaft brick kilns (VSBK) and tunnel kilns have also been implemented. A study by Dubey et al. (2021) found that the VSBK technology was found to be more energy efficient, environmentally sustainable and cost-effective than traditional technologies. The adoption of such innovative methods and technologies can significantly reduce carbon emissions and improve the sustainability of the brick manufacturing industry.

Cement is another essential building material that has a significant impact on carbon emissions. The production of cement is responsible for approximately 7% of global carbon emissions. The circular economy principles have been adopted to reduce carbon emissions in cement production. The use of alternative raw materials such as fly ash, slag, and limestone has been incorporated in cement production. The use of alternative fuels such as biomass, waste, and tires has also been successfully adopted to reduce carbon emissions. A study by Ali et al. (2021) found that the use of biomass in cement production could reduce carbon emissions by 70% compared to conventional fuels. The adoption of innovative methods such as carbon capture, utilization, and storage (CCUS) has also been incorporated in cement production. The adoption of such innovative methods and technologies can significantly reduce carbon emissions and improve the sustainability of the cement manufacturing industry.

Steel is another essential building material that has a significant impact on carbon emissions. The production of steel is responsible for approximately 8% of global carbon emissions. The circular economy principles have been adopted to reduce carbon emissions in steel production. The use of alternative raw materials such as scrap steel, pig iron, and direct reduced iron has been incorporated in steel production. The use of alternative fuels such as biomass, waste, and natural gas has also been successfully adopted to reduce carbon emissions. A study by Högselius et al. (2018) found that the use of hydrogen-based direct reduction technology can reduce carbon emissions by 90% compared to conventional technologies. The adoption of innovative methods such as carbon capture, utilization, and storage (CCUS) has also been incorporated in steel production. The adoption of such innovative methods and technologies can significantly reduce carbon emissions and improve the sustainability of the steel manufacturing industry.

Steel is a widely used material in the construction industry, and it is critical to achieving sustainable construction. The production of steel results in a considerable amount of greenhouse gas (GHG) emissions. Therefore, the use of circular economy principles can be helpful in reducing carbon emissions and achieving a more sustainable construction industry. One example of a circular economy approach to steel production is recycling. Recycled steel requires less energy to produce and generates fewer GHG emissions than virgin steel. Recycling steel scrap can save up to 60% of the energy required to produce new steel and reduce carbon dioxide emissions by up to 58% (European Steel Association, 2021). In addition, the use of Electric Arc Furnaces (EAF) is a more energy-efficient way to produce steel than the traditional Blast Furnace Basic Oxygen Furnace (BF-BOF) method (European Steel Association, 2021).

Another approach to reducing the carbon footprint of steel production is the use of alternative feedstocks such as biomass, waste plastics, and waste tires (Tata Steel, 2021). Such alternative feedstocks have the potential to replace coal and coke as the primary sources of energy in the steel production process. Additionally, using electric power from renewable energy sources such as solar, wind, or hydro can reduce the carbon footprint of steel production. Several steel companies worldwide have started using renewable energy to power their production processes (McKinsey & Company, 2020).

Recycling and the use of alternative feedstocks and renewable energy sources are effective ways to achieve a more sustainable steel production process. Therefore, the use of circular economy principles can significantly reduce the carbon footprint of the steel industry. Furthermore, public policies can play a significant role in incentivizing steel companies to adopt circular economy principles.

Life Cycle Assessment: Tools and Techniques

In India, the manufacturing of building materials such as red bricks, AAC blocks, cement, and steel have been traditionally done using energy-intensive processes, which leads to a significant amount of carbon emissions. However, with the growing concern for the environment and the need to reduce carbon footprint, the building materials industry is shifting towards more sustainable and low-carbon production methods.

Red bricks are the most commonly used building material in India, and their production process is highly energy intensive. The traditional method of manufacturing red bricks involves sun-drying of clay bricks, which consumes a significant amount of energy and results in high carbon emissions. However, there are some new low-carbon technologies available such as tunnel kilns, which can reduce energy consumption by up to 50% and emissions by up to 60%. AAC blocks, on the other hand, are made using fly ash, which is a waste product from coal-based thermal power plants. The production process of AAC blocks involves autoclaving, which is a steam-curing process, and is much less energy-intensive than the traditional brick-making process.

Cement production is also one of the significant contributors to carbon emissions in India. The cement manufacturing process involves the calcination of limestone, which releases carbon dioxide into the atmosphere. According to the Building Materials and Technology Promotion Council (BMTPC), the Embodied Energy (EE) consumption for cement production in India ranges from 3,000 to 3,600 MJ/tonne, and the CO2 emissions range from 850 to 950 kg/tonne. However, the cement industry is now adopting low-carbon technologies such as vertical roller mills, which require less energy for grinding, and using alternative fuels such as biomass, municipal waste, and plastic waste to replace fossil fuels.

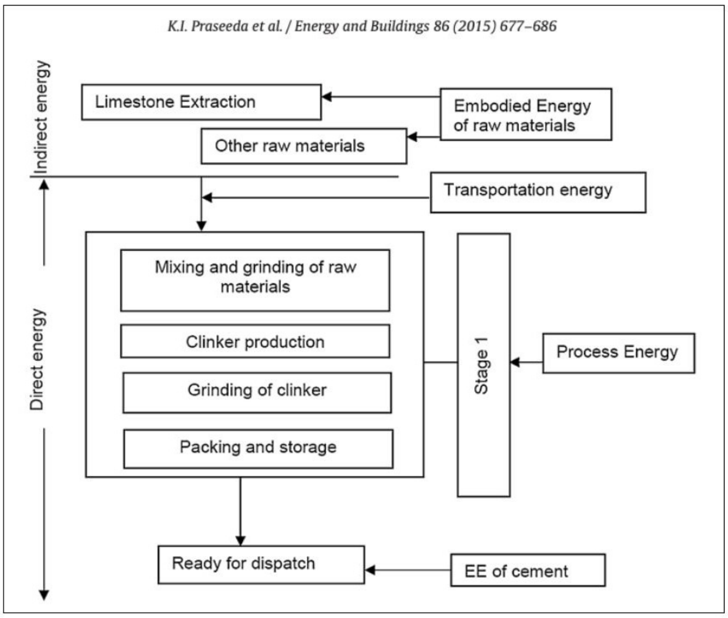


Figure 1: Framework for Embodied Energy in Cement production: Input/Output method

Figure 01 helps explain and provides a basic process flow about the selected manufacturing process in the Indian building materials manufacturing process and helps understand the Global Warming Potential (K.I. Praseeda et.al, 2015). The flow chart can help integrate the design process and selection of low-carbon materials during the design and construction phases.

According to a study by the Central Building Research Institute (CBRI) in India, the energy consumption for the production of one ton of cement ranges from 3,500 to 4,000 MJ, and the CO2 emissions range from 700 to 800 kg. The energy consumption for the production of one ton of steel ranges from 18,000 to 21,000 MJ, and the CO2 emissions range from 1,800 to 2,100 kg. The energy consumption for the production of one thousand bricks ranges from 1,500 to 2,000 MJ, and the CO2 emissions range from 200 to 300 kg.

In the context of circular economy principles, the building materials industry needs to adopt low-carbon technologies and sustainable production methods to reduce the environmental impact of building materials. The circular economy approach emphasizes reducing, reusing, and recycling materials to minimize waste and environmental impact. For example, in the case of cement production, using alternative fuels and replacing some of the cement with industrial waste or by-products can reduce the overall carbon footprint of the material. Similarly, using fly ash in the production of AAC blocks is an example of waste utilization, which is a key principle of the circular economy.

Table 1: Embodied Energy and Global Warming Potential - Indian Construction Materials Database

Buildings Materials Manufacturing	Embodied Energy (MJ/Kg)	Global Warming Potential (Kg CO2 equivalent)
Red Bricks (Bulls Trench Kiln)	3.6	0.32
Red Bricks (Hoffman's Kiln)	3.5	0.31
Red Bricks (Clamp Kiln)	6.3	0.57
Cement OPC	6.4	0.91
Basic Oxygen Furnace (BOF) Steel	24	2.8
Aluminum extruded profile (window frame)	280	26

Circular economy principles emphasize the reduction, reuse, and recycling of materials in the construction industry. Green building rating systems incentivize the use of recycled or upcycled materials, as well as the implementation of construction and demolition waste management strategies. By integrating circular economy principles, these rating systems aim to minimize the extraction of new resources and the generation of waste, thus promoting a more sustainable and regenerative approach to building design and construction.

The Intergovernmental Panel on Climate Change (IPCC) has recognized the crucial role that the building sector plays in contributing to global carbon emissions. In its fifth assessment report, the IPCC noted that buildings and construction are responsible for approximately 30% of global greenhouse gas emissions, which includes the embodied carbon emissions of building materials, as well as the energy consumption of buildings during their operational phase.

EPDs are standardized and independently verified documents that communicate the environmental impact of building products, including their embodied carbon emissions, to stakeholders and consumers. The use of EPDs encourages the adoption of sustainable materials, promotes recycling and waste reduction, and supports the transition towards a circular economy in the building sector. References from the IPCC report and standards include the "IPCC Special Report on Global Warming of 1.5°C" and the "ISO 14025 Environmental labels and declarations – Type III environmental declarations – Principles and procedures." These documents provide a comprehensive overview of the environmental challenges posed by the building sector and highlight the importance of adopting sustainable practices and the use of EPDs and LCA in achieving low-carbon building practices.

In the realm of carbon accounting and the pursuit of circularity in the construction industry, a new era of sustainability is dawning, setting the stage for transformative innovations. As global awareness of environmental concerns intensifies, the construction sector is increasingly embracing the principles of circularity and carbon reduction, ushering in a wave of change guided by ground-breaking research and industry-focused journal references.

Circularity, in the context of building construction, is a paradigm shift. It transcends the traditional "take, make, dispose" linear model and replaces it with a regenerative and restorative approach. Research by Wilson and Piper (2021) in the "Journal of Sustainable Construction" advocates for a circular economy in construction that revolves around reuse, refurbishment, and recycling of building materials. Circular design principles are gaining prominence, emphasizing modularity, adaptability, and durability. The work of Smith et al. (2022) in "Environmental Innovations in Construction" underscores the importance of designing buildings that can be easily disassembled and reassembled, minimizing waste and resource consumption.

Carbon Accounting in Building Construction

Carbon accounting in the construction industry is essential for achieving net-zero emissions targets. Pioneering research by Chen and Liu (2020) in "Environmental Science for Sustainable Building" elucidates the significance of Life Cycle Assessment (LCA) in evaluating the carbon footprint of building materials and processes. LCA, coupled with Building Information Modeling (BIM), enables real-time tracking of emissions throughout a building's life cycle.

Moreover, carbon accounting extends to embodied carbon and operational carbon. The work of Greenfield and Wong (2019) in the "Journal of Sustainable Architecture" explores the integration of carbon accounting into project management, promoting awareness of emissions at every construction phase. The concept of "carbon neutrality" is gaining traction, with projects aiming to offset emissions through innovative strategies, such as carbon sequestration in building materials, as highlighted by Williams et al. (2021) in "Sustainable Building and Design."

Embracing the Future

In conclusion, the building construction industry is on the cusp of a sustainability revolution. By embracing circularity and advancing carbon accounting practices, it is not only aligning with global environmental goals but also paving the way for a more resilient and regenerative future. The journey towards sustainable building practices is not just a necessity; it is a dynamic realm of innovation, driven by collaborative research and a commitment to a greener world.

Life cycle assessment (LCA) and embodied carbon assessment are crucial tools in achieving sustainable and low carbon building practices. Figure 02 explains about the Embodied energy and LCA workflows that helps to evaluate the environmental impact of building materials and products throughout their life cycle, including likely embodied and operational carbon emissions. The workflows helps establish the likely carbon emissions and associated environmental impact in the typical LCA model (D. Overbey, 2020). LCA model is based on the manufacturing data sheets, environmental product declarations and other actual or proposed integrated building information management systems used in the estimation of embodied energy and carbon calculations. This assessment allows designers and builders to identify and prioritize the use of low-carbon materials and sustainable practices in building design and construction. Embodied carbon and environmental product declaration (EPD) further supports the transition to a circular economy in the building and construction sector by enabling transparency and accountability in the end use of environmental friendly products and improve the embodied energy of the buildings.

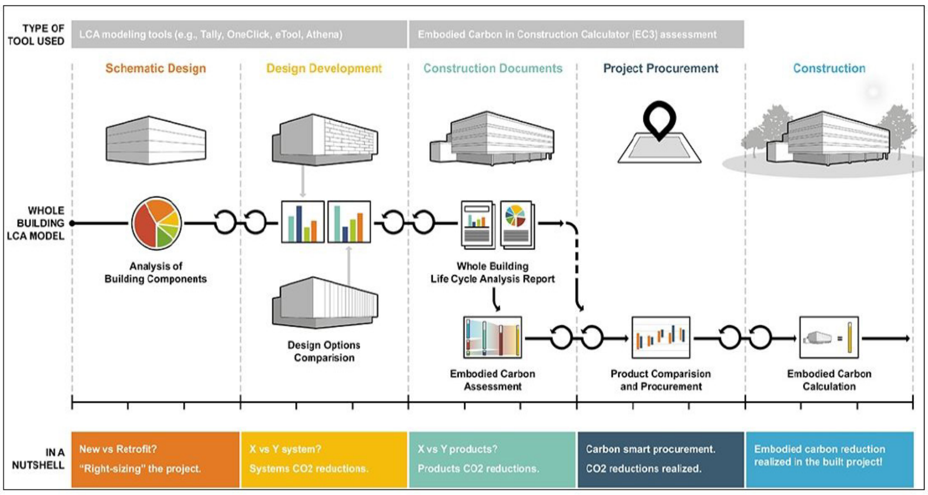


Figure 2: Embodied Energy to Carbon Modelling Workflow (Source: www.buildingenclosureonline.com/blogs)

In a recent development October 2023, MoEFCC, GoI, notified a scheme for environmental friendly products- Ecomark . Green Building practices ensure use of certified recycled products that are labelled.. The criteria may include energy efficiency, water conservation, site selection, materials selection, indoor air quality, and innovation. Higher star ratings or accumulated points indicate a more sustainable and environmentally friendly building. These criteria and rating systems provide a benchmark for measuring and improving building performance in terms of resource efficiency, carbon emissions, and overall environmental impact.

To illustrate the comparison between embodied carbon emissions reduction and environmental friendly products, we can consider a case study focused on a commercial building. The case study could analyse the various product categories of the building, which evaluates environmental product-based emissions per unit in terms of CO2 or kilowatt-hours per square meter or volume. Simultaneously, it could also assess the embodied carbon emissions reduction achieved through the use of low-carbon and environmentally friendly products applied during construction practices. On the other hand, Energy Performance Index (EPI) or Energy Use Intensity is a direct measure of Energy Efficiency and building operational energy consumption metrics. Whole building energy modelling provides EPI values to determine the energy consumption kilowatt hour per square meter per year and provides a benchmark and comparative analysis for the similar building types to determine the energy saving. Embodied energy, on the other hand, provides an overall Environmental Impact of the buildings. It calculates Carbon Footprint embodied CO2 per kg of materials, per square meter development impact on the environment of the proposed structure. While these metrics address different aspects of a building's energy profile, they are interrelated in the broader context of sustainability. Green rating systems apply case specific metrics to provide assessment of sustainable design strategies and evaluation methods. Construction practices often consider both embodied energy and operational energy efficiency to achieve overall environmental and energy assessment objectives.

A truly sustainable building should strive to minimize both embodied and operational energy. To fully assess a building's sustainability, it's essential to consider both aspects and balance them effectively.

A case study of the energy performance and carbon disclosure can be seen in the Delhi Metro Rail Corporation's (DMRC) Green Building Policy. The DMRC incorporated the GRIHA rating system to evaluate the environmental performance of their metro stations and buildings, ensuring compliance with energy efficiency, water conservation, and waste reduction standards. The policy also included a requirement for disclosing the embodied carbon emissions of building materials used in construction projects.

3. Results

Life cycle assessment (LCA) methods, tools, and software play a crucial role in predicting the total carbon and greenhouse gas (GHG) emissions associated with building materials, including bricks, cement, and steel manufacturing. LCA allows for a comprehensive evaluation of the environmental impacts associated with the entire life cycle of a product, from raw material extraction to disposal or recycling.

LCA enables architects, designers, builders, and construction professionals to assess and compare different design options and material choices based on their environmental performance. By quantifying the carbon and GHG emissions throughout the life cycle of building materials, LCA provides valuable insights into the environmental impacts of construction projects and helps identify opportunities for improvement.

To achieve the net zero target by 2070, it will be essential to continue to promote circular economy principles and resource efficiency policies in the building sector. We still lack in the larger database creation, unique and comprehensive standards, market incentives and promotion of good practices. The Green Products and BEE labelling programme for certain electronic products is regarded as a a best practice globally (BEE 2007). This will require a collaborative effort between the government, industry, and consumers. The government can incentivize the use of low-carbon embodied building materials through tax breaks and other financial incentives. Industry can prioritize sustainable design and construction practices, and consumers can demand sustainable buildings and products.

Tata Steel's revolutionary approach to sustainable steel production prioritizes recycling ferrous scrap over iron ore based methods for a reduced carbon footprint1. In India, a shortage of high-quality shredded scrap, vital for efficient steelmaking, adds complexity2. Tata Steel's pioneering efforts, exemplified by a scrap collection and shredding facility in Rohtak3, yielded commendable results in the first year despite COVID-19 challenges4. The FerroHaat app, a digital innovation with over 180 registered vendors5, facilitates scrap procurement.

Tata Steel's commitment extends to elevating clean scrap charging in their India operations, reflecting a growth from 4.8% in the prior fiscal to 6.6% in FY 2021-226. Inspired by their European counterpart in IJmuiden, Tata Steel continues to invest in scrap management infrastructure 6. Remarkably, their Thailand facilities exclusively employ steel scrap as a primary raw material7, culminating in a harmonious blend of innovation and sustainability.

With respect to case study reference, the circular economy principles and other national resource efficiency policies have a significant role to play in achieving India's net zero target by 2070. The case study of the NZEB at IIT Hyderabad demonstrates the effectiveness of these principles and policies in reducing carbon emissions and promoting sustainability in the building sector.

Digital platforms and CAD-based software technologies have revolutionized the building design and construction industry by enabling more efficient and accurate analysis and simulation. Architects, designers, and construction professionals can utilize these tools to integrate LCA into the early design phase of buildings and structures. These digital platforms provide a user-friendly interface for conducting LCA calculations, allowing users to input material properties, energy consumption data, and transportation distances to estimate the carbon emissions associated with different design options.

The role of LCA in predicting the carbon emissions and environmental impact of building materials is significant, especially for architects, designers, builders, and construction professionals. By using digital platforms and CADbased software technologies, professionals can predict the carbon emissions of a building project before construction begins. This helps in optimizing the design process by selecting low-carbon materials and reducing the carbon footprint of the building.

One such software is the REVIT Building Information Modelling (BIM) system, which enables designers to create a digital model of a building project. The system calculates the carbon emissions and environmental impact of the materials used in the building. Similarly, the Bentley systems software provides an LCA tool that helps in selecting low-carbon materials and predicting the carbon footprint of a building project.

Energy simulation tools like Design Builder and One Click Life Cycle Assessment are also used to predict the energy consumption and carbon emissions of building materials. These tools can help designers and architects to make informed decisions about the selection of materials in the early design phase of the building. By understanding the carbon emissions of the building materials, designers can optimize the design process, reduce the carbon footprint, and help in achieving the circular economy principles.

Considering the evaluation of different wall systems for a residential building can have better impact in the selection of right materials as well as reduce carbon emission at the building site level. The study used the LCA method to determine the environmental impact of the building materials. The results showed that using AAC blocks instead of red bricks resulted in a 37% reduction in carbon emissions. Similarly, using lightweight steel framing instead of conventional steel framing resulted in a 39% reduction in carbon emissions.

4. Discussion

Market Trend analysis

The adoption of circular economy principles and resource efficiency policies is crucial for achieving sustainability goals in the buildings and construction sector. India, recognizing the urgency of addressing climate change, has set an ambitious target of achieving net zero emissions by 2070. This article explores the contribution of circular economy principles, national resource efficiency policies, and the government's net zero target in the context of the buildings and construction sector in India. A case study will further illustrate the implementation of circular economy principles and the national plan for achieving the net zero target.

One example of a successful implementation of circular economy principles in the building and construction sector is the construction of the Mahindra World City, located in Chennai, Tamil Nadu. The developers of the project used locally sourced materials, including recycled construction waste and fly ash, to reduce carbon emissions and promote circular economy principles. The buildings were designed to be energy-efficient and incorporate renewable energy sources such as solar panels. The project received a platinum rating from the Indian Green Building Council (IGBC) and was recognized as one of the most sustainable and energy-efficient projects in the country.

A case study of the Net Zero Energy Building (NZEB) at the Indian Institute of Technology (IIT) in Hyderabad demonstrates the effectiveness of circular economy principles and resource efficiency policies. The NZEB is designed to generate as much energy as it consumes, and it features several sustainable design elements, including a green roof, solar panels, and energy-efficient lighting and appliances. The building's construction materials were also carefully chosen to minimize embodied energy and carbon emissions.

To achieve the net zero target by 2070, it will be essential to continue to promote circular economy principles and resource efficiency policies in the building sector. We still lack in the larger database creation, unique and comprehensive standards, market incentives and promotion of good practices. The Green Products and BEE labelling programme for certain electronic products is regarded as a best practice globally (BEE 2007). This will require a collaborative effort between the government, industry, and consumers. The government can incentivize the use of low-carbon embodied building materials through tax breaks and other financial incentives. Industry can prioritize sustainable design and construction practices, and consumers can demand sustainable buildings and products.

The circular economy principles and other national resource efficiency policies have a significant role to play in achieving India's net zero target by 2070. The case study of the NZEB at IIT Hyderabad demonstrates the effectiveness of these principles and policies in reducing carbon emissions and promoting sustainability in the building sector.

The use of alternative raw materials, fuels, cleaner production technologies, and innovative methods such as carbon capture, utilization, and storage (CCUS) have been successfully incorporated in the manufacturing of these materials. The adoption of such innovative methods and technologies can significantly reduce carbon emissions and improve the sustainability of the manufacturing industry. Public policies, management system requirements, and market strategies play a vital role in the adoption of circular economy principles in the manufacturing of building materials.

Additionally, management system requirements can also be a key factor in promoting circular economy practices. Manufacturers can adopt certification schemes such as the Cradle to Cradle (C2C) or Leadership in Energy and Environmental Design (LEED) to demonstrate their commitment to sustainability and circularity. Furthermore, adopting a circular business model can also provide long-term benefits by reducing costs and improving resource efficiency.

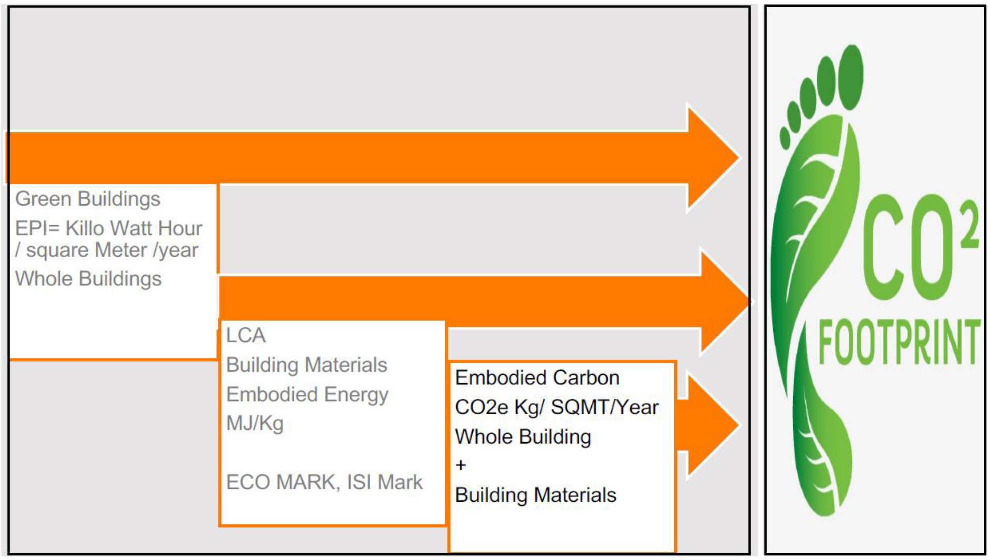
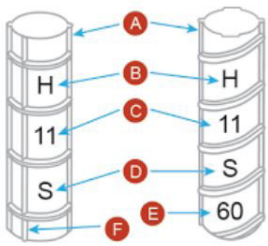


Figure 3: Flow chart explaining LCA model for Buildings Carbon-Emission based Products/Performance

Table 2: Carbon Emission-based Eco-Labelling

Product Type	**Carbon label**	**Consumer Price**
BRICK		**INR 35/ Unit** **0.75kg CO2e/ Unit**
STEEL		**INR 65/ kg** **0.75kg CO2e**

In the pursuit of a more sustainable built environment, the integration of circular economy principles and life cycle assessment (LCA) has paved the way for innovative strategies, including carbon emission labelling for building products. Figure 3 provides metrics for building Energy Performance Index (EPI, BEE 2007) measurements in kWh-per-meter-square to alternative carbon-emission-based CO2 (kg) equivalent-emission per-square-meter-per-year performance-based measurements. The metrics can help improve global standardization of India's building products and Whole Building performance standards and can enable support to active participation in voluntary carbon markets in India. Building owners are considered as designated consumers having connected load or contract demand above 100 kW (MoP, BEE, 2017). This approach emphasizes transparency, empowering stakeholders with information to make environmentally conscious choices. By quantifying carbon emissions in whole building energy performance modelling and embodied carbon of the building material/ product end use, such as steel, bricks, and cement, this labelling programme provides a comprehensive view of a buildings as well as product's ecological impact.

5. Conclusion

One of the key factors that can drive the adoption of circular economy practices in this industry is the role of public policies. The Indian government's net zero target by 2070 presents a clear objective for reducing carbon emissions, and the building materials and construction industry can play a critical role in achieving this target. To this end, the government can provide incentives for manufacturers to adopt more sustainable and best eco-labelling practices, and implement regulations to reduce waste and promote the use of recycled materials.

Material Reuse and Recycling:
Incorporating recycled materials and salvaged components in construction projects to minimize resource consumption

Modular and Prefabricated Construction:
Embracing modular and prefabricated elements for easier disassembly, reconfiguration, and reuse

Design for Deconstruction:
Implementing design principles that facilitate easy disassembly and material separation at end-of-

life Material Passporting:
Creating digital records of building materials, detailing their origin, composition, and potential for

reuse Carbon Emissions Standards and Measurement Methods:

Life Cycle Assessment (LCA):

Analysing the environmental impact of materials and construction processes throughout their life cycle Embodied Carbon Assessment:

Quantifying the carbon emissions associated with material production, transportation, and construction Global Carbon Standards:

Referencing international standards like ISO 14040/44 and EN 15978 for LCA methodologies and carbon assessment

Carbon-Neutral Construction:
Implementing strategies to offset construction-related carbon emissions through renewable energy and carbon sequestration methods

Today, the Green Pro program by IGBC is an important initiative that promotes sustainable building practices in India by certifying environmentally sustainable building materials and products. It helps to reduce the environmental impact of the building industry and supports the development of a more sustainable built environment in India.

Product Standardisation and Eco-labelling Programme

The Indian Green Building Council's Green Pro program was launched in 2010 and is recognized as one of the most stringent eco-labelling programs in the world. The program evaluates building materials and products based on their environmental impact across their entire life cycle, including raw material extraction, manufacturing, transportation, use, and disposal.

To be eligible for Green Pro certification, building materials and products must meet specific criteria related to environmental performance, health, and safety, and social responsibility. The certification process involves a thorough evaluation of the product's environmental impact, including greenhouse gas emissions, energy efficiency, water conservation, and waste reduction.

The Green Pro program offers several benefits to manufacturers and consumers. Manufacturers who obtain Green Pro certification for their products can differentiate themselves in the market by demonstrating their commitment to sustainability. Consumers can make informed choices about building materials and products that are environmentally responsible, healthy, and safe.

The Green Pro program has certified a wide range of building materials and products, including cement, steel, paints, insulation, and flooring. It has also certified several building projects, including commercial buildings, schools, hospitals, and residential complexes.

India has recently introduced the ECOMARK Scheme for environmentally friendly products and services, which falls under the purview of the Bureau of Indian Standards and is issued by the Ministry of Environment, Forest and Climate Change, Government of India (MOEFCC, GOI). This scheme sets criteria for products to attain ECOMARK certification, with a focus on various aspects including the production process, utilization of raw and natural materials, potential environmental impact, emissions, waste generated during manufacturing, product packaging disposal, adherence to Extended Producer Responsibility (EPR), substitution of hazardous materials, and product recycling. To achieve ECOMARK certification, products must undergo thorough due diligence and compliance checks, which are verified by an independent approved verifier.

Global Best practices in Environmental Friendly products Eco-labelling and Carbon Accounting

Environmental sustainability has become a global priority, with nations and organizations striving to promote eco-friendly and environmentally responsible products. To facilitate consumer choices and encourage sustainable production, many countries have adopted labelling programs. These programs not only help consumers make informed decisions but also incentivize manufacturers to adopt more sustainable practices. Several global best practices in eco and environmental labelling programs have emerged, each with its unique approach.

- ENERGY STAR (United States):

The ENERGY STAR program, established by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy, aims to identify and promote energy-efficient products. It covers a wide range of categories, including appliances, electronics, and building materials. The program provides consumers with information on a product's energy efficiency and helps them reduce their environmental impact. ENERGY STAR is a well-recognized and successful eco-labelling initiative in the United States and has influenced energy efficiency standards worldwide.

- EU Ecolabel (European Union):

The EU Ecolabel, a voluntary labelling program within the European Union, recognizes products with reduced environmental impact. It encompasses a broad spectrum of goods and services, from textiles to tourism. The EU Ecolabel evaluates products based on criteria that consider their entire life cycle, including raw material extraction, production, distribution, and disposal. This holistic approach sets a benchmark for eco-friendliness and promotes environmentally sustainable products across Europe.

- Nordic Swan Ecolabel (Nordic Countries):

The Nordic Swan Ecolabel, a collaborative initiative of the Nordic countries, focuses on products with minimal environmental impact. It has rigorous criteria covering diverse product categories. Notable for its stringent standards, this labelling program has contributed to the adoption of sustainable practices and the development of green products in Nordic nations.

- Cradle to Cradle Certified™ (Global):

The Cradle to Cradle Certified™ program evaluates products based on their sustainability throughout their entire life cycle. It assesses factors like material health, recyclability, and renewable energy use. This certification, accepted globally, encourages manufacturers to design products with the principles of circular economy in mind.

- Japan's Eco Mark (Japan):

Japan's Eco Mark is a nationally recognized label that signifies environmentally friendly products. It includes strict standards for a wide range of goods. The program has contributed to raising environmental awareness among consumers and fostering a culture of responsible consumption.

These global best practices in eco and environmental eco-labeling programs highlight the importance of transparent, credible, and comprehensive approaches to promoting sustainability. These programs inspire consumer confidence, guide manufacturers toward greener practices, and collectively contribute to a more sustainable and environmentally responsible global marketplace.

Why does carbon accounting need to evolve?

In order to establish the Circular Principle framework, evolution of carbon accounting is imperative in the present day context due to two critical challenges that must be tackled to enhance the credibility of sustainable companies and their decarbonization efforts: data quality and data accessibility.

Data Quality: Raising the Bar for Credibility

Effective carbon accounting hinges on the accuracy and reliability of the data it relies on. To truly measure and manage carbon emissions and environmental impacts, it is essential that the data collected is of the highest quality. This encompasses not only the precision of measurement but also the transparency and authenticity of the data sources. Without robust data quality standards and practices, sustainable companies may find it challenging to build trust and confidence among stakeholders. Research by Greenberg et al. (2021) in "Environmental Accountability" emphasizes that without stringent data quality protocols, the credibility of carbon accounting practices is at risk.

Data Access: Promoting Transparency and Accountability

Carbon accounting must also evolve to address the issue of data accessibility. Transparency and open access to carbon data are essential for accountability and benchmarking. Limited access to vital information not only inhibits comprehensive assessments but also obstructs benchmarking and best practice sharing. A study by Rodriguez and Chen (2019) in "Sustainable Business Practices" highlights the importance of promoting data accessibility to foster collaboration and innovation in the pursuit of decarbonization goals.

The evolution of carbon accounting is a critical step forward for sustainable companies in their journey to reduce their carbon footprint. By improving data quality and promoting data accessibility, these companies can enhance their credibility, gain the trust of stakeholders, and contribute more effectively to the broader mission of combating climate change and the circular economy..

Need for Comprehensive Carbon-emission Database Bank for Building products and Consumer views

A comprehensive database of environmental impact data specific to commonly used building products and materials in India is crucial for advancing the evaluation of buildings and enabling the assessment of construction materials. This database would serve as a foundation for a more thorough analysis of the environmental performance of buildings by considering the materials used. Building standards in Europe and the United States are progressively incorporating the assessment of building embodied impacts, following the lead set by the German Sustainable Building Council (DGNB). The assessment of environmental performance now includes the impact of materials used in construction. To ensure that architects and builders in India have access to world-class building assessments, it is essential to develop a set of market appropriate data on the embodied impacts of common building materials.

The one-click life cycle tool is a good example and best practice. It includes detailed technical descriptions about building products and comply with EN15804 and/or ISO 14025 standards. The online tool seamlessly quantifies carbon emissions and conducts life cycle assessments. Through automated processes, it swiftly gathers data, assesses environmental impacts, and generates comprehensive reports, aiding informed decision-making. This efficient solution empowers businesses and individuals to contribute to a more sustainable future effortlessly.

By establishing these databases, architects and builders in India will have access to reliable information on the environmental impact of various building materials (GreenPro, IGBC, 2016). This will enable them to make informed decisions during the design and construction phases, optimizing material choices and considering the life cycle of the building. Such an approach aligns with the principles of life cycle assessment (LCA), which considers the environmental impact of a product or system throughout its entire life cycle.

Measuring whole building performance in terms of embodied energy and embodied carbon emissions including building materials is a crucial aspect of assessing their environmental impact. The Indian Green Building Council's (IGBC) Green Pro certification program and eco-labelling programs in India incorporate this measurement to evaluate the sustainability of building materials and construction products.

The manufacturing methods for commonly used building materials in India have a significant environmental impact, contributing to greenhouse gas emissions and resource depletion. For instance, cement production accounts for 8% of global CO_2 emissions, making it a major contributor to climate change (Global Cement and Concrete Association, 2021). By evaluating the existing manufacturing methods and exploring alternative circular economy practices, such as using recycled materials or adopting green technologies, the construction industry can reduce its carbon footprint and contribute to a sustainable future.

- Sensitivity analysis of consumer behaviour in the building material prices and impact in the construction process

- A tool for the AEC community in pre-design evaluation of the environmental impact, prices and the construction process.

- Explore the willingness of Indian building material consumers to pay for circular economy products and services.

- Sustainable Interiors- Need for Health and Well being

Consumer behaviour plays a crucial role in the adoption of circular economy practices in the construction industry. Studies have shown that consumers are increasingly aware of the environmental impact of their choices and are willing to pay more for sustainable products (Fernández-Muñoz et al., 2019). By understanding consumer behaviour and preferences, the construction industry can better tailor its circular economy practices and products to meet the demand for sustainable and affordable building materials.

Green building products refer to materials that are manufactured, processed, or sourced in ways that have minimal environmental impact. These products are designed to reduce resource consumption, energy use, and emissions throughout their life cycles. They prioritize attributes such as low toxicity, recyclability, and durability. By incorporating green building products into interior design, professionals can contribute to healthier indoor air quality, reduced waste generation, and minimized depletion of natural resources.

Sustainable Interiors represent application-based design philosophy that goes beyond aesthetics and functionality to prioritize environmental responsibility and social well-being. This approach seeks to create interior spaces that are not only visually pleasing and functional but also minimize negative impacts on the environment. At the core of sustainable interiors lies the conscious selection and utilization of green building products, which encompass materials with reduced environmental footprints and are often accompanied by embodied energy and carbon emission labels.

Beyond aesthetics, Sustainable Interiors encompasses the responsible integration of eco-friendly practices, materials, and processes within interior design. Application of Life Style for Environment (LiFE) an idea to promote environmental sustainable lifestyle and best practices to promote behavioural change, innovative and climate-friendly solution (UNFCC COP26, 2021). This holistic approach considers the environmental, social, and economic dimensions, weaving a tapestry that harmonizes Architecture Design, Aesthetics, Health & Wellbeing and sustainability in Circular principles.

The integration of green building products and carbon emission labelling in interior design offers several benefits:

Reduced Environmental Impact: By selecting materials with lower embodied energy and emissions, interior designers contribute to lower carbon footprints and minimize resource depletion.

Healthier Indoor Environments: Green building products often have lower levels of volatile organic compounds (VOCs) and toxins, leading to improved indoor air quality.

Longevity and Durability: Sustainable materials are typically designed for durability, leading to longer-lasting interiors and reduced need for replacements.

Consumer Awareness: Carbon emission labels empower consumers to make environmentally conscious choices, fostering sustainability awareness.

Supporting Circular Economy Principles

Similar to EU Taxanomy the need for India specific Taxanomy is an important step to strengthen the existing green building and ECOMARK best practices. The EU Taxonomy significantly aids the decarbonization of the building construction industry by setting strict criteria for sustainable practices and technologies. Construction is a major contributor to carbon emissions, and the Taxonomy ensures that only projects and products meeting stringent environmental criteria can be Eco-labelled as sustainable. This has driven investments in energy-efficient building designs, renewable energy use, and sustainable materials. The Taxonomy thus plays a pivotal role in making the European construction industry more environmentally friendly and less carbon-intensive.

The EU Taxonomy aligns with circular economy principles by promoting resource efficiency and waste reduction (European Commission, 2021). To be considered sustainable, projects must demonstrate efficient use of materials and energy throughout their lifecycle. This has spurred innovations in recycling and reusing building materials, minimizing waste, and promoting the use of renewable energy sources. In essence, the Taxonomy encourages a closed-loop approach in construction and reinforces the circular economy's core tenets.

The adoption of circular economy principles in the building materials and construction industry in the Indian context can contribute to reducing carbon emissions, mitigating climate change, supporting Architects & Engineers and improving the quality of the building products. Best practices such as Clean Air Action Plan (CAAP) and Better Health programme (CABH) supported the initiatives of improving the indoor air quality within the built environment and enabled good practices for eco-friendly product development. A coordinated effort from various stakeholders, including the government, manufacturers, consumers, Architects, Engineers and Construction community, and other participants in the supply chain, are required to achieve this objective. Public policies, Buildings Product Embodied CO2 disclosure, financial institutions, consumers, home owners and existing best practices, market strategies can all play a crucial role and sharing of information in promoting circular economy practices. A concept of building's life-cycle cost and emission disclosure is something important for the success of a circular economy in the Indian construction market-based scenario. By embracing circularity and sustainability, the building materials and construction industry can pave the way for more sustainable and resilient built environment practices in India and across the globe.

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An experimental investigation on the impact of lime and cement mortar/ plaster material on the indoor hygrothermal environment of test spaces

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Abstract

The study's objective was to investigate and quantify the heat and moisture transfer through two walls of a 1m2 area facing south, located in Ahmedabad, Gujarat, India. One of the walls was constructed with lime mortar, and the other with cement mortar and XPS (Extruded Polystyrene) blocks of size 230 x 100 x 75 mm, coated with an inner plaster layer of the same materials. Other walls were made up of EPS (Expanded Polystyrene), thus limiting the heat and moisture transfer only through mortar layers. The mortar joints on the exposed wall accounted for 17% of the total surface area of the wall. The study monitored the temperatures, relative humidity, and surface temperatures inside the two identical test cells of 1 m3 volume each for 54 days from 1st March to 23rd April 2023. Also, a 3-day moisture test was carried out to check the effect of vapor permeability.
The research questions are as follows.

- Is the hygrothermal environment different for cement and lime mortar cells?
- Will the cement mortar produce higher heat ingress due to high conductivity?
- Will the higher thermal mass of cement make a difference in the hygrothermal environment of the cells?

Keywords - Lime plaster & mortar, hygrothermal behaviour, moisture buffer, thermal bridging, vapor transmission

1. Introduction

The world's energy consumption has been overgrowing in the construction sector, causing a 43% increase in CO2 emissions over the last two decades. In India, Energy consumption has doubled since 2000 [1] (IEA,2021) and is expected to double by 2040 [2] (IEA, 2020). India is required to decrease its greenhouse gas emissions to 35% by 2030 in response to the challenges posed by climate change [3] (INDC,2022). Therefore, there is a need to adopt "green technologies" based on renewable or recycled materials in construction, to significantly reduce buildings' carbon footprint and energy consumption (International Renewable Energy Agency [4] (IRENA),2019).

The need for study can be justified through results found in studies based on thermal bridging and moisture buffering through mortar. Mortar has been a thermal performance deficiency in the masonry wall [5] (Ismaiel et al.,2022, p.529), as it reduces 12% thermal resistivity of the wall [5] (Ismaiel et al.,2022, p.533) and 38% in an insulated wall [6] (Al-Sanea & Zedan,2012, p.591). Mortar joints cause an 11% increase in cooling and heating loads [7] (Zedan et al.,2016, p.17). Ignoring thermal bridging overestimates, the wall R-value by 26% [5] (Ismaiel et al.,2022, p.545). Hygroscopic interactions of the material change the room temperature by 2-3°C [8] (Gaur & Bansal, 2002, pp. 15-16). Moisture buffering can help with a 20% reduction in heating energy [9] (Damle and Rawal's,2018, p. 478). Therefore, neglecting these phenomena can overestimate energy loads and wall R-value. Studies on the effect of heat and moisture transfer through exposed walls with lime mortar have not received significant attention in the literature. Also, simulation tools do not consider the moisture buffering capacity of materials, resulting in overestimated energy use. Thus, the present study considers the effect of thermal bridging through mortar layers and its moisture buffering capacity by carrying out, one-to-one comparison between cement and lime mortar.

2. Methods

2.1. Selection of methodology

From the literature, it was found that most biobased hygrothermal research was based on a wall scale - using a climate chamber. The studies not based on the experimental approach suggested that there is a need to carry out experiments for realistic observations and under real variable climatic conditions [10] (Moujalled et al., 2015, p. 535). Therefore, an experimental study was undertaken in this study. Thomas Busser (2018), [11] (p.16) suggested that the scale models can be validated using experimental data within test walls, i.e., the characteristic sizes of samples - 1 m x 1 m x 0.11m thick. It was also stated that for testing purposes, the walls can be exposed to controlled conditions in climatic chambers or to outdoor conditions on one side. Therefore, the scale of the model selected in the current study is 1 m², and the models are tested in actual outdoor conditions. Experimental investigation study proves to be a better approach for this study as lime mortar composition varies with region, thus getting the exact values for its properties like conductivity, etc., is difficult. Hence a simulation approach would prove to be beneficial due to the uncertainty in the thermophysical properties. Moreover, for the comparison of two materials, getting two identical buildings with two distinct construction materials is difficult.

2.2. Test cell development

For the study, a location in Ahmedabad, Gujarat, India, has been selected. The city has a hot and dry climate. For this location, the shading mask of the two test cells was analysed using the Andrew Marsh Shading Box tool for any shadows falling on the cells. It was observed that the cells are not shaded by surrounding objects, there was no mutual shading, and both test cells have the same environmental conditions and solar exposure.

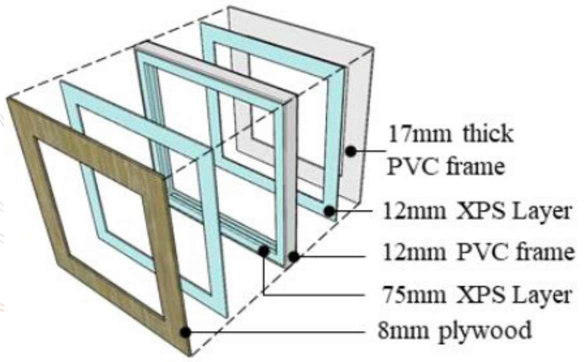

Figure 1: Schematic of the support frame

To ensure that the walls are made of the same size and mortar is of the same area, a 12mm PVC frame was made. Inside this frame, a 75mm thick XPS layer was added to provide insulation from edges and prevent edge effects. Along with that, layers of 12mm XPS were added on either side of the wall, between the outer frame and inner frame, to prevent direct contact of the outer frames with the wall. The outer frame was made of 8mm Plywood, and the inner frame was made of 17mm thick PVC, as seen in Figure 1. For the construction of walls, 120 XPS blocks were cut in the size of 230 * 110 * 75mm which corresponds to a typical brick size. A top and bottom groove of 10 mm was made in each brick for better bonding with mortar, as shown in Figure 2. Similarly, other EPS walls of 100mm thickness were also cut as per the requirement. The cutting process was followed by the laying of XPS blocks and mortar. Twelve layers of XPS block with a 10mm thick mortar layer between each layer were laid, as shown in Figure 3. A layer of 15mm thick plaster was given on the inside, as shown in Figure 4.

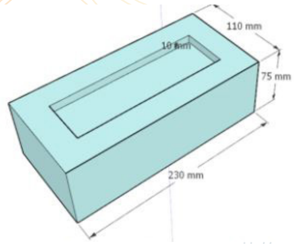

Figure 2: Size of one XPS block with 10mm groove


Figure 3: Laid blocks with mortar


Figure 4: Inner 15mm plaster in cement

2.2. Test cell development

As per IS 1661,1972, for a single layer of plaster, 10-15mm thickness of plaster is recommended with a mortar mix of 1:4 ratio of cement: sand. For lime, as per IS 2394, 1984, plaster thickness of 15mm is recommended. To keep the ratio the same in both test cells, lime mortar and plaster were also made with a 1:4 ratio of lime: sand. The exact mix ratio was used for plaster and mortar to maintain the same properties. The ready mix of lime mortar was delivered on site. To test the proportion of binder and aggregate in the lime mix, an acid dissolution test was carried out. The section in Figure 5, gives the entire detail of wall assembly. After wall construction, the cement and lime walls were cured for a period of 14 and 10 days, respectively (26th December to 8th January 2023). As per IS 456, 1978 curing period of 14 days in cement and 7 days for lime is sufficient. The walls were left to dry for 52 days before installing the loggers. The walls were transported to the site, and the test cells were assembled, as seen in Figure 7. Both the test cells have an inner volume of 1m3, and the exposed walls facing south have a 1m2 surface area. The mortar accounts for 17% of the total south wall surface area. The assembled test cell model with wall composition is shown in Figure 6.

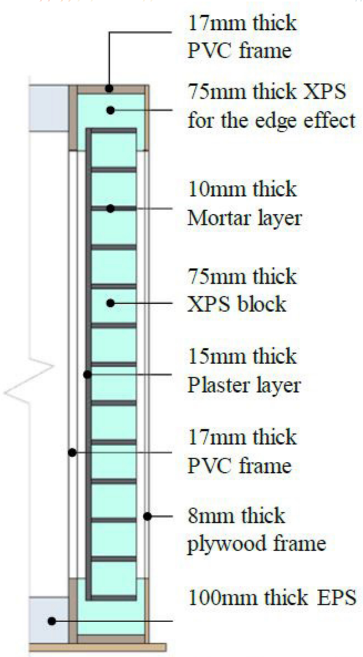

Figure 5: Section of test wall with outer support frame

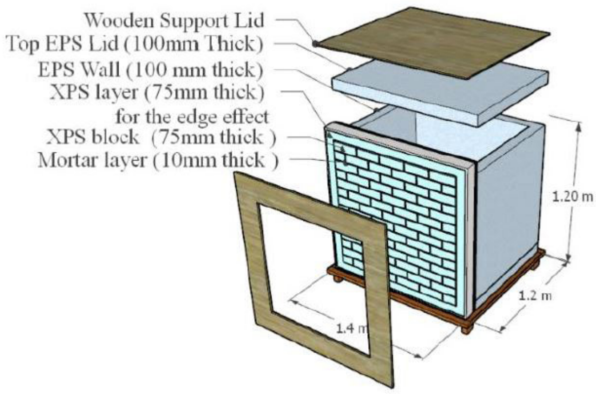

Figure 6: Experimental set-up showing wall composition.

Figure 7: Experimental set-up on-site

2.3. Material Selection Criteria

The main objective of the material selection is to make all the surfaces adiabatic and keep the mortar layer as the only element through which heat and moisture transfer occur. Also, for the wall, to nullify the effect of the masonry unit, XPS blocks have been used, which have low conductivity for minimum heat transfer. Both cells are identical, differing only in mortar material. This ensures a fair basis for comparison. Any differences observed can then be attributed to the plaster and mortar material. Simulation software does not capture the physics entirely due to the limitation of numerical models and uncertainty in hygrothermal properties of materials due to variable compositions. The experimental approach also gives an advantage over simulation as the models are exposed to real dynamic weather conditions.

2.4. Data gathering

Heat transfer and moisture transfer were studied by measuring variables like inside air temperature, inside and outside surface temperatures, and relative humidity using Hobo Loggers MX1104. Identified variables and instruments are shown in Table 1.

Table 1: List of variables and instruments used.

Legend	Variable	Instrument Used	Measurement
🔴	Air Temperature and Relative Humidity	Onset HOBO (MX1104) Analog/Temp/RH/Light Data Logger	10 Minutes Logging
🟡	Indoor Surface Temperature		
🟢	Outdoor Surface Temperature		

2.6. Measurement protocols

After calibration, the loggers were installed in the test cells, as shown in the perspective sectional schematic Figure 8. The surface probe was placed at the center of the inside and outside walls at a height of 480 mm from the finished floor level. This avoided the edge effect from the ceiling and floor as marked in red and yellow. The logger for measuring indoor conditions like air temperature and RH was placed at a height of 100mm above the finished floor. The logging period for the study started on 1st March 2023, with a logging interval of 10 minutes for each parameter. The readings for indoor conditions, relative humidity, and surface temperatures were taken till 23 April. While taking the measurements, the surface probe was covered with a foam layer, so that it does not get affected by air temperature or solar radiation falling on it. The outdoor logger was placed inside a well-ventilated box in the shade such that it was protected from direct sunlight, rain, and local effects.

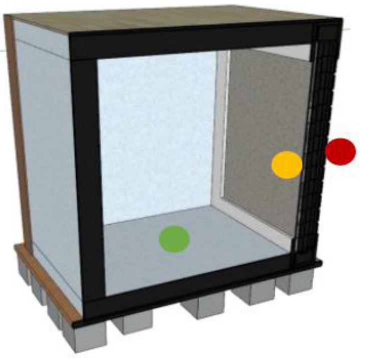

Figure 8: Perspective section of the cell, showing the placement of loggers.

2.7. Moisture test procedure

In this test, an equal amount of water was sprayed on the mortar layers of each test cell, using a spray bottle. The pressure of the spray and the distance of the nozzle from the wall were kept constant to have an even distribution of water on the entire wall. To ensure an equal quantity of water, the number of sprays on each mortar layer was maintained. The exact amount of water was filled in the bottle for each round of spraying. This test was carried out for 3 consecutive days from 10th April to 12th April in the evening hours starting from 5:30 pm. Figure 9 shows the spraying of water with the help of a spray bottle.

Figure 9: Spraying of water on the mortar layers.

2.8. Testing Properties of Material

Six samples (size of 9cm x 9cm x 2cm) of lime mortar and cement mortar were made and tested at CARBSE. The material properties were tested as per ASTM standards. Table 2 shows the properties derived from experiments.

Table 2: Material properties

Sample type	Density (Kg/m³)	Thermal Conductivity (W/mk)	Thermal Diffusivity (mm²/s)	Specific heat (kJ/kg.k)	Thermal Mass (kJ/m³.K)	Permeance of the test specimen (ng·m⁻²·s⁻¹·Pa⁻¹)	Permeability (ng·m⁻¹·s⁻¹·Pa⁻¹)
Cement Plaster	1875.5	1.14	1.09	0.57	1081.80	1763	33
Lime Plaster	1571.2	0.77	0.78	0.64	1011.70	2626	48

From the results, the conductivity and thermal mass of lime mortar were 32.45% and 6.5 % less than cement mortar, respectively. Water vapor permeability in lime mortar was 31.25% higher than in cement mortar.

2.9. Data analysis

The two test cells have identical geometry and construction, except for the plaster and mortar material. Thus, a student's t-test was employed to detect any differences in the behaviour of the two test cells. The t-test determines if there is a significant difference in the data being analysed. If the value for the calculated p-value is less than 0.05, then the data sets compared are considered significantly different. The gathered data from the instruments was analyzed by variance, which could be either unequal or equal. Outliers in the data were eliminated by utilizing the interquartile range (IQR) method.

3. Results & Discussion

In this section, observations from the measurements carried out for a period of 54 days from 1st March till 23rd April 2023 have been recorded and discussed. The results and observations have been covered in 3 sections, air temperature, surface temperature, and relative humidity. In the last section, indoor conditions of the test cells have been compared with the IMAC band for calculating comfortable hours.

3.1. Air temperature in test cells

To see the daily trend of the air temperature inside the test cells, two peak days with high outdoor temperatures were chosen in March month and compared with respect to the outdoor temperatures, as seen in Figure 10. By analyzing data from these 2 days, the inside air temperature peaks at around 40 °C whereas the outside temperature is around 35 °C. In comparison to the cement cell, the lime cell consistently displays indoor temperature readings that are 1 – 1.4 °C lower. Cement reaches a peak temperature of 40.5°C at 5:20 p.m., whereas lime reaches a maximum temperature of 39°C at 5:30 p.m. Both cells have a 10-minute difference. Looking at the 2 triangles under the curve, the heating rate is higher than the cooling rate in both cells by 4 hours. During the day, the temperature increases rapidly after 7:30 a.m. and decreases gradually after 5:30 p.m. A similar trend can be observed for other days. Figure 11 shows the difference in indoor air temperatures between cement and lime test cells that were analyzed and compared for two months. The positive values for both months show that the indoor air temperature inside the lime test cell stays cooler than the cement cell for the entire period of measurement from March to April. The maximum difference in the air temperature between the two cells is 1.44° C and 1.0° C. The average difference in the air temperature of both cells is 0.6 and 0.4 ° C for March and April, respectively. A t-test was conducted to examine the variation in indoor temperature between the lime and cement test cells, and the resulting p-value was found to be 0.0. As the p-value is less than 0.05, it can be said that the difference in the indoor temperatures of the test cells is significant.

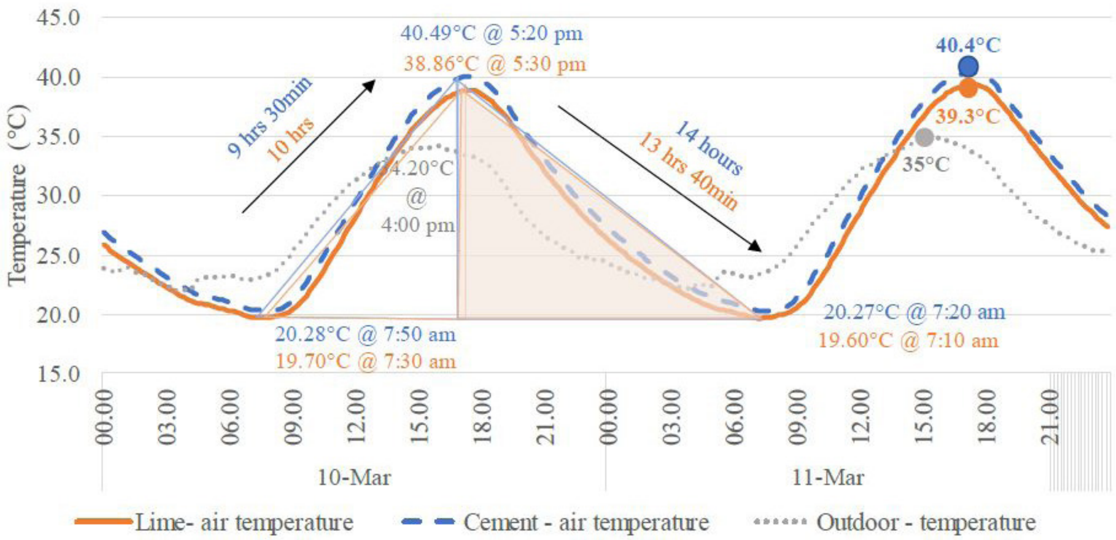

Figure 10: Comparison of air temperatures of both cells for 2 peak temperature days in March

From the above observations, lime cells consistently display indoor temperature readings that are 1 – 1.4°C lower than cement cells. With the higher temperatures during peak summer, higher differences are expected in the air temperatures inside the cells. Also, the rate of heating and the cooling of air temperatures inside the cement cell is higher than in the lime cell. The lime cell has 3% higher temperatures falling between 15 to 25 °C as compared to cement. This shows that lime cells stay cooler than cement cells. Therefore, cement cell has shown more heat ingress and more heat storage till date due to its 6.5 % higher thermal mass and 32.45% higher conductivity than lime. Therefore, the overall indoor.

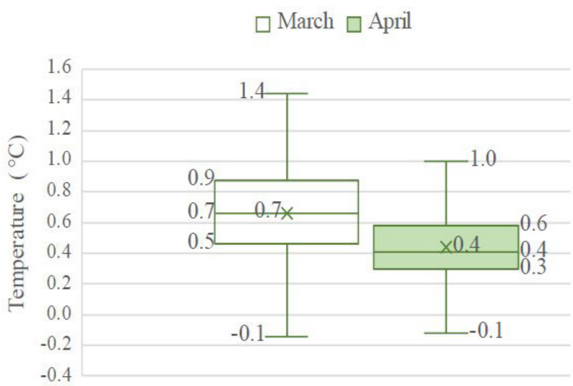

Figure 11: Difference of air temperature between temperatures are higher in the cement cell. cement & lime cell (Cement – lime)

3.2. Surface temperatures in the test cells

The difference in the air temperatures, as discussed in section 3.1, can be explained by the study of surface temperatures. It was observed that the air temperature is linearly in relation with the inside surface temperature in both the test cells. Therefore, as the inside surface temperature changes with respect to outdoor conditions, the air temperature inside cells is also being affected. To study the trend of surface temperatures, a week in April was selected. It was observed that the outside surface temperatures stayed higher than the inside surface temperatures for all the days. The outside surface temperatures reached up to 45°C during the day, due to solar radiation falling on the wall. The inside surface temperature stayed around 40°C during the day. There was a reduction in the amplitude of the inside surface temperature curve compared to the outside by around 5°C.

To understand the trends of outside and inside surface temperatures, as seen in Figure 12, the daily trends for 2 days in March month were selected. 10th and 11th March were the warmest days of March month, with the maximum outdoor temperatures of 35°C. From Figure 12, it can be observed that for 10th March, the maximum outside surface temperature (marked at point B) is 47.9°C and 47.65°C in the cement wall and lime wall, respectively. For the same day, the maximum inside surface temperature (marked at point D) is 41.18°C and 39.55°C in the cement wall and lime wall, respectively. Thus, having a reduction in amplitude of 6.7°C and 8.1°C in the cement wall and lime wall, respectively, which shows lime has a more damping effect (reduction in amplitude) than cement. A similar observation can be made for the 11th March. Also, the outside and inside surface temperature curves have a horizontal shift, showing the time lag. The maximum outside surface temperature (marked at point B) in the cement wall was at 3:10 p.m., and in the lime wall, it was at 3:00 p.m. The maximum inside surface temperature (marked at point D) in the cement wall was at 5:20 p.m., and in the lime wall was at 5:30 p.m. This shows that the time lag in the cement cell was 2 hours 10 minutes, and in the lime wall was 2 hours 30 minutes. The two cells have a 20 minute difference. This trend could be seen for all the other days, where lime always had more time lag than cement. The downward slope in both curves shows the cooling rate. It was observed that the cooling rate in the lime wall was slower than in the cement wall. The upward curve shows the heating rate. It was observed that the heating rate (from point C to D) for inside surface temperatures was slower in the lime wall as compared to the cement wall.

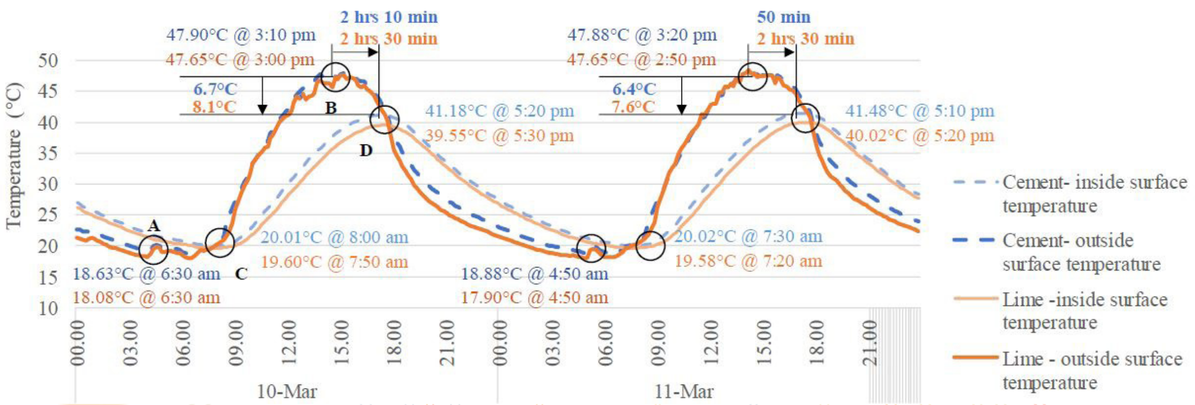

Figure 12: Comparison of cement and lime surface temperatures for 2 days

The difference in outside and inside surface temperatures of both cells for the entire period of measurement were observed. During the daytime, the maximum difference between outside and inside temperatures was 13°C in the cement cell, while the same for the lime cell was 15°C. At night the maximum difference between outside and inside temperatures was 8.7°C in the cement cell, and 10.8°C in the lime cell. Thus, lime walls always had a higher difference between outside and inside surface temperatures than cement walls. Figure 13 shows the surface temperature differences between the cells. Even though both cells were exposed to the same environmental conditions and facing south direction, the outside surface of the cement wall got heated up more than the outside surface of the lime wall. It can be observed that 75% of values lie above zero. This shows that cement wall surfaces remain warmer for more than 75% of the time than lime wall surfaces.

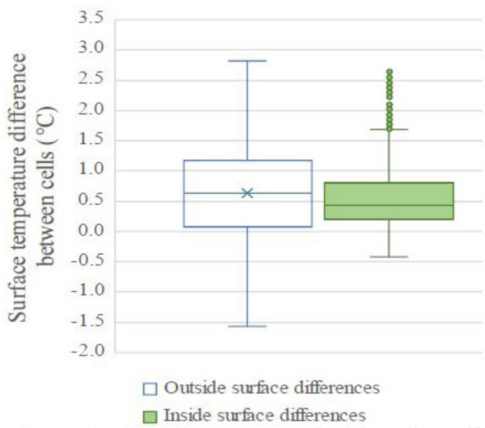

Figure 13: Difference in surface temperatures

From the above observations, it was found that there was more time lag (horizontal shift of temperature curve) and more damping (amplitude reduction) observed in the lime cell. Lime walls always had a higher difference between outside and inside surface temperatures than cement walls. Also, the outside surface temperature in the lime wall was lower than the cement wall (Figure 13). These observations can be attributed to 32% lower conductivity of lime mortar than cement mortar. Therefore, the rate of heat transfer in cement mortar wall was higher than in lime mortar wall. Inside surface temperatures of lime mortar wall are 2.7°C lower than cement mortar wall. This difference in surface temperatures would affect the MRT (Mean radiant temperature) and occupant comfort.

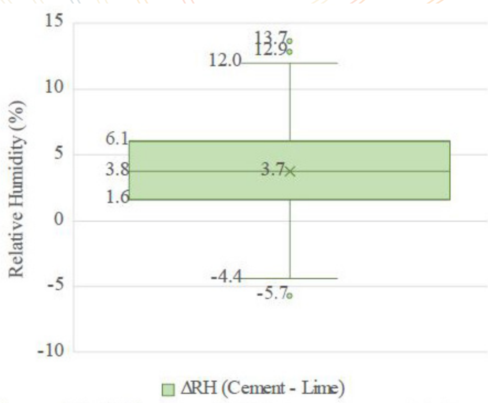

Figure 14: Difference of RH between cement & lime

3.3. Relative Humidity in the test cells

Figure 14 shows the difference between the RH of both cells for the entire period of measurement. The difference is calculated by subtracting lime RH from cement RH. The lime cell had a lower RH than the cement cell by a maximum of 13.7% and remained less than cement for more than 75% of the time. Figure 15 shows the RH evolution for 2 days. The same two days, 10th and 11th March, have been considered for analysis. It can be observed that the RH trend of lime cell and cement cell was similar for both days. The Δ RH line in the graph shows the difference between the RH of both cells, which stays above zero. This indicates that cement has 9% to 4% higher RH than lime cells throughout the day. Similar observations can be made for all the days. As lime mortar is more porous and less dense, it can absorb and release moisture better than cement mortar. The consistent lower level of RH inside the lime cell shows that lime mortar has more moisture buffering than cement mortar.

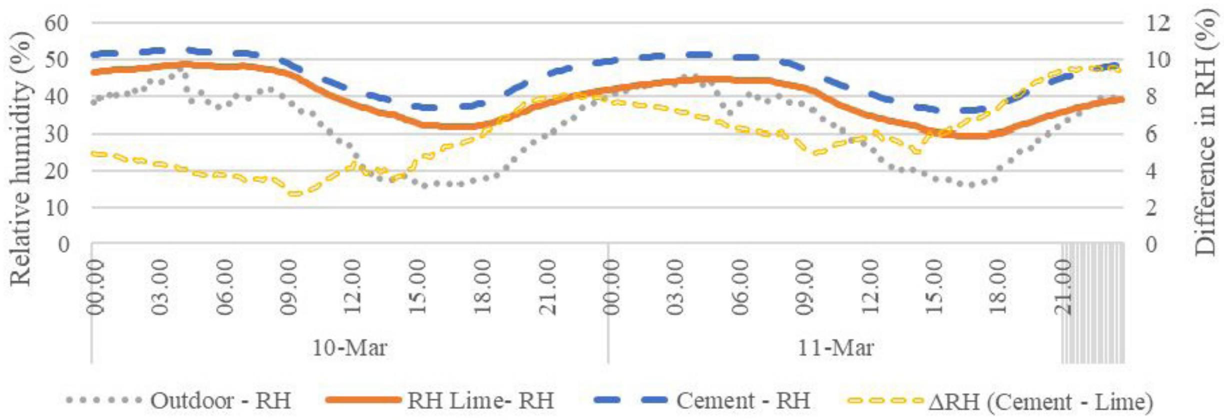

Figure 15: Comparison of RH in cement & lime cells for 2 days in March month

Figure 16 shows the result of a moisture test, which was carried out for 3 consecutive days, that is on 10th, 11th and 12th April. Before the test, the cement cell had more RH level than the lime cell throughout the day as can be seen on the 9th April trend in Figure 16. After the test, the lime cell shows 6 to 13% more RH than the cement cell for the next 7 days. After the 7th day from the test, the moisture in the lime cell reduced below the cement RH level. Even after the moisture test, the maximum RH level in the cement cell reached only till 50% whereas in the lime cell it reached 63%. This clearly shows that lime mortar has more vapour permeability than cement mortar.

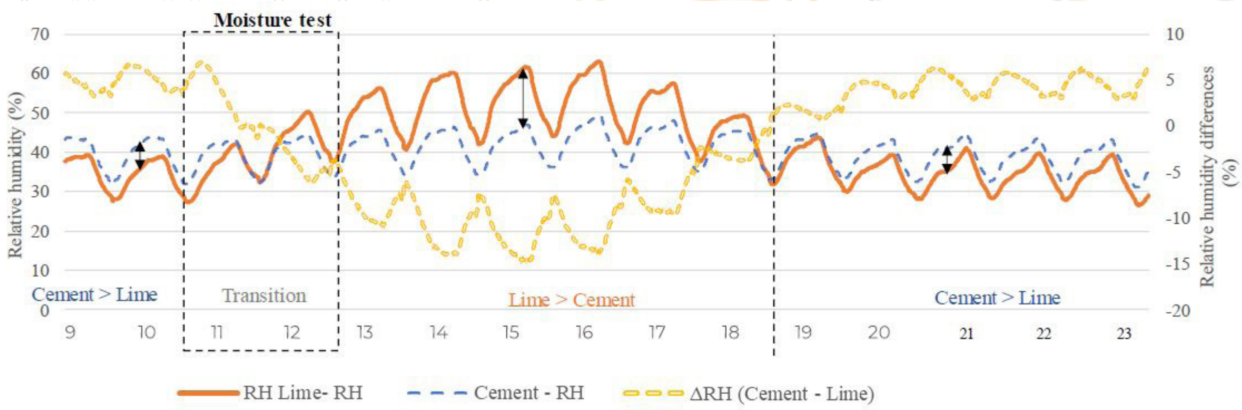

Figure 16: Comparison of RH of cement & lime cells for a period 12 days (moisture test from 10th to 12th April)

The above observations show that lime cell had lower RH than cement cell by a maximum of 13.7% and remained less than cement for more than 75% of the time. Also, the mean RH in lime remains lower than in cement by 6.5%. Lime has 24% more RH values falling between the band 20 – 40% and 24.7% lesser RH values falling between 40 -60% RH as compared to cement cell showing that and 24.7% lesser RH values falling between 40 -60% RH as compared to cement cell showing that lime moderates indoor RH. Thus, the RH inside the lime cell remains lower than the cement cell. From the moisture test, it could be seen that the lime cell reached more RH levels than the cement cell. This is because the lime mortar allowed the water to pass through the surface (more vapour diffusion) as it had 31% more water vapour permeability than cement mortar.

3.4. Limitations & Future scope of work

The study had a few limitations like the indoor surface temperature was measured only at the center of the plastered wall, assuming a homogenized distribution of temperature over the wall surface, due to the limitation of the number of instruments. The unstable weather conditions with rain, thunderstorms, and overcast skies did not allow higher ambient temperatures. The results were expected to increase with higher ambient temperature during peak summer months. For Future scope, to understand the hygroscopic nature of lime, the same experiment needs to be carried out during monsoon months or maybe in a warm and humid climate. Temperature sensors may be installed for each of the EPS walls to measure their contribution to the indoor conditions. Globe temperature may be measured to see the effect of MRT, for better assessing the indoor conditions.

4. Conclusion

The objective of the study was to investigate and quantify the heat and moisture transfer through two walls of a 1m2 area facing south. One of the walls was constructed with lime mortar, and the other with cement mortar along with XPS (Extruded Polystyrene) blocks, coated with an inner layer of plaster of the same materials. Other walls of the cell were made up of EPS (Expanded Polystyrene), thus limiting the heat and moisture transfer only through mortar layers. The mortar joints on the exposed wall account for 17% of the total surface area of the wall. The study monitored the temperatures, relative humidity, and surface temperatures inside the two identical test cells of 1 m3 volume each. The test cell has been located in Ahmedabad, Gujarat, India. The city has a hot and dry climate. The measurements were carried out for a period of 54 days from 1st march to 23rd April 2023.

The results showed that in the cement mortar wall, which had 6.5% higher thermal mass and 32% higher conductivity than the lime mortar wall, allowed the heat during the day to flow quickly through the mortar layers, and high thermal mass enabled the material to store the heat. Consequently, cement mortar wall showed lower differences between the inside and outside surface temperatures than lime mortar wall. The higher surface temperatures in the cement wall directly impacted the indoor air temperatures of the cement cell, which were 1 to 1.44°C higher than the lime cell. At night the cement mortar slowly released the stored heat, leading to a warmer indoor environment. On the contrary, the lime cell maintained a cooler temperature throughout the day and night and showed more time lag. As a result, the inside surface temperatures of the lime wall were 2.7°C lower than the cement wall. Surface temperature directly impacts the Mean Radiant Temperature (MRT) and the overall comfort experienced by occupants. Also, lime cell showed lower relative humidity (RH) than cement cell by a maximum of 14% and remained less than cement cell for more than 75% of the time during the measurement period. The mean RH in lime cells remained 6.5% lower than cement cell. This was due to the higher moisture buffering in the lime wall, which allowed the mortar to absorb and release moisture over time and regulate indoor humidity levels in the lime cell. The 31.25% higher vapor permeability of lime mortar than cement mortar also allowed the water vapor to pass through mortar layers more easily. When the indoor conditions, with an indoor temperature above 30°C and with optimum RH of 30 to 70 %, were compared in both test cells, the lime test cell was 9% cooler than the cement cell.

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Assessment of the Thermal Performance of Alternative Wall and Roof assemblies: a case in Vijayawada, AP

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Abstract

The world's climate, natural systems, and public health are all negatively affected by conventional building materials and construction methods. Buildings are highly resource-intensive, resulting in over exploitation of raw materials. The evolution and use of alternative building components to improve thermal performance has witnessed an increasing trend due to the growing awareness of energy efficiency and sustainable building techniques worldwide. This research paper focuses on a comprehensive assessment and evaluation of alternative wall and roof assemblies, such as natural materials, biomaterials, and salvaged materials. A wide range of alternative materials for the wall and roof assemblies were chosen for a residential building in Vijayawada based on their availability, featuring diverse combinations of insulation materials, thermal masses, and cladding options. Detailed modelling of heat transfer processes within the building envelope, including conduction, convection, and radiation, analysis is possible with software, while accounting for external weather conditions. The U-value, Time lag, decrement factor and heat gain / loss of the assembly were assessed through Opaque 3.0, developed by the Society of Building Science Educators (SBSE). A comparative analysis of alternate materials with conventional materials in the field of construction was performed to improve thermal performance for indoor occupant comfort to reduce energy consumption in a naturally ventilated residential building in Vijayawada. Further, suitable wall and roof assemblies based on their compliance with ECBC (Energy Conservation Building Code) standards were identified.

The findings offer useful information on how different wall and roof systems perform in comparison to the conventional materials. Straw bale with mud and lime plaster of U-value of 0.17 W/m².K performs best with a time lag of 9.9 hr among the various alternatives analyzed. Similarly, Mangalore tile with Palymra beam, which has an inclination of 45°, performs best comparatively, with a lowest U-value of 2.2 W/m².K and a time lag of 11 hours. It provides insight into the efficiency of advanced methods of construction in improving interior comfort, lowering energy use, and developing sustainable building design. In order to satisfy the demands of a continuously changing and energy-conscious built environment, the outcomes of this study provide architects, engineers, and policymakers with invaluable insights into the selection of suitable building assemblies.

Keywords - Alternative building materials, Building Envelope, Opaque 3.0, Thermal transmittance, Time Lag, Heat gain.

1. Introduction

Globally, increasing energy demand due to urbanization has been a serious threat to modern day lifestyle. Since the early 1970s until the present, research on building energy efficiency has drawn significant attention. Buildings consume 30–40% of energy throughout the year, and result in 30% of global CO2 emissions (UNEP, 2017). The way people live, work, and build our buildings will significantly influence climate change over time. The United Nations Framework Convention on Climate Change (IPCC) projects that between 1990 and 2100, temperatures would rise by 1°C to 6°C, in addition to occurrences of severe weather conditions in urban areas (Schiavon, S. & Zecchin, R. et al., 2007). Around 80% of the emissions produced during manufacturing are from conventional materials, including cement, steel, and burned clay bricks. It is feasible to utilise alternative sustainable materials that have a lower environmental impact and improve the thermal efficiency of buildings, which lowers energy consumption and helps minimize the depletion of material and resources. Therefore, using climate-sensitive passive construction techniques is essential to lowering energy usage (Venkatarama & Jagadish, 2003).

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Research in developed countries shows concerns about reducing energy consumption for heating and cooling. Developed countries can afford the costs towards heating and cooling demands. However, in most of the developing countries, it is not affordable to the majority of the population. In Mexico, it is possible to achieve thermal comfort with an adequate building design without using air-conditioning systems. Therefore, it is important to assess the thermal performance of envelope walls and roofs for natural buildings especially in developing countries. The building envelope plays an important role in the heat transfer between the exterior and interior spaces of the building. From a thermal point of view, a good building envelope is one that contributes to thermal comfort conditions inside the building without using active systems for heating and cooling or using them with minimum energy consumption (Barrios et al., 2012). J. Zhou et al. (2011) states that components of the building envelope, which include walls, windows, doors, roofs, etc., have different effects on heat exchange, and heat gain through unshaded windows and roofs, represent the largest proportion of the total amount of heat gain in buildings. In general, thick walls might improve the thermal resistance of the building envelope by reducing the heating period. However, analysis of the envelope materials wall/roof and their thermal properties in terms of their thermal performance is crucial in providing comfort.

The thermal performance of materials varies with climate. Designing buildings in warm and humid climates is the most difficult task, and the best strategy is to adopt light-weight construction for walls and roofs with a lesser U-Value and low heat capacity as heat storage is not desirable (Givoni, 1994). Walls and roofs are the primary sources of heat gain in tropical climates. Direct solar radiation on the roofs and walls in tropical climates elevates the surface temperature substantially, and hence reflective or resistive insulation can enhance indoor comfort (Haase & Amato, 2009). The appropriate choice of materials for the building envelope is the most critical aspect in improving comfort, especially in naturally ventilated buildings. A thermal performance study in North Cyprus revealed that inclined timber roofs with a ventilated attic space and terrace roofs with thermal insulation on the internal surface performed the best during overheated periods in summer (Özdeniz & Hançer, 2005). Materials with lesser conductivity are preferred because they are better insulators and would reduce the external heat gains from the envelope (Kumar et al., 2020). The use of thermal insulation is one of the most effective ways in reducing the energy demand in buildings for cooling and heating. Therefore, the selection of a proper insulation material and determination of optimum insulation thickness is vital (Yu et al., 2009).

The parameters for investigating the thermal performance of the building envelope (wall/roof) include thermal transmittance or U-value, time lag, and thermal resistance (R-value) which play a major role (Chowdhury & Neogi, 2019). Also, the smaller the U-value and the bigger the R-value, results in better thermal performance (ASHRAE handbook & ISO 6946). The rate of heat flow through various components of buildings, it's time lag as well as energy storage capability of a building are all governed by the construction materials used. In order to estimate and reduce energy consumption in building, the thermal performance of building envelope must be evaluated. In addition to the heat transferred by convection and conduction in the air, an entirely independent transfer takes place by radiation between the surface of the wall and its surroundings (Dusen and Finck, 2017).

In India, the building sector is the second largest consumer of electricity and it consumes around 30% of total electricity and India is working towards lowering its carbon emissions intensity from its 2005 level by 33% to 35% by 2030 (McKinsey & Company, 2009). Residential sector consumes 22% of the total electricity consumption in India. TERI, (2015) estimated, 2 times increase in the electricity consumption of the residential sector by 202. It is therefore imperative to adopt climate sensitive passive building strategies to reduce the energy consumption. According to the Central Electricity Authority of India the projected energy consumption load for 2030 is five times that of the current load. In India, the residential building sector which is 79.9% of total housing stock (Census of India, 2011), consumes around 21.98% of total energy 170,034 GWh (IEA report, 2010). Kumar at el., (2017) highlighted the importance of using other thermal properties/indices for a better understanding of thermal and energy performance instead of using U-values alone, which is a common practice among building material manufacturers/suppliers. The study compared the thermal performance of different roofing materials and found that despite the higher U-value of cement tiles, it exhibited better thermal performance. Abraham at el., (2018), compared the thermal efficiencies of concrete, mud, and laterite as masonry units and concluded that laterite would improve the thermal performance in tropical regions specifically in South India. In addition, insulation materials enhance energy efficiency in buildings (Kumar at el., 2014). Thus, the literature highlights the importance of alternative materials and construction techniques in achieving energy-efficiency and thermally comfortable buildings in India.

The India Meteorological Department (IMD) has classified the climate of India into five namely, Composite, Hot and Dry, Warm and Humid, Temperate, and Cold. The Energy Conservation Building Code (ECBC, 2017) has three compliance levels namely: ECBC, ECBC Plus, and ECBC Super based on their energy consumption pattern. The ECBC lists the parametric U-factor and thermal transmittance of opaque wall assemblies in the building envelope for compliance to various ECBC standards for different typologies in various climatic zones (BEE ECBC, 2017). Previous studies developed a material library and analyzed their suitability to different climate zones and building typology. The materials parameters such as the thickness, performance of various wall / roof assemblies were also assessed for ECBC compliance. Kishore et al., 2020 analyzed opaque wall assemblies in various climatic zones of India, and developed an evolutionary optimization model to minimize thermal transmittance while achieving ECBC and incremental compliance, which can further be applied to other opaque components, such as roofs, and can be used to refine the Energy Conservation Building Code. However, research on performance analysis between sustainable wall / roof assemblies that are ECBC compliant are limited at present, which can help in identifying the best suitable assembly and can further aid in developing / exploring new sustainable alternative materials. Therefore, the aim of this study is to analyze the thermal performance of various walls and roof assemblies using natural, bio and salvaged materials for buildings in the hot and humid climate of Vijayawada that are ECBC compliant.

2. Methodology

2.1. Building materials library

In recent years, there has been an increasing interest in utilizing natural materials, biomaterials, and salvaged materials as alternative building materials due to their sustainable and eco-friendly characteristics. These materials often have unique thermal properties that can contribute to the energy efficiency of a building and can be used in building components such as walls, roofs, and floors. Different alternative building materials have been selected in this study based on their potential benefits in terms of thermal performance and are climate sensitive. Table 1 shows the alternative wall and roof assemblies chosen for the study.

Table 1: List of Selected Alternative building materials

Alternative building materials for various building components		
Options	Wall	Roof
Base case	Brick	RCC
Natural Materials		
1	CSEB, Mud plaster	Limecrete, bamboo reinforcement
2	CSEB, lime plaster	Thatch, Palmyra beam and bamboo rafter
3	Straw bale, lime plaster	Thatch and bamboo rafters
4	Rammed earth	Bamboo roof
Bio Materials		
5	Timbercrete	Mangalore tiles
6	Porotherm	Burnt clay tiles filler slab
7	Mycelium bricks	BFRC
8	Hempcrete	Bamboo reinforced concrete slab
9	Rice husk ash brick	Mangalore tiles
10	Sawdust brick	Bamboo mat corrugated sheet
Salvaged Materials		
11	Stone masonry	PCC + China mosaic
12	FalG brick	Broken china mosaic tiles
13	FalG brick	Salvaged Brick
14	Medium density fiber board	Reclaimed timber
15	Fly ash brick	Reused cement + reused steel

2.2. Analysis method

The study assessed the thermal transmittance, Resistance, and Time lag of 15 alternative wall and roof assemblies as shown in "Table. 1" using Opaque 3.0 software as represented in "Fig.1". The conductivity values (K values- Thermal conductivity) of the selected materials (Table. 2) were derived from various literatures, as the software had limited material data stored in it. Hence, additional material data has been added to the software.

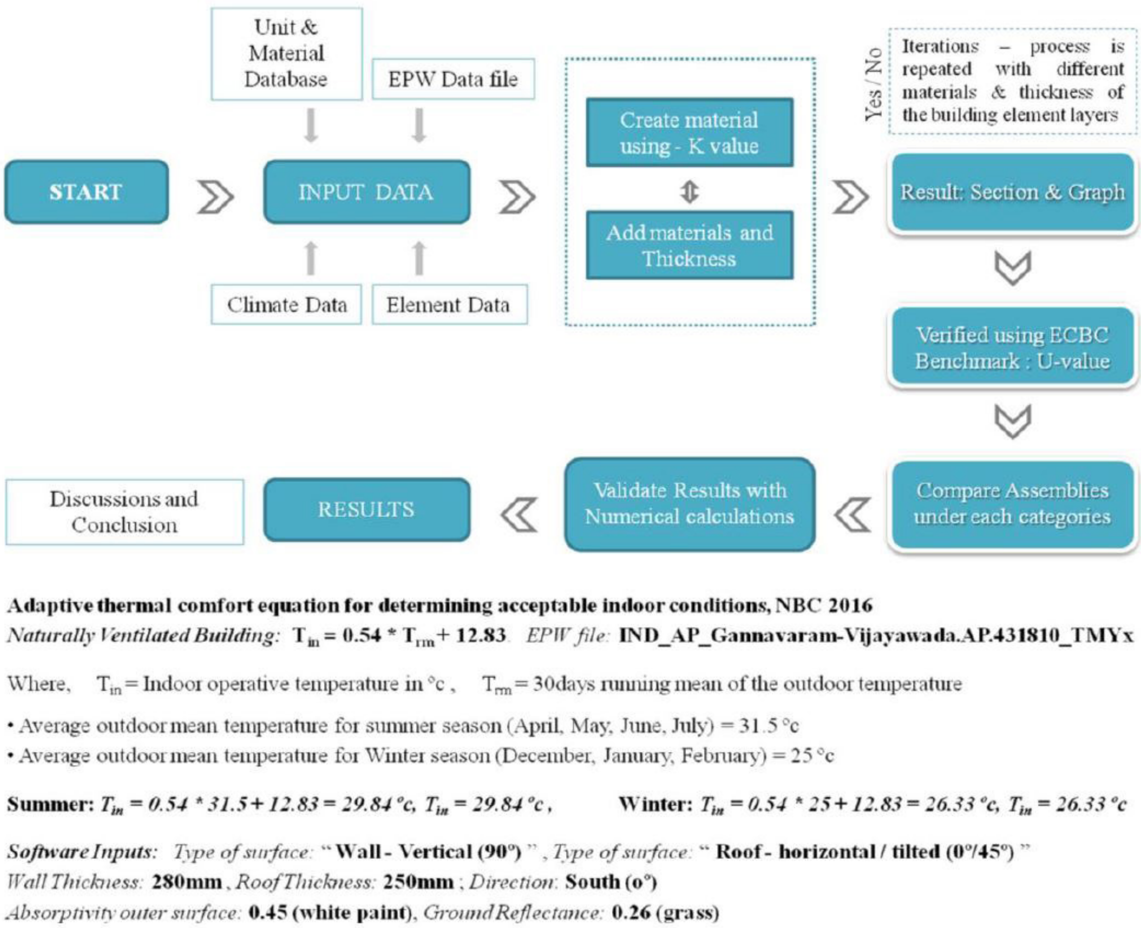


Figure 1: process for material identification and Assessment of components

The iteration of different material assemblies for opaque wall envelope were analyzed based on its compliance with the maximum U-factor (wall assemblies) for residential typology as per ECBC guidelines, i.e., ECBC, ECBC+ and Super ECBC which are 0.4 W/m²K, 0.34 W/m2K and 0.20 W/m²K respectively. The maximum Ufactor for roof assemblies as per ECBC and Super ECBC are 0.33 W/m²K and 0.2 W/m²K.

The thermal properties of the alternative materials were then compared with conventional construction materials to identify the best material assembly which can improve the indoor thermal comfort and also results in significant Energy savings with reduced environmental impact in a naturally ventilated building. Based on the thermal performance, the study identified the appropriate wall and roof assembly for enhanced thermal comfort and energy efficiency.

Table 2: K-value for alternative walls and Roof materials

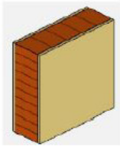
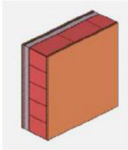
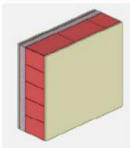
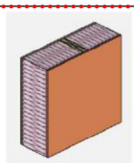
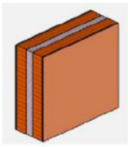
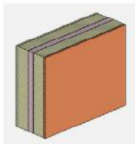
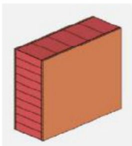
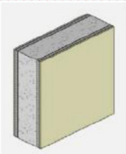
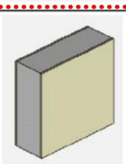
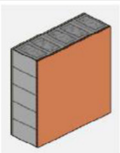
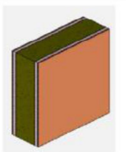
Wall materials				Roof materials		
Sl. No	Materials	Conductivity (W/m. K)	Source	Materials	Conductivity (W/m. K)	Source
1	CSEB	0.84	ECBC for residence (2017)	Limecrete	0.4	limecrete.co.uk
2	Straw bale	0.04	(Marques.B et al.,2020)	Bamboo rafter reinforcement	0.59	(Shah, D.U et al., 2016)
3	Rammed Earth	0.42	(Tinsley, J.T et al., 2019)	Thatch	0.07	ECBC 2017
4	Timbercrete brick	0.23	TIMBERCRETE.COM	Palymra beam	0.09	(Rao, P.J et al., 2008)
5	Porotherm brick	0.09	WEINERBERG	Bamboo shingle	0.18	(Wu, J et al., 2021)
6	Mycelium brick	0.05	(Xing, Y et al., 2018)	Mangalore tile	0.6	IS SP41
7	Hempcrete	0.08	(Abdellatef, Y et al., 2020)	Burnt clay filler slab	U-value: 2.34	ECBC for Residence 2017
8	Rice husk ash brick	0.21	(Huy, N.S et al., 2021)	BFRC	U-value: 1.60	BFRC
9	Sawdust brick	0.62	(Nagy, B.V et al., 2018)	Concrete slab	1.55	(Nagy, B.V et al., 2018)
10	Stone wall	10.4	ECBC (2017)	Bamboo matt corrugated sheet	0.19	Innovaroofing
11	FalG brick	0.85	(Gourav, K et al., 2017)	RCC	1.58	IS SP41
12	Med. Density fiber board	0.11	(Ustaömer, D et al., 2020)	China mosaic	1.5	ECBC for Residence 2017
13	Fly ash brick	0.63	ECBC for Residence 2017	Salvaged brick	0.5	ThermTest
14	Mud plaster (int.)	0.65	(Holzhueter, K et al., 2017)	Reclaimed timber	0.07	IS SP41
15	Lime plaster (ext.)	0.84	(Walker, R et al., 2016)	Reused cement + steel	0.6	IS SP41

Note: ***All the thermal conductivity (k-value) has been obtained from the main sources, such as manufactured company websites, literature reviews, and standards.***

3. Results

3.1 Wall Assembly

The study analyzed 4 natural materials, 6 bio-material and 6 salvaged material assemblies and compared their performance with conventional materials. The assemblies were assessed based on the U-value, Time lag and Decrement Factor.

Sl.No	Base materials	WALL ASSEMBLIES	IMAGES	U values (W/m2k)	R values (m2·K/W)	Time lag (hrs)	Decrement Factor
1	Conventional Brick Wall	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 Plaster (dense) 25.0 0.04 Brick 230.0 0.20 Plaster (dense) 25.0 0.04 Outside Air Film 0.0 0.04		1.97	0.51	8.05	0.36
2	CSEB, Mud plaster	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 15.0 0.03 CSEB 190.0 0.23 Polyurethane Foam 50.0 2.0 Gypsum Board 10.0 0.06 MUD PLASTER 15.0 0.03 Outside Air Film 0.0 0.04		0.39	2.51	9.9	0.14
3	CSEB, Lime plaster	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 LIME PLASTER 15.0 0.02 CSEB 190.0 0.23 Polyurethane Foam 50.0 2.0 Gypsum Board 10.0 0.06 LIME PLASTER 15.0 0.02 Outside Air Film 0.0 0.04		0.4	2.49	9.75	0.15
4	Strawbale-stud, Mud (int) & Lime plaster (ext)	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 15.0 0.03 Studs (wood) 250.0 1.92 STRAWBALE INBETWN 250.0 5.81 LIME PLASTER 15.0 0.02 Outside Air Film 0.0 0.04		0.17	5.61	9.94	0.18
5	Rammed earth	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 10.0 0.02 RAMMED EARTH 100.0 0.24 Insulation Board 60.0 2.0 RAMMED EARTH 100.0 0.24 LIME PLASTER 10.0 0.01 Outside Air Film 0.0 0.04		0.37	2.67	9.46	0.09
6	Timbercrete	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 15.0 0.03 TIMBERCRETE 100.0 0.45 Extruded Polystrene 50.0 1.43 TIMBERCRETE 100.0 0.45 LIME PLASTER 15.0 0.02 Outside Air Film 0.0 0.04		0.39	2.55	10.5	0.32
7	Porotherm	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 15.0 0.03 POROTHERM 250.0 2.5 MUD PLASTER 15.0 0.03 Outside Air Film 0.0 0.04		0.36	2.72	9.09	0.14
8	Mycelium bricks	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 LIME PLASTER 15.0 0.02 Gypsum Board 25.0 0.16 MYCELIUM BRICK 200.0 4.0 Gypsum Board 25.0 0.16 LIME PLASTER 15.0 0.02 Outside Air Film 0.0 0.04		0.22	4.51	3.1	0.01
9	Hempcrete	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 LIME PLASTER 15.0 0.02 HEMPCRETE 250.0 2.87 LIME PLASTER 15.0 0.02 Outside Air Film 0.0 0.04		0.32	3.07	10.7	0.32
10	Rice husk ash brick	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 15.0 0.03 RICE HUSK FLYASH BRICK 250.0 2.5 LIME PLASTER 15.0 0.02 Outside Air Film 0.0 0.04		0.36	2.71	6.01	0.69
11	Sawdust brick	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 10.0 0.02 Insulation Board 30.0 1.0 SAWDUST BRICK 200.0 0.32 Insulation Board 30.0 1.0 MUD PLASTER 10.0 0.02 Outside Air Film 0.0 0.04		0.39	2.52	11.72	0.04

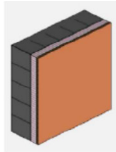
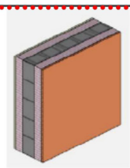
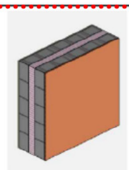
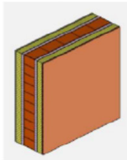
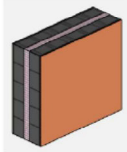
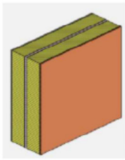
12	**Stone masonry**	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 10.0 0.02 MDF 10.0 0.09 Polyurethane Foam 60.0 2.4 STONE 200.0 0.02 Outside Air Film 0.0 0.04		0.37	2.69	5.58	0.52
13	**FalG brick**	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 15.0 0.03 Insulation Board 70.0 2.33 FalG 110.0 0.13 Insulation Board 70.0 2.33 LIME PLASTER 15.0 0.02 Outside Air Film 0.0 0.04		0.2	5.01	8.77	0.06
14	**FalG brick**	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 10.0 0.02 FalG 100.0 0.12 Polyurethane Foam 60.0 2.4 FalG 100.0 0.12 LIME PLASTER 10.0 0.01 Outside Air Film 0.0 0.04		0.35	2.83	9.25	0.31
15	**Medium density fiber board 1**	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 10.0 0.02 MDF 54.0 0.46 Polyurethane Foam 25.0 1.0 Brick 102.0 0.11 Polyurethane Foam 25.0 1.0 MDF 54.0 0.46 LIME PLASTER 10.0 0.01 Outside Air Film 0.0 0.04		0.3	3.23	10.08	0.06
16	**Fly ash brick**	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 10.0 0.02 FLY ASH BRICK 100.0 0.16 Polyurethane Foam 50.0 2.0 FLY ASH BRICK 100.0 0.16 LIME PLASTER 10.0 0.01 Outside Air Film 0.0 0.04		0.39	2.51	9.92	0.27
17	**MDF board 2**	Material / mm / R Value Inside Air Film (wall) 0.0 0.12 MUD PLASTER 10.0 0.02 MDF 120.0 1.03 Insulation Board 20.0 0.67 MDF 120.0 1.03 LIME PLASTER 10.0 0.01 Outside Air Film 0.0 0.04		0.34	2.91	6.99	0.08

Figure 2: Assessment wall assemblies

3.2 Roof Assembly

The study analyzed 4 natural materials, 6 bio-material and 5 salvaged material assemblies and compared their performance with conventional materials. The assemblies were assessed based on the U-value, and Time lag and Decrement Factor

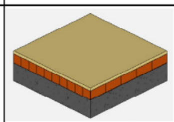
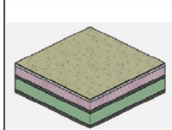
Sl.No	Base materials	Roof Tilt	ROOF ASSEMBLIES	IMAGES	U values (W/m2k)	R values (m2·K/W)	Time lag (hrs)	Decrement Factor
1	Conventional RCC + Brick Roof	0°	Material / mm / R Value Inside Air Film (ceiling) 0.0 0.16 RCC 150.0 0.1 Brick 75.0 0.08 Plaster (dense) 25.0 0.04 Outside Air Film 0.0 0.04		2.34	0.42	7.18	0.36
2	Limecrete, bamboo reinforcement	0°	Material / mm / R Value Inside Air Film (ceiling) 0.0 0.16 RCC 25.0 0.02 bamboo RAFTER 1 100.0 0.17 RCC 25.0 0.02 Insulation Board 75.0 2.5 limecrete 20.0 0.05 lime screed 5.0 0.06 Outside Air Film 0.0 0.04		0.33	3.01	7.28	0.37

Figure 3: Assessment Roof assemblies (contd.)

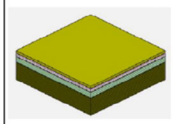
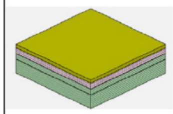
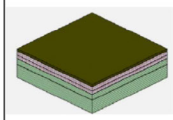
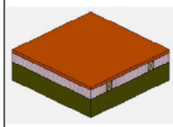
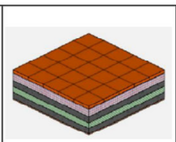
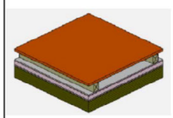
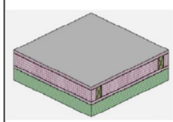
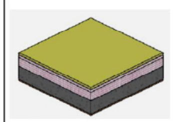
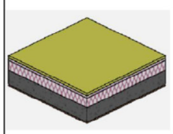
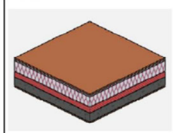
Sl.No	Base materials	Roof Tilt	ROOF ASSEMBLIES	IMAGES	U values (W/m2k)	R values (m2·K/W)	Time lag (hrs)	Decrement Factor
3	Thatch, palmyra beam and bamboo rafter	45°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 palymra beam 1 – 150.0 – 1.67 bamboo RAFTER – 50.0 – 0.08 Air Space (wall) – 50.0 – 0.15 Urea Formaldehyde (UF) Foam – 30.0 – 0.75 thatch – 20.0 – 0.29 Outside Air Film – 0.0 – 0.04		0.32	3.05	10.28	0.22
4	Thatch and bamboo rafter	45°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 bamboo RAFTER 1 – 120.0 – 0.2 bamboo RAFTER – 50.0 – 0.08 Air Space (wall) – 50.0 – 0.15 Polyurethane Foam – 50.0 – 2.0 thatch – 30.0 – 0.43 Outside Air Film – 0.0 – 0.04		0.33	2.98	4.6	0.67
5	Bamboo roof	45°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 bamboo RAFTER 1 – 115.0 – 0.19 bamboo RAFTER 1 – 50.0 – 0.08 Insulation Board – 30.0 – 1.0 Polyurethane Foam – 35.0 – 1.4 bamboo shingles – 20.0 – 0.11 Outside Air Film – 0.0 – 0.04		0.33	2.99	5.64	0.52
6	Mangalore tiles	45°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 palymra beam 1 – 150.0 – 1.67 Studs (wood) – 75.0 – 0.58 Polyurethane Foam – 75.0 – 3.0 manglore tile – 25.0 – 0.04 Outside Air Film – 0.0 – 0.04		0.22	4.47	11.61	0.15
7	Burnt clay tiles filler slab	0°	U-value: 2.34 (Source: ECBC for Residence 2017)					
8	BFRC	45°	U-value: 1.6 (Source: BFRC, https://glazingcentre.co.uk/)					
9	Bamboo reinforced concrete slab	0°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 MUD PLASTER – 10.0 – 0.02 RCC – 50.0 – 0.03 bamboo RAFTER 1 – 50.0 – 0.08 RCC – 50.0 – 0.03 Polyurethane Foam – 65.0 – 2.6 clay tile – 25.0 – 0.04 Outside Air Film – 0.0 – 0.04		0.33	3.01	8.56	0.24
10	Mangalore tiles	45°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 palymra beam 1 – 100.0 – 1.11 Insulation Board – 10.0 – 0.33 Blown Fibre – 35.0 – 0.88 Insulation Board – 10.0 – 0.33 Studs (wood) – 75.0 – 0.58 Air Space (wall) – 75.0 – 0.15 manglore tile – 20.0 – 0.03 Outside Air Film – 0.0 – 0.04		0.32	3.06	8.09	0.39
11	Bamboo mat corrugated sheet	45°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 bamboo RAFTER 1 – 100.0 – 0.17 Insulation Board – 25.0 – 0.83 Studs (wood) – 100.0 – 0.77 Expanded Polystrene (EPS) – 100.0 – 2.5 bamboo matt corrugated sheet – 25.0 – 0.13 Outside Air Film – 0.0 – 0.04		0.27	3.62	4.91	0.69
12	PCC + China mosaic	0°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 MUD PLASTER – 10.0 – 0.02 PCC – 120.0 – 0.08 Extruded Polystrene – 75.0 – 2.14 Insulation Board – 25.0 – 0.83 CHINA MOSAIC – 20.0 – 0.01 Outside Air Film – 0.0 – 0.04		0.3	3.28	6.75	0.26
13	Broken china mosaic tiles	0°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 MUD PLASTER – 10.0 – 0.02 RCC – 120.0 – 0.08 Blown Fibre – 80.0 – 2.0 Insulation Board – 20.0 – 0.67 CHINA MOSAIC – 20.0 – 0.01 Outside Air Film – 0.0 – 0.04		0.33	2.98	6.14	0.27
14	Salvaged Brick	0°	Material – mm – R Value Inside Air Film (ceiling) – 0.0 – 0.16 MUD PLASTER – 10.0 – 0.02 RCC – 75.0 – 0.05 salvaged brick – 50.0 – 0.1 Blown Fibre – 90.0 – 2.25 Insulation Board – 12.5 – 0.42 MUD PLASTER – 12.5 – 0.03 Outside Air Film – 0.0 – 0.04		0.32	3.06	5.67	0.38

Figure 3: Assessment Roof assemblies contd. (Note: Sl.no 7 and 8 not taken into consideration for comparison)

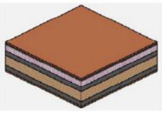
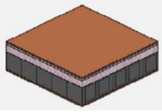
Sl.No	Base materials	Roof Tilt	ROOF ASSEMBLIES	IMAGES	U values (W/m2k)	R values (m2·K/W)	Time lag (hrs)	Decrement Factor
15	Reclaimed timber	0°	Material / mm / R Value Inside Air Film (ceiling) 0.0 0.16 MUD PLASTER 12.5 0.03 RCC 40.0 0.03 reclaimed timber 85.0 1.18 RCC 40.0 0.03 Extruded Polystrene 50.0 1.43 Insulation Board 10.0 0.33 MUD PLASTER 12.5 0.03 Outside Air Film 0.0 0.04		0.3	3.25	11.03	0.08
16	Reused cement + reused steel	0°	Material / mm / R Value Inside Air Film (ceiling) 0.0 0.16 MUD PLASTER 12.5 0.03 reused cement+steel 150.0 0.25 Polyurethane Foam 60.0 2.4 Insulation Board 15.0 0.5 MUD PLASTER 12.5 0.03 Outside Air Film 0.0 0.04		0.29	3.4	6.13	0.01

Figure 3: Assessment Roof assemblies

3.3 Wall Assemblies based on summer and Winter Heat Gain/Loss

The study analyzed 4 natural materials, 6 bio-material and 6 salvaged material assemblies and compared their performance with conventional materials. The assemblies were assessed based on the thermal gradient with Heat gain and Heat loss in summer and winter.

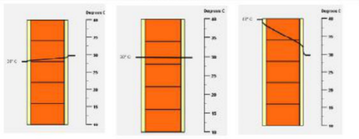
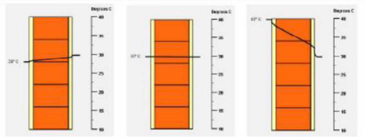
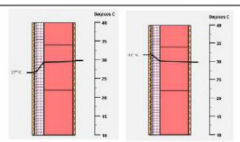
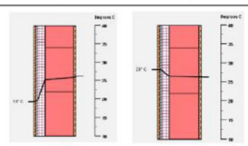
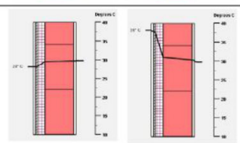
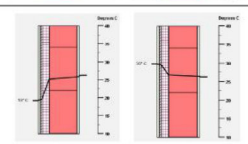
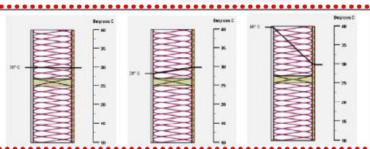
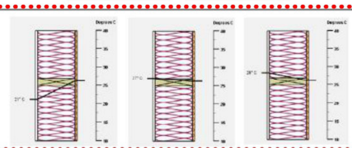
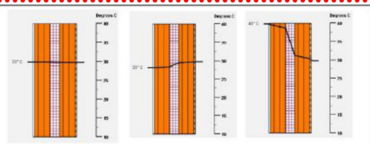
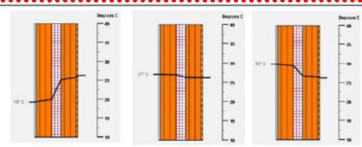
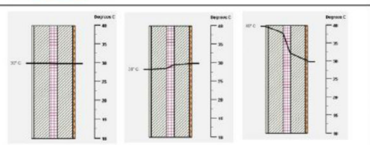
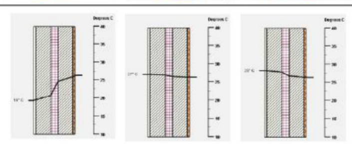
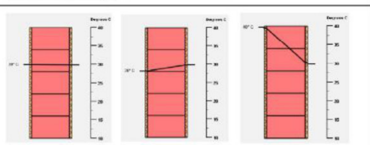
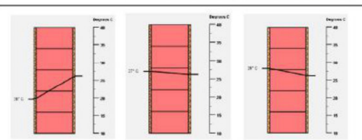
WALL ASSEMBLIES		SUMMER - MAY		WINTER - JANUARY	
Sl.No	Base materials	THERMAL GRADIENT - HEAT GAIN / LOSS (MidNight, 6AM, 4PM)	values (Wh/Sq.m)	THERMAL GRADIENT - HEAT GAIN / LOSS (6AM, Noon, 4PM)	values (Wh/Sq.m)
1	Conventional Brick Wall		May : 13 (wh.sq.m) April : 10 (wh.sq.m) June : 7.0 (wh.sq.m) July : 3.0 (wh.sq.m)		Feb : 32 (wh.sq.m) Jan : 30 (wh.sq.m) Dec : 29 (wh.sq.m)
2	CSEB, Mud plaster		May : 1.9 (wh.sq.m) April : 1.2 (wh.sq.m) June : 0.9 (wh.sq.m) July : 0.2 (wh.sq.m)		Feb : 1.1 (wh.sq.m) Jan : 0.3 (wh.sq.m) Dec : 0.3 (wh.sq.m)
3	CSEB, Lime plaster		May : 1.9 (wh.sq.m) April : 1.3 (wh.sq.m) June : 0.9 (wh.sq.m) July : 0.2 (wh.sq.m)		Feb : 1.1 (wh.sq.m) Jan : 0.4 (wh.sq.m) Dec : 0.3 (wh.sq.m)
4	Strawbale-stud, Mud (int) & Lime plaster (ext)		May : 0.9 (wh.sq.m) April : 0.6 (wh.sq.m) June : 0.4 (wh.sq.m) July : 0.1 (wh.sq.m)		Feb : 0.5 (wh.sq.m) Jan : 0.2 (wh.sq.m) Dec : 0.1 (wh.sq.m)
5	Rammed earth		May : 1.6 (wh.sq.m) April : 1.0 (wh.sq.m) June : 0.7 (wh.sq.m) July : 0.1 (wh.sq.m)		Feb : 0.9 (wh.sq.m) Jan : 0.1 (wh.sq.m) Dec : 0.1 (wh.sq.m)
6	Timbercrete		May : 2.3 (wh.sq.m) April : 1.8 (wh.sq.m) June : 1.2 (wh.sq.m) July : 0.4 (wh.sq.m)		Feb : 1.7 (wh.sq.m) Jan : 1.0 (wh.sq.m) Dec : 0.9 (wh.sq.m)
7	Porotherm		May : 1.7 (wh.sq.m) April : 1.1 (wh.sq.m) June : 0.8 (wh.sq.m) July : 0.1 (wh.sq.m)		Feb : 1.0 (wh.sq.m) Jan : 0.3 (wh.sq.m) Dec : 0.2 (wh.sq.m)

Figure 4: Thermal gradient in a wall assemblies using Heat Gain/Loss for summer and winter months (contd.)

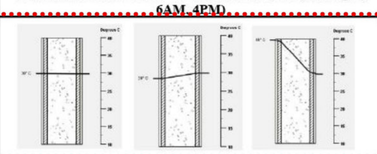
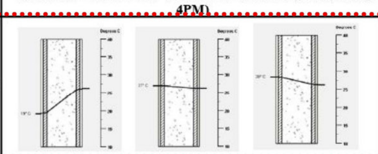
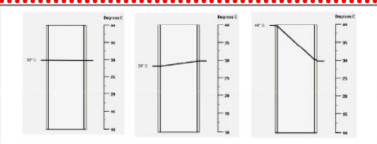
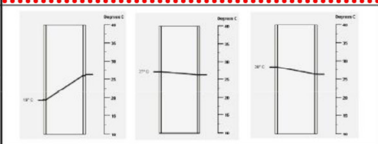
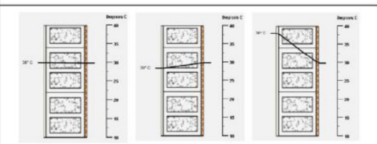
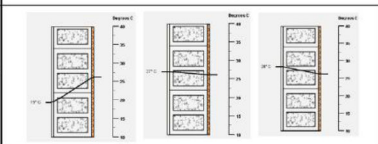
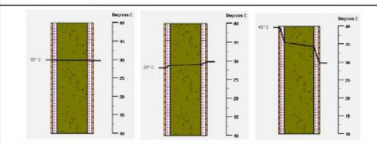
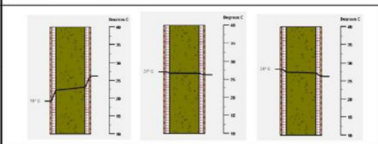
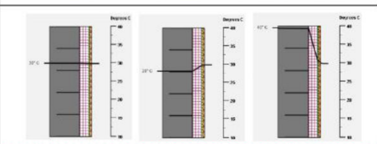
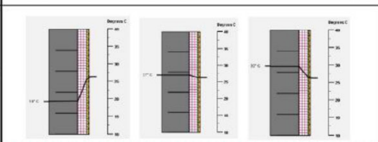
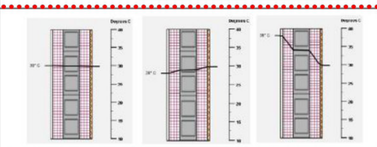
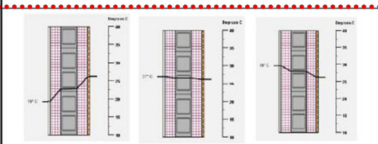
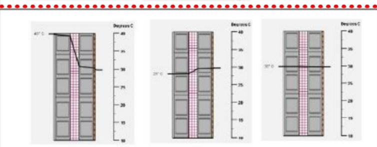
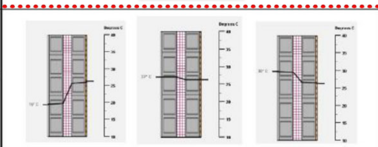
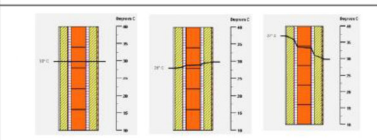
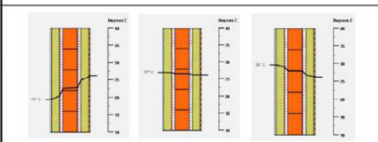
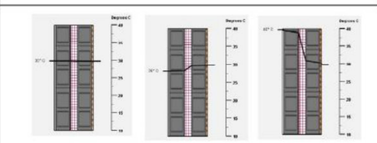
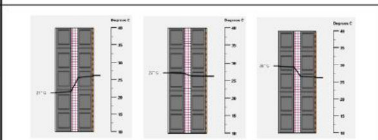
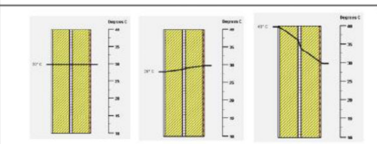
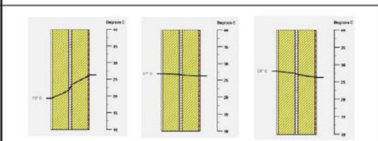
WALL ASSEMBLIES		SUMMER - MAY		WINTER - JANUARY	
Sl.No	Base materials	THERMAL GRADIENT - HEAT GAIN / LOSS (MidNight, 6AM, 4PM)	values (Wh/Sq.m)	THERMAL GRADIENT - HEAT GAIN / LOSS (6AM, Noon, 4PM)	values (Wh/Sq.m)
8	Mycelium bricks		May : 0.8 (wh.sq.m) April : 0.4 (wh.sq.m) June : 0.3 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.3 (wh.sq.m) Jan : 0.0 (wh.sq.m) Dec : 0.0 (wh.sq.m)
9	Hempcrete		May : 1.9 (wh.sq.m) April : 1.5 (wh.sq.m) June : 1.0 (wh.sq.m) July : 0.4 (wh.sq.m)		Feb : 1.4 (wh.sq.m) Jan : 0.8 (wh.sq.m) Dec : 0.7 (wh.sq.m)
10	Rice husk ash brick		May : 3.1 (wh.sq.m) April : 2.7 (wh.sq.m) June : 1.9 (wh.sq.m) July : 0.9 (wh.sq.m)		Feb : 2.8 (wh.sq.m) Jan : 2.2 (wh.sq.m) Dec : 1.9 (wh.sq.m)
11	Sawdust brick		May : 1.6 (wh.sq.m) April : 0.9 (wh.sq.m) June : 0.7 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.7 (wh.sq.m) Jan : 0.0 (wh.sq.m) Dec : 0.0 (wh.sq.m)
12	Stone masonry		May : 2.7 (wh.sq.m) April : 2.3 (wh.sq.m) June : 1.4 (wh.sq.m) July : 0.7 (wh.sq.m)		Feb : 2.3 (wh.sq.m) Jan : 1.7 (wh.sq.m) Dec : 1.4 (wh.sq.m)
13	FalG brick 1		May : 0.8 (wh.sq.m) April : 0.5 (wh.sq.m) June : 0.4 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.4 (wh.sq.m) Jan : 0.0 (wh.sq.m) Dec : 0.0 (wh.sq.m)
14	FalG brick 2		May : 2.6 (wh.sq.m) April : 1.1 (wh.sq.m) June : 1.0 (wh.sq.m) July : 0.4 (wh.sq.m)		Feb : 1.5 (wh.sq.m) Jan : 0.9 (wh.sq.m) Dec : 0.7 (wh.sq.m)
15	Medium density fiber board 1		May : 1.3 (wh.sq.m) April : 0.8 (wh.sq.m) June : 0.6 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.6 (wh.sq.m) Jan : 0.0 (wh.sq.m) Dec : 0.0 (wh.sq.m)
16	Fly ash brick		May : 2.2 (wh.sq.m) April : 1.7 (wh.sq.m) June : 1.2 (wh.sq.m) July : 0.4 (wh.sq.m)		Feb : 1.6 (wh.sq.m) Jan : 0.9 (wh.sq.m) Dec : 0.7 (wh.sq.m)
17	MDF board 2		May : 1.5 (wh.sq.m) April : 0.9 (wh.sq.m) June : 0.6 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.8 (wh.sq.m) Jan : 0.1 (wh.sq.m) Dec : 0.0 (wh.sq.m)

Figure 4: Thermal gradient in a wall assemblies using Heat Gain/Loss for summer and winter months

3.4 Roof Assemblies based on summer and Winter Heat Gain/Loss

The study analyzed 4 natural materials, 6 bio-material and 5 salvaged material assemblies and compared their performance. The assemblies were assessed based on the Thermal gradation with Heat gain and Heat loss in summer and winter.

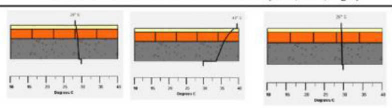
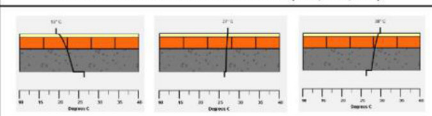
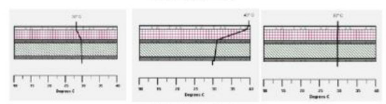
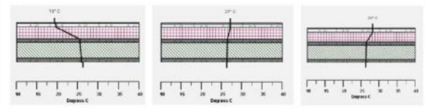
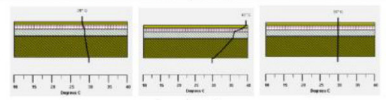
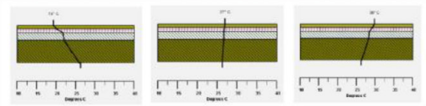
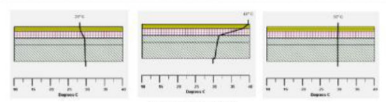
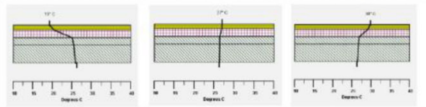
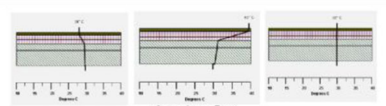
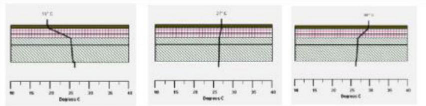
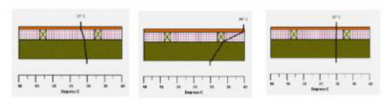
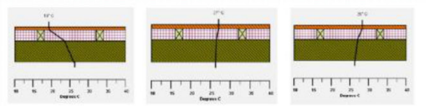
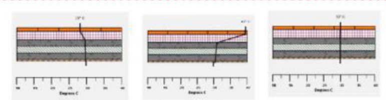
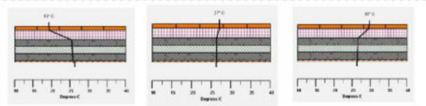
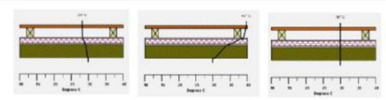
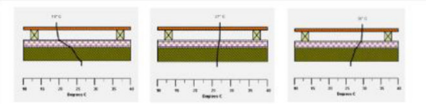
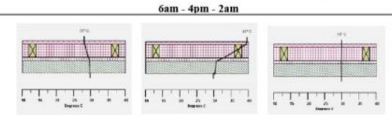
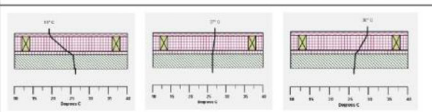
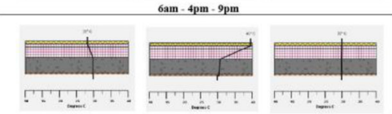
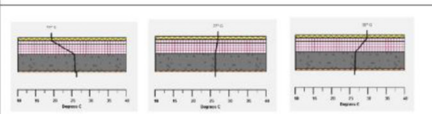
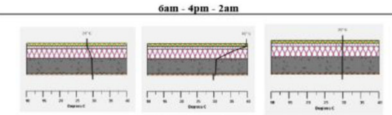
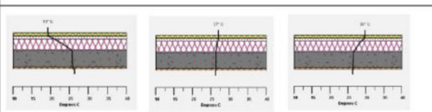
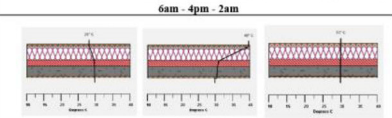
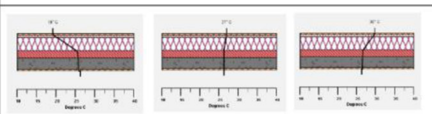
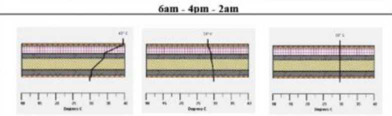
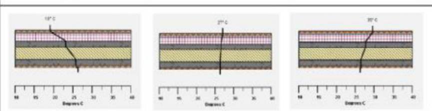
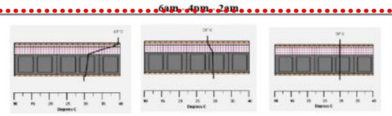
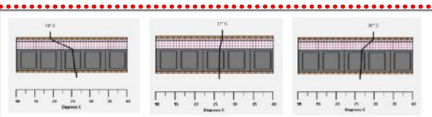
ROOF ASSEMBLIES		SUMMER - MAY		WINTER - JANUARY	
Sl.No	Base materials	THERMAL GRADIENT - HEAT GAIN / LOSS (6AM, 4PM, Night)	values (Wh/Sq.m)	THERMAL GRADIENT - HEAT GAIN / LOSS (6AM, Noon, 4PM)	values (Wh/Sq.m)
1	Conventional RCC + Brick Roof	 6am - 4pm - 3am	May : 15 (wh.sq.m) April : 16 (wh.sq.m) June : 6.0 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 4.0 (wh.sq.m) Jan : -1.0 (wh.sq.m) Dec : -3.0 (wh.sq.m)
2	Limecrete, bamboo reinforcement	 6am - 4pm - 3am	May : 2.0 (wh.sq.m) April : 2.0 (wh.sq.m) June : 1.0 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.6 (wh.sq.m) Jan : -0.1 (wh.sq.m) Dec : -0.3 (wh.sq.m)
3	Thatch, palmyra beam and bamboo rafter	 6am - 4pm - 7pm	May : 1.9 (wh.sq.m) April : 1.3 (wh.sq.m) June : 0.7 (wh.sq.m) July : 0.1 (wh.sq.m)		Feb : 0.9 (wh.sq.m) Jan : 0.2 (wh.sq.m) Dec : 0.1 (wh.sq.m)
4	Thatch and bamboo rafter	 6am - 4pm - 10pm	May : 3.0 (wh.sq.m) April : 3.0 (wh.sq.m) June : 2.0 (wh.sq.m) July : 1.0 (wh.sq.m)		Feb : 3.0 (wh.sq.m) Jan : 2.0 (wh.sq.m) Dec : 2.0 (wh.sq.m)
5	Bamboo roof	 6am - 4pm - 7pm	May : 2.9 (wh.sq.m) April : 2.4 (wh.sq.m) June : 1.4 (wh.sq.m) July : 0.7 (wh.sq.m)		Feb : 2.0 (wh.sq.m) Jan : 1.3 (wh.sq.m) Dec : 1.1 (wh.sq.m)
8	Mangalore tiles	 6am - 4pm - 2am	May : 1.1 (wh.sq.m) April : 0.7 (wh.sq.m) June : 0.4 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.4 (wh.sq.m) Jan : 0.0 (wh.sq.m) Dec : 0.0 (wh.sq.m)
9	Bamboo reinforced concrete slab	 6am - 4pm - 2am	May : 1.7 (wh.sq.m) April : 1.0 (wh.sq.m) June : 0.4 (wh.sq.m) July : -0.2 (wh.sq.m)		Feb : 0.2 (wh.sq.m) Jan : -0.5 (wh.sq.m) Dec : -0.7 (wh.sq.m)
10	Mangalore tiles	 6am - 4pm - 2am	May : 2.4 (wh.sq.m) April : 1.9 (wh.sq.m) June : 1.1 (wh.sq.m) July : 0.4 (wh.sq.m)		Feb : 1.5 (wh.sq.m) Jan : 0.8 (wh.sq.m) Dec : 0.6 (wh.sq.m)
11	Bamboo mat corrugated sheet	 6am - 4pm - 9pm	May : 2.9 (wh.sq.m) April : 2.5 (wh.sq.m) June : 1.5 (wh.sq.m) July : 0.8 (wh.sq.m)		Feb : 2.1 (wh.sq.m) Jan : 1.6 (wh.sq.m) Dec : 1.3 (wh.sq.m)
12	PCC + China mosaic	 6am - 4pm - 2am	May : 1.6 (wh.sq.m) April : 1.0 (wh.sq.m) June : 0.4 (wh.sq.m) July : -0.1 (wh.sq.m)		Feb : 0.2 (wh.sq.m) Jan : -0.4 (wh.sq.m) Dec : -0.5 (wh.sq.m)
13	Broken china mosaic tiles	 6am - 4pm - 2am	May : 1.8 (wh.sq.m) April : 1.1 (wh.sq.m) June : 0.5 (wh.sq.m) July : -0.1 (wh.sq.m)		Feb : 0.3 (wh.sq.m) Jan : -0.4 (wh.sq.m) Dec : -0.5 (wh.sq.m)
14	Salvaged Brick	 6am - 4pm - 2am	May : 2.0 (wh.sq.m) April : 2.0 (wh.sq.m) June : 1.0 (wh.sq.m) July : 0.0 (wh.sq.m)		Feb : 0.6 (wh.sq.m) Jan : 0.0 (wh.sq.m) Dec : -0.3 (wh.sq.m)
15	Reclaimed timber	 6am - 4pm - 2am	May : 1.0 (wh.sq.m) April : 0.3 (wh.sq.m) June : 0.0 (wh.sq.m) July : -0.5 (wh.sq.m)		Feb : -0.2 (wh.sq.m) Jan : -1.0 (wh.sq.m) Dec : -1.0 (wh.sq.m)
16	Reused cement + reused steel	 6am - 4pm - 2am	May : 0.7 (wh.sq.m) April : 0.0 (wh.sq.m) June : 0.0 (wh.sq.m) July : -0.6 (wh.sq.m)		Feb : -0.4 (wh.sq.m) Jan : -1.1 (wh.sq.m) Dec : -1.2 (wh.sq.m)

Figure 5: Thermal gradient in a roof assemblies using Heat Gain/Loss for summer and winter months

4. Discussion

All the wall and roof assemblies assessed were compliant with ECBC standards thus providing enhanced indoor thermal comfort. As per ECBC, the maximum U-value for opaque wall assemblies for residence is 0.4 W/m².K for ECBC, 0.34 W/m².K for ECBC PLUS+, and 0.2 W/m².K for SUPER ECBC. The maximum U-value for opaque Roof assemblies for residence is 0.33 W/m².K for ECBC and 0.2 W/m².K for SUPER ECBC. The performance of the selected natural, bio and salvaged assemblies were analyzed to identify the best performing material and its characteristics in each category.

4.1 Wall Assemblies

a) Natural materials: Straw bale with mud and lime plaster in the interior and the exterior performed the best, which was compliant with Super ECBC with a U-value of 0.17 W/m2.K and a time lag of 9.9 hrs, as shown in "Fig.2 ". Straw bale is an energy-efficient, affordable, and environmentally beneficial material, but it is moisture sensitive and requires maintenance, and it can only be used for ground structures. The heat gain of strawbale assembly is 0.9 wh/sqm during summer and 0.5 wh/sq.m during winter as shown in "Fig. 4", indicating its suitability for a low rise load bearing residential building and infill materials for medium rise structure. This has 11.5 times lesser U-value and 14.5 times lesser heat gain than the conventional brick wall. Both the CSEB block assembly and rammed earth were found to have higher heat gains of 1.9 wh/sqm and 1.6 wh/sq.m, during summer and 1.1 wh/sq.m and 0.9 wh/sq.m during winter respectively. This is 2 times the heat gain higher than strawbale wall assembly.

b) Bio materials: Mycelium brick with lime plaster performed the best, which was compliant with Super ECBC with a U-value of 0.22 W/m2.K and a time lag of 3.1 hours, as shown in "Fig.2 ". It is a low-cost, good insulating, and sustainable material in nature, but it has some disadvantages, such as being water-sensitive and low in compressive strength, and its availability is limited. The heat gain of mycelium assembly is 0.8 wh/sqm during summer and 0.3 wh/sq.m during winter; this can be used to construct buildings up to a maximum of 2 storeys for low rise residential buildings. This has 9 times lesser U-value of conventional brick wall.

c) Salvaged materials: FalG brick with mud and lime plaster in the interior and exterior performed better than all other materials in the category, which was compliant with Super ECBC with a U-value of 0.2 W/m2.K and a time lag of 9 hours, as shown in "Fig.2 ". FalG is a strong and lightweight material; it has a Heat gain of 0.8 wh/sqm during summer and 0.3 wh/sq.m during winter. It is also cost-effective and has good insulation. But its disadvantages are the size limitation of the material and the seasonal restriction. Based on the compression strength of the material, it can be used for medium rise residential building construction up to three storeys. This has 9.8 times lesser U-value and 16.5 times lesser heat gain than the conventional brick wall.

4.2 Roof Assemblies

Similarly, amongst the roof assemblies, the compliance with ECBC varied with each assembly which are further discussed below:

a) Natural materials: Thatch, Palmyra beam, and bamboo rafter performed the best amongst the natural materials roof category, with U-value of 0.32 W/m2.K (ECBC compliant) and time lag of 10.34 hours, as shown in "Fig. 3". The heat gain of this assembly is 1.9 wh/sqm during summer and 0.9 wh/sq.m during winter as shown in "Fig. 5". Here, the roof has good insulation, durability, flexibility, and strength but requires regular maintenance of thatch and Palymra beams, which are expensive. In general, thatch roofs are typically used for small buildings, such as cottages or sheds. Palmyra beam roofs can be used for larger buildings, such as houses or schools. Bamboo rafter roofs can be used for even larger buildings, such as warehouses or factories. It also depends on specific factors such as materials, climate, and design.

Limecrete, bamboo reinforcement assembly has the next lowest heat gains of 2.0 wh/sqm and 0.6 wh/sq.m, during summer and winter. Bamboo rafter roofing was found to be the highest heat gain of 3.0 wh/sqm and 3.0 wh/sq.m, during summer and winter respectively. This has 1.5 times higher heat gain than Thatch, Palmyra beam, and bamboo rafter assembly.

b) Bio materials: Mangalore tile with Palmyra beam performed the best amongst the biomaterial roof category, with a U-value of 0.2 W/m2K (Super ECBC compliant) and a time lag of 11.61 hours, as shown in "Fig. 3". The heat gain of this assembly is 2.4 wh/sqm during summer and 1.5 wh/sq.m during winter as shown in "Fig.5". The roofing material is durable, fire-resistant, and a good insulator, but it is also expensive, difficult to source suitable Palmyra beams, and requires regular maintenance. Mangalore tile with Palmyra beam roofing is typically used for single-storey buildings or buildings with two to three storeys. However, it is possible to use this type of roofing for taller buildings if the materials are properly chosen and the roof is designed by a qualified engineer. This has 6 times lesser heat gain than the conventional concrete roofing during the peak summer.

c) Salvaged materials: Reused cement and steel roofing with mud plaster on the interior and exterior performed better among all other salvaged roofing materials, with U-value of 0.29 W/m2K (ECBC compliant) and a time lag of 5.97 hours, as shown in "Fig. 3". The heat gain of this assembly is 0.7 wh/sqm during summer and -0.5 wh/sq.m during winter as shown in "Fig.5". It is a sustainable system that is cost-effective and durable, but it is also heavy in weight with limited availability, and is difficult to install without skilled labour. Reused cement and steel roofing can be used for multi-storey buildings. This has 20 times lesser heat gain than the conventional concrete roofing during the peak summer.

5. Conclusion

The study found strawbale wall assembly among natural materials, Mycelium among biomaterials and FalG 1 among the salvage material as best alternative wall assemblies which enhances the thermal comfort in both summer & winter. Straw bale with mud and lime plaster of U-value of 0.17 W/m2K performed best with a time lag of 9.9 hrs amongst the various alternatives analyzed. Similarly, from the above study it is found that Mangalore tile with Palmyra beam roof assembly among natural materials, Mangalore tile with Palmyra beam among biomaterials and Reused cement and steel roofing with mud plaster among the salvage material are best alternative roof assemblies which enhances the thermal comfort in both summer & winter. Where, Mangalore tile with Palmyra beam, with an inclination of 45°, performed the best, with a lowest U-value of 2.2 W/m2K and a time lag of 11 hours.

The study provided an insight into the efficiency of advanced methods of construction in improving interior comfort, lowering energy use, and developing sustainable building design. In order to satisfy the demands of a continuously changing and energy-conscious built environment, the outcomes of this study provide architects, engineers, and policymakers with valuable insights into the selection of suitable building assemblies. However, the limitation of the study is that it only concentrated on the U-value, time lag, and the heat gain/loss of the materials through simulation only. Therefore, it is better to explore further with real-time experimental setup with in-situ measurements to evaluate and address the real-time challenges.

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Characteristics of thermal comfort in the warm and humid climate of North-East India.

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Abstract

The building sector is considered to be one of the most energy-intensive sectors across the world. The building sector consumes about 40% of the world's primary energy and is responsible for a third of total CO2 emissions. Unprecedented high temperatures and heat waves experienced in many parts of India have disrupted everyday life and increased the energy consumption of buildings further. This posed a big question on the persisting indoor environment quality. North-East India is developing very rapidly, and the government of India is also looking to develop it as a hub to connect South Asian countries. The present study is conducted in Tezpur's naturally ventilated office buildings in warm and humid North-East India. Year-long thermal comfort surveys were carried out in 12 naturally ventilated office buildings, collecting 790 samples from July 2016 to June 2017. Data analysis shows that for Tezpur, neutral temperature through regression analysis and Griffiths method is 26.4°C. Tezpur offices' preferred temperature and relative humidity are 24°C and 55%, respectively. Probit analysis showed that occupants are more adaptive toward the warmer side of the thermal sensation scale. It was also found that the office subject's clothing behaviour was a non-linear function of temperature and impacted by local discomfort, creating a temperature difference between the occupant and back wall surface temperature. Data analysis also concluded that ceiling fan use increases exponentially as the indoor globe temperature in the offices reaches 24°C and plateaus or reaches almost 100% at the indoor globe temperature of 32°C.

Keywords - Adaptive thermal comfort, Offices, North-East India, Probit analysis, Preferred temperature.

1. Introduction

Buildings, for ages, have been an integral part of society because they provide shelter and ensure security and safety, socio-economic and sociocultural status [1–3]. Since industrialization and economic prosperity occupants, lifestyles are changing rapidly, requiring occupants to spend considerable time inside built environments. In recent years, more than 90% of the time is spent inside the built environment because of lifestyle and work-related requirements [4]. Buildings are simultaneously expected to meet the functionality requirement of occupants to support their day-to-day activity at an enhanced level of comfort. Typically, a building's life is about 70 years or more. It becomes very difficult for a building designer to apprehend and incorporate future energy requirements and energy efficiency laws into the buildings. This aspect and limitation have made the building hugely primary energy-intensive and one of the highest carbon emitters [5]. In India, buildings consume more than 33% of the nation's primary energy use, with an annual growth of 8% [6]. The residential and commercial sectors consumed about 32% of total generated electricity, and most of the increase in electricity consumption is due to the growing use of air conditioning in the building [6]. Over the past two decades, several studies have shown that climate change has severely impacted the building sector, leading to a shift in energy consumption because of heat stress and unpredictable extreme weather events [7–12].

North-East India is strategically crucial for India as it has the potential to become the gateway to Southeast Asia. Minimized energy consumption and occupant well-being must be ensured in all critical infrastructures. To address this research gap, the present study is being carried out in Tezpur, which lies in the warm and humid climatic zone of North-East India.

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2. The objectives of the study

Looking at the importance of thermal comfort in office buildings and its relation to the office subjects' productivity and well-being, it becomes important to carry out a thermal comfort study based on long-term data collection. In the present study, yearlong data collection and questionnaire-based surveys (July 2016 to June 2017) were carried out in North-East India's naturally ventilated and free-running office buildings. A study based on yearlong monitoring and data collection is critical because it captures the broad spectrum of thermal adaptation the subjects go through in the built environment. The present research is carried out with the following objectives.

a) To study the status of thermal comfort in the offices of warm and humid climate based on a yearlong thermal comfort survey and data collection.

b) Estimate the thermal preferences and comfort temperature range in an office environment.

c) Study the adaptative actions of subjects in an office-built environment.

d) To compare the developed adaptive comfort model against the IMAC model.

3. Methodology

Questionnaire-based thermal comfort study was carried out at Tezpur (26°37'N, 92°47'E), which lies in a warm and humid climate zone in North-East India. Tezpur is in the state of Assam (Figure 1). The elevation from the mean sea level of Tezpur is 48m. Thermal comfort surveys were done in naturally ventilated offices with assistance from the local support team. Socio-culturally, North-East India is very diversified and distinct compared to the rest of India, so it was exciting and challenging to coordinate and complete the thermal comfort surveys on time. To analyze the data IBM SPSS® statistical software platform SPSS V26 is used.

3.1 The climate and offices of Tezpur

North-East India has mountainous terrain and is heavily vegetated. This region also receives relatively high rainfall and has relatively high humidity throughout the year. Figure 1(a, b) shows the location of Tezpur in the warm and humid climate of North East India. Table 1 lists the range of climatic parameters corresponding to warm and humid climate zone. Figure 1 shows the sitting arrangement, working environment and traditional clothing of subjects in the offices. Offices in this part of India are designed to operate under NV mode throughout the year. Almost all the offices have operable windows with curtains and ceiling fans. A ceiling fan is shared among the office subjects. For lighting, all the offices are fitted with Fluorescent or LED lights. Subjects in the offices are free to wear a dress per their socio-cultural requirements and maintain public office decorum.

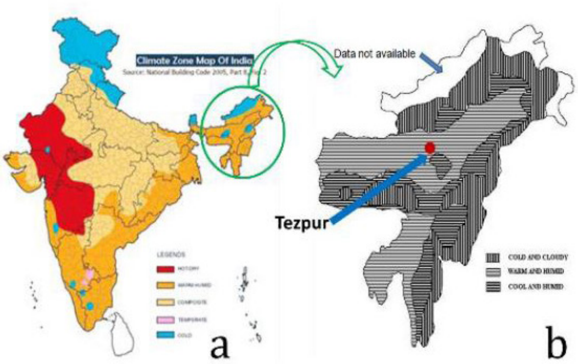

Figure 1: Location of Tezpur

Figure 2: Office environment

A thermal comfort study was conducted in 12 naturally ventilated office buildings across Tezpur. The office buildings were randomly selected out of normal office building stock for the study. All the selected offices were government buildings. Most of the selected office buildings in Tezpur are single-storey. Before the data was collected, it was ensured that the selected office building was operated as usual. The surveys were conducted only on clear and sunny days only.

Table 1: Climatic parameters specifications of bioclimatic zones of north-east India

Bio-climatic Zones		**Warm and humid**
Temperature Range	Summer	Maximum 30°C – 35°C Minimum 22°C – 27 °C
	Winter	Maximum 25°C – 30°C Minimum 10°C – 15°C
Relative Humidity (%)		75 – 90
Rainfall (mm)		1700 to 2100
Sky Condition		Generally clear sky but overcast during monsoon
Wind Direction		Low wind during summer and from SE, N & NE direction
Vegetation		Heavy vegetation

3.2 Questionnaire, protocol and scales

The questionnaire for the present study was sourced from ASHRAE standard 55-2020 information appendix L [14]. A transverse type of questionnaire was designed to capture the required information about the subject's present sensations (about the thermal environment, air movement, humidity, air quality), preferences (about the thermal environment, air movement, humidity, air quality), preferred adaptive actions to restore comfort and their views about probable reasons of discomfort. Most of the region's offices have open seating plans, and if the separation between the office occupants is more than 1.5 meters, then thermal environment parameters were recorded for each subject. Only those subjects sitting in the same place for over a year were selected. This was done to ensure a balanced response from the subject, as they would have experienced the variation in the thermal condition of the place across the four seasons of a year.

Corresponding to each subject, an average of 3 measurements were taken at an interval of 1 min. An interval of 3 min was considered for recording globe temperature. From moving one subject to another for recording the subject's thermal preferences and corresponding physical parameters, a gap of 20 min was considered to stabilize the globe temperature. It was also ensured that the subject was sitting at the same place and doing the same work/activity for at least 20 mins. Scales corresponding to thermal sensation and preferences were sourced from ASHRAE and Nicol [14, 15]. Nicol's five-point preference scale was used to record the preference of office subjects. Table 2 shows the different scales with their corresponding numerical values.

Table 2: Scales used in this study to record the response of the subject

Scale values	Thermal sensation	Thermal preference	Air movement preference	Humidity preference	Thermal acceptability
-3	Cold	-	-	-	-
-2	Cool	Much warmer	Much less air movement	Much more humid	-
-1	Slightly cool	A bit warmer	A bit less air movement	A bit more humid	-
0	Neutral	Neutral	Neutral	Neutral	Unacceptable
1	Slightly Warm	A bit cooler	A bit more air movement	A bit drier	Acceptable
2	Warm	Much cooler	Much more air movement	Much drier	-
3	Hot	-	-	-	-

3.3 Clothing value and Instruments

In the Indian subcontinent, clothing value estimation is the biggest challenge in thermal comfort surveys. The difficulty level was minimal for men in North-East India offices because very few male subjects wore traditional attire. However, in the case of female subjects, it was a challenge because traditional attire individual insulation values are absent in the database. During the field surveys, if the female subject was wearing a "Sari" (an Indian Clothing), then the values calculated by Indraganti et al. [16] were used for analysis. In North-East India, each state has distinct traditional clothing patterns for males and females, and they are allowed to wear traditional dress in offices. Instruments used in this study to record built environment parameters (air temperature, relative humidity, air velocity, globe temperature, CO2 concentration) are listed in Table 3. Figure 2 shows the deployment of the instruments at the field surveys. Ambient temperature and relative humidity at 30-min intervals were measured at each location using HOBO U12 data loggers for the entire study period.

Table 3: Details of instruments used for environmental parameters measurement

Description	Make	Parameter measured	Range	Accuracy
Thermo-hygro-CO_2 meter	TR-76Ui	Air temperature	0~55°C	±0.5°C
		Humidity	10~95% *RH*	±5% *RH*
		CO_2 level	0~9,999 ppm	±50 ppm + 5%
Globe thermometer	Tr-52i, Globe (ø75 mm)	Globe temperature	-60~+155°C	±0.3°C
Fluke 61 Infrared Thermometer	Fluke 61	Surface temperature	-18 ~+275°C	±2°C; Temperature: -18 ~+275°C
Testo 405-Thermal anemometer	Testo	Air velocity	0.01~10.00 m/s	0.01 m/s
		Air Temperature	-20 ~ +50°C	±0.1°C
HOBO U12 4-Channel loggers	HOBO U12	Air Temperature	-0 ~+50°C	±0.35°C; Air Temperature ~ 50°C
		Relative humidity	5% ~ 95%	3.5%; RH: 10 ~ 90%
		Lighting level	0~48 klx	±5%

3.4 Sample size characteristics

A total of 1156 valid thermal sensation votes were collected in warm and humid climate zone. The sample size contains about 32% female and 68 % male subjects. Looking at Figure 3, we see that the maximum number of subjects falls in the age bracket of 41-50 years at Tezpur. This ensures that occupants have spent a considerable amount of time in the same climate and can give a balanced response towards thermal sensation and preferences.

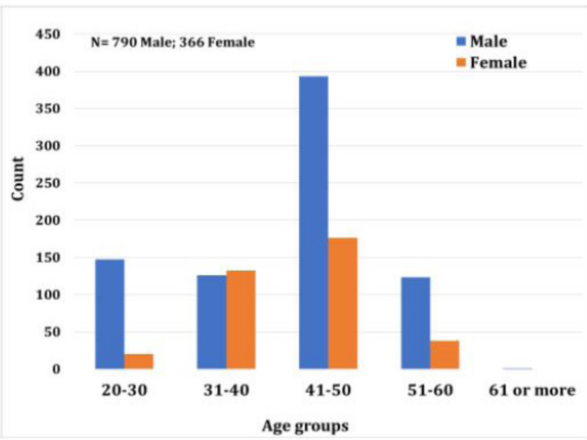

Figure 3: Sample size and characteristics

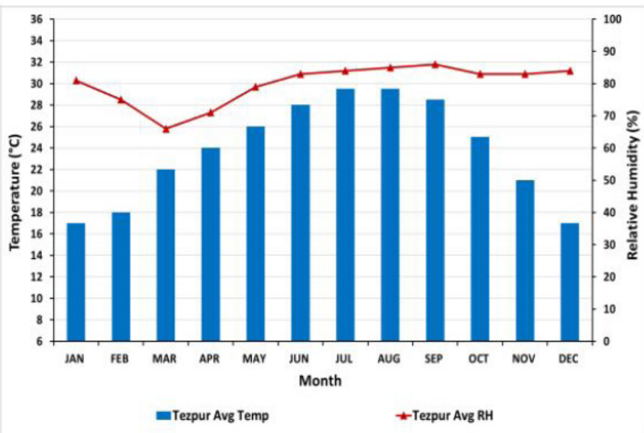

Figure 4: Tezpur outdoor temperature and relative humidity profile

4. Results and discussion

4.1 Outdoor and indoor environmental conditions

North-East India lies in the eastern part of India and is characterized by heavily vegetated uneven topography. Table 1 represents the climatic parameter specifications for the warm and humid climatic zone. Figure 4 shows Tezpur's monthly mean outdoor temperature and relative humidity profiles. The monthly relative humidity profile shows that relative humidity ranges from 70% to 95%. In the rainy season (May to September), relative humidity stays more than 80%. In the offices of Tezpur, the indoor air temperature varied from 19.8 °C to 35.2 °C. Maximum indoor air velocity in the offices of Tezpur varies from 0 m/s to 3.2 m/s. Similarly, the relative humidity in Tezpur's offices varies from 36% to 85%. High air velocity in the offices of Tezpur is evident because it helps subjects overcome discomfort due to persistent high temperatures and high relative humidity. To analyze the relationship between indoor air temperature, mean radiant temperature and indoor globe temperature, they are plotted against each other. It was found that indoor globe temperature better describes the variation in indoor air temperature. So, it is decided to use globe temperature to analyze further and report the results.

4.2 Metabolic rate and clothing characteristics

In this study, the activity level of office subjects at all three locations varies between 1 met (seated, reading) to 1.4 met (filing, standing). These activity values correspond to everyday office activity [14]. Estimating the clo values of the traditional attire was a challenge and a limitation in the study. For traditional dress, such as "saree" and "salwar-kameez" clothing, insulation was sourced from Indraganti et al. [6] and Kumar et al. [17 – 19]. Clothing insulation values vary throughout the year for Tezpur in the range of 0.29clo to 1.32clo. To understand the clothing behaviour of office subjects at all three locations, the mean clothing values with standard deviation are plotted against thermal sensation and indoor globe temperature. Figure 5 shows that the deviation in the clo value is higher on the cooler side of the thermal sensation scale. The reason for this behaviour can be attributed to the availability of more options for clothing in autumn and winter. From Figure 6, the inflexion points for Tezpur 24°C - 32°C. We also find that the difference between inflexion points at low and high temperatures is about 8°C for the climatic zone. The indoor globe temperature corresponding to inflexion points are the temperatures at which the clothing insulation value changes direction with a slight change in globe temperature. This also gives information about behavioural adaptation in the context of clothing insulation.

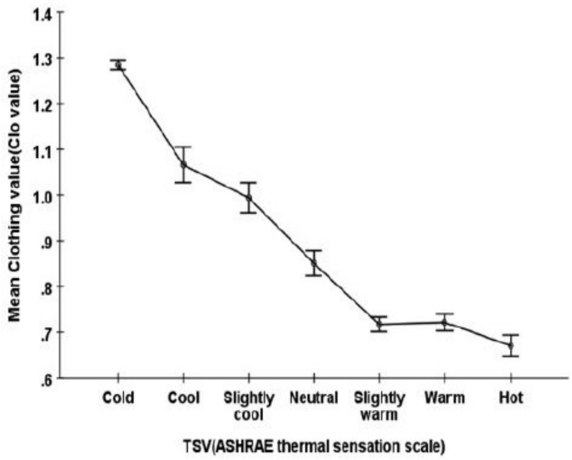

Figure 5: Clothing insulation corresponding to different sensations for Tezpur

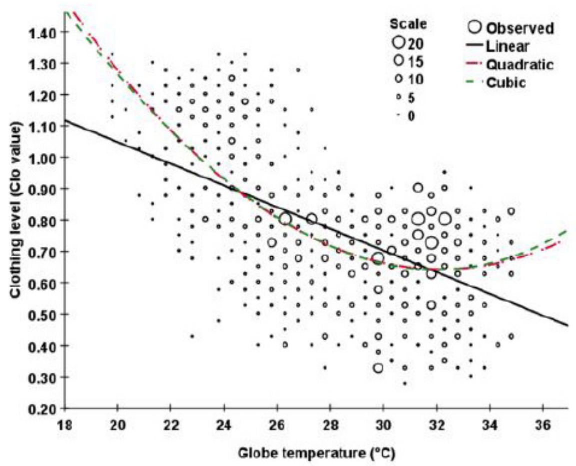

Figure 6: Relationship between clothing and globe temperature for Tezpur

4.3 Estimation of preferred temperature and relative humidity

One of the objectives of the study is to estimate the preferred temperature and relative humidity. Statistical methods can be used effectively on the data to estimate the same. In most cases, preferred environmental conditions are different but lie within the acceptable environmental conditions for the subjects in different built environments. A probit analysis technique was used to evaluate the preferred temperature and relative humidity [19, 20]. To apply this technique, it is required that the data must be in binary form. For this, the preference votes of the office subjects are transformed into binary format. The transformed binary data is now used to carry out ordinal regression with probit as the link function, and the proportion of votes is calculated using equation (1)

$$\text{Probability} = \text{CDF. Normal (Quant, mean, S.D.)} \quad (1)$$

Where "quant" is the independent variable on which the preference votes are impacted, and "CDF" is the cumulative distribution function for normal distribution. In this case, the parameter of interest is globe temperature and relative humidity. "mean" in equation 1 is calculated by dividing the constant of the regression equation by the coefficient attached to the independent variable, such as globe temperature and relative humidity. Standard deviation (SD) is estimated by taking the inverse of the coefficient attached to the independent variable of the regression equation. To estimate the preferred temperature, the proportion of votes that preferred warmer and preferred cooler are calculated for Tezpur is plotted in Figure 7. Figure 7 shows that lines corresponding to preferred warmer and preferred cooler intersect for different locations at different globe temperatures plotted on the X-axis. From the figure, we can conclude that Tezpur's preferred temperatures and relative humidity are 24 °C and 54% (Figure 8). Table 4 presents the Probit analysis statistics for the preferred temperature and preferred relative humidity.

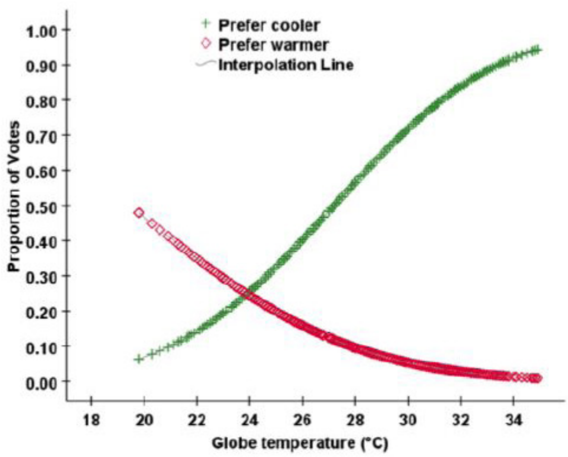

Figure 7: Preferred temperature for Tezpur

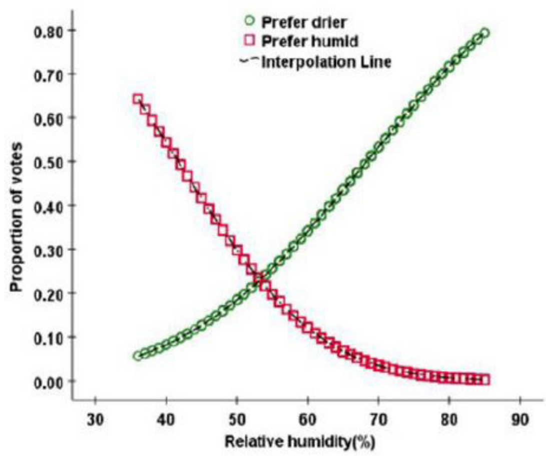

Figure 8: Preferred humidity for Tezpur

Parameter	Equation	Mean	Standard deviation estimated	Sample Size (N)	The standard error estimated (S.E.)	R^2
Temperature	$P_w = -0.15T_g - 2.98$	19.5	6.54	1156	0.016	0.09
	$P_c = 0.21T_g + 5.60$	27.2	4.85	1156	0.013	0.23
Relative humidity	$P_h = -0.04Rh - 1.17$	27.1	23.26	1156	0.004	0.05
	$P_d = 0.03Rh + 1.98$	60	30.30	1156	0.006	0.06

Table 4 Probit analysis statistics for the preferred temperature and preferred relative humidity for Tezpur

4.3 Estimation of thermal neutrality by Probit analysis

The characteristics of thermal comfort votes can also give information about adaptation limits and external thermal stimuli of subjects in a built environment. For this, ordinal regression analysis is carried out using probit as a link function to globe temperature. The process of carrying out this analysis is described in detail by Singh et al. [20, 21]. This analysis resulted in the proportion of votes for each thermal sensation corresponding to globe temperature. Figure 9 presents the plots of the proportion of votes for each thermal sensation on the Y-axis and corresponding values of globe temperature on the X-axis for Tezpur.

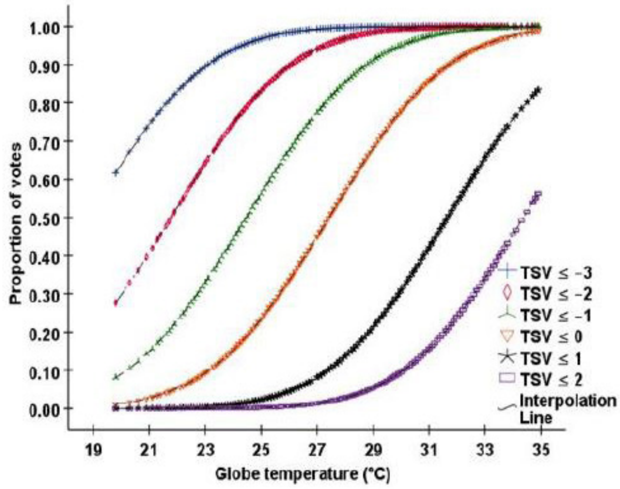

Figure 9: Probit analysis for Tezpur

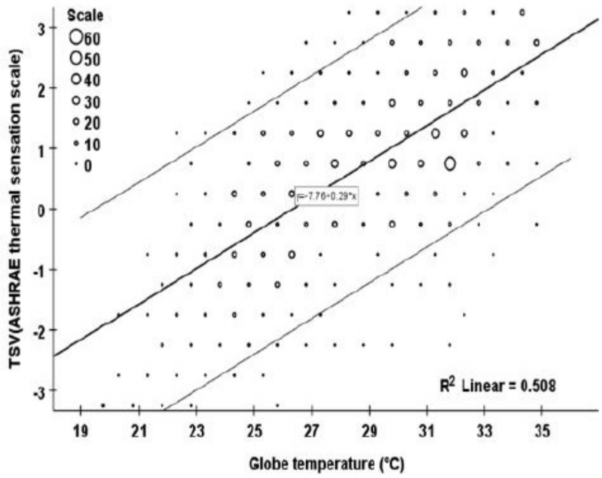

Figure 10: Plot of TSV versus the globe temperature for Tezpur

To find neutrality, if a vertical line is dropped from the sigmoid curve for "TSV = 0" at probability 0.5, the corresponding globe temperature value obtained is neutral temperature. The neutrality value for Tezpur is 27°C. On further analysis of the plots, it can be found that the width of the sigmoid curves corresponding to each thermal sensation for a particular location is not identical at probability 0.5. This means that the thermal stimuli required to shift/change the sensation on the thermal sensation scale are different. This contradicts the assumption regarding the 7-point thermal sensation scale defined in ASHRAE standard 55[22 - 24]. Figure 9 shows that different thermal stimuli (different areas under the curve for each sensation) are required to shift one sensation point on the thermal sensation. The width of each sigmoid curve corresponding to each thermal sensation represents thermal inertia/adaptation potential.

4.4 Comfort temperature estimation and analysis

In a thermal comfort study, the estimation of neutrality or neutral temperature and range of comfort temperature is one of the prime objectives. In this section, regression analysis is carried out to estimate the comfort temperature, as shown in Figure 10, with a 95% confidence interval of the data point. Regression analysis resulted in equation 2. Equation 2 implies that Tezpur subjects require a 3.3°C change in indoor globe temperature to shift one thermal sensation to another. The neutral temperature derived from the regression analysis is 26.4°C for Tezpur. The slope of the regression equations proposed in the present study is comparable to the other studies of India done in office settings.

$$TSV_T = 0.29T_g - 7.76 \ (N=1156, R^2=0.51, S.E.=0.009, P<0.001) \quad (2)$$

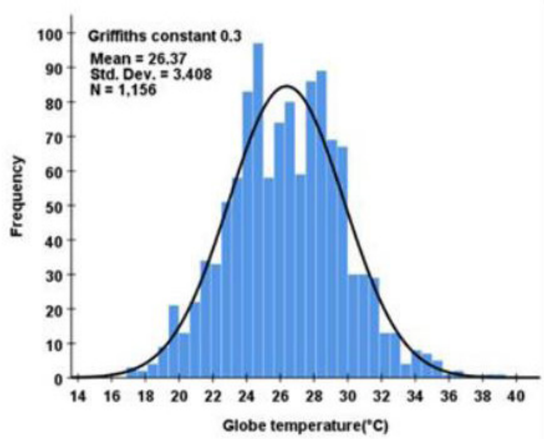

Figure 11: Griffiths comfort temperature

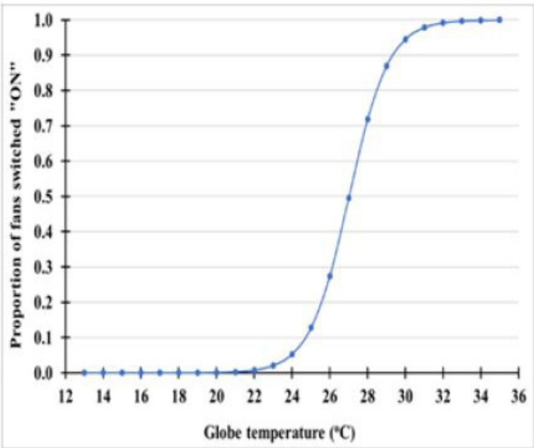

Figure 12: Fan in use characteristics

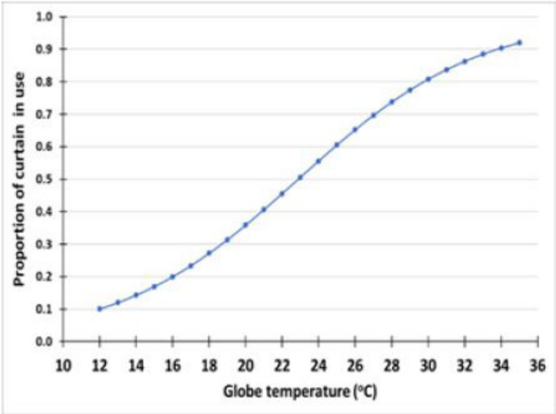

Figure 13: Window curtains use characteristics

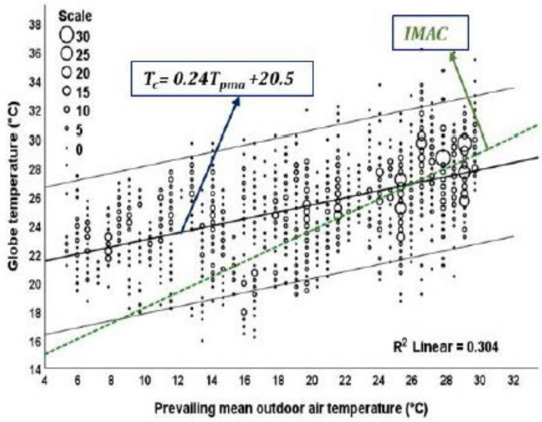

Figure 14: Comparison of the proposed adaptive comfort model with the IMAC model

Equation (3), proposed by Griffiths, is used to estimate the comfort temperature for Tezpur. Griffiths constant was found to be 0.3, for Tezpur. Figure 11 shows the distribution of Griffiths comfort temperature corresponding to the different Griffiths constants for Tezpur. Figure 11 shows that in Tezpur, many subjects expressed comfort with temperatures beyond 30°C. The reason for this can be found when the air velocity data is analysed. During the field measurements, high air velocity (maximum 3.2m/s) was recorded in the offices of Tezpur.

$$T_{cg} = T_g + \left(\frac{0 - TSV}{G}\right) \quad (3)$$

Where T_{cg}: Griffiths comfort temperature

T_g: Globe temperature

0: Neutral on the thermal sensation scale

TSV: Thermal sensation vote

G: Griffiths constant (0.3, 0.4 and 0.45)

4.5 Adaptation characteristics

In a thermal comfort study, analysis of the adaptation characteristics of subjects is important to justify the results. Adaptation of subjects is responsible for the deviation in thermal sensation votes. Adaptation also provides the opportunity and degree of freedom to the subjects in the built environment to restore their comfort [16, 25 – 33]. The use of fan and window curtain data was collected in binary form during the comfort surveys. So, to understand the characteristics of these two adaptive behaviours of subjects, logistic regression was carried out, and output in terms of probability was analyzed. Equation 4 -5 shows the mathematical expressions related to logistic regression. Figure 12 shows the ceiling fan use characteristics. Figure 12 shows that as the indoor globe temperature crosses 24°C, ceiling fans in the offices are gradually switched on, and at 31°C, almost all the fans are switched on. A similar pattern is seen in curtains used in the office windows. It can be seen in Figure 13 that some curtains are not always in use, but as the temperature increases, the window curtains are applied to block the incoming direct sun. At 31°C, more than 80% of curtains are used in the offices.

The logistic function can be written as follows.

$$F(x) = \frac{1}{1 + e^{-y}} \quad (4)$$

Where β is the coefficient and C is a constant. Now equation 17 becomes.

$$F(x) = \frac{1}{1 + e^{-(\beta x + C)}} \quad (5)$$

$F(x)$ gives the probability of the "happening of an event".

4.6 Adaptive comfort equations

In this study, authors tried to propose adaptive comfort equations for three locations in respective climatic zones. The methodology described in standard ASHRAE-55-2020, Section 5.4 and Appendix J (Occupant controlled Naturally Conditioned Spaces) was followed to develop the adaptive comfort equations. To calculate the prevailing daily mean outdoor air temperature [14], we used the following equation (6).

$$\overline{t_{pma}} = (1-\alpha)\left[t_{e(n-1)} + \alpha t_{e(n-2)} + \alpha^2 t_{e(n-3)} + \alpha^3 t_{e(n-4)} + \alpha^4 t_{e(n-5)} + \alpha^5 t_{e(n-6)} + \alpha^6 t_{e(n-7)}\right] \quad (6)$$

$$\overline{t_{pma}} = (1-\alpha) t_{e(n-1)} + t_{rm(n-1)} \quad (7)$$

Where,

$\overline{t_{pma}}$ - Prevailing daily mean outdoor temperature

$t_{e(n-1)}$ - mean daily outdoor temperature for the day before the day in question

$t_{rm(n-1)}$ - Running mean temperature for 7 days before the day in question

α = 0.7 is used to calculate the prevailing daily mean outdoor temperature. It means today's prevailing mean outdoor temperature would be the combined impact of 30% of yesterday's mean daily outdoor temperature and 70% of yesterday's running mean outdoor temperature (which is again calculated as 7 days running mean temperature before the day in question). Figure 14 shows the regression analysis where indoor globe temperature is plotted against prevailing daily mean outdoor air temperature with a 95% confidence interval and IMAC model. For plotting, we considered the comfort votes calculated by Griffiths method for all data. In this study, instead of indoor operative temperature, authors have considered indoor globe temperature because the indoor environment of the offices of North-East India is naturally ventilated, and most of the time, the indoor air speed was more than the upper threshold limit of 0.1 m/s used to calculate the operative temperature. Equation 8 represents the developed adaptive comfort equations for North-East India.

Adaptive thermal comfort equation.

$$TCA = 0.24\,Tpma + 20.52 \; (N=2326, R2=0.30, P<0.001) \quad (8)$$

From the developed equation, it can be concluded that the office occupants are adapted to the outdoor temperature changes. The slope of the regression line for all data is less than that of the slope of the IMAC model [14, 34, 35]. To validate the findings, the authors compared the slope of adaptive equations developed in the present study to the studies done by authors in India in different built environments. It was found that the slope of adaptive comfort equations developed in the present study is comparable to the slope of adaptive comfort equations of other studies done in office settings [36, 37]. In the present study, the slope is lower than that of the proposed IMAC because the socio-cultural setting of the subject in North-East India is very different from that of the rest of India. The region has not that harsh summer and winter conditions compared to the rest of India. Also, the diurnal and seasonal temperature differences are lower than in other parts of India. Moreover, the IMAC model lacks thermal comfort data from North-East India.

5. Conclusions

The present study was conducted in the randomly selected naturally ventilated offices of North-East India at three locations (one in the three climatic zones). Thermal comfort surveys were conducted in 12 offices, resulting in 1156 valid responses. The field study reported here evaluated the thermal comfort condition in office buildings and provided the basic prerequisites for a customized comfort standard for the region and guidelines for designing and operating low-energy, adaptively comfortable buildings and retrofits. Various statistical techniques were employed to analyse the data, resulting in the following conclusions.

▪ In the offices, occupants felt local discomfort due to the significant temperature difference between external walls and occupants.

▪ The difference between inflexion points at low and high temperatures is about 8°C for Tezpur.

▪ The preferred temperatures and relative humidity for Tezpur is24°C and 54%, respectively.

▪ Probit analysis concludes that different thermal stimuli (different areas under the curve for each sensation) are required to shift one sensation point on the thermal sensation scale for warmer and cool climates.

▪ Almost 80% of office occupants are comfortable in the temperature range of 25°C to 30°C.

▪ Use of ceiling fans and curtains are the prominent global adaptation opportunities available to office occupants.

▪ Ceiling fans in the offices are switched on at 23°C, and almost all the fans are switched on at 32°C.

▪ The slope of the proposed adaptive thermal comfort equation is less than the IMAC model.

The study estimated the range of comfort temperature, preferred temperatures and, relative humidity and characteristics of prominent adaptive opportunities for warm and humid climates of North-East India. In future research, the authors aim to create a database of the region's traditional dress for use in similar studies. This study also put forth the potential to design NV offices in North-East India with improved comfort duration utilizing adaptive opportunities. The study's findings and utilization are not limited to India, but it enriches the global database of thermal comfort studies and subjects adaptation to the built environment. This study also gives architects and engineers the opportunity and degree of freedom to design occupant-centric, sustainable, low-energy buildings. The authors also hope that the results of this study will be helpful to researchers, architects and building engineers and motivate them to carry out their research.

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Applicability of existing models for predicting thermal comfort in sports facilities through the analysis of a case study

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1. Abstract

Ensuring thermal comfort within sports facilities is crucial for occupants' well-being. However, often indices designed for sedentary spaces are applied, leading to inaccurate comfort assessments. Hence, this study examines the adaptive capacities and model applicability in sports facilities, using a fencing hall located in Pisa as a case study.

Data encompassed 142 subjective responses correlated with environmental parameters. Athletes' neutral and preferred temperatures were notably lower than sedentary individuals' (15.1°C and 16.8°C, respectively). Fanger's PMV tended to overestimate thermal sensation at high metabolic rates, and occupants felt more varied sensations than predicted, displaying greater acceptance of warmth than cold. Athletes' adaptive capacities differ from sedentary occupants', with neutral temperatures frequently below comfort standards. This study underscores the necessity of analysing athletes' comfort and exploring adaptation possibilities due to distinct needs and preferences compared to sedentary occupants.

Keywords - Adaptive thermal comfort, Offices, North-East India, Probit analysis, Preferred temperature.

2. Introduction

In the past decade, enhancing indoor comfort in terms of air quality, thermal, visual, and acoustic aspects has grown increasingly important (Bluyssen, 2019). While researchers have investigated spaces like offices (Lou & Ou, 2019), schools (Torriani et al., 2023), and dwellings (Peeters et al., 2009), few studies exist for sports facilities (Fantozzi & Lamberti, 2019). Indeed, sports halls are multipurpose structures hosting various activities, which pose a challenging comfort issue that researchers must address, given the rising significance of sports in daily life. Studies on indoor environmental quality in sports facilities have increased, focusing notably on air quality and thermal comfort (Andrade et al., 2017). Indoor air quality significantly impacts athletes' health, with exercise environments influencing practitioners' well-being, and the thermal environment's assessment, particularly concerning energy consumption, has also gained attention (Braniš et al., 2009).

This research has focused on swimming pools (Cianfanelli et al., 2016; Rajagopalan & Luther, 2013; Revel & Arnesano, 2014b), gyms (Berquist et al., 2019; Khalil & Al-hababi, 2016; Revel & Arnesano, 2014a), and climate chambers (Zhai et al., 2015; Zora et al., 2017), and indices such as operative temperature (Kisilewicz & Dudzińska, 2015) and humidex (Lebon et al., 2017) have been examined. Objective-subjective comparisons via questionnaires to assess occupants' responses were also carried out (Berquist et al., 2019; Cianfanelli et al., 2016), as the perception of the thermal environment correlates may vary among different individuals. Recent studies have employed Infrared Thermography to examine athletes' thermal behaviour (Lamberti et al., 2020), enhancing thermal state evaluation.

Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are commonly used indices to assess thermal comfort (Kisilewicz & Dudzińska, 2015; Rajagopalan & Luther, 2013), even with warm-humid correction ePMV (Revel & Arnesano, 2014b) and its relation to Rate of Perceived Exertion (RPE) (Zora et al., 2017).

Yet, the suitability of these models for sports facilities remains unexplored. PMV and PPD, developed in climate chambers, lack occupant adaptability consideration (Singh et al., 2011), which is crucial for athletes. Real-world comfort involves wider conditions than the models acknowledge, impacting energy consumption and HVAC usage (Yang et al., 2014), and inappropriately applied models may increase energy use and reduce comfort.

Given high energy usage in sports facilities, examining existing models is therefore needed. Thus, this paper aims to evaluate the adaptive capacities of athletes and the applicability of current thermal comfort models in this building type.

3. Methods

3.1 The case study

The evaluation of thermal comfort was carried out in the fencing hall "Club Scherma Pisa Antonio di Ciolo" located in Pisa, Italy, which is a pillar of national and international fencing.

The fencing hall is characterised by a rectangular area of about 390 m^2, with a ridge height of 5.90 m. It is a tensile structure with laminated wood beams and steel columns, covered with a white double membrane of PVC polyester fabric. The 12 fencing pistes occupy a space of approximately 228 m^2. The fencing hall is naturally ventilated, with a heating system constituted by a generator of warm air, located at about 3 m of height on the north side.

3.2 Monitoring campaign

The measurement campaign was carried out during spring 2019, from 17:00 to 21:00, when the athletes were training. The activities in the sports hall can be divided into four parts, as shown in Table 1. The air (Ta), globe temperatures (Tg), relative humidity (RH), air velocity (Va), and CO2 concentration were measured with a microclimate data logger in compliance with ISO 7726 (ISO7726, 2001). Outdoor temperature (Tout) and relative humidity (RHout) were also measured. Probes were located in representative locations of the hall, at a height of 1.1 m to evaluate the standing position of the fencers. Then the clothing insulation (Icl) was evaluated from ISO 9920 (ISO 9920, 2001) and considering the specific characteristics of the fencing uniforms (Leon Paul, 2016), taking into account the pumping effect. Values of clothing insulation are reported in Table 1.

Table 1: Activities carried out during the training and the corresponding clothing insulation and metabolic rate.

	Time	Activity	Clothing ensemble	I_{cl} (clo)	M (met)
Part 1	17:00 – 18:00	Warm up – Physical exercises	Underwear, T-shirt, Sport trousers	0.45	3.8
Part 2	18:00 – 19:00	Fencing	Fencing uniform	0.82	2.7
		Warm up – Physical exercises	Underwear, T-shirt, Sport trousers	0.45	2.7
		Warm up – Fencing	Fencing uniform	0.82	2.4
Part 3	19:00 – 20:00	Fencing	Fencing uniform	0.82	2.8
Part 4	20:00 – 21:00	Fencing	Fencing uniform	0.82	2.8

The metabolic rate was determined by considering ISO 8996 (ISO 8996, 2005) and the values provided for different sports provided by the Compendium of Physical Activity (CPA) (Ainsworth et al., 2011). In this study, the method developed by Fletcher et al. (Fletcher et al., 2020) for the calculation of metabolic rate in sports facilities was applied. This method states that "for varying metabolic rates, a time-weighted average should be estimated during the previous 1-h period", thus the following equation was used:

$$M = \frac{1}{T}\sum_{i=1}^{n} M_i \cdot t_i \qquad (1)$$

Where M is the time-weighted metabolic rate for the work cycle (Met), T is the total duration of the work cycle (min), Mi is the metabolic rate of activity in the work cycle (Met) and ti is the duration of the activity in the work cycle (min). Each activity was observed during the study and then the M was used to calculate PMV.

For the input parameters, the international standard for PMV calculation prescribes an upper limit of 4 Met. Many sports activities present higher values, but for the case study, the metabolic rate for the complete work cycle never exceeded this threshold value.

3.3 Subjective measurements

During the monitoring campaign, questionnaires in compliance with ISO 10551 (ISO 10551, 2019) were submitted to the athletes after at least one hour of exposure. Questionnaires were submitted in Italian, as it is the language spoken by athletes in the fencing hall. The following questions were asked:

1. General information (age, gender, date, time);
2. Thermal Sensation Vote (TSV) on ASHRAE's 7-points scale;
3. Thermal Comfort Vote (TCV), expressed as a vote from 1 (comfort) to 4 (much discomfort);
4. Thermal Preference Vote (TPV), expressed as a vote on a 7-points scale.

The validation of the questionnaires was ensured with the observation of the congruence between the answers.

3.4 Data analysis

The mean radiant (Tr) and operative (Top) temperatures were calculated according to the ISO 7726 standard (ISO 7726, 2001).

Then, the running mean outdoor temperature (Trm) was calculated in compliance with the EN 16798-1 standard (EN 16798-1, 2019).

Fanger's PMV and PPD indices were calculated in line with the ISO 7730 standard (ISO 7730, 2006). Subsequently, the objective and subjective measurements were analysed to establish a link between the environment's perception and students' exposure, and each athlete's response was associated with the environmental parameters to which they were subjected at the time and in the position under consideration. In total, 142 samples of subjective responses associated with environmental parameters were collected.

4. Results and discussion

4.1 Evaluation of the environmental parameters

Table 2 presents a statistical overview of the parameters recorded from the measurement campaign. Indoor temperatures consistently remained below 20°C, indicative of the relatively cool environment. Relative humidity predominantly remained within comfort parameters, averaging 61.9%. Air velocity registered a consistently low average of 0.02 m/s. Metabolic activity varied between 2.4 and 3.8 met, while clothing insulation averaged 0.82 clo, representative of the fencing uniform's thermal insulation.

Air quality maintained a healthy condition, with CO_2 concentration averaging below 1410 ppm. Notably, this level remained acceptable despite athletes' heightened activity, potentially due to the naturally ventilating characteristics of the tensile structure.

The structure's high permeability aligns indoor conditions (Tout and RHout) closely with outdoor conditions, albeit with higher indoor temperatures and relative humidity.

Table 2: Statistical overview of the monitored parameters in the fencing hall.

	T_a	RH	V_a	T_r	T_{op}	M	I_{cl}	T_{out}	RH_{out}	CO_2
Mean	15.9	61.9	0.02	15.8	15.9	2.8	0.82	11.3	48.1	1410
SD	1.8	11.7	0.01	1.8	1.8	0.2	0.10	1.4	18.5	240
Maximum	19.1	81.3	0.11	19.1	19.1	3.8	0.45	13.3	80.8	1808
Minimum	12.2	38	0.00	12	12.1	2.4	0.82	8.2	29.5	862

4.2 Definition of neutral and preferred temperatures

To evaluate athletes' thermal comfort, the neutral (TN) and preferred (TP) temperatures were calculated. TN corresponds to the operative temperature where thermal sensation is neutral (TSV=0), and TP indicates the temperature at which occupants express no change in the thermal environment (TPV=0).

TN and TP were calculated through the weighted linear regression between Top and TSV and TPV, as shown in Figure 1, binning data considering 0.5°C steps. The regressions, shown in Figure 1, were statistically significant (p-value<0.05).

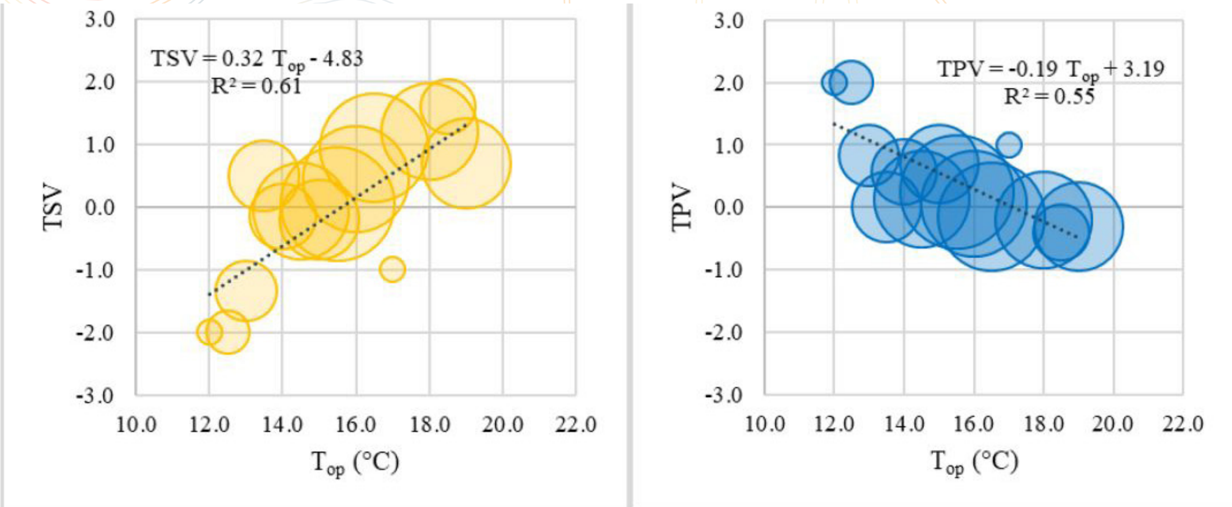

Figure 1: Relationship between Top, TSV, and TPV in the fencing hall.

Examining the correlation between Top and TSV reveals a notable sensitivity of athletes' thermal sensation to operative temperature, as evidenced by the steep slope. Instead, the relation between Top and TPV shows a shallower slope, which highlights that changes in thermal preference are less dependent on operative temperature. Regression analysis yielded TN and TP values of 15.1°C and 16.8°C, respectively, for athletes. Remarkably, TP is higher than TN, implying athletes perceive thermal neutrality at lower temperatures while favouring warmer conditions.

These relatively low TN and TP may be attributed to two factors. Firstly, heightened metabolic rates significantly lower comfort temperatures. Secondly, athletes exhibit robust adaptive capacities during winter, even under challenging indoor climate conditions.

4.3 Applicability of Fanger's PMV to sports facilities

The applicability of the Fanger model to sports facilities was analysed using three methods (Cheung et al., 2019): (i) the analysis of the Bias, Mean Absolute Error (MAE), and Root Mean Square Deviation (RMSD) error indices; (ii) the analysis of the relationship between PMV and TSV; and (iii) the comparison between thermal sensation and the percentage of dissatisfied.

4.3.1 Analysis of error indices

To assess the predictive ability of Fangers' method, the MAE, RMSD, and Bias between the calculated PMV and individual TSV were determined.

The MAE was 1.13, which shows that the PMV is, on average, more than one scale unit different than the real thermal sensation in sports facilities. This result is consistent with the findings reported by Humphreys and Nicol (MAE=1.00) (Humphreys & Nicol, 2002), Doherty and Arens (MAE=1.26) (Doherty & Arens, 1988), and Cheung et al. (MAE=1.02) (Cheung et al., 2019) for everyday environments. The RMSD, which shows the average difference between the predicted and the measured thermal sensation, was compared to the standard deviation of TSV (Koelblen et al., 2018). RMSD was 1.34 and remained below the Standard Deviation of TSV (SD=1.41).

The Bias between the PMV and the TSV was 0.04, which remains in the acceptable range of ±0.25 given by Humphreys and Nicol (Humphreys & Nicol, 2002). Nevertheless, there is to notice that the use of the Bias only as an indicator may lead to misinterpretation of the data because positive and negative errors cancel out.

4.3.2 Relationship between PMV and TSV

To account for the fact that PMV predicts the thermal sensation of a group of individuals subjected to specific environmental conditions, the data were clustered according to the environmental parameters. To this aim, a weighted regression analysis was carried out, considering 0.5°C increments in the indoor operative temperature (Torriani et al., 2023).

Figure 2 shows the relationship between TSV and PMV, revealing a consistent correlation (R2=0.67). PMV=0 (neutral sensation) yields a TSV below zero (cold sensation), again highlighting PMV overestimation of the thermal sensation for high metabolic rates. Moreover, PMV predictions remain restricted in range compared to recorded TSV values, emphasizing the discrepancy, especially on the cold side of the ASHRAE scale.

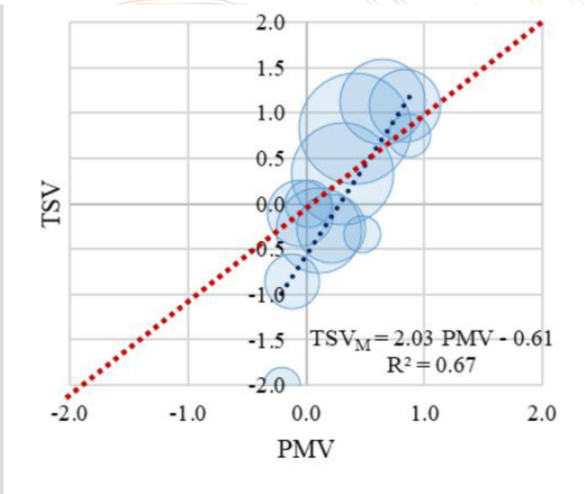

Figure 2: Relation between PMV and TSV. The blue line shows the recorded relationship between PMV and TSV, while the red line the ideal one. The dimensions of the circles show the dimension of the clusters.

4.3.3 Relationship between thermal sensation and the percentage of dissatisfied

This section examines the relationship between TSV and the Percentage of Dissatisfied (PD) and Fanger's PMVPPD curve. For PD calculation, those voting +3 (discomfort) or +4 (much discomfort) on the TCV were considered dissatisfied.

Figure 3 shows the TSV-PD relationship (blue) against the PMV-PPD curve (red). Unlike the PMV-PPD curve, the observed TSV-PD relationship is asymmetrical. The Percentages of Dissatisfied are significantly higher in cold environments (98% vs. 31% in warm conditions). Athletes tended to accept warmer sensations, probably due to their association with exercise. This aligns with the curve's minimum shifting toward positive values (around +1), reflecting athletes' preference for warmth. Moreover, the curve reaches a minimum dissatisfaction percentage of 0%, diverging from the PMV-PPD curve with a 5% minimum.

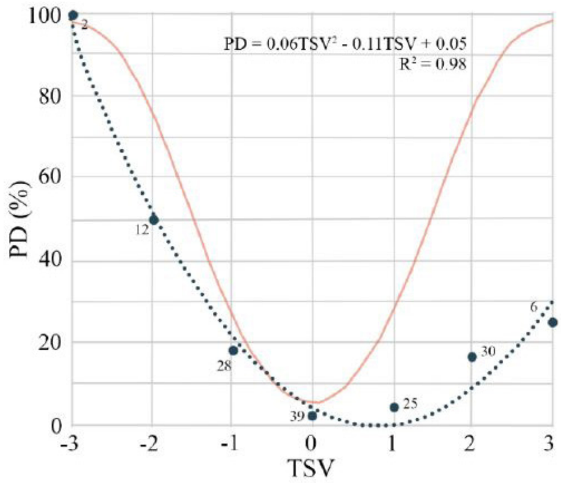

Figure 3: Relationship between the thermal sensation and the percentage of dissatisfied. In blue, the relationship between TSV and PD, while in red the Fanger's relationship between PMV and PPD. The numbers on the points show the dimension of the clusters.

4.4 Investigating adaptation in sports facilities

Neutral temperatures were then analysed in relation to the adaptive relationship. Since adaptation can also take place under winter conditions (Lamberti et al., 2023), the cases in which Trm was below 10°C were taken into account, considering constant comfort areas (Nicol et al., 2012), as shown in Figure 4.

To derive the athletes' neutral temperatures, the Griffiths method was used, considering a sensitivity coefficient (Griffiths' constant) of 0.5°C-1, in compliance with the SCATs project (Nicol et al., 2012). This value was chosen because there are currently no studies defining the thermal sensitivity of athletes during sports and thus can give a first indication of the values that the neutral temperatures can assume.

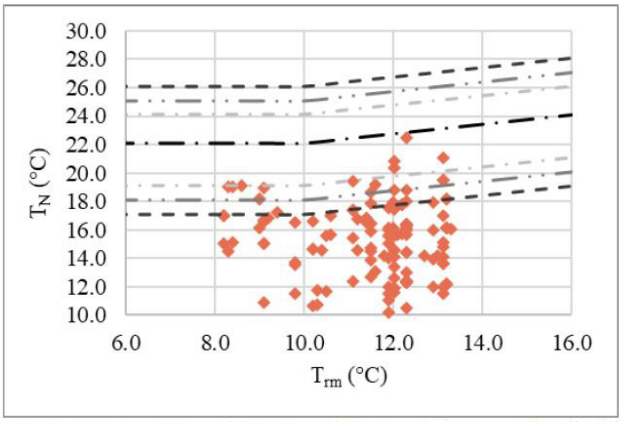

Figure 4: Neutral temperatures and their relationship with the adaptive relationship.

Displayed in Figure 4 is the adaptive connection alongside user-determined TN assessed via Griffiths' method. Notably, Griffiths' calculated neutral temperatures often fall remarkably low, considerably beneath the comfort thresholds specified by standards for sedentary environments.

These outcomes underscore the starkly contrasting thermal comfort requirements for athletes. Even implementing an adaptive model may not necessarily ensure their comfort. Given the potential impact of accurate thermal sensation assessment on comfort and energy usage, a comprehensive examination of comfort within sports facilities becomes imperative, including the prospect of developing tailored adaptive models for such structures.

4.5 Limitations

While highlighting athletes' thermal perception, this study presents some limitations necessitating consideration. Notably, the dataset comprises a modest 142 responses. Although comparable sample sizes have informed previous studies, a more extensive survey pool would be needed for deriving adaptive models pertinent to athletes. Then, the calculation of neutral temperatures via Griffiths' method employed thermal sensitivities from the SCATs project, which doesn't encompass sports settings. While offering valuable insights into athletes' TN, their distinct thermal sensitivity might vary. Furthermore, the application of Griffiths' method occasionally yields notably low neutral temperatures, as documented in earlier studies across different settings. (Rupp et al., 2019).

5. Conclusion

This study analyses comfort within sports facilities, focusing on the experiences of international fencing athletes during their training sessions. A comprehensive analysis was conducted, gathering a total of 142 subjective responses that were linked to measured environmental parameters.

The findings highlighted that athletes' neutral and preferred temperatures diverge from those of sedentary individuals (TN=15.1°C, TP=16.8°C). This disparity can be attributed to the heightened levels of metabolic activity exhibited by athletes during their training.

An examination of Fanger's model highlights that the Predicted Mean Vote (PMV) tends to overestimate the thermal sensations experienced by athletes, particularly when their metabolic rates are high. Moreover, the responses from the fencers indicate a broader spectrum of sensations than what the model projected.

The relationship between thermal sensation and dissatisfaction rate, as observed in sports facilities, displays an asymmetry. Notably, there exists a minimum threshold for warmth sensation (TSV=+1), which aligns with the athletes' engagement in physical exertion, which corresponds to the recognized association between warmth and optimal exercise conditions.

Finally, despite the athletes' adaptability to varying conditions, the application of Griffiths' method frequently yields neutral temperature recommendations that fall below the lower limit defined by the adaptive model. Given the evident disparities in preferences and responses between athletes and sedentary individuals, future research should focus on understanding the adaptive capacities that pertain specifically to sports facilities. The distinct requirements of athletes necessitate a focused exploration to enhance their training environments effectively.

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Thermal comfort and occupants' behavior in Japanese condominium

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1. Abstract

Occupant behavioral setting is one of the parameters that can affect indoor comfort. This research aimed at investigating the thermal adaptation of residential occupants in Japanese condominium. Therefore, a field survey on occupants' behaviors for adaptive thermal comfort together with indoor air temperature measurement was conducted from November 2015 to November 2017, in which 32,988 votes were collected. The data was categorized into free-running (FR), heating (HT), and cooling (CL) mode. The results showed that the indoor air temperature was highly correlated with outdoor air temperature in FR mode. In CL mode, the mean indoor air temperature was 27.2°C, which was close to the recommended air temperature for summer in Japan (28°C). In HT mode it was found that indoor air temperature was maintained at an average of 20.4°C. The occupants' thermal sensation votes were most likely to be neutral. The mean clothing insulation was 0.43 clo in summer and 0.82 clo in winter during FR mode. The occupants were found to take passive adaptive measures along with the use of air conditioning unit for cooling. The findings can be useful in designing more suitable residential spaces which can lead to the reduction of energy consumption.

Keywords - Indoor environment, Thermal comfort, Residential building, Thermal adaptation, Occupant behavior

2. Introduction

The topic of thermal comfort in residential buildings is highly relevant nowadays as it could improve the resident's comfort level while reducing the energy consumption. The conditions of occupants' thermal comfort, thermal sense, and behavioral habits are the key elements which could influence the energy usage. Moreover, it is well-known that occupant's behavior is a factor that affects building energy performance [1]. Several studies [2– 4] have shown that the variety of occupant behaviours can lead to a difference of energy usage in a building. Even a single activity of occupants can have an impact on building energy consumption. For example, Sorgato et al. [5] in their study, evaluated the influence of the occupant behavior regarding the window opening ventilation control and the building thermal mass on the energy consumption related to HVAC systems in residential buildings in Brazil. The window opening behaviour of occupants has been widely studied within various building types in differing climates [1, 5–7]. The possibility of variability in preferences and uses of the residents may result in a gap between predicted and actual building performance [4]. As mentioned by Branco et al. [8], the differences between the real and estimated energy use were due to the real condition of utilisation, the real performance of the technical system and the real weather conditions. They found out that the real energy use was 50% higher than the estimated energy use.

Other than that, occupant behaviour is also connected to comfort, perceived health, and productivity. Fabi et al. [1] highlighted that if an individual is in a state of discomfort in an environment, he or she will take actions such as opening or closing windows, controlling blinds, adjusting the thermostat, changing clothes, or turning lights on and off that would restore a state of well-being based on the adaptive approach. Many previous studies [9–13] have been focused on occupant behaviour regarding thermal comfort. As occupant behaviour assumes more significance, it is necessary for it to be taken into account during the design process. This study aims to determine the relationship between outdoor and indoor air temperature during voting time in different operation modes, to investigate the relationship between comfort temperature and outdoor temperature and to understand the adaptive behaviors (clothing insulation and window opening) of the residents in Japanese condominiums.

3.Methods

3.1 Outdoor air temperature

The outdoor temperature variation in Figure 1 was obtained from data from theTokyo meteorological station. It was located almost 13 km away from the targeted building. As the study site was in Shinagawa, southern part of Tokyo, it lies in the humid subtropical climate zone with hot and humid summer and generally mild winter. The climate is warm and temperate. The hottest month of the year is August with 31.6oC mean daily temperature and January as the coldest month has 3.6oC of mean daily temperature.

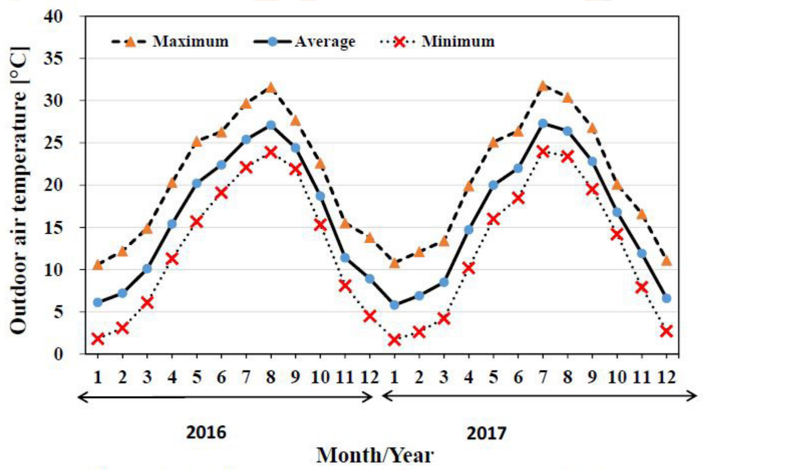

Figure 1: Monthly variation of outdoor temperature in Tokyo

3.2 Building selection and field measurement

The building is an 18-stories condominium in Shinagawa, Tokyo that can accommodate 356 families (Figure 2). For each floor, this Katsushima condominium has 21 flats. The area for each flat ranged from 71 to 90 m2. Katsushima condominium was equipped with Home Energy Management System (HEMS) and a compact fuel-cell based cogeneration system ("Ene-farm" residential fuel cell).

Figure 2: Field measurement location and targeted building. (Source: Google Map).

Indoor air temperature, relative humidity and illuminance were measured in the living room at 2 to 10 min intervals using a data logger as shown in Figure 3. It was placed in the center of the living room. The field measurement and survey were conducted in 64 flats from November 2015 to October 2017. In total, around 32, 988 votes in free-running (FR), cooling (CL) and heating (HT) operation mode. Online questionnaire survey was conducted to understand the thermal comfort level of the residents. The thermal comfort scale as shown in Table 1 was used. The collected data were analyzed by Statistical Package for Social Sciences (SPSS) Statistics version 27.

Figure 3: Sensor used during field measurement.

Table 1: Thermal sensation scale

Scale	TSV
1	Very cold
2	Cold
3	Slightly cold
4	Neutral (Neither hot nor cold)
5	Slightly hot
6	Hot
7	Very hot

4. Results and discussion

4.1 Outdoor and indoor air temperature in different operation modes

The relationship between indoor and outdoor air temperature during the voting time throughout the whole measurement period is shown in Figure 4. We classified the data into three operation modes (FR, HT, CL). The linear equations (1) – (3) represent the regression equation for each mode. The indoor temperature during FR mode is much more dependent on the outdoor temperature than the one in the other modes. Similarly, the coefficient of the determination between indoor and outdoor temperature for the FR mode is much higher (0.74) than for the HT (0.22) or CL (0.11) mode.

$$\text{FR: } T_{in} = 0.31T_o + 17.0 \quad (1)$$
$$(n = 11559, R^2 = 0.74, S.E. = 0.002, p<0.001)$$
$$\text{HT: } T_{in} = 0.19T_o + 21.9 \quad (2)$$
$$(n = 6818, R^2 = 0.22, S.E. = 0.005, p<0.001)$$
$$\text{CL: } T_{in} = 0.11T_o + 24.24 \quad (3)$$
$$(n = 2453, R^2 = 0.11, S.E. = 0.007, p<0.001)$$

Where T_o indicates the outdoor temperature (°C), Tin is the indoor temperature (°C), n is the number of the sample, R^2 is the coefficient of determination, S.E. is the standard error of the regression coefficient and p is the significant level of regression coefficient.

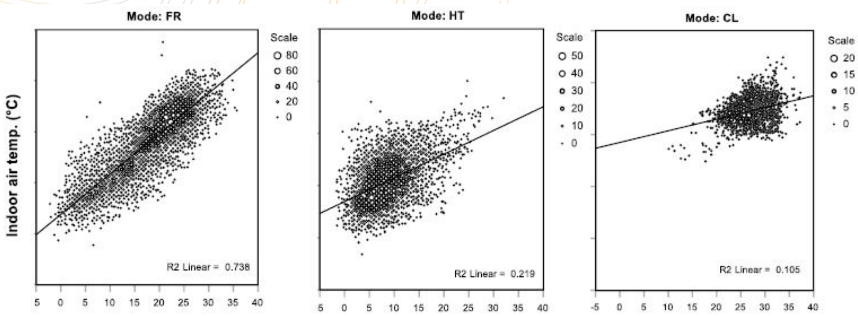

Figure 4: Relation of indoor and outdoor air temperature in different operation modes.

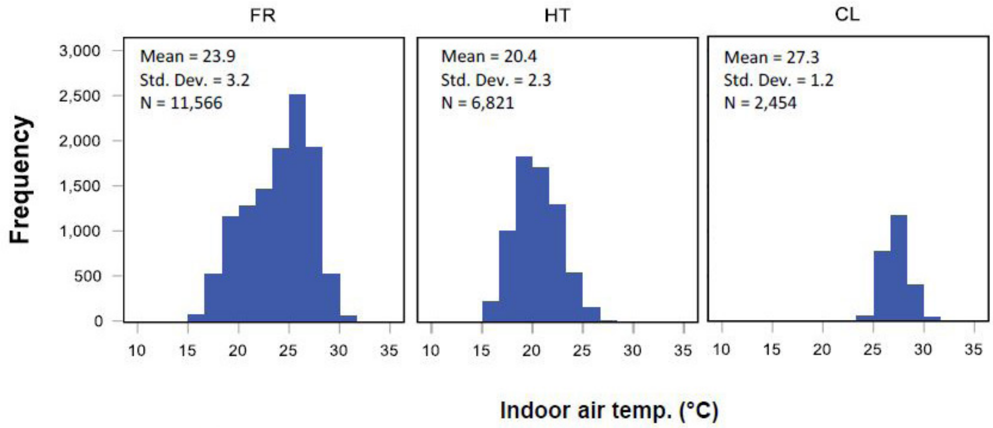

Figure 5: Distribution of the indoor air temperature during different modes.

The distribution of indoor air temperature during FR, HT, and CL modes was shown in Figure 5. The mean was 23.9°C, 20.4°C, and 27.2°C for FR, HT, and CL modes respectively. The Japanese government recommends indoor temperature of 20 °C in winter and 28 °C in summer for energy saving [14]. The results show that the mean indoor temperatures during HT and CL were close to this recommendation.

4.2 Comfort temperature by Griffiths' method

Griffiths' method is a widely used method to determine the comfort temperature ranges in the buildings. Considering the occupants' thermal sensation votes in correspondence with measured indoor air temperature, comfort temperature is predicted using equation below:

$$T_c = T_{in} + (4 - \text{TSV}) / \alpha \qquad (4)$$

Where, Tc is comfort temperature (°C) and α is Griffiths' constant. Griffiths' approach can determine an estimation relationship between comfort vote and temperature when the expected comfort temperature is established for each comfort vote [15]. The comfort temperature may vary due to thermal adaptation, building designs, and seasons [16]. When adopting a seven-point thermal sensation scale (1 to 7), '4' represents the neutral situation, and α is the Griffiths constant, which is the regression coefficient. The value for α [17] was determined to be 0.50. Because the Griffiths constant or the resident's thermal sensitivity level is assumed, the comfort temperature can be set with a single vote. The comfort temperature calculated using a coefficient 0.50 is a representation of 2 °C rise for a unit change in thermal sensation vote.

Figure 6 shows the mean comfort temperature obtained by the Griffiths method which are 23.7°C, 21.0°C, and 26.9°C for FR, HT, and CL, respectively. Even though the Japanese government recommends an indoor temperature of 28°C for cooling and 20°C for heating, it was found that in these buildings the comfort was 1.0°C higher in HT mode and 1.1°C lower in CL mode. In another study, the comfort temperature by the Griffiths' method was 17.6 °C in winter, 21.6 °C in spring, 27.0 °C in summer and 23.9 °C in autumn in FR mode [18].

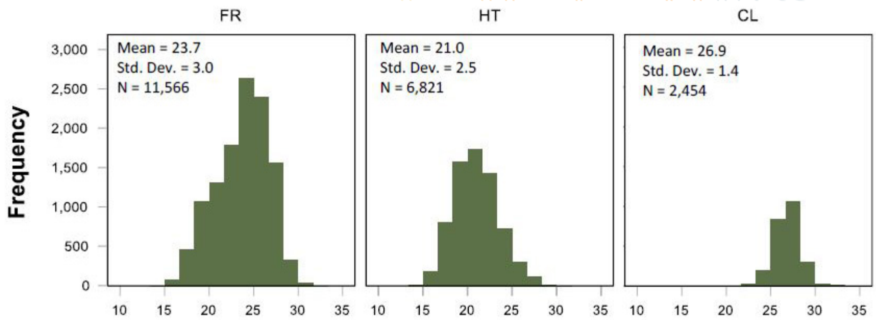

Figure 6: Distribution of comfort temperature.

4.3 Relationship between comfort temperature and outdoor temperature

The equation to calculate the running mean outdoor temperature (Equation 5) is referred to McCartney and Nicol [19]:

$$T_{rm} = \alpha T_{rm-1} + (1 - \alpha)\, T_{od-1} \quad (5)$$

Where T_{rm-1} is the running mean outdoor temperature for the previous day (°C) and Tod-1 is the daily mean outdoor temperature for the previous day (°C). α is a constant between 0 and 1 that defines the speed at which the running mean responds to outdoor air temperature. The value for α is 0.8 used in the derivation of the CEN standard. A linear regression has been analysed between the comfort temperature obtained by the Griffiths' method and the running mean outdoor air temperature as shown in the Figure 7. The equations are as follows:

$$\text{FR mode } T_c = 0.38\, T_{rm} + 16.91; \ (N= 11{,}566,\ R^2 = 0.67,\ S.E. = 0.006,\ p < 0.001) \quad (6)$$

$$\text{HT mode } T_c = 0.35\, T_{rm} + 17.65; \ (N= 6821,\ R^2 = 0.19,\ S.E. = 0.003,\ p < 0.001) \quad (7)$$

$$\text{CL mode } T_c = 0.17\, T_{rm} + 22.39; \ (N= 2454,\ R^2 = 0.07,\ S.E. = 0.001,\ p < 0.001) \quad (8)$$

Where, S.E. is the standard error of the regression coefficient. The regression coefficient and coefficient of determination is higher in FR mode than the HT or CL mode. Also, it is higher than the CEN standard (FR=0.33). However, the CEN standard is based on the field investigation in office buildings, thus it may not be suitable to be compared with residential buildings in this study as the occupants will have more freedom to adapt. In a recent review study that focuses on residential building, the regression coefficient in FR mode is 0.40 and 0.27 in CL mode [20]. It may be also because of the differences of occupant's behaviours and the climatic variations of different regions.

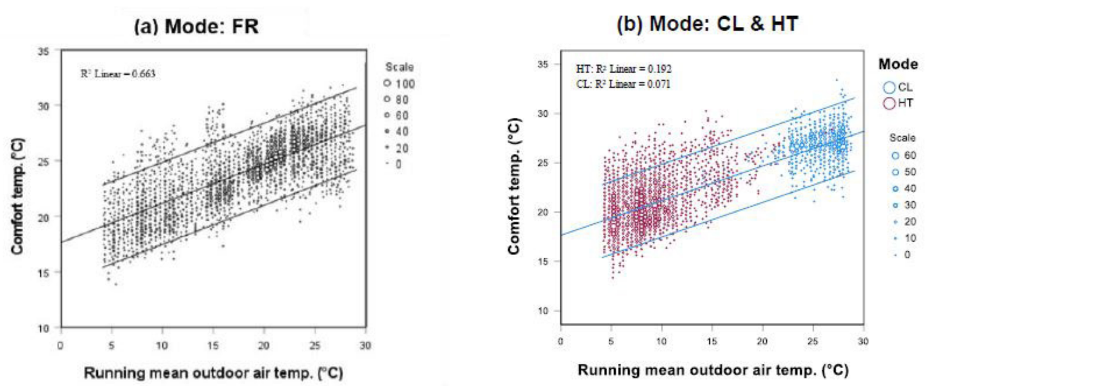

Figure 7: Relationship between comfort temperature and running mean outdoor temperature:(a) FR mode; and (b) CL and HT modes. 95% data band is shown in the figure.

4.4 Clothing adjustment

The comfort temperature varies greatly in residential buildings more than the one that has been found in Japanese offices [21]. The reason might be that the occupants are adapting well in their own homes using various behavioral, physiological and psychological adaptations. One of them is clothing insulation. Figure 8 shows how the clothing insulation of the occupants varies according to the season. The mean clothing insulation can be seen to start decreasing from 0.82 clo in winter to 0.68 clo in spring and 0.43 clo in summer. In autumn, the mean clothing insulation starts to increase to 0.54 clo. Seasonal variation of clothing insulation can also be analysed by regression as shown in Figure 9. Table 2 displays the equations for the relationship between clothing insulation and indoor air temperature. Due to no constraints, the residents could freely adjust their clothing at their own house. Therefore, it is important to investigate how the mean clothing insulation varies with indoor air temperature. The occupants' clothing insulation decreased when the indoor air temperature increased. The slope of the linear regression for autumn and spring seems to be higher than the others. This indicated that the residents had a more sensitive clothing adjustment as indoor air temperature. The similar result can be seen in Ning et al. [22].

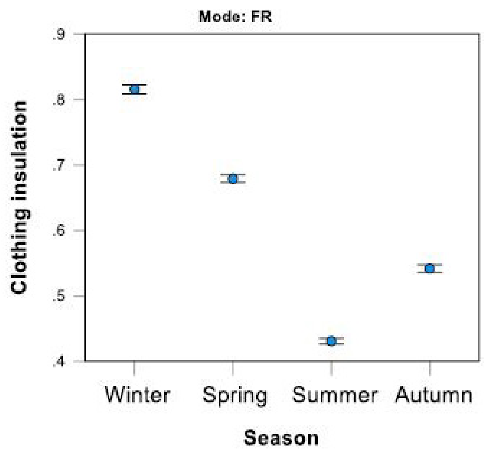

Figure 8: Means of clothing insulation by season with 95% confidence interval (mean ± 2 S.E.).

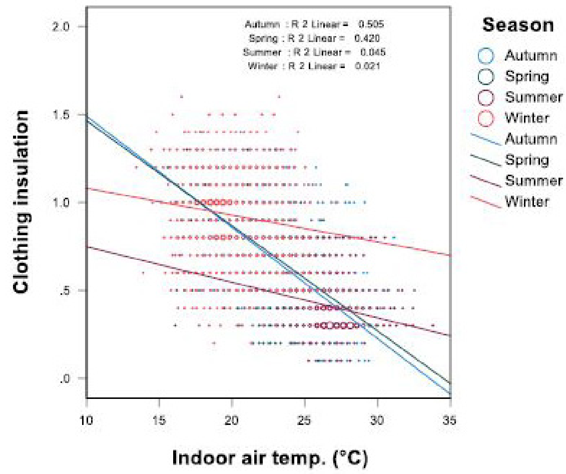

Figure 9: Relationship between clothing insulation and indoor temperature in FR mode.

Table 2: Regression equations in FR mode

Season	Equation	R^2	S.E.	p
Winter	$I_{cl} = -0.02\ T_{in} + 1.23$	0.02	0.03	< 0.001
Spring	$I_{cl} = -0.06\ T_{in} + 12.06$	0.42	0.02	< 0.001
Summer	$I_{cl} = -0.02\ T_{in} + 0.95$	0.05	0.02	< 0.001
Autumn	$I_{cl} = -0.06\ T_{in} + 2.12$	0.51	0.04	< 0.001
All	$I_{cl} = -0.06\ T_{in} + 2.14$	0.57	0.03	< 0.001

I_{cl}: Clothing insulation, T_{in}: Indoor temperature (°C), R^2: coefficient of determination, S.E.: standard error, p: significant value of the regression coefficient.

4.5 Window opening behaviour

Opening a window allows indoor and outdoor air to circulate together, therefore if it is cooler outside than inside, opening a window lowers room temperature. Figure 10 shows the seasonal variation in indoor air temperature for cases when windows are open and closed. The mean indoor air temperature for the window open condition during autumn and spring has the most significant difference. The indoor air temperature for the condition when the window was open is 24.2°C in spring and 26.6°C in autumn, which are 1.2°C and 3.3°C, respectively higher than for the condition of when the window was closed. Rijal et al. [7] found out that the mean indoor air temperature for the window open condition is 27.6°C in the living room and 27.1°C in the bedroom, which is higher by 5.5 K and 6.4 K, respectively, than the condition when the window was closed.

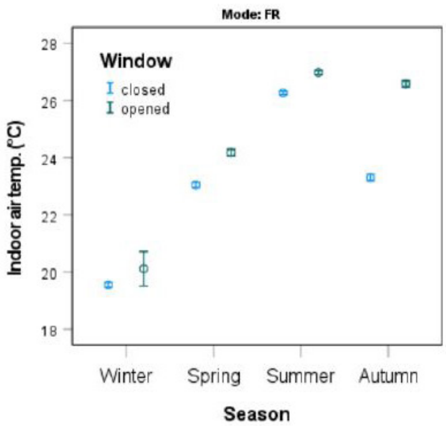

Figure 10: Mean indoor air temperature for windows open and closed in FR mode by season with 95% confidence intervals (mean ±2 S.E.) in FR mode.

5. Conclusions

This paper examined the thermal comfort and occupant behaviours of the residents in a Japanese condominium. The following conclusions are obtained:

1. The correlation between indoor and outdoor temperature for the FR mode is much higher (R=0.86) than for the HT (R=0.47) or CL (R=0.33) mode which indicates that the indoor air temperature is highly related to outdoor air temperature.

2. The regression coefficient of the adaptive model (i.e. the relation between comfort temperature and running mean outdoor temperature (FR = 0.38; CL = 0.17; and HT = 0.35) are higher than CEN standard (FR = 0.33). This might be due to more freedom to adapt in residential buildings.

3. Occupants conducted various behavioural adaptations like clothing adjustments and window opening. The slope of the linear regression for autumn and spring seems to be higher than the others. This indicated that the residents had a more sensitive clothing adjustment as indoor air temperature.

4. By opening the window, the rise in indoor air temperature can be limited in warm weather. In cool weather, closing the window will keep the temperature from decreasing too far. Thus, the window effectively controls the indoor thermal environment.

6. Acknowledgements

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Development of simulation-based strategy for mixed-mode operation of buildings

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Abstract

This study examines optimal operation strategies for mixed-mode buildings located in 8 tropical Indian cities. In order to evaluate the potential for mixed-mode operation, a small, single storey building with provision for natural ventilation (NV) is considered. The building performance is simulated using OpenStudio-EnergyPlus. EnergyPlus Typical Meteorological Year (TMY) data is used for generating the results. Depending upon the predicted inside conditions, decisions are taken whether to operate the building in non-air conditioned mode or air conditioned mode. PMV-PPD based thermal comfort model is used when the building is operated in air conditioned mode, while suitable adaptive thermal comfort model is used when the building is operated in non-air conditioned mode. An algorithm for optimal mixed-mode operation is developed, utilizing simulation data to guide window usage and HVAC systems. The algorithm enables users to input location, date, and time to determine whether to keep windows open or closed and whether to use mechanical cooling or heating systems. Results show that mixed-mode operation has a huge potential for saving energy without sacrificing thermal comfort.

Keywords - Mixed-mode buildings, Thermal comfort, Algorithm, OpenStudio-EnergyPlus, Indian tropical climate.

1. Introduction

With the growing concern about climate change and ever increasing energy consumption, there is a need to develop energy-efficient strategies in all sectors. Worldwide, buildings consume a significant amount of primary energy. A large fraction of the building energy is used for maintaining thermal comfort. Hence there is a need for smart building operation strategies that can reduce building energy usage and carbon footprint without sacrificing thermal comfort. The operation strategies depend both on the nature of the building and the climatic zone in which the building is located. Mixed-mode (MM) operation ensures thermal comfort throughout the year by making use of outdoor air whenever possible through ventilation, and the mechanical air conditioning system when required. Thus, MM operation holds great promise in reducing building energy consumption. However, there are not many studies on the potential of mixed-mode buildings for Indian conditions. The present study is focussed on improving building energy efficiency through MM operation, while considering the unique climatic conditions of tropical Indian cities. The major objectives are to determine the optimal pattern of opening area for ventilation in order to maximize the number of annual hours when indoor conditions are comfortable without operating the mechanical air conditioning system, and to operate the heating, ventilation and air conditioning (HVAC) system when it is not possible to maintain the required thermal comfort through ventilation alone. Using the building simulation tools the energy consumption trends of a building operating in only HVAC mode is compared against the natural ventilation mode condition for the same climate. The hourly indoor zone conditions are classified based on the simulation results for different city climates so as to develop a mixed-mode strategy that uses HVAC systems when indoor conditions are uncomfortable. Finally an algorithm is developed for optimal mixed-mode building operation, which can be used to make informed decisions about building operations.

1.1 Thermal comfort and comfort models

ASHRAE defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." To assess the level of satisfaction based on subjective evaluation, different comfort models have been developed by researchers over the years.

Fanger's Predicted Mean Vote (PMV) model [4], is a well-known and widely used method for evaluating thermal comfort in buildings. The model is based on the principle that humans have certain physiological responses to thermal stimuli, which can be measured and used to assess thermal comfort. The model considers six factors that influence thermal comfort: air temperature (t_a), mean radiant temperature (t_r), air velocity(V) , humidity ratio (W_a), clothing insulation (I_{cl}) , and metabolic rate (M). Based on energy balance, the thermal comfort equation is written in the form given by Eq.1.

$$f(t_a, t_r, W_a, V, M, I_{cl}) = 0 \qquad (1)$$

Equation 1 has 4 environmental factors (t_a, t_r, V and W_a) and 2 personal human factors (I_{cl} and M). The difference between left and right hand sides of Eq.1 yields the thermal load, which is then used to determine the Predicted Mean Vote (PMV). Using PMV, the Predicted Percentage Dissatisfied (PPD) is calculated for a given space. The PMV-PPD model does not take into account individual differences in thermal sensitivity. In addition, the model assumes that occupants are in steady-state conditions and does not account for transient conditions such as changes in outdoor temperature or sudden changes in metabolic rate. However, the model is thoroughly tested and is widely used for buildings with mechanical air conditioning all over the world.

Adaptive comfort refers to the range of thermal conditions that individuals can perceive as comfortable [6], which may vary based on factors such as clothing, activity level, and culture. The adaptive thermal comfort models recognize the fact that people can adjust to a wide range of thermal conditions, and that their preferences and behaviour are influenced by a variety of factors, including clothing, activity level, and expectations. These models consider the past interactions between the occupants and the environment to create a more nuanced and accurate understanding of thermal comfort. ASHRAE Standard 55, provides guidelines for thermal comfort in occupied spaces. It is the most commonly used standard worldwide. The adaptive thermal comfort equation for neutral temperature based on outdoor running mean temperature according to ASHRAE Standard 55 is given as:

$$T_n = 0.31 \times T_{RMT} + 17.8 \qquad (2)$$

Where, Tn is the neutral temperature in °C and T_{RMT} is the outdoor running mean temperature of 30 days in °C. The allowable range of outdoor running mean temperatures is between 10 and 33°C. In any adaptive thermal comfort model, the 80% acceptability range refers to the temperature range (across neutral temperature) within which 80% of occupants are likely to find the indoor environment thermally acceptable. This range is calculated based on field studies and statistical analysis of thermal comfort surveys. For equation 2, the 80% acceptable limits are Tn ± 3.5°C. If air velocity control is also available with the occupant then the comfort temperature can vary even further and the correction for increased air velocity as given by this standard is $3- < V_a < 0.6- \equiv 1.2$ ℃

Research indicates that Indians prefer higher indoor temperatures and relative humidity levels compared to people from temperate climates [8]. Comparative assessment of adaptive thermal comfort models for Indian tropical environments were conducted by Mishra [9]. In that study the adaptive cooling degree days were calculated using various standards. It was reported that the thermal comfort model EN15251 [10] is more accurate in predicting neutral temperatures for Indian conditions. Hence it was recommended until further studies on Indian climate are done. In India, where a significant portion of the population lives in hot and humid climates, there is a growing interest in understanding how to design buildings that promote adaptive comfort.

The Indian model for adaptive comfort [7] suggests that people in India have unique thermal preferences due to hot and humid living conditions. The IMAC study analysis of 6320 responses from various buildings showed that Fanger's PMV model consistently over-predicted warmer sensations, leading to unnecessary thermostat adjustments to low temperatures, which in turn lead to increased energy consumption during summers. To improve energy efficiency, the study advocates integrating passive cooling strategies and climate-responsive building designs, reducing reliance on energy-intensive systems. This approach can substantially save energy and lower carbon emissions, which can be crucial in a rapidly growing energy demand market like India [5]. An example on how to use these adaptive standards to analyse indoor conditions is shown in Fig.1, where comfort range can be seen coloured and indoor operative temperatures observed after an hour of simulation are scattered. Points lying outside the 80% zone are uncomfortable periods.

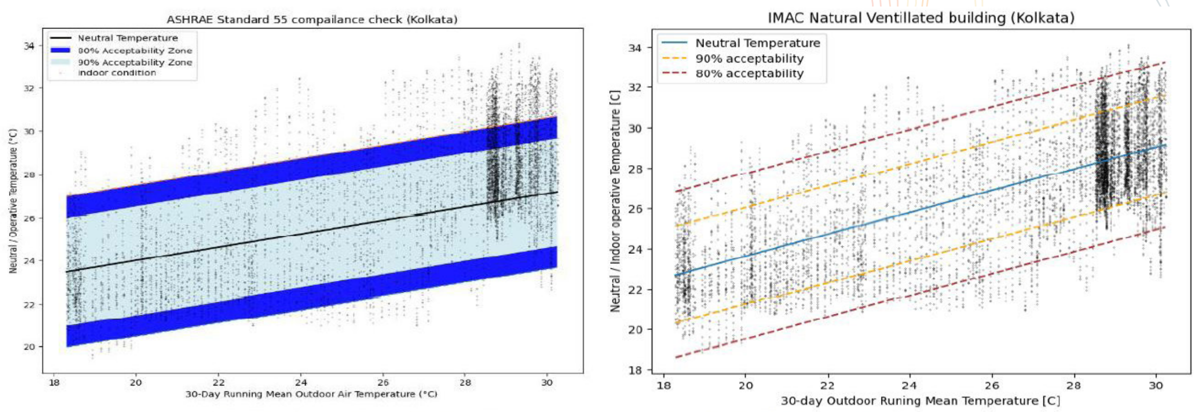

Figure 1: Applying adaptive thermal comfort models (a) ASHRAE-55 (b) IMAC

1.2 Exceedance metric and mixed-mode strategy

Numerous studies indicate that static models like Fanger's PMV-PPD over-predict discomfort in naturally ventilated or mixed-mode buildings. Though people living in naturally ventilated buildings tolerate higher indoor temperatures, extreme outdoor conditions can cause exceedance from comfort ranges, in which case it may be required to provide comfort through a mechanical air conditioning system, i.e., operating buildings in mixed mode. Quantifying exceedance, defined as uncomfortable hours, helps set occupant comfort expectations. For air-conditioned buildings, thermal comfort limits are based on PMV and PPD values. If PMV falls outside -0.5 to +0.5 or PPD exceeds 10%, thermal comfort is considered exceeded. For naturally ventilated building exceedance is considered to occur if the indoor temperature is beyond the 80% acceptability range. Generally, the exceedance metric aims for 3 to 5% of the occupied hours, as lower exceedance relates to higher HVAC installation costs or higher energy consumption.

In the study "Comfort Standards and Variation in Exceedance for Mixed-Mode Buildings" [1], the authors categorize exceedance metrics as: a) 'Percentage outside the range': Percent of occupied hours when PMV or operative temperature deviates from the range, b) 'Degree-hours criteria': Time the operative temperature exceeds the range during occupied hours, weighted by the degrees beyond the range and c) 'PPD weighted criteria': Accumulated time indoor temperatures fall outside the comfort range is weighted by PPD. Mixed-mode buildings require a tailored exceedance metric due to varying comfort temperatures which is currently not available. Adaptive model exceedance applies to them during natural ventilation (NV), while PMV exceedance applies when the air conditioning system is turned on.

Optimal opening and closing of external windows depending upon outside conditions plays an important role in mixed-mode buildings. A suitable control strategy is needed to control the window operation and the air conditioning system operation for an effective operation of mixed-mode buildings. The study "Optimal Control of HVAC and Window Systems for Natural Ventilation Through Reinforcement Learning (RL)"[2], compared a rule based heuristic control strategy with a reinforcement learning controller. The controller had five possible actions: [open window, cooling on], [open window, cooling off], [close window, cooling on], [close window, cooling off], and [close window, on heating], represented as [(1,1), (1,0), (0,1), (0,0), (0, -1)]. Specific cost and reward functions were designed to aid algorithm training. The model was simulated for Miami (hot-and-humid) and Los Angeles

(mild-warm) climates. The RL controller successfully maintained an indoor temperature of 24.5°C and relative humidity below 70%, outperforming the heuristic controller. In Miami, a 19% energy savings was achieved, while Los Angeles experienced 23% less energy consumption. The rationale behind selecting that particular temperature and humidity targets was however not provided in the publication. However, such studies are not available for Indian conditions. Many Indian houses have room air conditioners which are operated manually and sparingly whenever required to reduce energy bills. However, for large office or commercial buildings with potential for operation under mixed-mode, suitable control schemes are not available. Considering the increasing usage of air conditioning in large buildings, such as classroom complexes, mixed mode operation would be highly beneficial provided they are controlled optimally. Hence in the present study, the optimal, mixed-mode operation of a small building is proposed based on building simulation and appropriate thermal comfort standards. Though results are obtained for a small building, the methodology can be applied for any building given its specifications.

2. Methods

Before constructing naturally ventilated or mixed-mode buildings, climate suitability must be considered. For instance, regions consistently exceeding 35°C require mechanical cooling alongside natural ventilation. Thus, climate analysis is essential. This study's climate analysis is inspired by Borgeson's work [3] on Californian climatic zones. Examined cities, marked in red in fig. 2 [13], are major Indian tropical cities with moderate winter temperatures. Distances between these cities lead to substantial outdoor climate variations, allowing broader analysis of cooling loads and comfort across diverse conditions. The data needed for the present analysis was sourced from https://energyplus.net/weather uploaded by Indian Society for Heating Refrigeration and Air Conditioning (ISHRAE) in EnergyPlus weather format (.epw). Annual hourly TMY (Typical Meteorological Year) weather data captures median weather conditions over years.

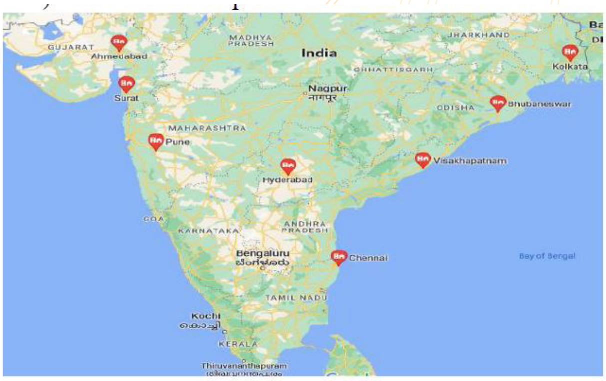

Figure 2: Location of the 8 cities considered for analysis

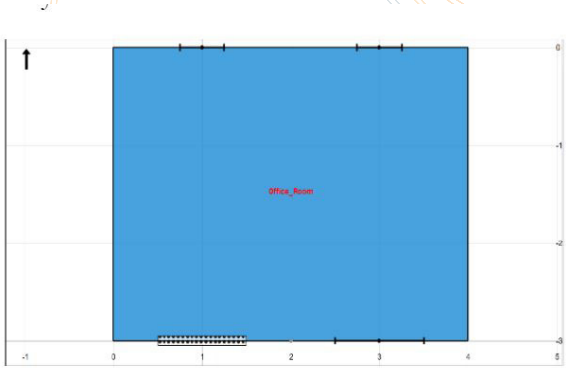

Figure 3: Building plan view. Typical hostel room size at IIT KGP

The climate analysis shows different city conditions and their impact on comfort. Climate isn't the only factor affecting comfort, building design matters too. Even if outside conditions are good for natural ventilation, a building's shape and orientation still affect thermal comfort of the occupant. So, the next step is creating a model of the building and analysing it in conjecture with outdoor conditions. OpenStudio - EnergyPlus package was used for this purpose. The model was created using FloorSpace JS available in the OpenStudio geometry tab, the plan can be seen in Fig-3. 3-D view of the model can be seen in Figs. 4 & 5. No windows or doors were placed on east and west side walls to reduce solar and fenestration loads.

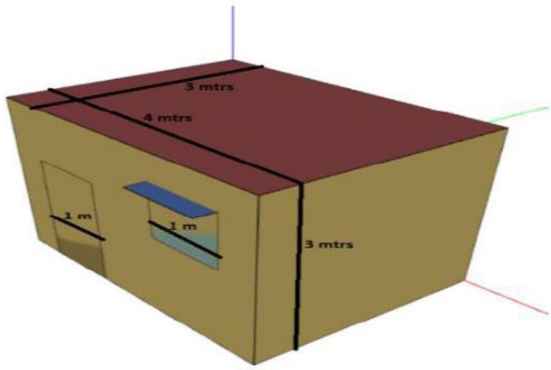

Figure 4: South facing view

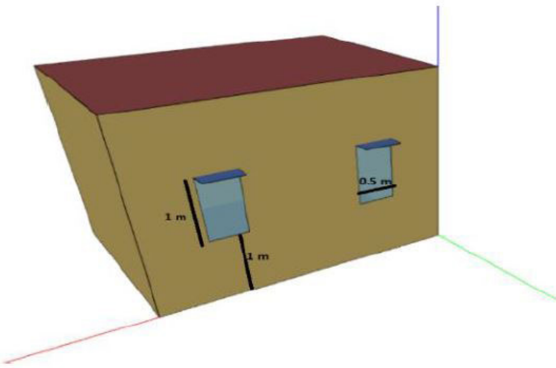

Figure 5: North facing view

The selection of materials of construction was based on ASHRAE 189.1-2009. The zone was assigned an occupancy of 2 people assumed to be present inside throughout the year (except heating design day). Of the total metabolic heat produced, 30 % was considered to be lost by radiation. Internal load of a computer (200W, fraction radiant=0.8) was added and an appropriate general scheduled usage was set for it. Similarly, an internal lighting load (60W, fraction radiant=0.5) with schedule was set. Constant infiltration rate of 0.5ACH (Air Changes per Hour) was set using LBNL method with 200 cm^2 effective leakage area. The daily indoor air velocity schedule was maintained at 0.1m/s from night 10PM to 6AM, from 7AM to 10 AM at 0.25m/s and from 10AM to 10 PM - 0.8m/s. While this assignment may appear arbitrary, it was designed to replicate the typical thermal loading conditions encountered within a standard hostel room at the institute (IIT Kharagpur). All the results obtained after the simulation of the model from the OpenStudio-EnergyPlus engine were converted to .csv format with the help of DView. Then statistical analysis on different city results was conducted with the help of Python libraries. All the Python codes developed during this study are available on GitHub public repository [12]. Using the simulation results an optimal window opening pattern was arrived at to maximise the indoor conditions (annual hours) at which 80% people feel comfortable (according to ASHRAE-55). Sensitivity analysis with this area opening pattern was performed by systematically altering some parameters, including room dimensions, door and window orientations, and window sizes, in the model room to obtain the impact of room design on occupant comfort.

3. Results and discussion

3.1 Climate Analysis

The primary driver of cooling loads and natural ventilation is the outdoor dry bulb temperature (DBT). Figure 6 illustrates the count of 'moderate' months in tropical climates, where the average daily maximum DBT is below 28°C and the average daily minimum DBT is above freezing point (0°C). Pune's climate aligns favourably with natural ventilation trends. To quantify favourable natural ventilation conditions, a better metric would be to examine the annual hours ideal for it. Figure 7 depicts the fraction of hours with DBT between 15°C and 28°C, coupled with outdoor relative humidity below 70%. Approximately 50% of annual time across these cities presents suitable conditions for natural ventilation. When humidity is high, fans can be used as they are generally available in every residential building. The ability to adjust clothing can further influence perceived comfort. Figure 8 shows the annual hours with outdoor DBT surpassing 28°C, portraying diverse nationwide conditions and illustrating the magnitude of cooling load scale. No specific threshold is set due to the fact that hot days can be followed by cold nights. Still it is obvious that Chennai and Ahmedabad will exhibit high cooling loads, with prolonged higher outdoor temperatures.

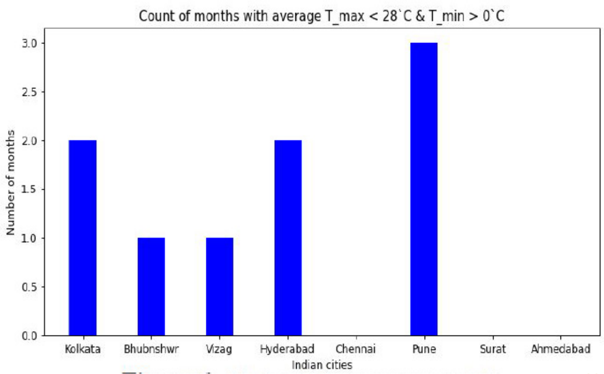

Figure 6: Moderate Temperature months

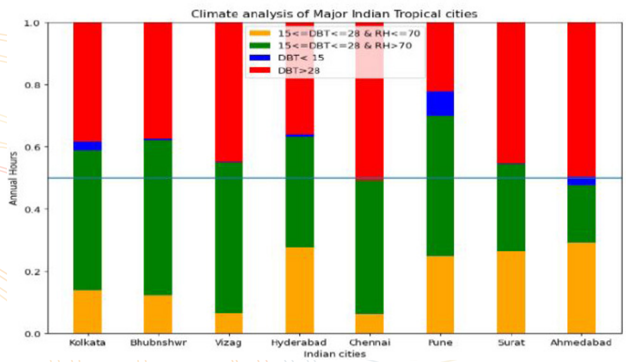

Figure 7: Natural Ventilation Favouring hours annual fraction

Evaluation of free cooling systems and structures considers available cooling resources. In absence of site-specific heat exchangers (e.g., water or earth), air around the structure is the primary heat exchange medium. Figure 9 shows yearly hours with DBT below 18°C for the eight cities. Insufficient overnight low temperatures might render radiant cooling systems ineffective the following day. It can be seen in Figure 9 Pune has the most annual hours for building envelope-air heat exchange, while Chennai has the fewest.

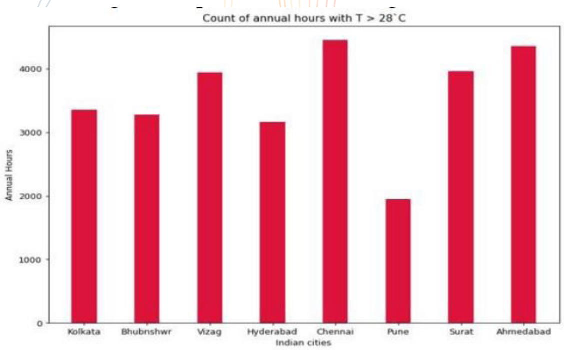

Figure 8: Annual hours above 28°C

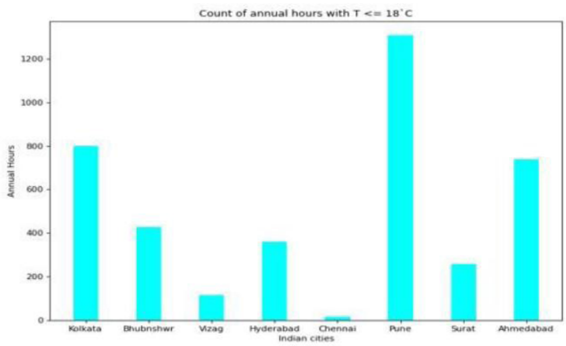

Figure 9: Annual hours equal or below 18°C

3.2 Window opening optimization

To emphasize the importance of windows, three cases were simulated: windows closed year-round, windows open constantly, and windows opened for favourable natural ventilation. Table-1 presents the results with simulations carried out for the city of Kolkata. As seen, open windows align room temperature with outdoor DBT. Thermal comfort varies as the outdoor temperature changes relative to ASHRAE-55 neutral temperature.

Table 1: Importance of proper window control

Case Type	Annual No. of hours when 80% are Comfortable (ASHRAE-55)	Number of hours annually when heating is required	Number of hours annually when A.C is required
Windows always open	6404	1177	986
Windows always closed	7002	35	1474
Optimized Window opening	7641	161	787

To emphasize the importance of windows, three cases were simulated: windows closed year-round, windows open constantly, and windows opened for favourable natural ventilation. Table-1 presents the results with simulations carried out for the city of Kolkata. As seen, open windows align room temperature with outdoor DBT. Thermal comfort varies as the outdoor temperature changes relative to ASHRAE-55 neutral temperature.

Optimizing window control involves understanding complex human behaviour. Various researchers indicate varied views on key factors influencing window opening—indoor vs. outdoor temperature debate is still on. Simple window models used were in this study. Natural ventilation (NV) models in OpenStudio-EnergyPlus require optimization to maximise the number of hours indoor temperature is comfortable for occupants. EnergyPlus provides two objects "Design Flow Rate" and the "Wind and Stack with Open Area" object which can be added in the OpenStudio building model in the thermal zones tab to simulate it for NV. The former is named as ZoneVentilation:DesignFlowRate object and calculates a design flow rate of air that is modified by environmental conditions. The latter is based on equations of wind & stack effect as outlined in Chapter 16 of the ASHRAE Handbook of Fundamentals 2009, and is named as ZoneVentilation:WindandStackOpenArea object. If multiple ZoneVentilation: objects are defined for a single zone (as is the case in our model), the total zone ventilation flow rate is the summation of the ventilation air flow rates determined by each ZoneVentilation object After numerous simulation results and statistical analysis, the Key Performance Indices (KPIs) were set to optimum value by comparing the results. Delta Temperature (ΔT) indicates air temperature difference between indoor mean DBT & outdoor DBT below which the NV is shut down (i.e. area openings are closed). Results indicate that a value of ΔT=1°C provides best results, as it focuses on reducing indoor temperatures above 80% comfortable limits, considering tropical climate adaptability. Minimum Indoor Temperature(T_{zone_min}) and Minimum Outdoor DBT (T_{ODB_min}) below which NV will be closed are set at equal values, these serve as lower limit for NV, to avoid overcooling; varying these shut-off values from 15°C to 19°C, reduced number of hours heating was required. Maximum Indoor Temperature (T_{zone_max}) and Maximum Outdoor DBT (T_{ODB_max}) sets upper limit for NV shutoff as the area openings will be closed above if the temperature exceeds this value. Changing this threshold from 34°C to 40°C showed no change in the annual number of comfort hours. Analysis of the simulation results using pythermalcomfort [11] library supports these findings.

After the optimal natural ventilation area opening pattern was identified, the building model was then simulated for all the 8 cities using this pattern. Observed hourly indoor conditions were classified as comfortable, uncomfortable-heating required, and uncomfortable-cooling (air conditioning) required using the ASHRAE 55 Adaptive Thermal Comfort standard (Fig.10). From the bar graph it is evident that Bhubaneshwar, is having the best conditions for operating a mixed mode building as 7947 hours are comfortable. Whereas these hours are least for Ahmedabad, which can still operate in natural ventilation mode providing comfortable indoor conditions for 70% of annual hours (6476 hours). The same process repeated with IMAC model equations to get comparative assessment and to validate the simulation results. The regional sensitivity can be seen by comparing Figs. 10 and 11 as IMAC equation for mixed-mode buildings is classifying more hourly conditions as comfortable because it considers higher indoor temperatures as model comfort. However, this needs to be verified by conducting actual occupant comfort surveys.

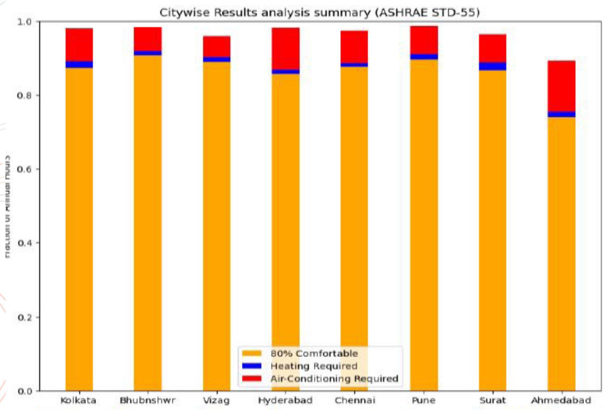

Figure 10: Annual Hours classified according to ASHRAE Std

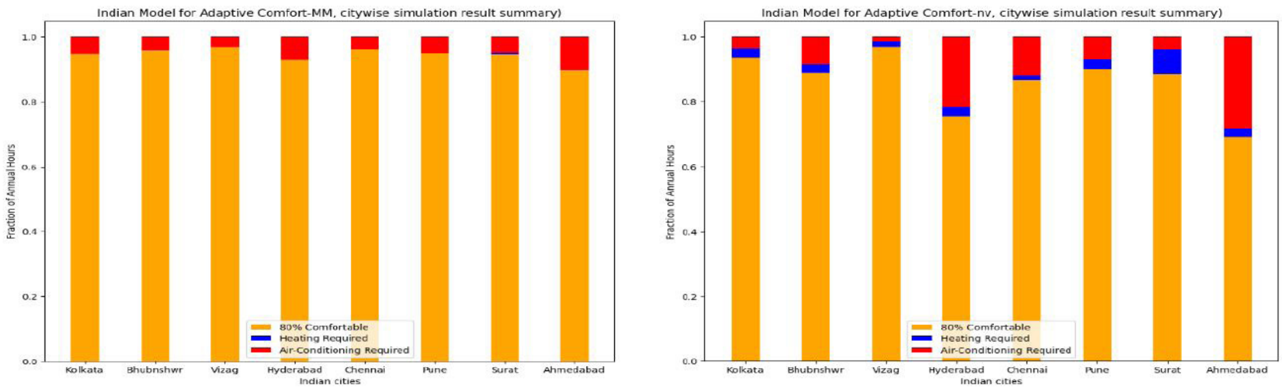

Figure 11: Annual Hours classified according to IMAC model (a) MM equation (b) NV equation

3.3 Sensitivity Analysis

In the context of Kolkata's climate, a 50% reduction in window size within the room led to a reduction in cooling demand by 137 hours and heating demand by 48 hours, illustrating the significance of smaller window openings in minimizing temperature fluctuations due to their reduced heat exchange area. Changing the room's window and door orientation from south-north to east-west resulted in a decrease in heating demand by 41 hours, while cooling demand remained largely unaffected, underscoring the influence of solar exposure on heating requirements. Moreover, increasing the room size from 12 m² to 20 m² decreased cooling demand by 678 hours but increased heating demand by 115 hours, implying that larger room dimensions may necessitate more heating in colder climates but reduce cooling demands in warmer climates due to the greater thermal mass involved. Using these simulation results and with the help of Python libraries mentioned earlier a mixed mode

Using these simulation results and with the help of Python libraries mentioned earlier a mixed mode assistance program code was developed. Mixed-mode buildings which blend natural ventilation and mechanical systems for energy-efficient comfort, face operational complexity due to weather, design, and occupant dynamics. Hence the proposed EnergyPlus simulation results driven algorithm for optimal mixed-mode operation can be very useful. The algorithm requires inputs like location, date, and time, then using the database, it helps occupants by guiding window, air-conditioning, and heating choices to sustain comfort and curb energy usage. Informed occupant decisions empowered by the algorithm will yield substantial energy reductions, contrasting conventional air conditioning-dependent strategies as can be observed by looking at Table 2. The total site energy was converted from kBtu to kWh and only electrical energy is used in this model. Visual examples illustrate the algorithm's efficacy in Fig.12.

. *Table 2: Annual Power consumption trends*

City	Annual electricity with HVAC [kWh]	Annual electricity without HVAC [kWh]	Potential electrical energy savings annually using MM [kWh]
Kolkata	7322.09	1258.45	6063.64
Bhubaneshwar	7144.49	1258.45	5886.04
Vishakhapatnam	7472.14	1258.45	6213.69
Hyderabad	5938.79	1258.45	4680.34
Chennai	7742.64	1258.45	6484.19
Pune	4883.44	1258.45	3624.99
Surat	7069.46	1258.45	5811.01
Ahmedabad	7141.56	1258.45	5883.11

```
Mixed-mode operation assistance provider

Select the city where you are located by entering the number mentioned in front of it:
 1.) Kolkata
 2.) Bhubaneshwar
 3.) Vishakhapatnam
 4.) Hyderabad
 5.) Chennai
 6.) Pune
 7.) Surat
 8.) Ahmedabad
 3

Now provide date, first by selecting the appropriate month:
 1.) January
 2.) February
 3.) March
 4.) April
 5.) May
 6.) June
 7.) July
 8.) August
 9.)Septemper
 10.) October
 11.) November
 12.) December
1
```

```
Enter date of the month
1

Enter the time approximated to nearest hour mark for which you require information in 24-hour format {Eg. 6PM = 18 hrs 10AM = 10 hrs}
12

The annual hour {Starting from 00:00 AM on 1st January} provided by the user date and time is =  12


Based on our simulation results analysis, For the selected city and the time provided by the user.
At this hour
User should keep the windows:  Closed
Air-Conditioning System should be turned:  Off
Heater should be turned:  Off
```

Figure 12-*Mixed-mode assistance algorithm demonstration*

The algorithm's present static nature lacks adaptation to occupant behaviour changes or abrupt external influences on indoor conditions. To overcome this constraint, future enhancements could involve creating a model predictive controller capable of accommodating dynamic shifts in building operation and environmental variables, enabling more precise control signals. Also, future refinements should address limitations, such as assuming doors as area openings for stack effect, which may not consistently reflect real-world door usage and can impact the accuracy of predicted ventilation rates for indoor comfort. Different size building models can be studied and added as an option to enhance usability. IoT integration for real-time control of openings by a building management system can be done and verifying energy savings through meter data can be done.

4. Conclusions

The study on 8 major tropical Indian cities identifies optimal window opening criteria based on outdoor and indoor temperatures for efficient natural ventilation. Indoor conditions were assessed using 2 different adaptive comfort models. Sensitivity of indoor conditions to the room design was assessed. Mixed-mode suitability was established for all cities, particularly Bhubaneshwar and Pune. The technique developed can be replicated for any city and any building model. The developed algorithm aids residential building operation for comfort and energy reduction.

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Thermal performance analysis of thermoelectric radiant panel system for indoor space heating

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Abstract

The study is focused on the thermal performance analysis of a thermoelectric radiant heating panel (TERHP) system in a test chamber for cold climatic conditions. Three radiant panels with eight thermoelectric modules (TEM) each are installed on the three different walls of the study chamber to evaluate the performance of the panels to achieve the thermal comfort temperature inside the chamber of 1.2 × 1.2 × 2 m. All TEMs in a single TE panel of size 0.75 x 0.50 m are attached in a triangular arrangement to obtain a uniform temperature. The water block is used as a heat sink to maintain the temperature difference between the cold and hot sides of TEMs. The water circulation circuit with the "I" configuration has been used. Hot water at a constant temperature is supplied to the water block, and cold water obtained at the outlet is collected and circulated back after thermoregulation in a closed loop. The experiment is conducted by supplying inlet water at 18°C and applying operating voltages to the TERHP system of 12 V, 16 V, and 20 V. The surface temperature of panels, mean radiant temperature, operative temperature, air temperature, heating capacity, and coefficient of performance are measured on these inputs.

Keywords - Thermoelectric module, Thermal performance, Radiant heating, Heating capacity, Low energy heating.

1. Introduction

A commitment to cut hydrofluorocarbon (HFC) consumption by 80% by 2047 was made when representatives from over 150 nations signed the Kigali Amendment in 2016. This would be a significant step in our attempts to lessen the effects of climate change since, if successful, it would prevent more than 0.4°C of global warming by the end of the century [1]. According to the IEA's 2019 report, India's energy demand for air conditioning is anticipated to triple by 2050. This points out the requirement for energy-efficient and sustainable air conditioning solutions [2]. Buildings account for a sizable portion of global energy consumption and carbon dioxide emissions. Hence, a new viable solution is required to tackle the above mentioned issues. Thermoelectric radiant cooling or heating systems for buildings can be a beneficial option due to its compact size, less maintenance, no use of refrigerant and long operating life.

A thermoelectric module (TEM) working on the Peltier effect has a thermoelectric element that is powered by direct current (DC). Depending on the direction of the current flow, TEM can transfer heat one way or another. The possible application options of this technology are the integration of thermoelectric (TE) radiant panels on the ceiling and walls of a building. Numerous studies have been carried out to assess and optimize the performance of thermoelectric systems.

The experiments performed by Cosnier et al. [3] confirmed the feasibility of heating air using thermoelectric modules in the system. The investigation shows that coefficient of performance (COP) of 2 can be easily reached by applying a current of 4-5 A while keeping the hot and cold side temperature difference of 5-10°C. Shen et al. [4] have developed a mathematical model to optimize the TE radiant panel design for better cooling and heating performance. Results show that for better performance of the radiant panel, the number of thermoelectric modules should be 16/m2. Lim et al. [5] developed an empirical model to predict energy consumption as well as the heating capacity of radiant panels in the heating mode. This prediction model can be integrated into building energy simulation programmes. Allouhi et al. [6] also found that the thermoelectric heating system can provide an energy savings of 55–64% compared to conventional electric heaters. Zuazua-Ros et al. [7] constructed a ventilated active thermoelectric envelope to assess its performance. Six TEMs were integrated into a building façade. Depending on the voltage input, they achieved a maximum COP of 2.1.

Liu et al. [8] worked on an open type of thermoelectric heating system with multiple channels. The effects of insulating layer thickness, airflow rates through the hot and cold sides, temperatures on the hot and cold sides, electric current direction, and numbers of TEMs were examined in the thermoelectric heating systems. This system attained an average heating coefficient of 1.3, which was higher than that of electric heating. Koohi et al. [9] designed a setup for space heating that consists of a thermoelectric system powered by a photovoltaic panel. Experimental investigation shows that a temperature difference of 6°C from the ambient temperature was observed with a maximum COP of 1.6 during the experiment period of 4 hours. Ibanez-Puy et al. [10] assert that it would be better to run the unit using more modules operating at lower voltage rather than fewer modules at higher voltage input. Wang et al. [11] performed tests in a room of 1 m3 and observed that for ambient temperatures ranging from 1 to 10°C, TE modules require high voltage (6–8 V) to ensure an adequate temperature level, whereas for ambient temperature greater than 10°C, more modules operating at low voltage (3-5 V) are required to make the system energy efficient.

Kim et al. [12] developed a model for a hydraulic thermoelectric radiant cooling system and found that cooling water temperature has the most significant influence on the COP of the system affecting it by 38.6-45.7%. Xie et al. [13] proposed a water-cooled thermoelectric component model which showed the increase in the COP and cooling capacity of TEC with increase in water flow rate and air flow rate. The earlier investigations, however, were carried out in low supply air conditions with low radiant surface temperatures. Few studies have been found using a water based heat sink for a thermoelectric radiant heating system inside a chamber. Water has higher heat carrying capacity than air, thus it is utilized in this study as the heat sink source. As a result, it is important to investigate the TERP's properties and assess how well it works in heating mode.

The study is focused on the thermal performance analysis of a thermoelectric radiant heating panel (TERHP) system in a test chamber for cold climatic conditions. The water block is used as a heat sink to maintain the temperature difference between the cold and hot sides of TEMs. The experiment is conducted by supplying inlet water at 18°C and applying operating voltages to the TERHP system of 12 V, 16 V, and 20 V. The surface temperature of panels, mean radiant temperature, operative temperature, air temperature, heating capacity, and coefficient of performance are measured on these inputs.

2. Methodology

The experiment is performed inside the insulated chamber of 1.2 x 1.2 x 2 m dimensions in the lab. There are three TE panels installed on the left, right, and front walls of the chamber.

2.1 Experimental setup description

The experimental setup includes TE radiant panels, a DC power supply, a water tank, submersible pumps, a water heater, a data logger, and a temperature controller as shown in Fig. 1. The radiant panel was constructed by attaching eight thermoelectric modules in a triangular arrangement to an aluminium panel of dimensions 0.75 x 0.50 m. According to a previous study, painting an aluminium panel black increased its heating performance by 2.3 to 2.8 times and its cooling performance by 1.5 to 1.7 times when compared to a non-painted panel [14]. Three TE radiant panels were painted matte black. The "I" water circulation circuit showed better performance in cooling studies. Water was supplied at 18°C, circulated in a closed loop. The experiment was conducted by applying operating voltages to the TERHP system of 12 V, 16 V, and 20 V in lab ambient temperatures of 17-18°C.

The study utilized a TEC1-12706 single-stage thermoelectric module with 127 semiconductor couples and 6 A current carrying capacity. The other technical parameters and their values are shown in Table 1. Thermal paste was applied on both sides of TEMs to attach the water block and metal panel surface to avoid internal resistance between them.

Q_{max} (W)	ΔT_{max} (K)	I_{max} (A)	V_{max} (V)	Resistance (Ω)	Size
50	66	6	14.4	1.98	4mm x 4mm x 3.9mm

Three TE radiant panels were electrically connected in parallel, having each TE panel with 8 TEMs in 4S x 2P configuration, as shown in Fig. 2 (b). Selected three pumps each having flow rate of 0.044 kg/s circulated water at a 0.0146 kg/s flow rate through each water block via smaller pipes connected with TE panels, as shown in Fig. 2 (a). which comes in range of 0.01 to 0.03 kg/s water flow rate as per previous studies through water blocks [16]. The remaining area of the rear side of the TE panels was thermally insulated.

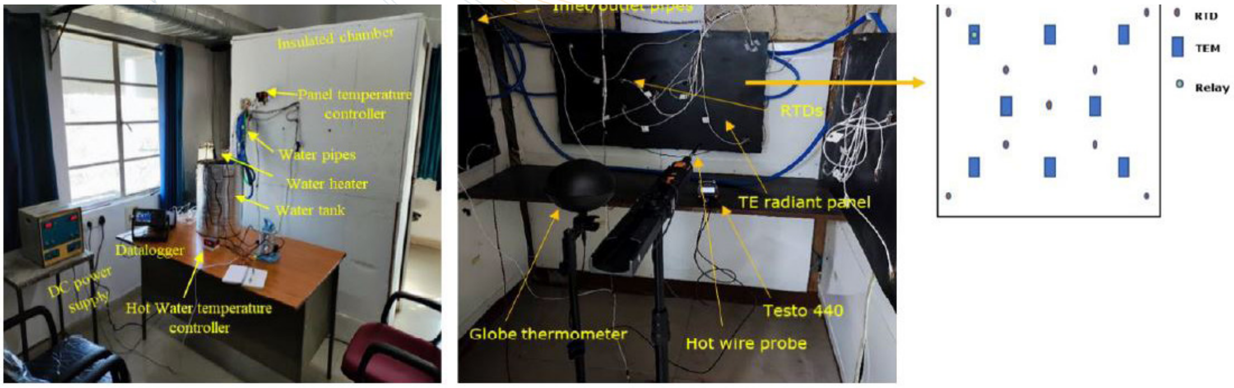

Figure 1: Outside and inside view of experimental setup for the present study and schematic of RTD placement on the TE panel

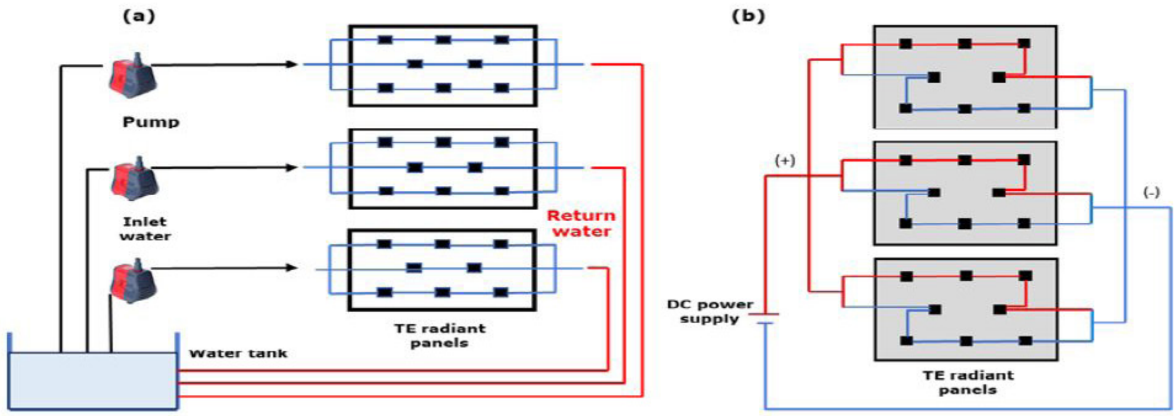

Figure 2: (a) Water circuit with "I" configuration and (b) Electric circuit for of TERHP system

Each thermoelectric radiant panel has nine RTD placed at positions as shown in Fig. 1 for better temperature measurement. Thus, the total number of RTDs attached to three radiant panels is 27. The spatial average is the number average of the air temperatures at the ankle level, the waist level, and the head level. These levels are 0.1, 0.6, and 1.1 m for seated occupants and 0.1, 1.1, and 1.7 m for standing occupants, according to ASHRAE. Four RTDs were attached vertically at these heights. One relay probe is attached to the center of the TEM as shown in Fig. 1 to maintain the required temperature on the TE radiant panel. One thermocouple was placed outside the test chamber to obtain ambient temperature data. A total of nine runs of experiments were performed for 12 V, 16 V, and 20 V. Each set of experiments is repeated three times with a water temperature range of 17-18°C for 2 hours each for a set point Th value of 28°C, 30°C, and 33°C. Experiments utilized a DC power supply (Testronix 92 D), changing polarity for heating study, and recording temperature data using a data logger All temperature data were recorded by a data logger (Keysight DAQ973A, 20-channel multiplexer DAQM901A, 2 units) and Testo 440, a hotwire probe, and a globe thermometer for thermal comfort assessment.

2.2 Assumptions, duration, and measurements

The following assumptions were adopted during this experimental study:

a) Thomson effect and heat losses by radiation and convection from the rear are neglected, electric resistance and thermal conductivity of TEMs are constant.

b) The Seeback coefficients (α) of p- and n-type elements in TEMs are constant and equivalent.

c) The temperatures of the bottom surface of the water block and panel surface are considered equal to the temperatures of the hot side and cold side of TEM, respectively.

In this study, the heating capacity and COP of a TE radiant panel were calculated. Temperature data were recorded mainly from the surface of the radiant panels. The heating capacity and COP of TEM ($Q_{h,panel}$, $COP_{h,panel}$) and TE radiant panels ($Q_{h\text{-}TEM}$, $COP_{h,\text{-}TEM}$) can be calculated based on Equations (1)-(9) [12], [17-18]. Equations (5)(10) were used in this study to calculate the heating capacity of the panel and COP. Terms used in the following equations were added in the nomenclature section.

$$Q_{h,TEM} = \alpha I T_h + 0.5 I^2 R - K(T_h - T_c) \tag{1}$$

$$Q_{c,TEM} = (T_{ws} - T_c)/R_w = \alpha I T_c - 0.5 I^2 R - K(T_h - T_c) \tag{2}$$

$$P_{TEM} = \alpha I (T_h - T_c) + I^2 R \tag{3}$$

$$COP_{h,TEM} = \frac{Q_{h,TEM}}{P_{TEM}} \tag{4}$$

$$Q_{h,rad} = \sigma A \varepsilon (T_s^4 \text{-} MRT^4) \tag{5}$$

$$Q_{h,conv} = hA(T_s - T_{i,a}) \tag{6}$$

$$Q_{h,panel} = Q_{h,rad} + Q_{h,conv} \tag{7}$$

$$P_{panel} = V\ X\ I \tag{8}$$

$$COP_{h,panel} = \frac{Q_{h,panel}}{P_{panel}} \tag{9}$$

$$MRT = \left[(T_g + 273.15)^4 + \frac{(0.25 \text{ x } 10^8)}{\epsilon_g} \left(\frac{|T_g - T_{i,a}|}{D} \right)^{\frac{1}{4}} (T_g - T_{i,a}) \right]^{\frac{1}{4}} - 273.15 \tag{10}$$

$$T_{op} = \frac{T_a + MRT}{2} \tag{11}$$

$$Nu = 0.59\ (Ra)^{0.25} \text{ for } 10^4 < Ra < 10^9 \tag{12}$$

Heating experiments were performed in the lab-based test chamber during February of the winter season. The data was logged at a 10 second interval during the experiment. The current values were noted, corresponding to the applied voltage in the DC power supply. As the three TE radiant panels were electrically connected in parallel, the operational voltages for the experiment were selected as 12 V, 16 V, and 20 V, considering panel surface temperature and COP variations. The minimum and maximum operational voltages for the study are selected as 12 V and 20 V, respectively. Maximum panel temperature was achieved as 27.45°C and 32.30°C at 12 V and 20 V, respectively, which comes under the same range selected in previous research for heating mode [19]. Thus, a 2-hour experiment was performed to achieve these surface temperatures. Rayleigh number at all voltages found to be in the range of 104 to 108 thus for vertical mounted panels Nusselt number was calculated using Equation (12).

A combination of random error (py) and propagation error (by) results in the total uncertainty (Uy) of measured values, as shown in equation (13). According to Equation (2), the propagation error (by) is calculated by a constant error term (bxi) that is obtained by multiplying the temperature sensor error by the standard deviation of the measured temperature (Sr). Equation (14), which includes the standard deviation and mean value (M) of the measurements, defines the random error (Py) [20]. Total uncertainty is shown for measured parameters in Table 2.

$$U_y = \sqrt{(b_y^2 + p_y^2)} \tag{13}$$

$$b_y = \sqrt{\left[\sum_{i=1}^{n} \left(\frac{dy}{dx_i} b_{x_i} \right)^2 \right]}, p_y = \frac{2S_r}{\sqrt{M}} \tag{14}$$

Parameters	Uncertainty
Temperatures	0.2-0.5°C
Heating capacity (Q_h)	0.067 W
COP_h	0.06

3. Results

Testing of the radiant panels is performed under three voltage inputs of 12, 16, and 20 V, with an initial indoor temperature kept at 20.6 °C ± 0.1°C. MRT, $Q_{h,panel}$, and $COP_{h-panel}$, were computed using Equations (10), (7), and (9) in accordance with T_s, $T_{i,a}$, T_g and the current measured during the test. The variation of panel temperature under different voltages of the experiment during the period of 2 hours is shown in Fig. 3(a). For the first 830 seconds, the panel temperature rises sharply, and as time passes, the rise of the panel surface continues but at a slower rate.

The variation of the mean radiant temperature under the applied input voltage is shown in Fig. 3(b). The mean radiant temperature (MRT) increases with the increase in panel surface temperature with respect to time, as there is no other heating source except the panel. Indoor air temperature increments under different input voltages are shown in Fig. 3(c). The maximum indoor temperature increment for 12 V, 16 V, and 20 V was 2.06 °C, 2.86°C, and 4.02 °C, respectively. Operative temperature was calculated using Equation (11) which is the mean of the indoor air temperature and the MRT. Operative temperature shows a similar kind of variation as obtained in MRT, as shown in Fig. 3(d).

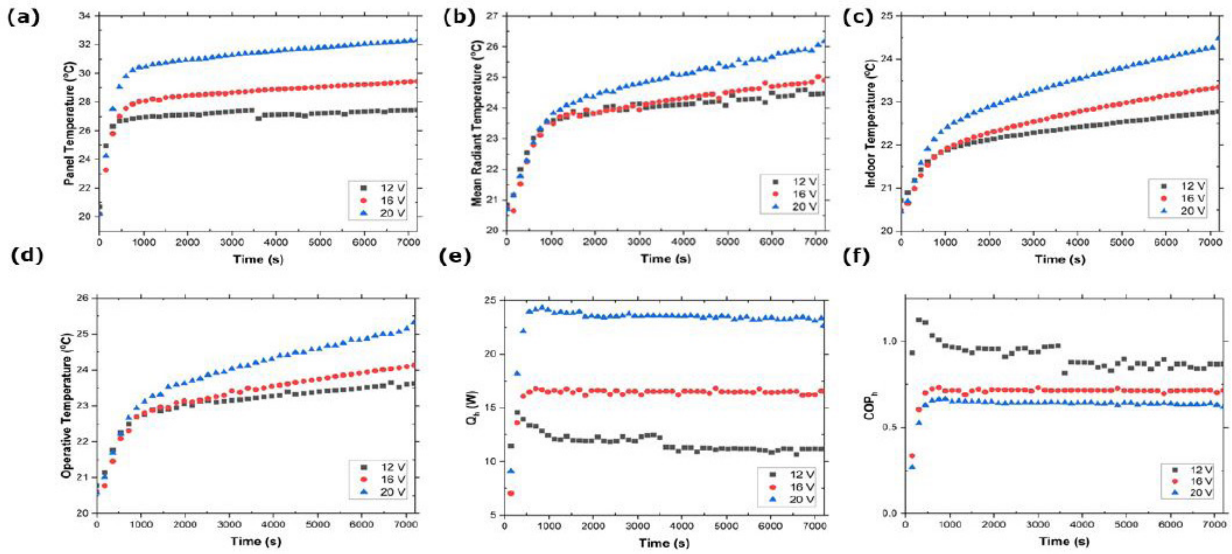

Figure 3: Temporal variation of (a) Panel Temperature (b) Mean Radiant Temperature (c) Indoor Temperature (d) Operative Temperature (e) Heating Capacity (Q_h) of TE panel (f) COPh of TE panel

Increasing the voltage value raises the current, which increases the temperature differential due to the Peltier effect, resulting in a higher temperature on the hot side of the module. The change in the heating capacity under different voltages with respect to time is shown in Fig. 3(e). Heating capacity for the higher input voltage can be seen to be higher, and it first increases very sharply with time, reaches a maximum value, and then starts to decrease at a slower rate as the difference between indoor air temperature and panel temperature decreases. The maximum heating capacity obtained was 14.7 W, 17.13 W, and 24.41 W for 12, 16, and 20 V, respectively.

COP_h, depending on the heating capacity, shows similar variation for constant input electrical voltage (V) with respect to time, it first increases and reaches a maximum value, after that, the COP_h decreases. The maximum COP_h was found to be 1.14, 0.74, and 0.66 for 12, 16, and 20 V respectively. COP_h decreases with an increase in the input electrical voltage, as can be observed from Fig. 3(f). This shows that the increase in the heating capacity is less as compared to the voltage applied or power input.

The temperature distribution at the active side of the panel at different voltage values of 12 V, 16 V, and 20 V captured by a thermal camera is shown in Fig. 5, which is nearly the same as measured by RTDs. The vertical air temperature at heights of 0.1 m, 0.6 m, 1.1 m, and 1.7 m is shown in Fig. 5 with respect to 12 V, 16 V, and 20 V. The vertical air temperature distribution was obtained for the sitting and standing positions of a person according to ASHRAE.

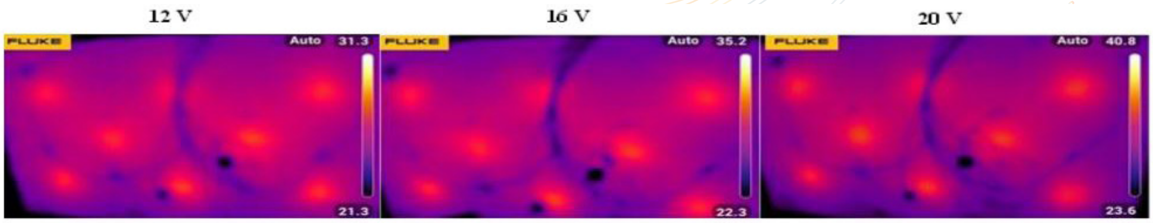

Figure 4: IR camera images of actual temperature distribution at the active side of panel at 12 V, 16 V and 20 V.

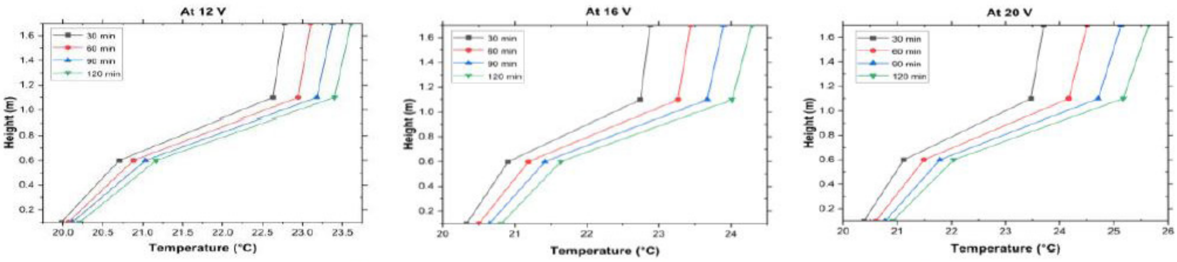

Figure 5: Vertical air temperature distribution at 12 V, 16 V and 20 V

4. Discussion

The indoor temperature rise occurred due to heat exchange between the TE panels and the study chamber. As the temperature difference between the hot and cold sides of TEM increases, TE modules require more energy to push electrons from the cold side to the hot side. A high supply voltage is required for higher surface temperatures. As shown in Fig. 3(a), the panel temperature rises sharply for 830 seconds because, ΔT_{TEM} increases fast, and then the rise of the panel surface continues but at a slower rate because of stable ΔT_{TEM}. The cold side temperature is maintained with a supply of constant temperature water. MRT, indoor air temperature, and operative temperature increase with time, as shown in Figs. 3 (b) - 3 (d).

According to ASHRAE, the inside design condition for winter with a 90% acceptability requirement is that the operative temperature persists within a range of 20-23.5°C for a 0.9 clo condition with an occupancy having activity less than 1.2 met. The upper limit of 23.5°C is achieved within 98 minutes, 59 minutes, and 27 minutes at 12 V, 16 V, and 20 V, respectively. The desired value of operative temperature is achieved in less than 2 hours at the lowest voltage, i.e., 12 V, with the present setup. The preceding line illustrates that to obtain the necessary operative temperature within the range of thermal comfort at a faster pace, power input must be increased, which comes at the expense of a low COP value. Optimization of the TE radiant heating panel necessitates a trade-off between COP and power input to TEM, which is dependent on ambient temperature, duration, and power cost.

Heating capacity, which is the combined effect of radiation and convection near the TE panel, initially rises fast, then goes down and becomes nearly constant because panel surface temperature rises at a faster rate initially than MRT and air temperature; further, all three temperatures rise slowly. With higher voltage selection, power consumption for the panel increases, leading to a decrease in COP at higher voltages, as shown in Fig. 3(f). The power supplied to each TE panel is 12.84 W, 23.09 W, and 36.66 W. Air with a high temperature is lighter, and due to the density difference, buoyant forces act upon it, raising it to a higher level.

5. Conclusion

This paper experimentally examines the thermal performance of a thermoelectric radiant panel system for indoor space heating. The heating performance of the TERHP system in a test chamber with designed TE radiant panels for optimum voltage or energy-efficient criteria was investigated. The outcomes of this study are concluded as follows:

- At 12 V, the TERHP system attained the highest COP of 1.14, which suggests that at lower voltages, the energy efficiency of the system increases, while for higher heating requirements at lesser energy efficiency, 20 V or high voltages should be supplied to the TERHP system. Thus, the electric connection of TEMs in a TE panel is important for determining the energy efficiency of the system.

- A water-based heat sink enhances TERHP system COP and heating capacity more than an air-based one used in previous studies. Water supply temperature (Tws) should be near to ambient temperature for a higher COP of the system, and for higher heating capacity, a high Tws can be selected. In this study, water at 17-18°C was supplied. With a high figure of merit, better COP and heating capacity are expected with TEM.

- In this study, the upper limit of thermal comfort temperature (i.e., Top) at the highest voltage was achieved within 27 minutes. The same level of thermal comfort can be achieved by a TERHP system at a lower air temperature. This results in lower energy consumption.

6. Nomenclatures

α	Seeback coefficient (V/K)
K	Thermal conductivity (W/m²·K)
V	DC voltage supplied to each TE panel (V)
Th	Hot side temperature of TEM (K)
Ts	TE panel surface temperature (K)
Tg	Globe temperature (K)
MRT	Mean radiant temperature (K)
εg	Emissivity of globe thermometer
Nu	Nusselt number
A	TE panel area (m2)
R	Electric resistance of TEM (Ω)
R_w	Thermal resistance of water block (K/W)
I	Input current to each TE panel (A)
T_c	Cold side temperature of TEM (K)
$T_{i,a}$	Indoor air temperature (K)
T_{ws}	Supply water temperature (K)
T_{op}	Operative temperature (K)
D	Globe diameter (m)
Ra	Rayleigh number

7. Acknowledgement

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Passive cooling strategies for better comfort during weather extremes – adapting the existing building stock in German cities to future climatic conditions

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Abstract

Global warming is causing a shift in climate zones. Focusing on German cities, this phenomenon is leading to changes in precipitation patterns, strengths of storms and to the duration and intensity of heat and cold periods. A large part of the built environment in German cities is not prepared to handle these changes. This paper aims to explore how existing buildings can be upgraded to incorporate passive cooling strategies to ensure comfortable indoor environments even during extremely hot periods. The study highlights the pressing need for such strategies and underscores their effectiveness. The techniques include thermal massing, cross ventilation, improved insulation, better window sealing and the use of suitable building materials. First, the passive enhancements are analyzed independently and subsequently evaluated in terms of their collective efficacy. Through a prioritisation process, it is demonstrated that the most efficient outcomes are achieved by relatively simple and cost-effective approaches. To substantiate the viability of the proposed interventions, a case study serves as demonstration and provides an illustrative model for retrofitting efforts aimed at adapting the existing building stock to the challenges which are expected to be posed by climate change. The findings underscore the feasibility of passive cooling strategies.

Keywords - Climate change adaptation, retrofitting, building performance analysis, passive cooling

1. Introduction – An unprepared built environment

In the context of German cities, a crucial aspect to underscore is the unpreparedness of the prevailing architectural inventory. The majority of structures lack appropriate provisions to mitigate the effects of these impending alterations. Remarkably, the absence of air conditioning systems or other cooling mechanisms exacerbates the situation. Given the projected surge in summer heat waves over the upcoming decades, a considerable number of residential and commercial spaces are projected to experience conditions that significantly exceed the bounds of comfort. The installation of conventional air conditioning units might appear as a quick fix, but it is neither a sustainable nor a feasible solution. Instead, a pressing requirement arises for the implementation of passive systems that offer a more environmentally conscious and enduring remedy. This emphasizes the necessity for innovative approaches that can ensure habitable indoor environments amidst the forthcoming climatic challenges.

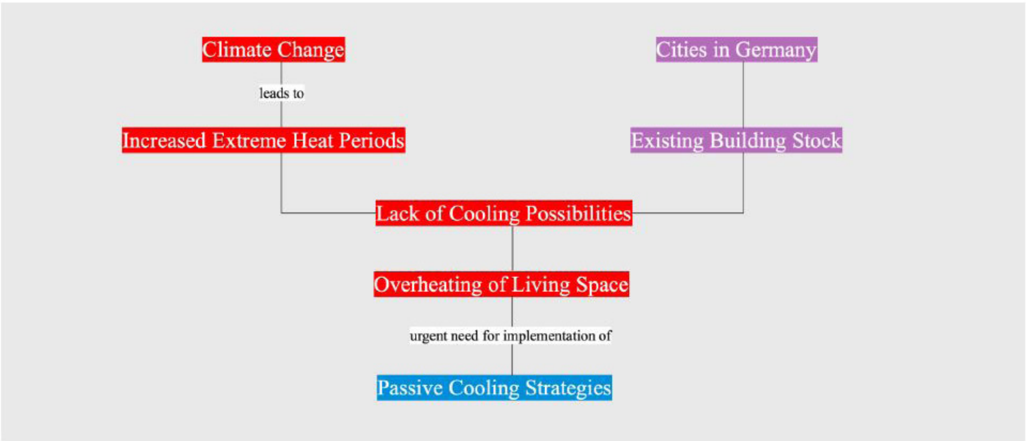

Figure 1: German cities are facing an increase in urban overheating and are not prepared enough

1.1 Rationale

This paper aims to investigate the retrofitting of existing building stock to enhance interior comfort during periods of summer heat. The investigation will focus on the implementation of passive cooling strategies to achieve this objective. Beyond the theoretical elucidation and advancement of principles for integrating passive cooling techniques into preexisting building frameworks, the paper also underscores practical implementation. This is achieved through a detailed showcase of how a selection of these principles is being effectively applied within the context of a retrofitting project involving two multifamily residences dating back to the early 20th century in Potsdam, Germany. The primary objective of this study is to investigate the potential retrofitting options that can ameliorate indoor comfort conditions amidst episodes of heightened summer temperatures. By investigating the deployment of passive cooling methodologies, the paper seeks to address the critical issue of maintaining pleasant interior environments without relying on energy-intensive solutions such as conventional air conditioning. In addition to this conceptual inquiry, the paper pivots towards a hands-on illustration, taking form through the retrofitting undertaking in Potsdam. The project in question encompasses a duo of multifamily dwellings, structures that carry the architectural heritage of the early 20th century. This case study encapsulates a practical application of the theoretical insights presented earlier in the paper. The overarching significance of this paper rests in its dual approach: it bridges the gap between theoretical considerations and practical execution, fostering a comprehensive understanding of how passive cooling strategies can be integrated into historical building contexts. This synthesis of theory and application stands as a testament to the viability and potential of passive cooling as a sustainable means to navigate the challenges posed by rising temperatures in our built environment.

1.2 Passive cooling

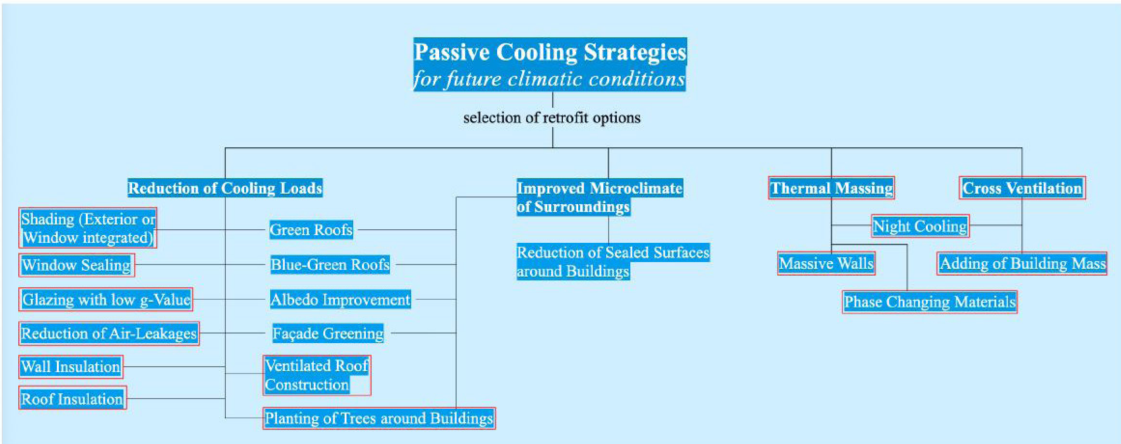

Figure 2: General passive cooling strategies which might be applicable to retrofits of existing buildings in Germany with selected strategies for the case study buildings in Potsdam indicated in red

Passive cooling strategies have been extensively used in hotter climate zones for thousands of years, but their application in northern European countries is gaining relevance only recently, generated by the new summerly weather conditions (heat waves) which are expected to significantly increase in the future. The implementation of passive cooling strategies on a broad scale in conventional existing buildings in German cities, may provide a solution to solve the problem of summer overheating many of the buildings will be faced to in the future, especially rooftop and upper floor apartments exposed to the sun. Already today every year many (mostly elderly) people die due to urban overheating during heat waves and the lack of the possibility to cool their apartments. Therefore, adaptation strategies for the transformation of existing buildings on a broad scale are urgently needed (Shukla et al., 2022). The implementation of passive cooling principles would provide an ideal solution for these buildings.

1.3 The case study buildings

Villa Moritz and Villa Michaelis in Potsdam represent typical examples of brick constructed buildings of the Wilhelminian era as they have been built in large quantities in German cities between 1890 and 1918. The two villas are multifamily residential houses with four floors and a total area of 1336 square meters of living space containing 17 apartments in total (Villa Moritz: seven apartments, Villa Michaelis: ten apartments). The buildings' heritage protection status allows only interventions which are not modifying the buildings' exterior appearance. This is a special challenge typical for the retrofits of many historical buildings in Germany. The improvement potential in many other, non heritage protected buildings is even higher, since measures like external sun protection, façade greening etc. might be applied additionally.

Figure 3: Villa Moritz in Potsdam

Figure 4: Villa Michaelis in Potsdam

1.4 Summer temperatures today and predicted for 2070

As the figure below shows, overheating of indoor spaces in typical German dwellings occurs only during the three summerly months of June, July and August. Within the graphic we can see the periods when indoor temperatures are rising above the comfort zone. In many multi-storey residential buildings, the rooftop apartments are most exposed to the sun and therefore most affected. For this reason, the values of the present case study are focused on the rooftop apartments.

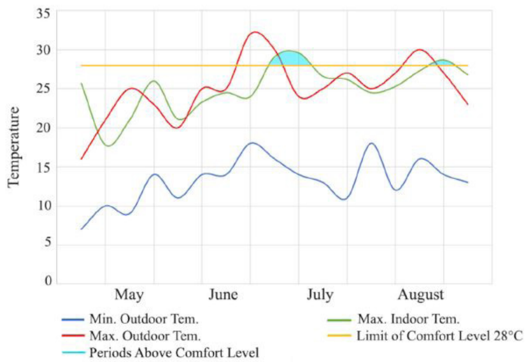

Figure 5: Outdoor and indoor temperatures during the summer months from May to August 2022 (before retrofit works have started) with illustration of indoor temperatures of the rooftop apartments above comfort level (ClimateStudio simulation)

In the case study buildings' rooftop apartments, it has been measured that around 262 hours on 17 days are beyond the comfort zone. The measurements have taken place during summer 2022 and, even though the values of 2022 have been typical and are not very different to previous years, an alignment to previous years still needs to be done to obtain a mean value for a more precise evaluation. With future climate change and rising temperatures, however, it is expected that the heat waves in Germany will significantly increase (Shukla et al., 2022).

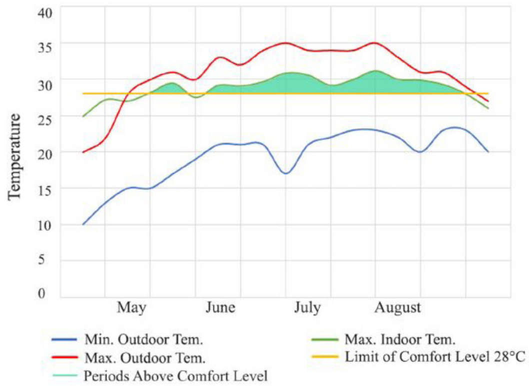

Figure 6: Expected outdoor and indoor temperatures during the summerly months from May to August for 2070 with illustration of indoor temperatures of the rooftop apartment above comfort level (ClimateStudio simulation)

The figure above is illustrating a future climate estimation of 2070 and showcases how this may have an effect on the indoor temperatures of the rooftop apartments of our case study buildings. As we can see in the figure, the hours and days during which the interior spaces of the rooftop apartments are in uncomfortable condition is dramatically higher than today. The predictions are vague and still need to be verified, but it is safe to assume that in general the occurrence, intensity and duration of heat periods will significantly increase in the future (Shukla et al., 2022). In our simulations, and as illustrated in the figure above, in 2070 the interior temperatures of our rooftop apartments of Villa Moritz and Villa Michaelis would be around 1082 hours on 68 days above the comfort zone of 28°C. Even though in the future we may get more used to higher interior temperatures, the interior spaces of the rooftop apartments could be seen as inhabitable future summer periods, if there would not be taken any measures against overheating.

2. Methods – Synthesis of theory and practice

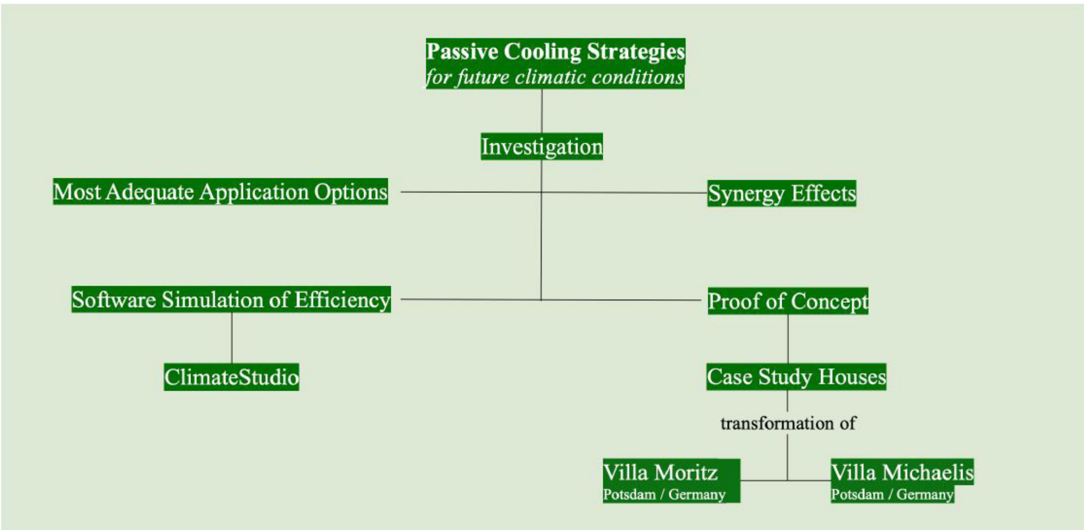

Figure 7: Diagram showing the study's methodological approach

After an introductory demonstration of the paper's rationale and an explanation of the urgent need to find ways of how to energetically retrofit our built environment with passive implementations, the focus will be set on an investigation of how the existing building stock can be retrofitted in order to provide a better interior comfort during summerly heat periods due to the implementation of passive cooling strategies. Besides the theoretical elaboration and further development of the principles to integrate passive cooling into existing building structures, it will be shown how some of these principles have been implemented as part of the retrofitting construction site in Potsdam.

Backed up with simulations by the environmental performance analysis software ClimateStudio, the planned cooling strategies have been integrated into a retrofit project of the two multifamily houses in Potsdam. Synergy effects of combinations of individual passive cooling techniques are highlighted. The actual cooling performance of the two case study buildings is compared with the simulation results in order to test and possibly verify the predicted performance results. Additionally, the feasibility in regard to costs and construction effort is evaluated and compared with techniques which are applied during conventional retrofit projects. The predicted construction costs and efforts are also proven by monitoring the real costs and efforts which are spent for the two exemplary retrofit construction projects. Last but not least, this study should help to clear the way to integrate passive cooling strategies into the German building regulations, which until today are not sufficiently considering passive cooling techniques in an adequate way.

3. Results – Passive cooling is a viable solution to keep our buildings comfortable in future climates

3.1 Implementation of passive retrofit strategies

Based on the energy performance analyses on one hand and the limits given by the legal requirements (e.g. heritage protection of the buildings) as well as financial limits, a series of enhancements to be implemented has been carefully selected. The major interventions, in regard to passive cooling, are: interior insulation, thermal massing, window improvements, enabling natural cross ventilation for all rooms (and thus the possibility of night cooling), and the installation of window integrated sun blinds. The following figures are illustrating more in detail the corresponding retrofit interventions.

Figure 8: Photo of installation of wall insulation from interior side

Figure 9: Photo of window enhancements

Figure 10: Installation of roof insulation (18 cm mineral wool)

Figure 11: Thermal massing with additional brick walls

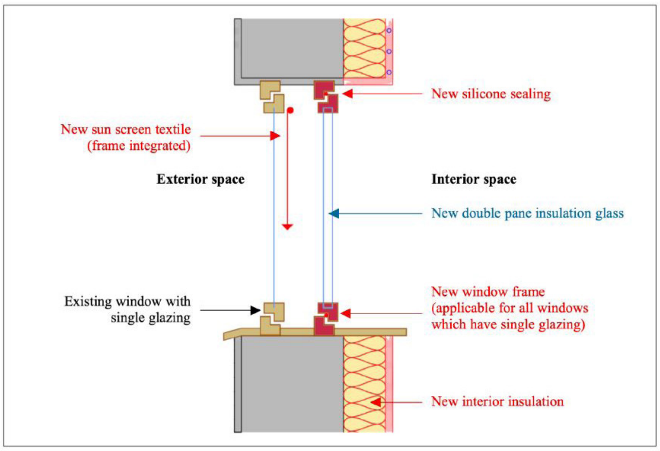

Figure 12: Window enhancement concept and installation of interior installation

3.2 Simulation results

The following figure illustrates the simulation results of the indoor temperatures after applying the above mentioned strategies of interior insulation, thermal massing, window enhancements, cross ventilation, and night cooling. The simulation has been made for the same estimated temperatures in Potsdam during 2070, as already presented in chapter 1.4. As we can see, the interior spaces could be kept within the comfort zone for the entire summer and conventional air conditioning systems would be unnecessary.

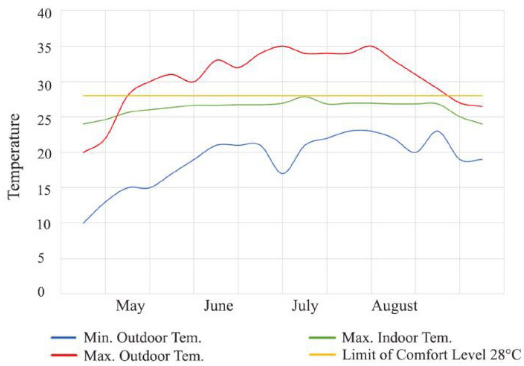

Figure 13: With the application of several passive cooling measures, the indoor temperatures could be kept low enough to completely maintain comfortable indoor temperatures also for temperatures predicted for 2070 (ClimateStudio simulation)

3.3 Analysis and comparison of savings, costs and carbon footprint

The figures below show the efficacy of each individual retrofit intervention in relation to the overall heat reduction achieved by the passive cooling measures. The aim is to envision the impact of each individual intervention on the total heat excess and then compare it with two other important factors: the related costs and the respective carbon footprint.

The figure at the left shows the total reduction of overheating subdivided into the five individual interventions. The figure in the middle contains a cost comparison of the individual interventions. The figure illustrates the proportion of each intervention from the total installation costs of the passive cooling implementations. The total costs for the implementation of the passive cooling interventions are 143,776 €. The highest spending has been made for the window enhancements (55,340 €), followed by the insulation of the exterior walls from the interior wall side (34,112 €) and the thermal massing (24,849 €). Significantly lower were the costs to enable cross ventilation (15,243 €) and for the installation of window integrated sun shading (14,232 €). The overall living space for the two buildings is 1,336 sqm. Therefore, the total cost for the passive cooling installations is 143

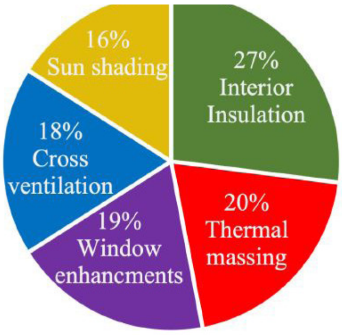

Figure 14: Percentage of reduction of overheating achieved by each intervention in relation to total

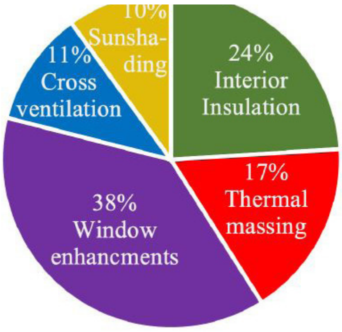

Figure 15 - Percentage of cost of the individual cooling strategies in relation to their total expenditures

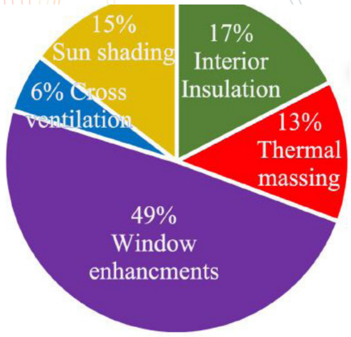

Figure 16 - Percentage of carbon footprints of the single strategies in relation to their total footprint

€ / sqm living space. All costs indicated are exclusive to the German VAT which is currently 19%. And the figure on the right showcases an estimated carbon footprint comparison of the individual passive cooling interventions.

4. Discussion – How to develop the best passive cooling solution

An evaluation and development of a prioritization concept can become a powerful tool for the recognition of which combinations of interventions are most efficient in regard to energy and CO2 consumption as well as from an economical point of view. Thus, significant insights can be gained on which interventions to focus for the best overall outcomes.

4.1 Comparison of results

The efficiency of an intervention regarding the reduction of excess heat is not the only relevant factor to decide which strategy to choose. For sustainability aspects, the initial carbon footprint of the production, delivery and installation of a passive cooling component has to be as low as possible. Therefore, the carbon footprint has to be considered as well. A third aspect relevant for the decision which interventions to choose is a cost comparison. The next subchapter is providing the corresponding comparisons in the form of a table.

4.2 Prioritization of passive design implementation options

The following table shows which enhancements are most efficient in regard to savings, costs and embodied energy.

Table 1: Prioritisation of retrofit interventions in regard to efficiency, costs, carbon footprint

Priority	Type of retrofit intervention for passive cooling	Efficiency (percentage of total heat reduction)	Cost / sqm living space and percentage of total costs	Carbon footprint of intervention (metric tons of CO_2e) and percentage of total	rank
1	Enhancements on windows, doors, ex- and interior walls to enable cross ventilation	18%	15 €, 11%	1.6 t, 6%	
2	Thermal massing (incl. effect of night cooling)	20%	25 €, 17%	3.8 t, 13%	
		27%	34 €, 24%	5.0 t, 17%	
3	Wall insulation (from interior side)				
4	Installation of sun protection screen at window	16 %	14 €, 10%	4.2 t, 15%	
5	Window enhancement by reduction of thermal heat gains through new glass layers with low u-values	19%	55 €, 38%	14.1 t, 49%	
	total	**100%**	**143 €**	**28.7**	

For the selection of the most reasonable cooling strategies, one has to consider all relevant factors, not only the efficiency in regard to cooling load reduction. Therefore, the costs and the carbon footprint of each intervention have been taken into consideration as well. Thus, it becomes evident that those interventions have to be preferred, which have the best relation between efficiency and costs (such as cross ventilation and thermal massing). And the intervention's carbon footprint is of relevance as well, since with a high carbon footprint, the duration time until the carbon savings have outbalanced the carbon spent for the production, delivery and installation, can extend to a very long time period. From the elaborated values it can be extracted that enabling cross ventilation is one of the most advisable implementation strategies for passive cooling. A relatively large reduction of the indoor temperature can be reached (18%) with proportionally low costs (11%) and a very low CO2 footprint (1.6 t). Thermal massing is another exceptionally effective cooling strategy. In the present case study, the overheating reductions achieved by thermal massing constitute 20% of total savings, with a cost of 17% and a CO2 footprint of only 13% (3.8 t). Wall insulation has a heat reduction of 27% from the total, while its costs are 24% of the total and the CO2 footprint is only 17%. The installation of sun blinds has 16% of savings but only 10% of the costs, while its carbon footprint is 4.2 tons, which equals to 15% of the total CO2 footprint. The overall lowest effectiveness has been observed in this study by the window enhancement strategy. Reason for this is not the amount of heat reduction (19%) but the high production cost (38%) and the large carbon footprint required for the manufacturing of the glass and frames (14.1 t, 49%).

4.3 Synergy effects by combining the implementation options

Some of the interventions can become most efficient in combination with each other. For example, can a window enhancement be combined with a window integrated sun shading roller blind, and it can be equipped with a tilt mechanism in order to facilitate the air flows necessary for cross ventilation and thus also significantly increase the effect of thermal massing. On the other hand, there are also interventions, which reduce the efficiency of other strategies. For example, can a wall insulation from the interior side reduce the thermal massing capacity since its mass is not anymore directly exposed to the interior space but separated by the insulation material.

4.4 Limitations of present study

The approach and depth of this paper is on a conceptual level and intends to show a path how we may use passive cooling strategies to transform our existing building stock to adapt to the future conditions. All data derived by calculations, software based simulations and measurements are on a conceptual level and need to be verified and intensified by deeper studies. Even though in this study only energy efficiency, costs and carbon footprint have been compared, there are several other very relevant factors as well, such as aesthetics, durability, re-usability and recyclability of the material, and maintenance effort. They also play an important role and may as well be considered in further studies.

5. Conclusion – How to pave the way for a successful implementation of passive cooling strategies on a large scale

This study aims to demonstrate ways how it is possible to retrofit our existing building stock in a way that it can respond to the new climatic conditions in a passive way without the need of installing conventional air conditioning systems. The fact that air conditioning systems are not yet installed in Germany on a broad scale, can be seen as an opportunity to go a more sustainable way to keep our buildings cool in the future and promote the installation of passive cooling systems instead. This would be an essential step of the climate neutral city of tomorrow. A prioritization, on which combinations of interventions are most efficient in regard to energy and CO2 consumption as well as from an economical point of view, proofs that the best outcomes can be reached with the combination of rather simple and less expensive interventions such as thermal massing, night cooling and night cross ventilation as well as the use of adequate materials. The presented case study construction site serves as a proof of practicability and constitutes an exemplary intervention proposal for the retrofitting in order to adapt our building stock to the impact of climate change.

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Experimental assessment of various control algorithms for direct evaporative cooling systems

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Abstract

Direct evaporative cooling systems are an energy-efficient alternative to conventional air conditioning systems, particularly in hot and dry climate. The evaporative coolers offer a significant reduction in indoor air temperature while providing a desirable indoor air quality. However, maintaining indoor relative humidity levels in a comfortable range is a challenge with evaporative cooling systems. This study aims to explore the potential for improving the comfort hours offered by the direct evaporative cooling system, operated through control algorithms developed to modulate the system performance through fan operation, airflow rate or water pump operation. The study follows a novel approach to using the experimental data to generate characteristic performance curves for the DEC system through experiments in a controlled environment, as opposed to assuming fixed saturation efficiency for simulations. The experimental and simulation data are used to assess the comfort hours and energy savings achieved by the controlled system. The findings from the simulations imply that the hours within the comfortable range for temperature are increased from 56% for baseline system to up to 76% for a controlled system. While the hours with both temperature and relative humidity in the comfort range were increased from 21% to 53%. Thus, the results suggest that direct evaporative cooling systems coupled with control algorithms have the potential to replace the conventional air conditioners.

Keywords - Direct evaporative cooling, Control Algorithms, Thermal comfort

1. Introduction

The use of air conditioning systems for comfort and space cooling is a major driving factor for the rising energy demand, currently accounting for nearly 10% of all the global electricity consumption today, and expected to be tripled by 2050 [1]. The evaporative cooling systems offer low-energy and affordable low maintenance solutions for space cooling with a potential to replace conventional air conditioners. Direct evaporative cooling systems are dependent on direct contact of air and water mediums for space cooling. They are based on the principle that sensible heat is exchanged for latent heat to provide a cooling effect. Thus, the thermodynamic process of evaporative cooling is ideally an adiabatic process, in which the wet-bulb temperature of the air remains constant, but the dry-bulb temperature drops as the humidity rises[2] .These cooling systems often lead to elevated indoor humidity levels, offering poor occupant thermal comfort. Thus, they are best suited for Hot and Dry climates with wet-bulb temperatures lower than 25°C, where there is a need for humidification along with cooling [3]. However, its application can be extended to other climates if coupled with advanced control algorithms to maintain the indoor air temperature and relative humidity within the comfortable range.

The purpose of this study is to evaluate the comfort hours and energy-saving potential of control algorithms for direct evaporative cooling systems by experimental assessment. In this study, control algorithms were developed to achieve an improvement in comfort hours offered by the direct evaporative cooling system by maintaining the indoor air temperatures as well as relative humidity levels in a comfortable range. The benefits of control algorithms were then assessed through simulations. The study follows a novel approach to using the experimental data to generate characteristic performance curves for the DEC system, as opposed to assuming fixed efficiency for simulations to evaluate the performance of the system. The experimental assessment of an evaporative cooling unit was conducted in a controlled environment. The results of the experimental assessment were used to generate a characteristic performance curve for the direct evaporative system, which was used in simulations to estimate its benefits in a building.

Saturation efficiency is an important performance parameter in DEC systems. It can be defined as as the extent to which the temperature of leaving air approaches the wet-bulb temperature of the entering air[2]. In a study by Jain & Hindoliya (2014) [4], it was found that the saturation efficiency (ε) of a DEC system depends upon the geometry of the cooling pad and the mass flow rate of the inlet air (ma), given by equation (1). Thus, in a practical scenario, the saturation efficiency varies with inlet conditions. i.e., dry bulb temperature and wet bulb temperature of the entering air.

$$\varepsilon = 1 - e^{\frac{-4.606}{m_a^{0.2}}} \quad (1)$$

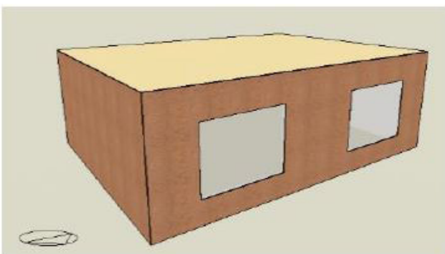
In another study[5], control algorithms for DEC systems were developed based on temperature and/or relative humidity, and were assessed through simulations using the co-simulation approach. The study uses the mathematical corelation between Saturation efficiency and mass flow rate of inlet air (Equation (1)) developed by Jain & Hindoliya (2014) [4], to account for the variable saturation efficiency in simulations. In the study [5], the simulation results for control algorithms suggest that with only temperature as a control, the indoor temperatures remained within the comfort range, but it resulted in higher levels of indoor relative humidity. When both temperature and relative humidity were used as controls, the indoor relative humidity levels were reduced but the temperature rose, due to the inactivity of the system for longer durations.

From the literature review, it was observed that to assess the impact of control algorithms on the performance of the DEC system it is necessary to consider the variable saturation efficiency in simulations. However, to use the variable saturation efficiency in simulations, only theoretical equations were available. This suggests the need for experimental assessment to generate realistic performance data for DEC systems to estimate the benefits of control algorithms in buildings. The experiments were conducted to derive the relationship between the saturation efficiency and wet bulb temperature, which helped to assess the gap between the simulation results and the real-time performance of the system

2. Methods

2.1 Modeling & Simulations

The control algorithms were evaluated through simulations using EnergyPlus. The building geometry and the Direct Evaporative Cooling system was modelled in DesignBuilder. A standard test model, BESTEST Case 600 from ANSI/ ASHRAE Standard 140 – 2007, was adopted to avoid uncertainties in simulations about the building geometry and envelope properties. The building unit (Figure 1(L)) was modelled in DesignBuilder as a lightweight construction with single-zone space measuring 8m in length and 6m in width with fixed glazings on the North façade, considered to be located in Ahmedabad, India. The evaporative cooling system (Figure 1(R)) was modelled in DesignBuilder with an Airloop AHU unit consisting of a Direct Research Special evaporative cooling pad and a variable air volume blow-through fan. The supply side of the airloop AHU includes an Outdoor Air Mixer which is connected to the Airloop zone mixer to provide return air from the zone. The demand side of the airloop consists of a Zone Splitter connected to the single-zone model. The DEC system was modelled as per the specifications provided by the manufacturer for the system used in the experimental assessment.



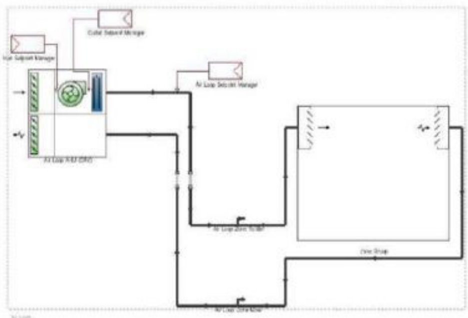


Figure 1: (L) Building Geometry, (R) DEC System schematic modeled on DesignBuilder

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The building geometry and evaporative cooling system modelled in DesignBuilder were exported into EnergyPlus version 9.4 for simulations. The TMY weather file for Ahmedabad from the year 2004 to 2018 was used for simulations. EnergyPlus offers an object called Energy Management System (EMS) which is similar to the building management system and offers the types of controls offered in real buildings. It is a high-level control method which can override the model inputs during simulations. The control algorithms were implemented in the simulation model using EMS to avoid the use of a third tool to couple the energy simulations with control algorithms. The EMS programme overrides the model inputs as per the requirement, on being called during simulation and can access a wide variety of "sensor" data to implement various control actions. It uses the EnergyPlus Runtime Language (Erl) for custom programming of control routines[6]. The "AfterPredictorAfterHVACManagers" calling point was used in the program to call the EMS program at each timestep after the execution of predictor and after calling the SetpointManager and AvailabilityManager.

2.2 Control Algorithms

The factors affecting the performance of a DEC system were identified through literature study and categorized into the input, control and performance parameters. The input parameters include indoor and outdoor temperature and relative humidity, which were used to generate conditions for the control logic. The control parameters include system operation, water pump operation and modulation of fan speed. These parameters were controlled based on the results obtained by the conditions in control logic. Finally, the performance parameters were used to assess the impact of control algorithms on the system performance in all scenarios. The algorithms are divided into two categories, simple and advanced. Simple algorithms involve the ON/OFF operation of the DEC system, whereas the advanced algorithm also includes the modulation of fan speed, as specified in Table 1. The primary goal of all the control algorithms was to maximise the number of hours with indoor temperature and relative humidity within the comfort range.

Table 1: Control Algorithms

Control Algorithm		Input parameter	Control parameter	Performance parameter
Simple Algorithms				
Schedule Based	1	Schedule	Evaporative Cooler ON/OFF	Power consumption, Comfort hours, Saturation Efficiency
Outdoor Conditions based	2A	Outdoor Dry bulb Temperature		
	2B	Outdoor Dry bulb Temperature, Outdoor Relative Humidity		
Outdoor & Indoor Conditions based	3	Outdoor Dry bulb Temperature, Outdoor Relative Humidity, Room air Temperature, Room Relative Humidity		
Advanced Algorithms				
Modulation of Fan speed, Water Pump operation	4	Outdoor Dry bulb Temperature, Outdoor Relative Humidity, Room Air Temperature, Setpoint Temperature	Evaporative Cooler ON/OFF, Evaporative Cooler Fan speed, Evaporative Cooler Water Pump ON/OFF	Power consumption, comfort hours, Saturation Efficiency

2.3 Experimental Assessment

The experimental assessment of the evaporative cooling system was conducted in a controlled environment equipped with an environmental chamber to control the conditions. The unit was an Indirect Direct Evaporative Cooling (IDEC) System, consisting of two heat exchangers, for sensible and adiabatic cooling respectively. The system worked in three modes: Only ventilation mode; With only 1 heat exchanger; With both heat exchangers (IDEC mode). To suit the scope of the study to test the Direct Evaporative Cooling system, the sensible heat exchanger was disabled by bypassing the water pump. The details of the system used for experiment are mentioned in Table 2.

The dry bulb temperature, wet bulb temperature, relative humidity and pressure difference were measured for the inlet, return and outlet conditions, along with the power consumption for unit and fan. Error! Reference source not found.Error! Reference source not found. shows the schematic of a typical DEC system and the required measurement locations in the system. An air sampler box, balometer and code tester was used to measure inlet, outlet and outlet conditions, whereas temperature sensors are installed inside the evaporative cooling unit to measure the air temperature after it passes through the heat exchangers. The conditions in the environmental chamber were altered to achieve the required testing conditions. The tests were run for a set of different dry bulb and wet bulb temperatures for three fan speeds, 40%, 70% and 100%. At each condition, the measurements were recorded for nearly 2 hours.

2.4 Assessment of control algorithms

The comfort hours evaluated based on the IMAC[7] comfort model for Mixed Mode buildings as it is more suitable for the Indian context for buildings running in natural ventilation and mixed modes of operation. The setpoint temperature was calculated based on the following relation given by the IMAC Model,

$$Indoor\ Operative\ Temperature = 0.28 * 30 - day\ running\ mean + 17.87 \quad (2)$$

Table 2: Evaporative Cooler Unit Specifications

Evaporative Cooler Unit Specifications	
Unit Details	
Manufacturer	ATE
Model	HMX1K (850 CFM)
Overall Unit Dimensions	700x2500x(1050+300) (WxDxH)
Static Pressure	45 mm wg
Water Tank Capacity	120L
Fan	
Model	BDB 200 CM
Capacity	850+298 CFM
Thickness	500mm
Material	Engineering Polymer
Heat Exhanger: Adiabatic	
Thickness	200mm
Material	Cellulose Pad (7mm flute)

Figure 2: Evaporative Cooler Unit

The upper and lower limit for the comfort band was calculated from the upper and lower limit of 90% acceptability range of the indoor operative temperature. The comfort hours were assessed based on two conditions, first, based on T – Indoor temperature within the upper and lower limit of comfort band, and second, based on T + RH - Indoor temperature within the upper and lower limit of comfort band and Indoor relative humidity between 30- 70%. The power consumption by the system was calculated by adding the power consumption by the water pump and fan.

3. Results

The simulations for all the cases were carried out in two stages, first, using the default performance data provided in EnergyPlus, i.e., a fixed value of saturation efficiency, and second, using the actual performance curve, generated with the experimental data, i.e., variable saturation efficiency.

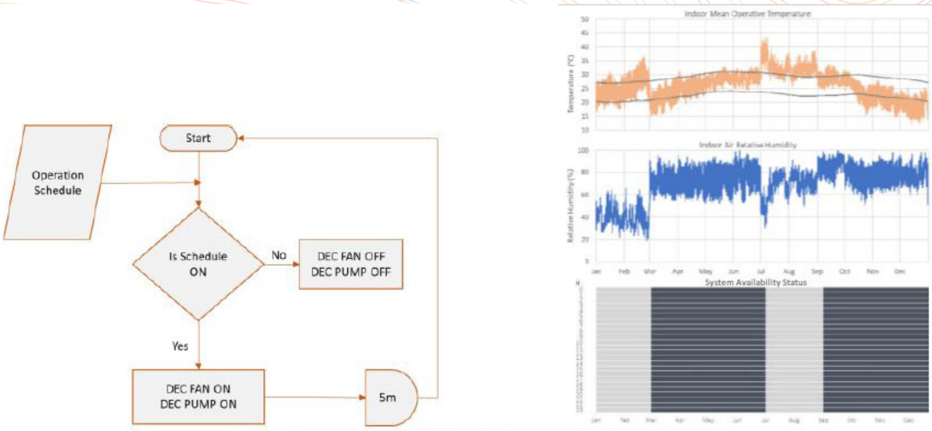


Figure 3: (L) Algorithm 1, (R) Simulation Results

https://doi.org/10.62744/CATE.45273.1181-296-304

Algorithm 1 (Simple- schedule based) was considered as the base case scenario for the comparative assessment. The operation schedule was derived from the prevalent outdoor conditions of Ahmedabad. The system is scheduled to turn OFF during Jan-Feb and Jul-Aug, due to high humidity levels during these months. Algorithm 1 (Figure 3 (L)) results in stable indoor operative temperatures between March-June, as shown in Figure 3 (R), as the system is always ON for the selected months. However, the indoor relative humidity levels exceed 70% due to the continuous addition of moisture in the air by the evaporative cooling system. In the monsoon months of July- August, the system is turned OFF as per the schedule, this results in slightly lower indoor relative humidity levels inside, but the indoor temperature remains above the upper limit of the comfort range. The schedule-based algorithm does not take into account the immediate favourable outdoor conditions and hence fails to benefit from them. With algorithm 1, 54% of hours out of all the hours lie in the comfortable range of temperature, but only 21% of hours are within the comfortable range for both temperature and relative humidity. The system operates for 66% of the hours in a year.

In, Algorithm 2A (Figure 4(L)), the system is scheduled to turn ON when the outdoor DBT rises above 30°C. The summer temperatures lie above the upper limit of the comfort band, whereas in winters, the temperature is within the comfortable range. Since there is only a temperature constraint for the operation of the system, the system operates during the monsoon months of July to September as well. This results in higher indoor relative humidity levels, reaching almost 90%, as shown in Figure 5(L). Here, the system operates for only 41% of the hours, with 70% of hours in the comfortable range of indoor temperature and 46% of hours in the comfortable range of indoor temperature and RH. Overall, the hours with comfortable temperature and RH were increased by 37% from baseline case 1.

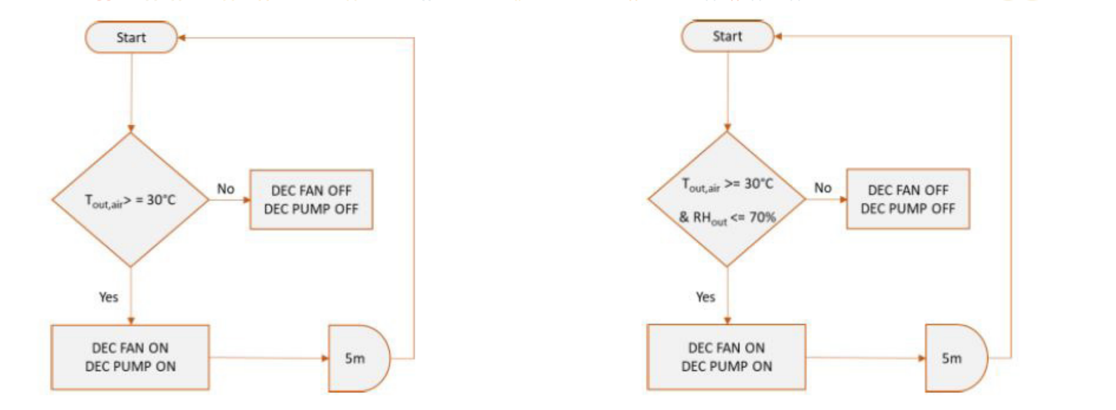
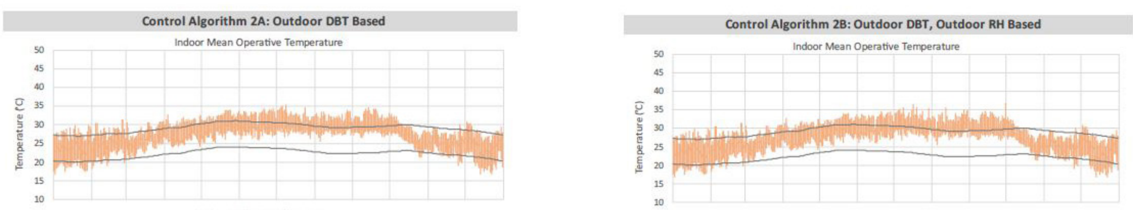


Figure 4: (L) Algorithm 2A and (R) Algorithm 2B

To further streamline the operation of the system in an attempt to maintain the indoor relative humidity levels within desired range, in algorithm 2B (Figure 4(R)), the system was scheduled to operate when outdoor DBT is greater than 30°C and RH is less than 70%. The constraint of both temperature and relative humidity results in the reduced operation of the system in monsoons (July-Aug). The operational hours of the system were reduced to 38% from 41% in previous case 2A. Thus, due to the unavailability of the system, here, the temperatures are higher (Figure 5(R)) than that in the previous case 2A, with comfort hours reduced from 70% to 67%. However, the comfortable hours for both temperature and RH were increased to 47%.



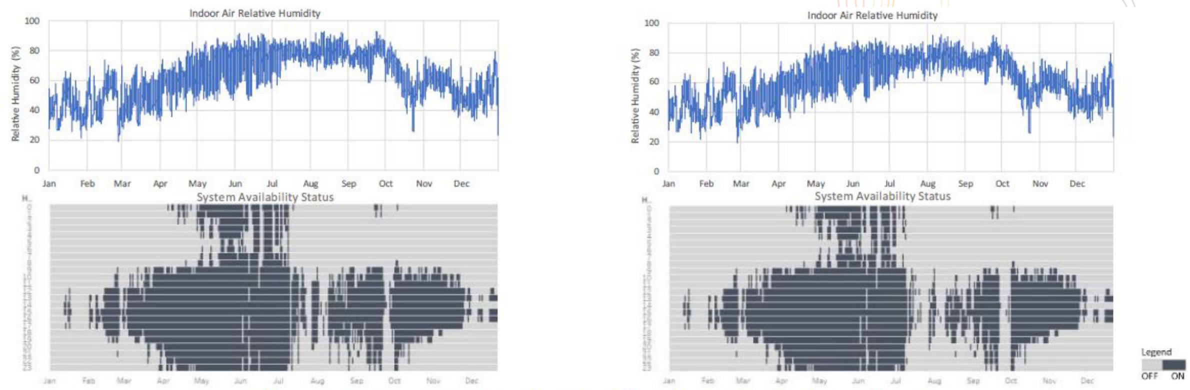


Figure 5: Simulation Results (L) Algorithm 2A, (R) Algorithm 2B

In algorithm 3(Figure 6(L)), in addition to the outdoor conditions controls, the system was scheduled to operate only if the indoor temperature is higher than the cooling setpoint temperature and if the indoor humidity is below 70%. In this case, the frequency of operation of the system was reduced to cater to the indoor and outdoor relative humidity constraints, thereby reducing the operational hours to only 33%. Also, the indoor temperature-based

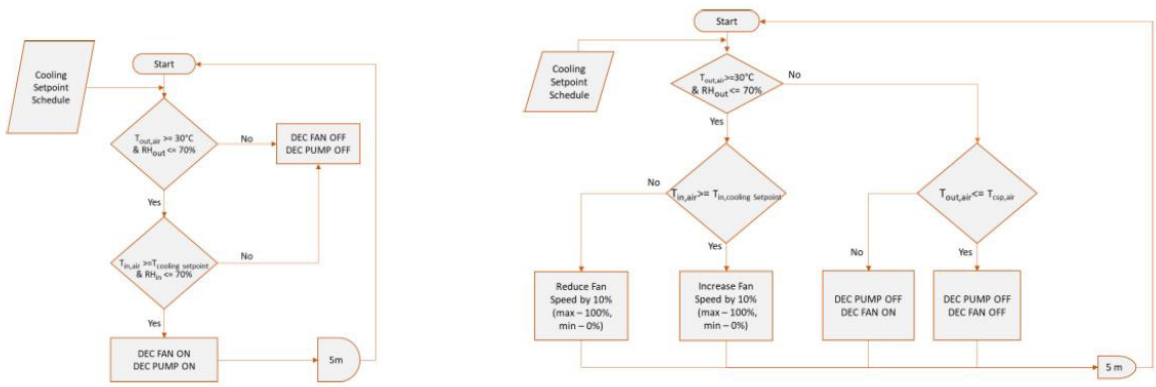


Figure 6: (L) Algorithm 3, (R) Algorithm 4

conditions helped in avoiding the overcooling of space in winters (Figure 7(L)), thereby reducing the power consumption by the system. However, due to low operational hours, the hours within the comfort range of temperature were reduced to 62%, while the comfort hours for both temperature and RH were increased to 48%.

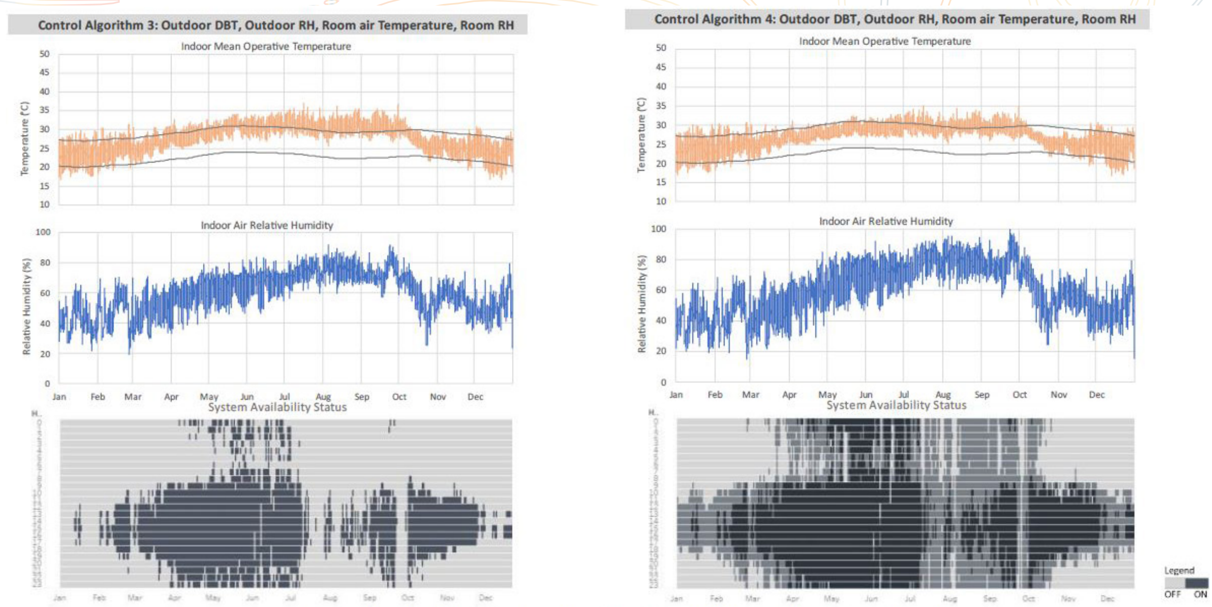


Figure 7:Simulation Results (L) Algorithm 3, (R) Algorithm 4

The advanced algorithm 4 (Figure 6(R)) was developed to operate the system based on outdoor and indoor conditions and modulate the fan speed to achieve optimum indoor conditions. In this case, the system is scheduled to operate in three modes: system OFF; free cooling- water pump OFF and only fan ON; and system ON with variable fan speed. A variable air mass flow rate is achieved as opposed to Case 1 (Figure 8(L)).

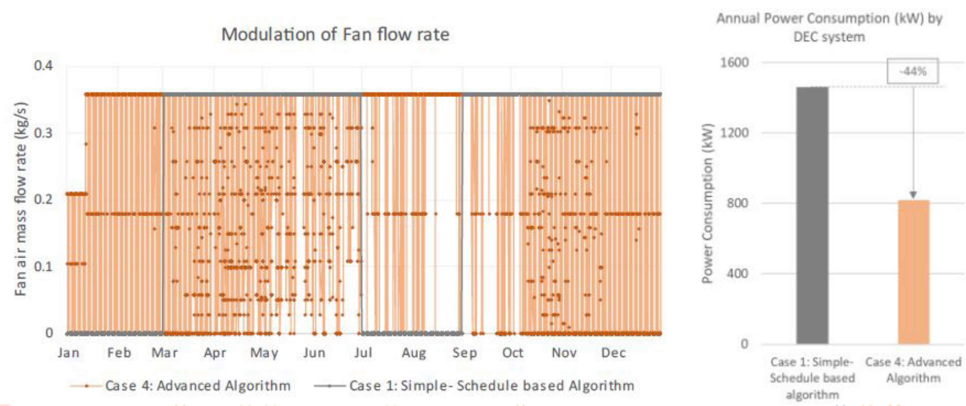


Figure 8: (L) Control Algorithm 4: Modulation of fan slow rate and (R) Annual Power Consumption by Fan

This helped in increasing the hours of operation to 69%, but with lower power consumption by the system. The power consumption by the fan was reduced by 44% from Case 1 (Figure 8(R)). The operation mode with only the fan ON, or the free cooling mode, helps in reducing the indoor temperature when the outdoor conditions are favourable, without adding moisture to the air Figure 7(R). Due to the variable fan speed mode and free cooling mode, the system operates for 69% of the hours, thus increasing the comfortable temperature hours to 76%. The highest number of hours with comfortable temperature and RH (53%) was achieved in this case.

3.1 Experimental Assessment Results

The data recorded from the experimental assessment of the evaporative cooling system was processed to form the relationship between saturation efficiency (ε) and wet bulb depression (WBD), given by,

$$\varepsilon = 0.146 \ln(WBD) + 0.3977 \tag{3}$$

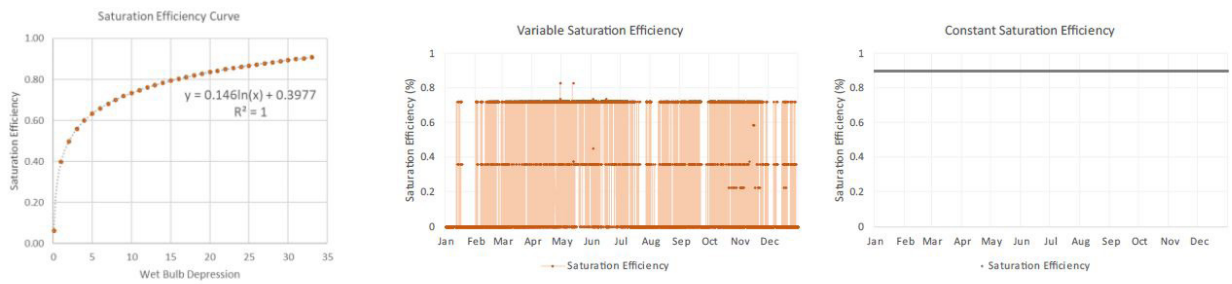


Figure 9: (L) Variable saturation efficiency curve, (R) Constant and Variable Saturation Efficiency

The variable saturation efficiency curve is shown in Figure 9(L). The above equation was added to the simulation model as the effectiveness flow ratio modifier curve, to obtain the variable saturation efficiency. With the experimental performance curve, the saturation efficiency varies from up to 84.7% as opposed to the constant saturation efficiency of 90%, as shown in Figure 9(R). The indoor temperatures were higher for variable saturation efficiency by up to 2.5°C. In case of algorithm 4, the comfort hours were reduced from 76% to 69% for temperature and 53% to 50% for both temperature and relative humidity with variable saturation efficiency because of the reduced resultant value of saturation efficiency. Thus, there is a significant difference in the comfort conditions offered in both cases.

4. Discussion

The schedule-based algorithm 1 forcefully turns the system OFF even if the outdoor conditions are favourable for evaporative cooling. The temperature-based controls in algorithm 2A helped in maintaining indoor temperatures within the comfort range to some extent but in turn resulted in higher levels of indoor humidity, due to higher hours of system operation. In algorithm 2B, the inclusion of outdoor relative humidity-based controls led to reduced hours of operation, thus reducing the comfort hours. With both indoor and outdoor conditions as controls, it was possible to reduce the indoor relative humidity levels, thus comfortable RH hours were increased. However, all the control conditions were met for a smaller number of hours, thus the system operational hours were reduced, leading to reduced comfort hours for temperature. With the addition of control conditions from algorithm 2A to 3, the hours within the comfortable range of temperature decreased from 70% to 62%, while the hours with both temperature and RH in the comfortable range increased from 46% to 48% (Error! Reference source not found.). The advanced algorithm with the free cooling strategy helped in using favourable outdoor conditions to maintain indoor conditions without the addition of moisture in the air. The combination of free cooling mode along with evaporative cooling in algorithm 4 resulted in the highest number of comfortable hours.

The use of variable saturation efficiency in simulations reduced the comfortable hours by 2-9% in all the cases. The average temperature for variable saturation efficiency was higher by nearly 1-2°C for all the cases than the constant saturation efficiency. The lower values of saturation efficiency results in reduced performance of the system, and hence higher indoor temperatures. The simple algorithms led to low operational hours (33-41%), thus the power consumption was significantly reduced. The modulation of fan speed in algorithm 4 helped in reducing the power consumption by the system even at higher operational hours (69%). The impact of variable saturation efficiency on power consumption is visible, as the power consumption increased in most of the cases, due to lower saturation efficiency in the practical scenario as opposed to the higher value of constant saturation efficiency in simulations. The difference of 1-10% in power consumption was observed in all cases, with the use of variable efficiency in simulations. The results for all the algorithms are summarised in Table 3 below. The algorithm 4 offers the best performance among all the control algorithms.

Table 3. Results summary

Algorithm	Saturation Efficiency	Control	Comfort Hours		Power Consumption (kW)
			T	T + RH	
1	Constant	Schedule based	54.1%	21.1%	1459.0
	Variable		51.2%	26.8%	1459.6
2A	Constant	$T_{out,air}$	69.5%	45.6%	562.4
	Variable		60.6%	43.1%	562.4
2B	Constant	$T_{out,air}$ & RH_o	67.0%	45.5%	514.3
	Variable		58.2%	43.1%	514.3
3	Constant	$T_{out,air}$, RH_o, $T_{in,air}$ & RH_{in}	62.1%	48.5%	403.9
	Variable		55.8%	44.1%	450.9
4	Constant	$T_{out,air}$, RH_o, & $T_{in,air}$	**75.9%**	**52.9%**	**819.7**
	Variable		68.7%	50.4%	832.2

It is evident that even with the control algorithms, it is difficult to maintain the relative humidity levels within the comfortable range. The modulation of water recirculation rate may have the potential to reduce the addition of moisture in the air. However, due to the limited scope for modelling the control algorithms in EnergyPlus it could not be included in the study. The scope of the work can be extended to develop control algorithms which take quantities such as water temperature, water recirculation rate, water quantity etc. apart from outdoor and indoor conditions as input parameters. The inclusion of such parameters may help in achieving comfortable levels of indoor relative humidity. The research can also be extended to conduct the experimental assessment for Indirect Direct Evaporative Cooling (IDEC) systems, for different materials of cooling media and for various climatic conditions.

5. Conclusion

The research aims to evaluate the qualitative and quantitative benefits of control algorithms, i.e. comfort hours and power consumption respectively for DEC systems. The results suggest that for the climate of Ahmedabad, the DEC systems along with advanced control algorithms, can offer upto 75.9% of comfortable hours. Presently, evaporative cooling systems are widely used in domestic applications, especially in hot and dry climates. The control algorithms can help in widening the scope of application of DEC systems to larger buildings with various typologies by improving their thermal performance. It is also observed that in a practical scenario, the saturation efficiency varies with inlet conditions. i.e., dry bulb temperature and wet bulb temperature of the entering air, resulting in 2-9% of variation in the comfort conditions offered by the system. Thus, it is necessary to account for the variation in the performance of system due to the variations in inlet conditions, to obtain realistic performance of the system through simulations.

6. Acknowledgments

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A Holistic Approach to Hotel Design in Delhi NCR

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Abstract

Hotels, with their high energy demand and reliance on air-conditioning present significant design challenges. The paper draws upon occupancy patterns, guest surveys and energy use in built precedents to conduct detailed research on indoor and outdoor design strategies that balance guest comfort with minimal energy usage. These combine passive and mixed-mode approaches that invite protected use of outdoor and transitional spaces and a courtyard. Balconies feature elements such as jaalis, optimized facades, ceiling fans, and misting for comfort. Findings from extensive analytical studies show that use of non-renewable energy can be reduced by 70% while thermal comfort conditions in and around the hotel premises can be improved. The final design offers an attractive, immersive, and energy-efficient experience to guests while providing cost-saving options for hoteliers. It sets an example for future hotel designs in similar urban settings, inspiring sustainability in architecture and energy efficiency.

Keywords - Hotels, Subtropical Climate, Passive Cooling, Adaptive Thermal Comfort, Innovative Design

1. Introduction

Energy consumption in hotels is driven by the high comfort expectations of guests. Some 60% of revenue is reported as being allocated to energy expenses [6], with cooling representing half [15]. The paper reports on research conducted for a new hotel building in the National Capital Region of India. The region boasts more hotels (22,159) than Agra (2,260) and Jaipur (5,426) combined, other top regional tourist destinations in North India [10]. A prominent business hub and a major tourist destination in India, Delhi NCR attracts both business travellers (about 70%) and tourists year-round [11], ensuring high occupancy throughout the year.

The aim of the research was to explore strategies for reducing the high cooling loads characteristic of this building type in the climate of New Delhi. Selected design strategies were rigorously tested and combined in the design. The research outcomes are discussed, considering the unique site, context, and climate, with consideration given to their potential applicability to similar hotel projects. The site is situated within a commercial area surrounded by residential buildings. It covers approximately 2.5 acres, with each side measuring 100 meters.

2. Methods

Design research conducted for the project included surveys and site microclimate studies, dynamic thermal simulation, and daylighting studies. Analysis of Delhi's climatic conditions highlights critical parameters that pose challenges and offer opportunities for informing a hotel design (reference climate file: INDIRA_GANDHI_DELHI-hour.epw):

Solar protection: Optimum shading depths based on solar angles mitigate solar gain during summer while facilitating passive heating from the winter sun.

Variation in Summer and Winter temperature: Delhi experiences high summer temperatures with cool temperatures in the winter months (November to February).

Diurnal Temperature Range: The substantial diurnal temperature variation between October and June offers an opportunity for night-time ventilation for cooling during summers.

Wet Bulb Temperature: During summer months, the substantial difference between Dry Bulb and Wet Bulb temperatures encourages evaporative cooling to enhance comfort.

Prevailing Wind Patterns: To capitalize on prevailing winds that come from the Northwest and Southeast in summer, design elements should encourage a wind chill effect during this season. Incorporating shaded water bodies in their path can further enhance the evaporative cooling effect for outdoor areas.

1.1 Passive design strategies

The research took a base case of a prototypical air-conditioned hotel room interior, double-loaded corridors, fixed windows with Window-to-Wall Ratio (WWR) exceeding 60% and single glazing and conventional double-brick wall construction. The key parameters of this scenario are listed in **Table 1.** The variants studied by simulation with Energy Plus are summarized in **Table 2**.

Table 1: Typical hotel room - thermal simulation model details (CIBSE Guide A)

Room area	Floor height	Window wall ratio	Exterior wall u-value	Windows u-value	Floor u-value	Brick density	Brick specific heat	Concrete density	Concrete specific heat
22 m^2	3.6 m	60%	1.54 W/m^2.K	2.61 W/m^2.K	2.2 W/m^2.K	1750 kg/m^3	1000 J/kg-k	2100 kg/m^3	1000 J/kg-K

Table 2: Typical hotel room - thermal simulation loads

Occupants	Equipment load	Infiltration	Lighting density	Ventilation/area	Ventilation/person
2 persons/ room	7.32 W/m^2	0.000227 m^3/s-m^2@4Pa	11.84 W/m^2	0.000305 m^3/s-m^2	0.00236 m^3/s

The hotel guest room blocks were aligned along the site perimeters, incorporating courtyards between building blocks, with smaller wings housing other hotel functions. These design choices give rise to lower terraces accessible to guests and upper terraces for potential photovoltaic (PV) panel installation.

Solar protection: Provided by balcony projections and additional elements designed to shield against direct solar exposure.

Thermal Mass and Night Ventilation: Use of high thermal capacity materials such as rammed earth walls, exposed concrete flooring, and exposed cement coffered ceilings [2, 9]. Doors with reduced WWR of 50% enable guests to access balconies and enhance air exchange **(Table 3).**

Evaporative cooling: Passive Downdraught Evaporative Cooling (PDEC) systems applied to guest rooms for cooling [3, 4]. Air is circulated through shower towers located within the hotel premises. Cooled air is then distributed to rooms via mechanical ventilation systems (**Figure 1**). In tandem with these mechanical systems, solar chimneys are incorporated, inspired by a hotel design in Amsterdam [13], strategically positioned throughout the building to generate negative pressure and expedite the expulsion of hot air from the rooms. The sizing and distribution of the shower towers and solar chimneys align with specifications presented in Table 4. The overall building mass is configured to optimize solar access to these chimneys, thereby enhancing their operational efficiency, as depicted in **Figure 2**. The indoor temperature is calculated according to [7].

Table 3: Improved hotel room - thermal simulation model details (CIBSE Guide A)

Room area	Floor height	Window wall ratio	Wall u-value	Windows u-value	Floor u-value	Earth density	Earth specific heat	Concrete density	Concrete specific heat
22 m^2	3.6 m	50%	1.43 W/m^2.K	1.38 W/m^2.K	1.62 W/m^2.K	1500 kg/m^3	1800 J/kg-k	2100 kg/m^3	1000 J/kg-K

Table 4: Data to calculate size of solar chimneys and shower towers [13]

	No. of rooms (A)	Total area of rooms (estimated m^2) (B)	No. of units (C)	Height (m) (D)	Sectional area (estimated m^2) (E)	Total area (m^2) = CxD (F)	Rooms per unit = A/C (G)	Room area per unit area = B/E (H)
Solar chimneys	198	3606	2	33	2.275	4.55	99	792.5
Shower towers	195	3606	1	33	3.62	3.62	198	996.1

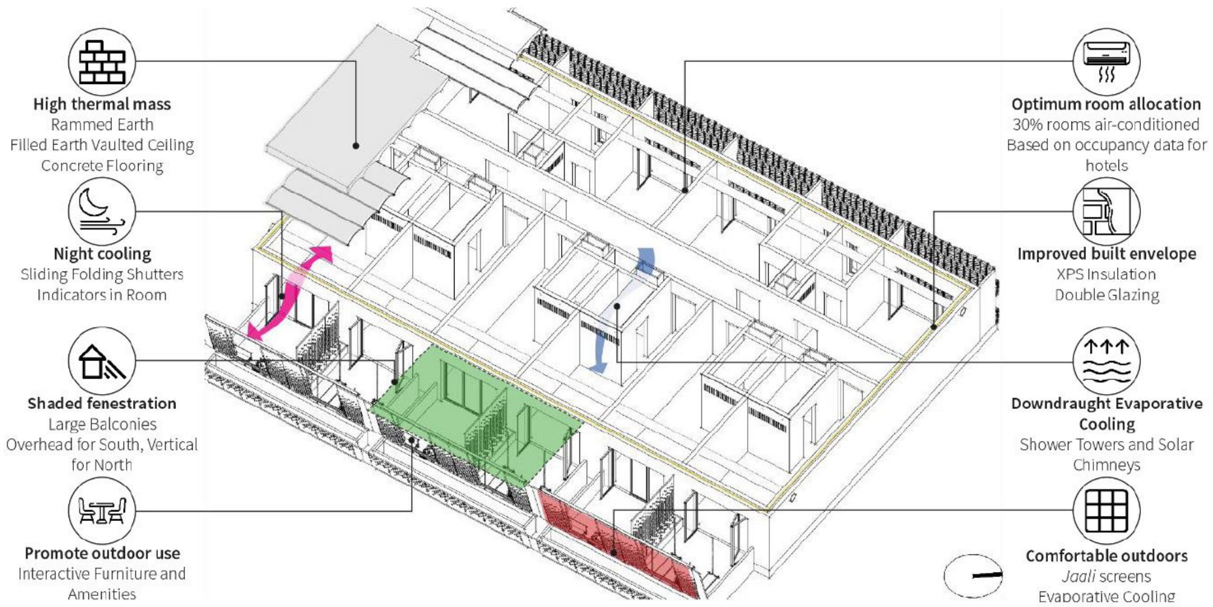

Figure 1: Indoor comfort strategies

1.2 Reducing cooling demand

Optimum room allocation: Hotels often contend with low daytime occupancy rates, particularly between 9 am and 6 pm when outdoor temperatures are at their highest. In such instances occupancy levels are as low as 10%, leaving a substantial majority of hotel rooms vacant during these hours [8]. To address this issue of unnecessarily using A/Cs when not even required, a stringent approach has been adopted where only 40% of the rooms are equipped with the option to utilize mechanical air conditioning (Figure 1). This is substantiated by an extensive survey conducted for this project among 126 North India hotel guests. The survey results revealed that while approximately 58% of respondents expressed a preference for alternative cooling methods over traditional air conditioning, a notable 40.5% of guests still opted for air conditioning even when it was not necessary.

Promotion of Outdoor Use: The survey also unveiled that guests (up to 65%) prefer spending time outdoors, if such facilities such as swimming pools or interactive landscape are made available. In addition to the provision of such amenities, we emphasize the importance of designing outdoor spaces for maximum comfort. To achieve this, a UTCI study identified outdoor areas requiring intervention (Figure 3), subsequently implementing passive design strategies, as discussed in the subsequent sections.

Solar Control: The approach to solar control involves winter sun access to south-facing facades (Figure 2). To further enhance solar control, the façade feature jaali screens [15] with their efficacy tested in Honeybee radiation analysis for both southeast and northwest facades, to arrive at an efficient geometric pattern (Figure 4). Additionally, by creating voids in building mass, shaded spaces are introduced to serve as outdoor seating areas (Figure 2).

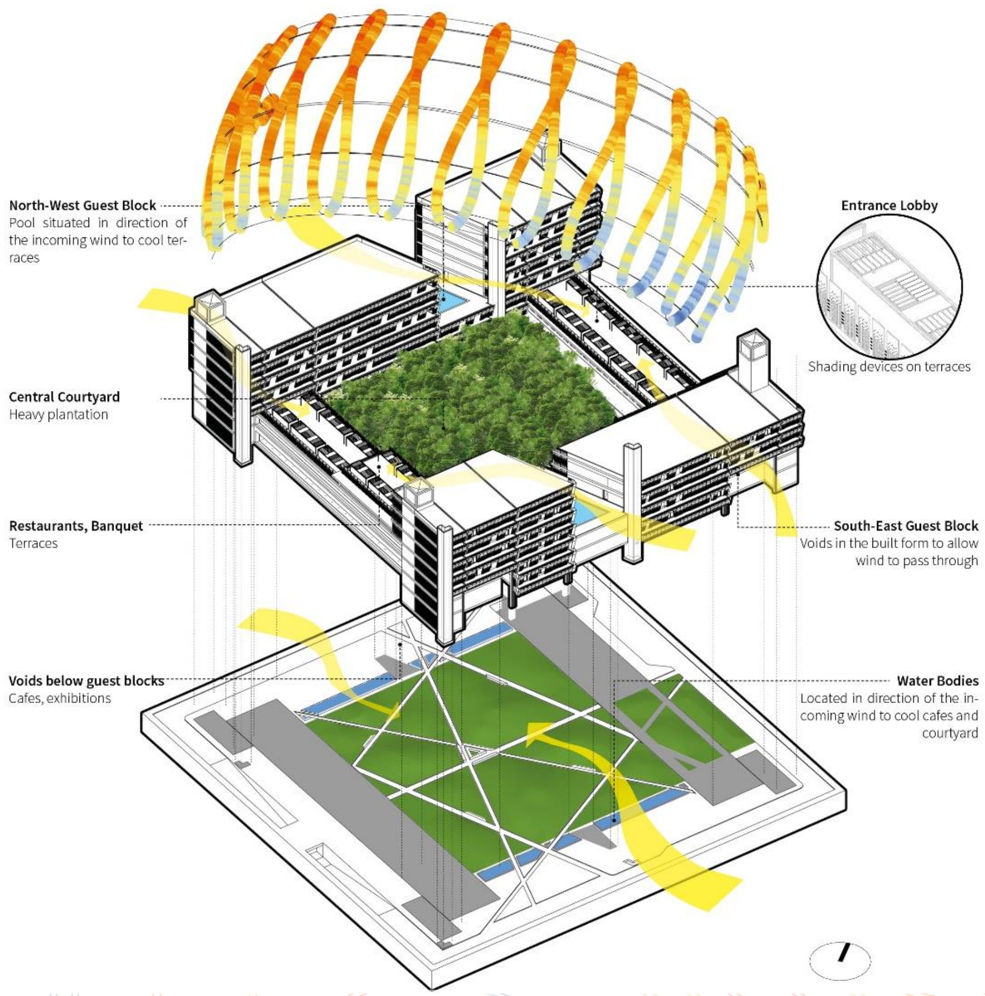

Figure 2: Development of building form and Outdoor comfort strategies

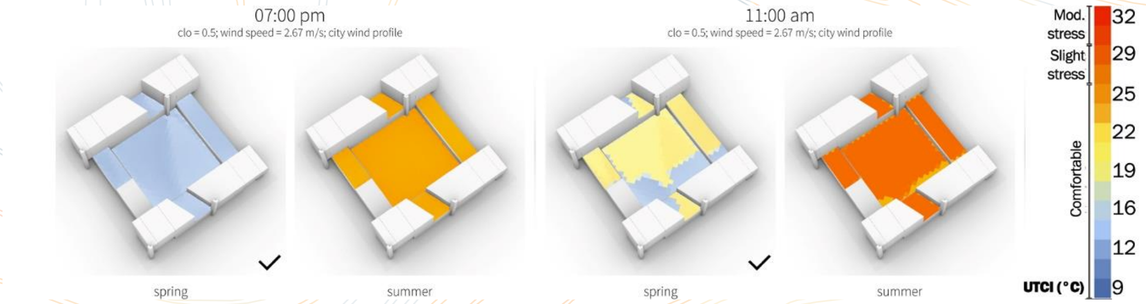

Figure 3: UTCI at 11am and 7pm on Spring Equinox and Summer Solstice

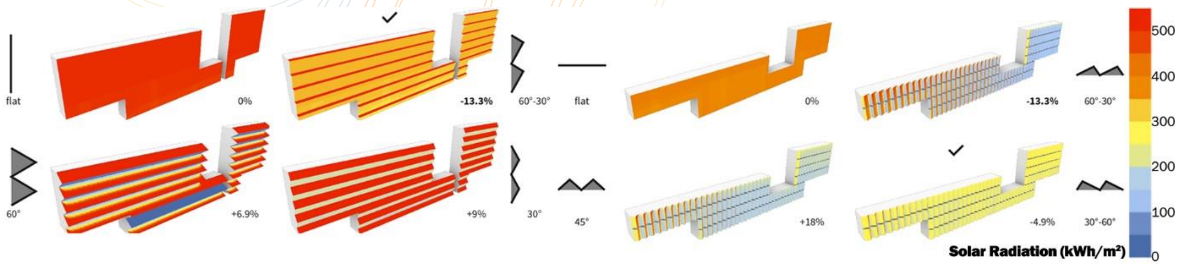

Figure 4: Solar radiation analysis for SW (left) and NW (right) facade from March 21 to Sept21 for different facade designs

Wind Chill Effect: To harness the benefits of natural ventilation, Computational Fluid Dynamics (CFD) studies informed the sculpting of the building mass to facilitate the ingress of wind into courtyards and terraces (Figure 2). To augment guest comfort on balconies, low-energy ceiling fans have been provided, further enhancing the wind chill effect.

Evaporative Cooling: Covered water bodies and swimming pools in alignment with the prevailing wind direction (Figure 2) enhance comfort levels through evaporative cooling for guests frequenting the courtyard and terraces. Moreover, balconies have been equipped with the option for misting, further enhancing guest comfort.

1.3 Renewable energy generation

Based on a usable roof area of 1400 m2 (60% of the total roof area), and an average solar radiation of 5.45 kWh/m2/day for Delhi [1], a plant size of 210 kW generates an annual yield of approx. 301,000 kWh/year, which translates to 83 kWh/m2, when accounting for the total area encompassing the guest rooms (Table 4). Assumptions include approx. 19% nominal efficiency (Standard Module type), fixed array modules, 14% system losses and 20% PV panel tilt towards south).

3. Results

Figures 5 and **Figure 6** illustrate the comprehensive deployment of these strategies on an exceptionally hot day in May and throughout the hottest month of June. The data shows the combined efficacy of the proposed strategies in managing energy loads, resulting in a noteworthy reduction of 21 to 43 kWh/day/room compared to a conventionally air-conditioned room (**Figure 7**).

Achieving outdoor thermal comfort is relatively straightforward except during summer daytime **(Figure 3)**. Nonetheless, solar protection and evaporative cooling alongside harnessing favourable airflow can significantly ameliorate the Universal Thermal Climate Index (UTCI) to a notably more comfortable range **(Figure 8).**

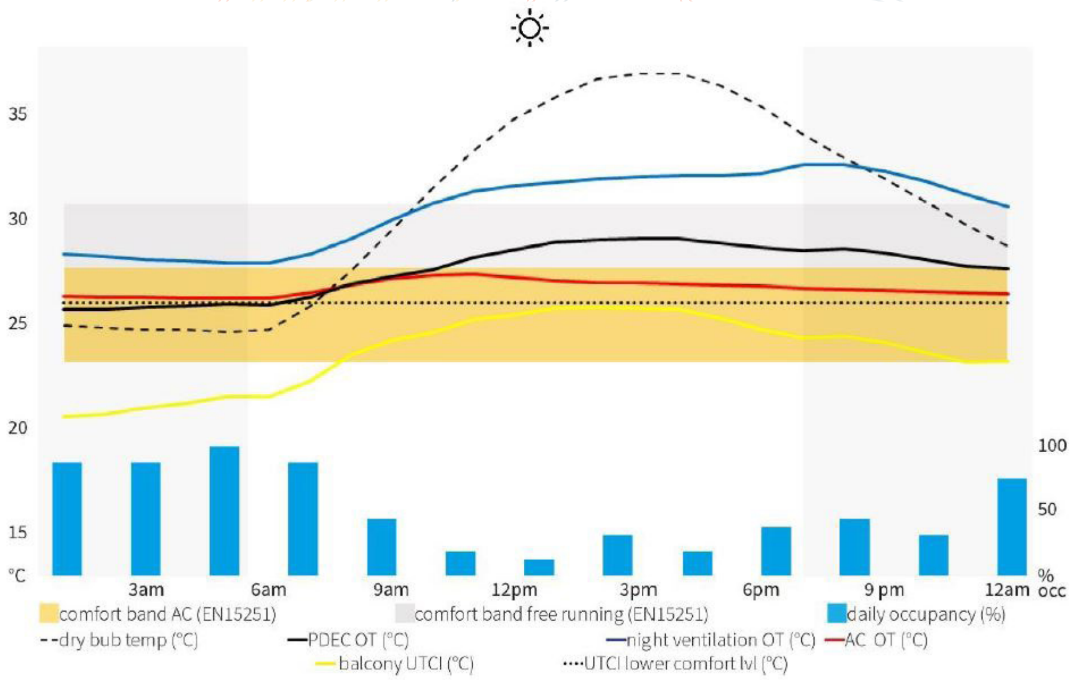

Figure 5: Thermal performance of final guest room design for an extremely hot day

A benchmark comparison against the Bureau of Energy Efficiency (BEE) India energy standards for hotels, stipulating 279 kWh/m²/year [5], showcases that the proposed target achieves an Energy Performance Index (EPI) of approx. 158 kWh/m²/year. Furthermore, the PV panels present the potential to further reduce energy consumption to approx. 75 kWh/m²/year. Consequently, this results in savings exceeding 200 kWh/m²/year when juxtaposed with hotel guest rooms (**Table 5**) relying solely on air-conditioning (**Figure 9**).

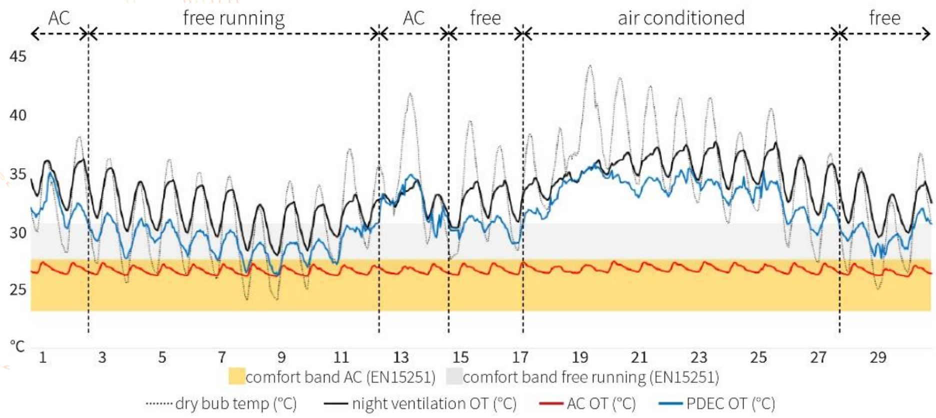

Figure 6: Thermal performance of final guest room design for a mixed mode room - depicting durations when a guest can use AC or not in June

Table 5: Assumptions for guest room energy consumption

Free running room area	Mixed mood (AC) room area	Lighting loads	Equipment loads	Total rooms in hotel
22.06 m^2	18.4 m^2	54 kWh/m^2/year	28.4 kWh/m^2/year	222

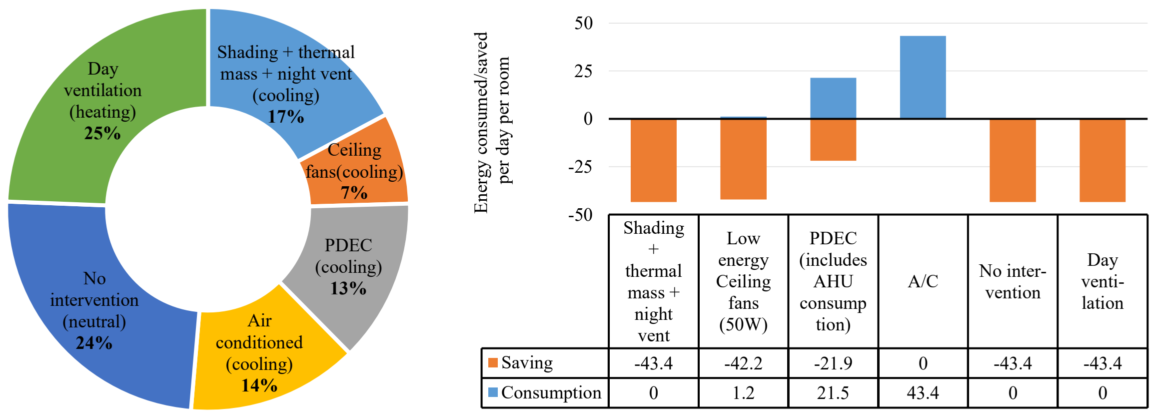

Figure 7: Annual hourly energy distribution (total hours 8760) for different strategies (left) and Energy consumption/savings of these strategies per guest room (right) in kWh/day/room compared to an air conditioned guest room

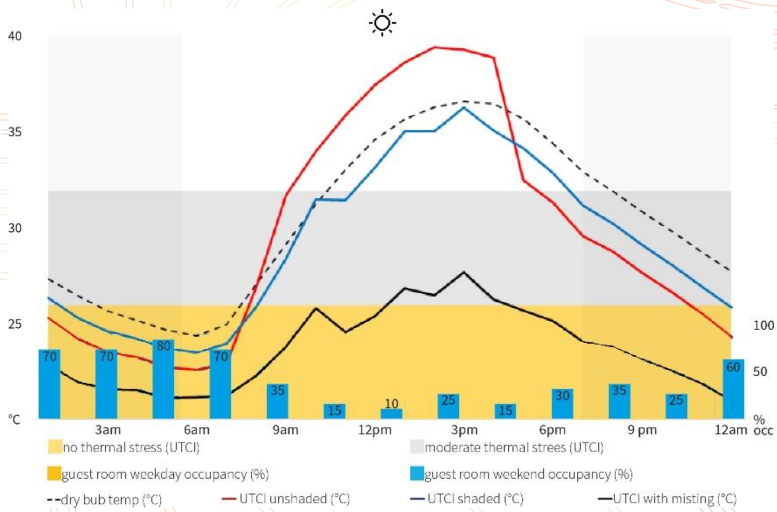

Figure 8: UTCI performance for courtyard - without shading, with shading by trees and for areas with misting or effective evaporative cooling by water bodies

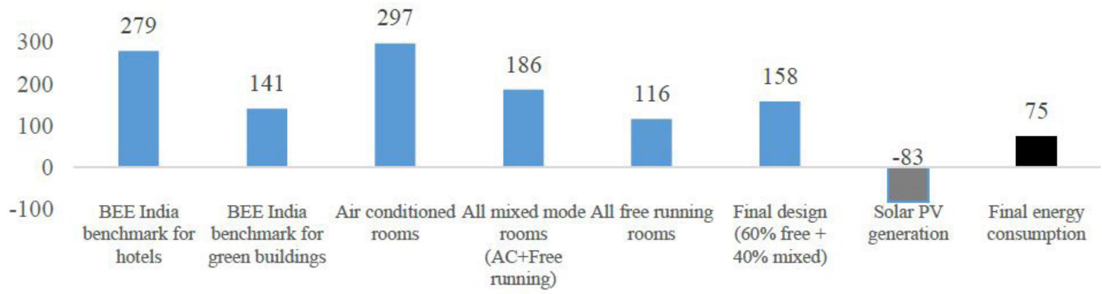

Figure 9: Final energy consumption of proposed hotel rooms compared to energy benchmarks (kWh/m2/year)

4. Discussion

In Delhi's extreme weather conditions, particularly during the sweltering summer peak, complete abandonment of air conditioning may not be a feasible proposition. This limitation stems from the high standards of guest comfort that such establishments are committed to providing. Nevertheless, the research has shown that a judicious fusion of passive cooling strategies, smart allocation of air-conditioned and non-air-conditioned rooms, and informed influence on guest behaviour, guided by contextual insights, can significantly mitigate the excessive reliance on air conditioning.

Outdoor areas, conventionally not subjected to conditioning, can achieve thermal comfort conditions through prudent application of passive design strategies. Encouraging their use can effectively reduce the necessity for guests to seek refuge indoors thus according outdoor spaces an equal significance in the design process. The adoption of sustainable building practices, encompassing the utilization of high thermal mass materials for construction and finishes, as well as the incorporation of local sandstone jaali for facades, contribute to an aesthetically pleasing architectural language (Figure 10) that is attuned to the specific climatic context while simultaneously appealing to the sensibilities of hotel visitors.

Furthermore, the research paper accentuates the role of building managers in comprehending the local climate and being equipped with the knowledge to judiciously apply specific strategies. The integration of technology can be instrumental in facilitating this process. Ultimately, in an era where hotels actively promote sustainability and cultivate a green image, the accrued carbon and monetary savings can be promoted and shared with guests.
It is imperative to acknowledge that the practical implementation of the aforementioned practices necessitates tailored research tailored to specific projects. These projects may vary in accordance with location, climate, user occupancy patterns, and the unique branding associated with a particular type of hotel.

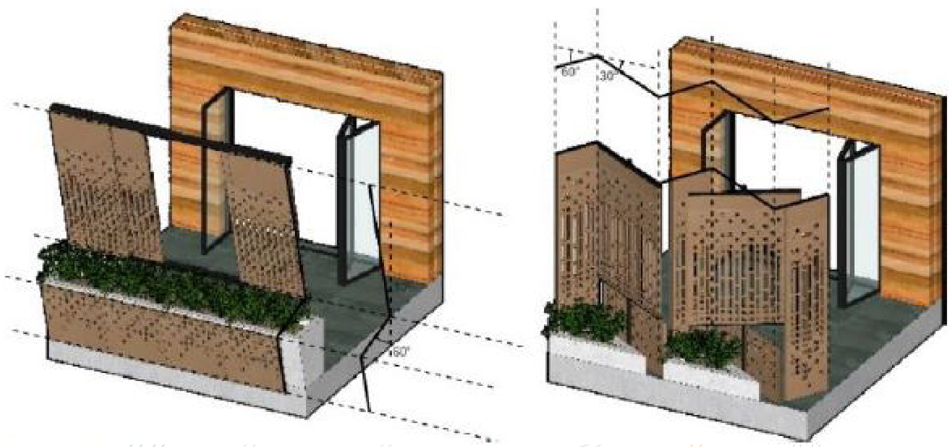

Figure 10: Typical south east facade (left) and typical north east facade (right)

5. Conclusion

The goal of this research paper has been to enhance guest comfort while simultaneously reducing energy demand. The examined design strategies are applicable to hotels of various scales and can help achieve lower energy targets. The study has revealed that basic enhancements, such as effective solar protection and night ventilation, can extend thermal comfort hours in guest rooms by up to 40% over the year. Moreover, during hot-dry periods, evaporative cooling techniques can enhance comfort by an additional 27%, effectively addressing typical summer daytime conditions. Combining shower towers with solar chimneys can prove effective in efficiently circulating air. These findings underscore the importance of adaptable building designs that cater to different seasons, with strategies ranging from PDEC in summers to simple ventilation in monsoons and material with high thermal mass in winter.

This research has underscored the significance of comfortable and inviting outdoor spaces. Guests are naturally drawn to outdoor amenities designed for thermal comfort. Applying principles like those used indoors—shaded spaces, induced air movement, and evaporative cooling—dramatically enhance outdoor user comfort. Thoughtful design, such as well-placed jaali screens for shading, adds to building aesthetics. The final design seeks to offer an aesthetically pleasing, engaging, and comfortable experience for guests.

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Skin temperature and thermal perceptions over the day: a case study in a hybrid-ventilated living lab

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Abstract

This study assesses the dynamic relations between thermal perceptions and skin temperatures across the day in a hybrid-ventilated office environment. Data were collected during the morning (from 9:00 up to 12:00) and afternoon (from 13:30 up to 16:00) across the summer, autumn, and winter. Through the experiments, participants reported their thermal perceptions of the environment every 30 minutes via online surveys. Results indicated that mean skin temperatures were influenced by time of day and participants' gender, with afternoon temperatures generally higher than morning temperatures. Results also supported that the skin temperatures of female subjects varied more rapidly according to the operative temperature, especially during the afternoon. Finally, participants tended to prefer warmer conditions when skin temperatures were lower and vice-versa. The findings emphasize the complex interplay between thermal comfort, occupants' gender, and circadian rhythms, highlighting the importance of in-depth characterizations of occupants' thermal preferences.

Keywords - Circadian rhythm, Thermal perception, Skin temperature, Thermal comfort.

1. Introduction

The circadian rhythm is a biological clock that regulates rhythmic changes in the behavior and physiology of most living beings. These cycles occur over a 24-hour period and are influenced by external time signals, which can endure even without these signals [1]. Circadian rhythms regulate the sleep-wake cycle, locomotor activity, body temperature, hormone secretion and metabolic changes during each day/night cycle [2]. In healthy subjects, body temperature shows cyclical fluctuations and slightly higher temperature in the daytime than at night. Also, gender significantly influences body-temperature circadian rhythm [3]. Mean skin temperature is an important physiological aspect that reflects the heat exchange between the human body and the environment, with an evident relation with human subjective assessment of such a thermal environment.

Also, recent studies emphasize the effect of the time of day on human thermal perception due to autonomic thermoregulatory processes influenced by the circadian rhythm [4]. Previous studies are more conclusive considering variations in the circadian transition periods (morning and evening). However, a common understanding still needs lacking since contradictory information is found in the literature. Despite finding higher skin and rectal temperatures in the evening, Fanger et al. [5] concluded that participants preferred similar ambient temperatures in the morning and the evening. However, Kakitsuba et al. [6] concluded that, in controlled conditions (28°C with 70% and 80% RH), participants moved from "warm" in the morning to "neutral" or "slightly warm" in the evening. Vellei et al. [7] reported a higher rate of changes in skin temperatures in the evening compared to the afternoon, and greater thermal sensations were reported from the subjects when warming transients were applied to the skin.

Although contradictory, the literature on such topics still needs to be explored to conduct meta -analysis and determine reliable trends. Indeed, the recent literature review by Vellei et al. [4] reported only 21 articles that included "time of day" as a variable. The lack of information regarding real-life environments is also a key point since the majority (15 out of 21) of the previous studies were conducted under controlled laboratory conditions. Another limitation is that little information is reported about the middle of the day – when more minor changes are expected. Understanding physiological and perceptual variations throughout the day – and in different seasons – is essential and may directly impact offices' operations.

This study examines the variability of skin temperatures and thermal votes among women and men during morning and afternoon in a hybrid-ventilated office located in Florianópolis, Brazil. The main hypothesis is that such variabilities may lead to varied thermal requirements from occupants, which may be included in the building operation loop instead of pre-defined and fixed schedules.

2. Methods

2.1 The experiment protocol

The study was conducted at the Living Lab of the Laboratory of Energy Efficiency in Buildings at the Federal University of Santa Catarina (UFSC) in Florianópolis, Brazil. The experiment involved monitoring the environmental conditions and the participants' physiological variables during regular working hours. The daily monitoring period encompassed the hours from 9:00 to 12:00 and 13:30 to 16:00. Data were collected for the summer, autumn, and winter seasons of the southern hemisphere, with each participant contributing at least two workdays per season. Each experiment day was designed to set the participants (maximum of 4 per day) allocated near each other. The strategy was implemented to use a single environmental measuring device and ensure that the monitored variables represented the microclimate closest to the participants' workstations.

Throughout the monitoring period, participants responded to online questionnaires every 30 minutes. During the first half-hour of each session, no questionnaire was administered, allowing participants to acclimate to the environment. The questionnaire was divided into sections with varying numbers of questions: Anthropometric and behavior questions (14), Comfort questions (03), and Thermal perception and preference questions (12). It is important to note that the initial questions regarding anthropometry and behavior were answered only during the participants' first-day response. Subsequent responses encompassed only thermal perception assessments. This study focuses on occupants' thermal preferences, evaluated by the votes of the participants assessed with a 7-point scale: 01 – Much cooler, 02 – Cooler, 03 – Slightly cooler, 04 – Without change, 05 – Slightly warmer, 06 – Warmer, and 07 – Much warmer.

2.1.1 Environmental variables monitoring

The air and globe temperatures were monitored at 0.6 m height on one side of the participant at a distance of about 40-50 cm (Fig.1). The mean radiant temperature was computed from the globe temperature. A Testo 400 climate universal measuring device was used in a tripod structure, including a temperature and humidity sensor, an omnidirectional air velocity sensor, and a 150 mm-diameter globe probe.

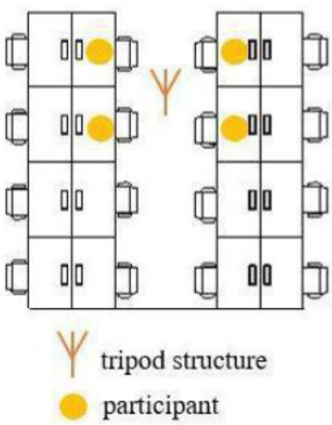


Figure 1: Tripod Structure located between worktables and close to the participants

2.1.2 Physiological signals monitoring

The measurement of human physiological variables encompassed skin surface temperatures and heart rate variability. The present study focuses on skin temperatures. Thermochron Ibutton temperature gauges were used, with an accuracy of 0.0625 °C and recording every 60 seconds, positioned on the skin surface. The chosen method (defined in [8]) considers ten measurement points distributed in different human body regions, identified by letters in Figure 2.

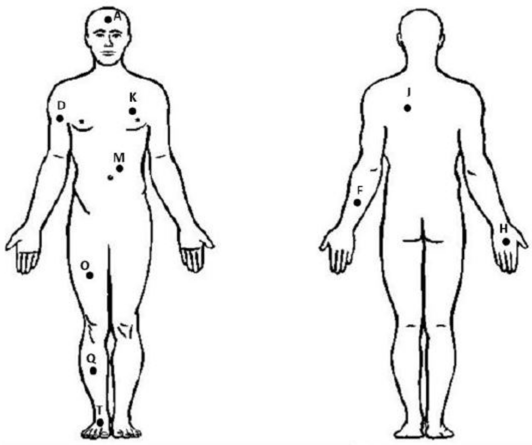


Figure 2: Tripod Structure located between worktables and close to the participants

2.2 Building characteristics

The Living Lab has approximately 250 square meters and a ceiling height of 2.65 m. It consists of a shared workspace with 36 workstations, two workrooms, two meeting rooms, and a kitchen, as identified in the layout according to Fig. 3. The shared space has windows along the entire northeast and southeast facades, allowing cross-ventilation. There are five cassette-type air conditioners in the shared area and one unit for each work and meeting room. Participants can also use PECS (Personalized Environmental Control Systems, like fans and evaporative coolers) on their work desks.

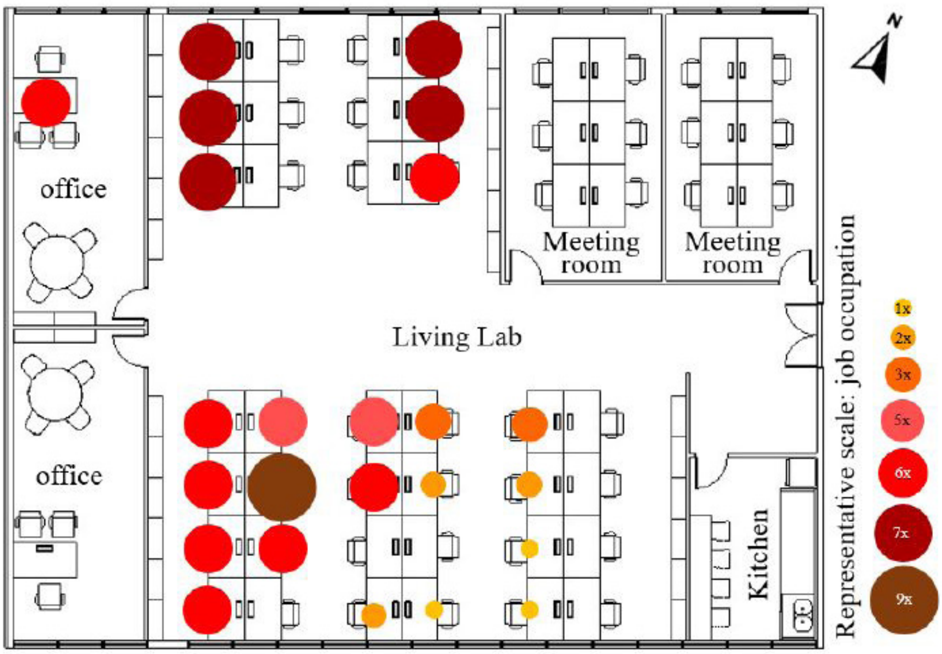


Fig. 3: Living lab layout with the representative scale of occupation in the experiment

The workspaces were occupied as usual concerning the activities carried out, the clothing used, and the operation of the air conditioners. It should be noted that typical office activities are carried out in this environment. Using a single piece of equipment to measure environmental variables required some participants to move from their workstations to optimize data collection, maintaining the measurements with 3 or 4 participants. In addition to the Living Lab layout, Figure 3 includes a representative scale of the number of times a particular workstation was occupied during the experiment. The scale increases in the direction of higher usage of a given workstation.

2.3 Participants

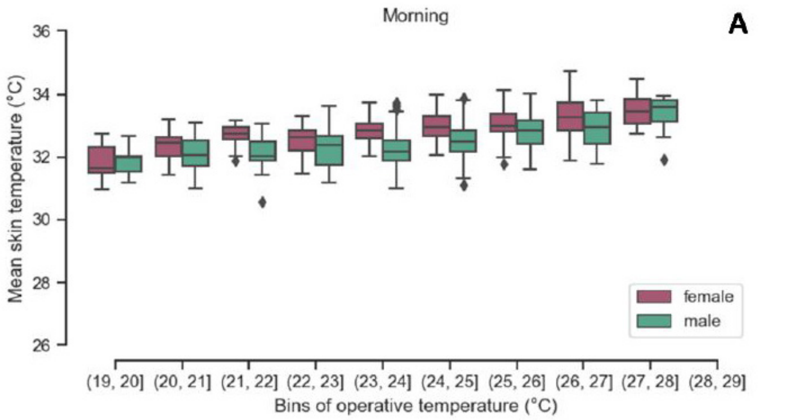
The participants consisted of 19 adults (11 females and 8 males). Male participants were aged between 23 and 32 years, with an average height of 1.75 m and an average weight of 75 kg. Female participants were aged between 22 and 49 years, with an average height of 1.63 m and an average weight of 59 kg. Participants were instructed to wear clothes of their preference and follow their regular eating routines. During the experiment, participants carried out everyday office activities (studying, reading, using the computer).

2.4 Analysis

Initially, the data collected in the experiment were segmented into two groups: a) morning and b) afternoon. Next, the same groups were subdivided by male and female gender. The analysis in the four groups correlated the mean skin temperatures, measured by the MST-10 method [8], with bins of operative temperature. Regarding the thermal preference votes, since the responses were mostly "Without change", a 3-point scale was used. The "cooler" options (1, 2, and 3) and the "warmer" (5, 6, and 7) were grouped. The preference votes were evaluated in terms of the mean skin temperatures and the hand skin temperature, since clothes generally uncover the participants' hands.

3. Results

The data collected from the participants (skin temperatures and thermal preference votes) and operative temperature were segmented according to time of day (morning and afternoon) and gender (female and male). The results obtained from the experimental campaign indicate slightly smaller mean skin temperature (MST) in the morning (μ = 32.91°C; σ = 0.59°C for females; μ = 32.47°C; σ = 0.70°C for males) compared to the afternoon (μ = 33.38°C; σ = 0.75°C for females; μ = 33.00°C; σ = 0.66°C for males). This difference is statistically significant at 1% (t-statistic: -12.93; p-value ≈ 0.00). Importantly, indoor air speeds were similar in the morning (μ = 0.08 m/s; σ = 0.06 m/s) and in the afternoon (μ = 0.07 m/s; σ = 0.07 m/s). In the graphs shown in Figure 4, the medians and quartiles of the average skin temperatures were presented versus ranges of operative temperature for each analysis group. All the means and medians of skin temperatures were higher in the afternoon compared to the morning according to the bins of operative temperatures for both genders. The only exception was observed for females when the operative temperatures ranged from 20°C up to 21°C, in which morning temperatures were slightly higher. Importantly, in this specific case, only three votes were registered in the afternoon, which may have impacted the outcome. Another takeaway from Figure 4 is that local temperatures at the hands of female participants are observed to be lower than the males for most operative temperatures across the day.



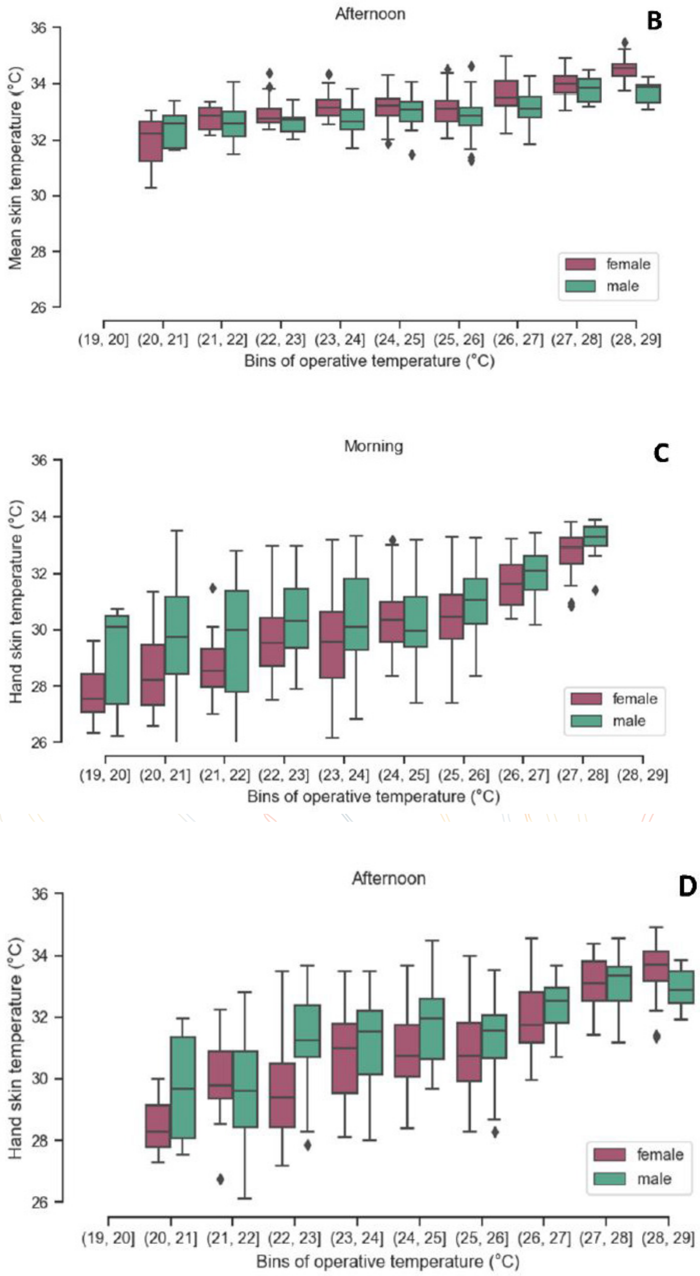


Figure 4: Morning (A) and afternoon (B) mean skin temperatures, and morning (C) and afternoon (D) hand skin temperatures according to bins of operative temperatures

A follow-up analysis comprised the relation between mean skin temperatures (Tskin) and participants' thermal preferences. Figure 5 shows combinations of scatter plots (relationship between Tskin and thermal preference) and histograms (distributions of thermal preferences and Tskin). Results show similar tendencies (preferring to be warmer with smaller Tskin and preferring to be cooler with bigger Tskin) for both genders. However, such a tendency is more evident for women, especially during the afternoon, as shown by the regression coefficients calculated. A further regression analysis of mean skin temperatures and operative temperatures was conducted. All the coefficients were positive (indicating increases on Tskin with higher operative temperatures); however, higher regression coefficients were observed for females (R^2_morning: 0.34; R^2_afternoon: 0.41) compared to males (R^2_morning: 0.23; R^2_afternoon: 0.26).

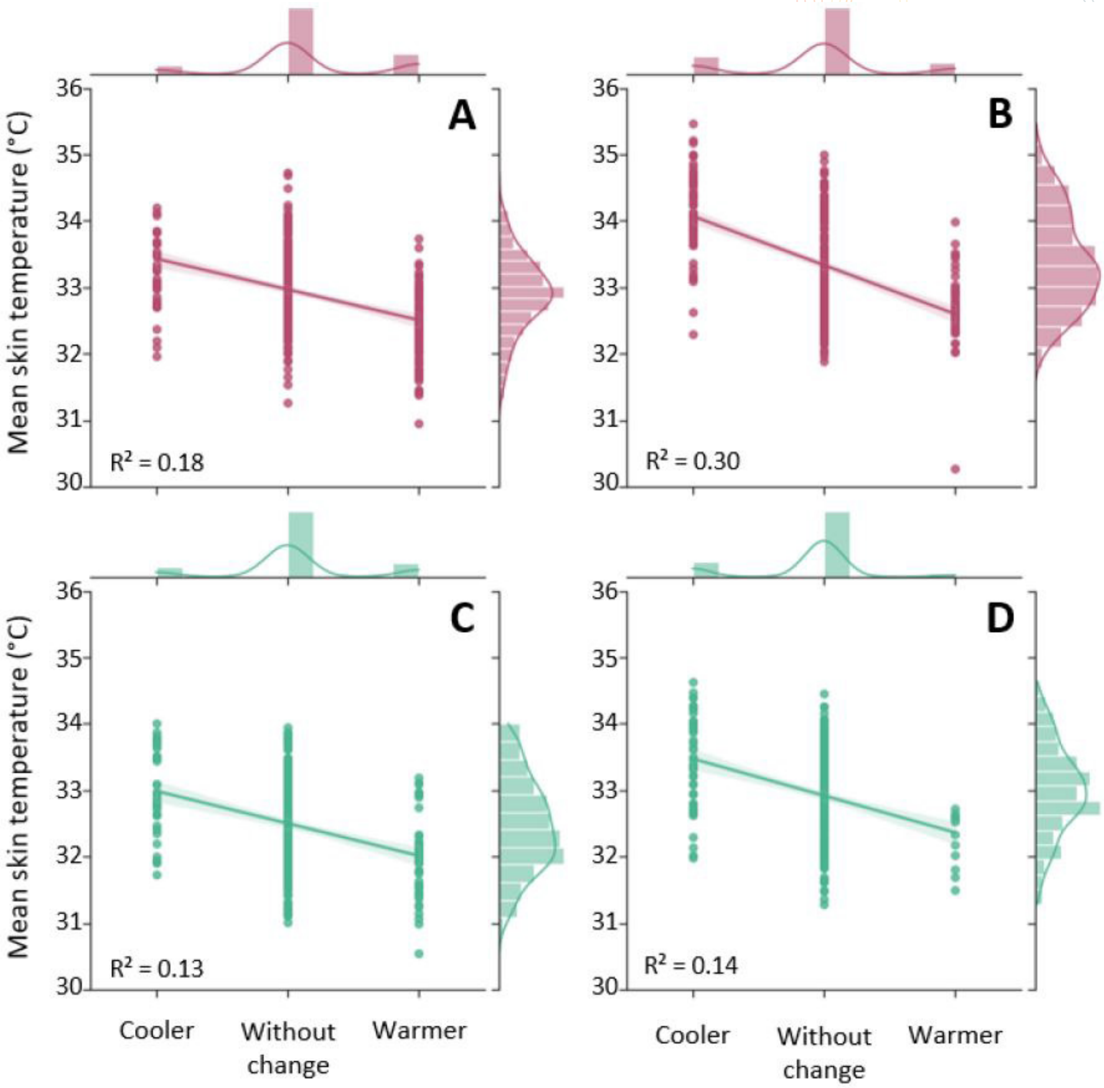


Figure 5: Preference x Mean skin temperature for females in the morning (A) and afternoon (B), and males in the morning (C) and afternoon (D)

Finally, descriptive statistics for the operative temperature were calculated according to the stated thermal preference at the moment (cooler, without change and warmer) and grouped by the time of day and participants' gender. Table 1 shows this synthesis and the count of votes in each category. Mean and median operative temperatures associated with all thermal preferences were higher for females than males.

Table 1: Descriptive statistics for operative temperature by preference and gender

		Operative temperature (°C)							
Preference	Gender	Morning				Afternoon			
		mean	median	std	count	mean	median	std	count
Cooler	Female	26.08	26.74	1.60	35	27.35	27.68	1.56	68
	Male	25.72	25.91	1.46	34	27.07	27.27	1.24	52
Without change	Female	24.39	24.51	1.87	257	25.19	25.30	1.96	248
	Male	23.69	23.88	1.99	229	24.46	24.87	2.09	222
Warmer	Female	23.09	23.13	2.08	83	23.76	23.25	1.47	45
	Male	21.65	20.88	1.87	51	22.15	22.01	1.48	11

4. Discussion

The results about mean skin temperatures of females and males differ from some previous studies. Schellen et al. [9] found smaller skin temperatures for females than males under different experimental conditions. Similar trends were seen by [10]. However, scientific literature also supports that female skin temperatures are lower in cooler environments and higher in warm environments [11]. Additionally, the mean skin temperatures of female subjects varied more rapidly according to the operative temperature [10]. Similar trends were observed in this study as shown by the regression coefficients presented in the results section: higher R^2 (Tskin versus operative temperatures) were found for women, especially during the afternoon. This tendency is also related to the higher influence of Tskin on thermal preferences for women. The present study adds some evidence about the influence of the time of day on psychophysiological responses of building occupants. Since previous studies reported that women are more sensitive to indoor temperatures [12,13], understanding to what extent circadian cycles may impact such sensitiveness across the day is key to further developments. In-depth knowledge of this possible tendency may encourage the dissemination of Personalized Environmental Control Systems (PECS) instead of adopting fixed operation strategies across the day.

Previous studies have emphasized that gender plays an important role in the psychophysiological responses of building occupants [13,14]. Looking specifically at gender differences, the present study supports that mean and median values of operative temperatures associated with each thermal preference (cooler, without change and warmer) were bigger for females than males. Additionally, such values were higher in the afternoon compared to the morning. Although this case study was conducted in a hybrid-ventilated office where afternoon temperatures tend to be higher than those observed in the morning, this tendency is aligned with possible variations in occupants thermal perceptions across the day. Again, a combination of gender and time of day tendencies were observed, since both aspects played a role in determining typical operative temperatures associated with thermal preferences. The outcomes reached with this study deserve some attention when confronted with previous research considering the intrinsic characteristics of Living Labs. When compared to previous studies, mostly conducted in climate chambers. It is important to consider that Living Labs provide a wide range of personal adaptations, including choosing and adjusting personal clothing throughout the day. Conducting thermal comfort studies in Living Labs is important to determine actual conditions and preferences reached in typical environments and occupancy conditions. This is a key aspect to complement knowledge gathered in controlled conditions (e.g., climate chambers or test rooms). When focusing on localized temperatures at hand (a body part uncovered by clothing for all the participants), smaller temperatures were observed for females, especially in smaller operative temperatures. This aspect may be leading to the overall thermal perceptions of female participants, as previously reported by other studies [9].

Finally, this case study presents some limitations, including the centralized instead of a personalized collection of environmental variables, as well as the sample size, variability of age among participants, variability of clothing adopted and variable thermal conditions throughout the day. Also, no control over the menstrual cycle of female participants have been made. Some of these limitations are intrinsic to the Living Lab approach adopted herein, and results from such a typical office environment may add practical knowledge to the field .

5. Conclusion

In this study, skin temperatures and thermal preferences of 18 adults (10 females and 8 males) were collected in a Living Lab of a typical office environment across three seasons (summer, autumn, and winter). The experiments were focused on typical full days, with data being continuously collected during the morning and the afternoon. The results of this study indicate:

- Time of day influences psychophysiological responses of office occupants, which emphasizes the need to better understand the influence of circadian rhythm on occupants' thermal sensitivity and preferences.

- Occupants preferred higher mean operative temperatures in the afternoon compared to the morning.

● Higher means and medians of operative temperatures were associated with all the thermal preferences (cooler, without change and warmer) reported by females compared to males.

● Skin temperatures from women varied more rapidly according to operative temperatures than those observed in men. This aspect was even more evident during the afternoon.

6. Acknowledgements

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Study on behavioral adaptation for the adaptive thermal comfort and energy saving in Japanese office buildings

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Abstract

Office workers use a variety of adaptive opportunities to regulate their indoor thermal environment. The behavioural adaptations such as window opening, clothing adjustments, and use of heating/cooling are important factors for adaptive thermal comfort. It is well-known that they are the most important contributors in the adaptive thermal comfort model. Thus, if we understand the behavioural adaptation properly, we can explain the mechanism of the adaptive model. The indoor thermal environment is often adjusted using the air conditioning in Japanese office buildings to improve thermal comfort and productivity. Thus, it is necessary to conduct research on the behavioural adaptation in the offices because the occupant behaviour is different from behaviour in dwellings. In order to record the seasonal differences in behavioural adaptation and to develop an adaptive algorithm for Japanese offices, we measured temperatures in seven office buildings and conducted the thermal comfort and occupant behaviour survey for over a year. We collected 1,228 samples. The proportion of 'open windows' is significantly high in the free running and air conditioned modes. The behavioural adaptation is related to the outdoor air temperature. The clothing adjustments, heating and cooling use can be predicted by regression equations. These findings can be applied to building thermal simulation to predict the behavioural adaptation and energy use in office buildings.

Keywords - Office buildings, Occupant behaviour, Window opening, Clothing adjustment, Heating and cooling use.

1. Introduction

People use a variety of adaptive opportunities to regulate their indoor thermal environment. The behavioural adaptations such as window opening, clothing adjustments, heating/cooling use are some of the important factors for adaptive thermal comfort. It is well-known that they are the most important contributors in the adaptive thermal comfort model. Thus, if we understand the behavioural adaptation properly, we can explain much of the mechanism of the adaptive model. In addition, the indoor thermal environment is often adjusted using the air conditioning in the Japanese office building to improve the thermal comfort and productivity. However, temperature control using window opening can reduce environmental impact by reducing the use of air conditioning as much as possible. Thus, it is necessary to conduct research on the behavioural adaptation in the offices because the occupant behaviour is different from adaptive behaviour in dwellings.

A number of projects have researched occupant behaviour in offices [1-12], and dwellings [13-20]. The occupant behaviour model developed for office buildings in other countries [3] may not apply to Japan and research about occupant behaviour is needed for Japanese offices, for results from one region of the world cannot be assumed to apply to another where there is a different culture and building design. Thermal simulation packages often assume a fixed schedule of window opening [4], so more realistic data on occupant behaviour will help to improve the thermal simulations and an adaptive algorithm becomes a useful passive design tool. In order to record the seasonal differences in behavioural adaptation and to develop adaptive algorithms for Japanese offices, we measured temperatures in seven office buildings and conducted occupant behaviour surveys for over a year in the Aichi prefecture of Japan.

2. Methods

2.1 Field Survey

Occupant surveys were conducted and corresponding thermal measurements made in seven office buildings in the Aichi prefecture of Japan from July 2021 to October 2022 (see Table 1). The indoor air temperature, globe temperature, relative humidity and air movement were measured 1.1m above floor level, away from direct sunlight, using a data logger (Table 2). Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

Table 1: Description of the investigated buildings [21, 22]

Building code	Location	Structure	Mode	HVAC control	Window	Number of floor	Investigated floor*
N1	Ichinomiya	SRC	MM	Local	Openable	3F	2F
N2	Nagoya	RC	MM	Local	Openable	6F	1F~3F
N3	Nagoya	SRC	HVAC	Central (Local control)	Openable (For disaster prevention)	1B, 8F	4F
N4	Nagoya	SRC	MM	Local	Openable	1B, 5F	2F
N5	Nagoya	SRC	MM	Local	Openable	1B, 17F	4F
N6	Nagoya	S, Some parts SRC	HVAC	Central (local control)	Fixed	4B, 34F	27F
N7	Nagoya	RC	MM	Local	Openable	1B, 8F	5F

HVAC: Heating, ventilation and air conditioning, MM: Mixed mode (heating in winter and cooling in summer), *: The floor is counted by American system, SRC: Steel Reinforced Concrete, RC: Reinforced concrete, S: Steel, F: Floor, B: Basement

We conducted both longitudinal [21] and transverse surveys [22] in open-plan offices. This paper analyses only the data from the transverse survey. Transverse surveys were conducted 1 day each month by researchers visiting each building with measurement instruments and with questionnaires filled by each subject. On each visit, one set of responses was collected from each subject. As for the method of collecting the data, the instruments were set up on the office table, and questionnaires distributed to all people seated near to the instruments. While people were filling the questionnaire, the researcher recorded the common environmental controls and the physical data from them. Window opening, heating use and cooling use were recorded in binary form at the time of completing the questionnaire (0 = window closed or heating/cooling off, 1 = window open or heating/cooling on). We collected 1,228 votes.

Table 2: Description of the instruments

Parameter measured	Trade name	Range	Accuracy
Air temperature, Relative humidity (RH)	TR-76Ui	0 to 55 °C, 10% to 95% RH	±0.5 °C, ±5%RH
Globe temperature	Tr-52i	−60 to 155 °C	±0.3 °C
	SIBATA 080340-75	Black painted 75 mm diameter globe	-

2.2 Estimating the Occupant Behaviour

Nicol and Humphreys [3] made use of logistic analysis to predict occupant control behaviour in naturally ventilated buildings. We have adopted this method here, using SPSS version 23 for the calculations. The relationship between the probability of heating use or cooling use (p) and the outdoor air temperature (To) is of the form:

$$\mathrm{logit}(p) = \log\{p/(1-p)\} = bT_o + c \quad (1)$$

$$p = \exp(bT_o + c)/\{1 + \exp(bT_o + c)\} \quad (2)$$

where exp (exponential function) is the base of the natural logarithm, b is the regression coefficient for To and c the constant in the regression equation.

3. Results and Discussion

The data were divided into three groups. If heating was in use at the time of the survey visit, the data were classified as being in the heating mode (HT). If cooling was in use at the time of the visit, the data were classified as being in the cooling mode (CL). If neither heating or cooling were in use, the data were classified as being in the freerunning mode (FR).

3.1 Outdoor and Indoor Temperature during the Voting

As shown in Figure 1, the seasonal range of the indoor temperature was quite small, while there was a wide seasonal range of outdoor temperature. The indoor globe temperature is highly related to the indoor air temperature [22], and so the results can be presented using the globe temperature alone. The mean globe temperatures during the voting were 25.0 °C, 24.2 °C and 25.5 °C for FR, HT and CL modes respectively [22]. The Japanese government recommends indoor temperature of 20 °C in winter and 28 °C in summer for energy saving respectively. The results showed that the mean indoor temperatures during heating and cooling were quite different from those recommended values.

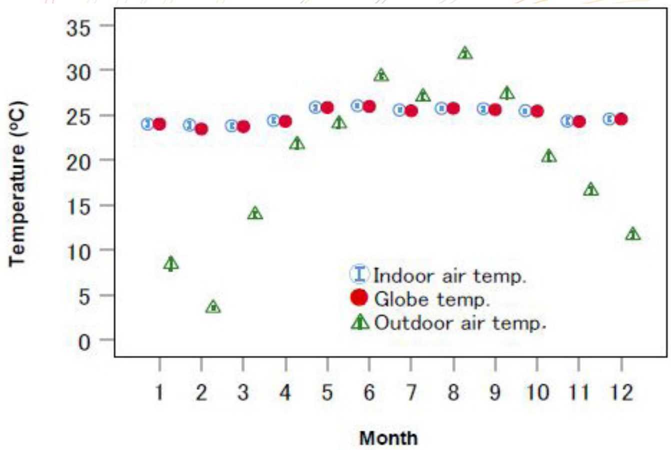

Figure 1: Variation of outdoor and indoor temperatures (Mean±2S.E.) [22].

3.2 Window Opening Behaviour

Figure 2 shows the proportion of window opening in mixed mode buildings. The mean 'open window' for all data is 0.59 (n=1,022). When we compared by building, the mean value ranged from 0.50 to 0.80. The mean window opening is 0.68, 0.59 and 0.48 for FR, HT and CL modes respectively. The mean window opening in UK office buildings was 0.70 in NV mode and 0.04 in AC mode [4]. The mean windows open in Pakistan office and commercial buildings was 0.33 in NV mode [5]. The results showed that the mean windows open in FR mode is close to the UK and much higher than the Pakistan. Due to the COVID-19, the window opening is very high in the HT and CL modes. During the COVID- 19 pandemic, guidance has been issued by Japanese authorities that windows must be left open in many building types, even when the AC is in use, to purge spaces of the virus, because many HVAC systems recycle air from room to room, so increasing the risk of cross transmission of the pathogen indoors [10, 23-25].

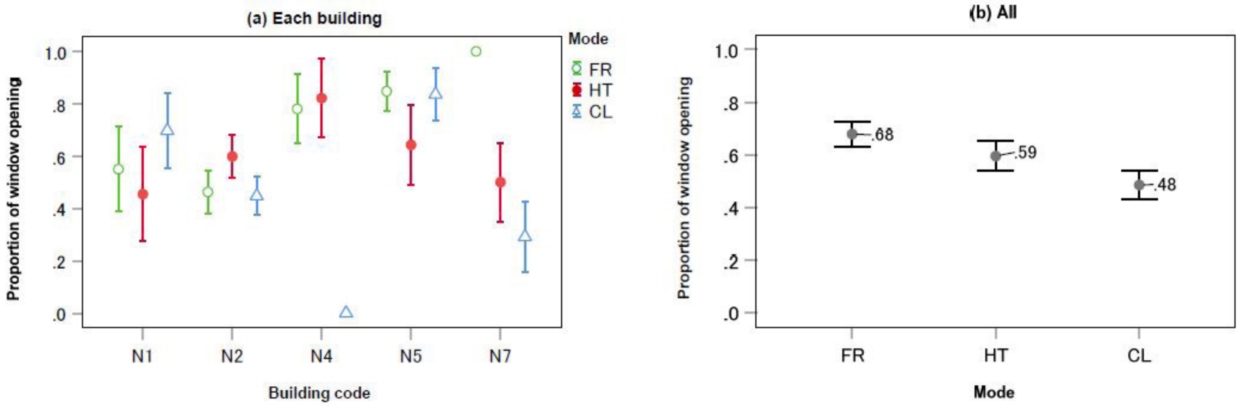

Figure 2: Proportion of window opening in mixed mode buildings

3.3 Clothing Adjustments

Figure 3 shows the mean clothing insulation by mode in mixed mode building. The mean clothing is 0.73 clo in FR mode which is slightly higher than CL mode and lower than HT mode. The results show that people adjusted their clothing considerably in each mode.

In order to predict the clothing insulation, regression analysis of the clothing insulation and outdoor air temperature is conducted. Figure 4 shows the relation between the clothing insulation and outdoor air temperature with the 95% confidence interval of the individual clo-values in MM and HVAC buildings. The following regression equations were obtained between the clothing insulation (Icl, clo) and outdoor temperature.

MM $I_{cl} = -0.02T_o + 1.2$ (n = 41030, $R^2 = 0.40$, S.E. = 0.001, $p<0.001$) (3)

HVAC $I_{cl} = -0.01T_o + 01.0$ (n = 196, $R^2 = 0.27$, S.E. = 0.0001, $p<0.001$) (4)

All $I_{cl} = -0.02T_o + 1.1$ (n = 1226, $R^2 = 0.37$, S.E. = 0.001, $p<0.001$) (5)

R^2 is the coefficient of determination. The regression coefficients are negative for all equations. It shows that the clothing insulation decreases when outdoor air temperature is increased.

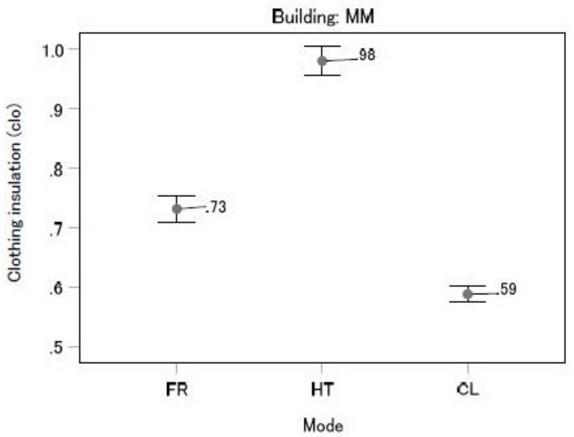

Figure 3: Clothing insulation by mode in the mixed mode buildings (Mean±2S.E.).

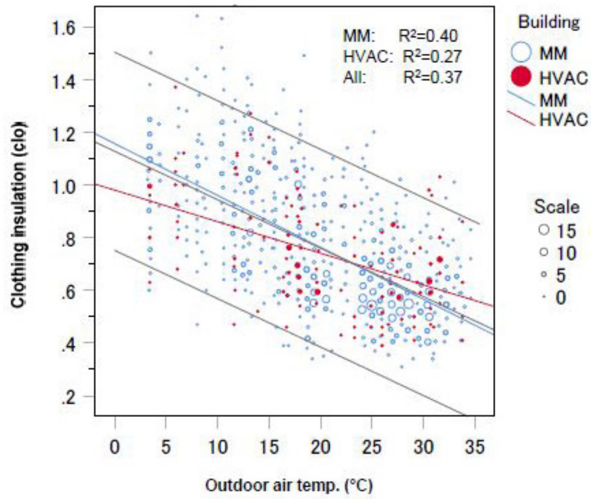

Figure 4: Relation between the clothing insulation and outdoor air temperature.

3.4 Heating and Cooling Use

In this section, we will analyse the heating and cooling use. These behaviours are needed for the thermal simulation of buildings. Table 3 shows the logistic regression equations obtained for each building and all data in between the heating use or cooling use and the outdoor air temperature. These equations are presented in Figure 5. The proportion of the heating use rises as the outdoor temperature decreases, and the proportion of the cooling use rises as the outdoor temperature increases.

Table 3: Regression equations for heating and cooling use

Behaviour	Building	Equation	n	S.E.	R^{2*}	p
Heating	N2	logit(p)=-0.511T_o+8.4	474	0.051	0.55	<0.001
	N4	logit(p)=-0.635T_o+7.3	95	0.158	0.58	<0.001
	N5	logit(p)=-1.169T_o+18.1	189	0.238	0.52	<0.001
	N7	logit(p)=-0.627T_o+8.6	146	0.137	0.59	<0.001
	All	logit(p)=-0.530T_o+8.1	1022	0.038	0.54	<0.001
Cooling	N1	logit(p)=0.431T_o-11.5	116	0.089	0.44	<0.001
	N2	logit(p)=0.810T_o-19.9	474	0.094	0.60	<0.001
	N5	logit(p)=695T_o-18.0	186	0.141	0.61	<0.001
	N7	logit(p)=1.123T_o-28.4	148	0.364	0.63	<0.001
	All	logit(p)=0.688T_o-17.2	1019	0.053	0.58	0.002

T_o: Outdoor air temperature (°C), n: Number of sample, S.E.: Standard error of regression coefficient, R^{2*}: Cox and Snell R^2, p: Significance-level of the regression coefficient.

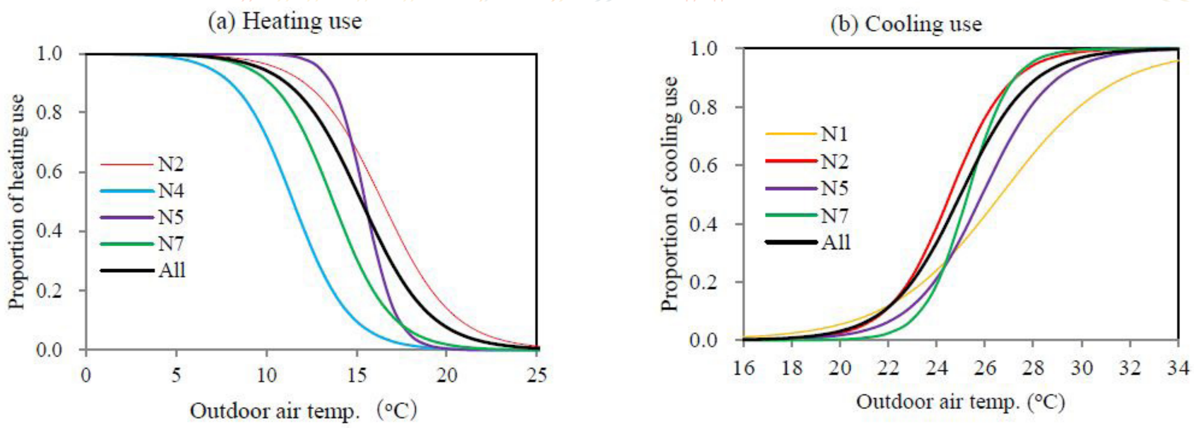

Figure 5: Proportion of window opening in mixed mode buildings.

4. Conclusions

We have conducted occupant behaviour surveys in seven Japanese office buildings. The following results were found:

- Due to the COVID-19, the proportion of 'open windows' is high in free running, heating and cooling modes.

- The behavioural adaptations (clothing adjustments and heating/cooling use) are related to the outdoor air temperature.

- The occupant behavioural models can be applied to building thermal simulation to predict the behavioural adaptation, indoor temperature and energy use in office buildings.

5. Acknowledgements

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Paper Presentation - Session 11

Session 11A - Health and Well being in Buildings

- Analysing indoor thermal comfort in LIG housing with respect building materials and openings, a case of Trivandrum
- Perceptions of IEQ, well-being and work performance in work-from-home settings
- Evaluation of the occupant perception of air quality within the indoor setting in the composite climate of Delhi
- Study on WBGT for heat stroke evaluation during summer in Japanese living rooms

Session 11B - Urban Heat Island and Outdoor Comfort

- The climate spatial variability and its impact on the thermal energy simulation of buildings: a case study of São Paulo, Brazil
- An assessment of the Universal Thermal Climate Index of Urban Outdoor Spaces- A case study of Central Business District (CBD), Ahmedabad
- Study on the role of vegetation towards thermal comfort in outdoor urban areas
- Impact of extreme weather events on the thermal comfort of vulnerable populations in the city of Sao Paulo

Session 11C - Climate Resilience Buildings and Communities

- A reinterpretation of vernacular strategies for building envelopes in hot and arid climates: cuidelines for façade design
- Reducing extreme discomfort in the global South – Comparison of a calibrated model and locally measured data from informal housing in Peru
- Urban Oasis for Adaptation to Climate Change: Analysis of Climate Adaptation Plans (CAP) around the world
- Energy Usage in Buildings for future climate: A case study of Concordia University Buildings in Montreal

Note: The Presenting Author has been marked with an asterisk (*)

Analysing indoor thermal comfort in LIG housing with respect building materials and openings, a case of Trivandrum

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Abstract

In India, population growth, demand for housing, and rapid urbanisation have led to higher energy consumption in the building sector. According to the Government of India report, 80% of the buildings that will exist by 2050 are yet to be constructed and a larger percentage is contributed by the housing sector, the population using affordable housing is higher compared to other developed countries. The occupants tend to achieve the desired level of thermal comfort by personal adjustments and mechanical means. Using energy-intensive methods for comfort is not feasible for a country, like India, with a low-energy economy. This study analyses indoor thermal comfort in low income group housing with respect to the building materials and openings used. Two typologies of low income housing were identified - a row housing constructed using conventional materials and a vertical stacking multi-dwelling constructed using Laurie Baker's sustainable construction technology. The first section of the study explores the current scenario of housing based on a thermal comfort field study to understand the current scenario by questionnaire survey and onsite measurements (following ASHRAE class II protocol) and a detailed analysis of the results from the computed data. The second part of the study is software simulation of the existing case with different approaches to improve thermal comfort using design builder simulation. And analysing the results to understand the improvement in indoor thermal comfort with respect to the existing model. From the results, it can be concluded that building material with higher thermal mass can cause a significant reduction in indoor temperatures and PMV thus improving indoor thermal comfort. Passive design strategies to improve indoor thermal comfort with respect to envelope material and openings for future projects at the study area under the low-income housing category, without breaking the concern of cost-effectiveness in affordability, are developed.

Keywords - Thermal comfort, low-income group housing, adaptive comfort, neutral temperature, window-to-wall ratio.

1. Introduction

Housing for all has long been a goal of India's economically disadvantaged groups, especially in metropolitan regions. However, a "home" is made up of more than just four walls and a roof. Affordable housing is really about moving beyond simply framing walls and buildings to creating structures that offer "comfort" to the occupants. The Urban housing shortage survey with respect to socio-economic classes, conducted by MOUHA shows that only 4 percent of the total housing shortage is in MIG/HIG and the rest of 96 percent of the houses are required in economically weaker sectors. (MOUHA, 2013) Studies show that the housing sector is the most energy intrusive sector, so using energy intensive methods for comfort is not feasible for a country with a low energy economy.

The thermal efficiency of the built environment and the occupants' preferred indoor quality are important factors in how much energy is used by buildings. The occupant's thermal preferences and expectations affect the indoor thermal environment. These are determined by the occupant's sensitivity to the current indoor environment. This factor influences how much control occupants need to feel comfortable in a designed setting. The comfort of the indoor environment is intimately related to the accessibility and availability of energy. (Singh, 2016) Thermal comfort is defined as 'that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation' (ANSI/ASHRAE Standard 55-2017, 2017). Investigating affordable housing's environmental performance in relation to human comfort is essential, given the importance of affordable housing.

135, Analysing of Trivandrum. in the development of a sustainable built environment. The extent of the associated health implications makes thermal comfort a crucial environmental factor (Malik, 2021).

From the literature reviews referred to, in the Indian context the studies on thermal comfort assessment in social housing projects are not much explored. The studies conducted related to thermal comfort in affordable housing were more to understand occupants' methods of environmental and behavioural adaptation and impediments in using controls to attain thermal comfort. The behavioural studies conducted on indoor thermal comfort, we can see that for attaining thermal comfort, occupants tend to depend on personal adjustments and mechanical means. Using energy intensive methods for comfort is not feasible for our country. This study, identifies passive measures of indoor thermal comfort, is required in this climate to reduce the load on energy consumption. Here, through this study, we are trying to address two aspects - openings and envelope materials, and bring out a better design solution for future construction.

The main aim of this study is to study indoor thermal comfort in low income housing in Trivandrum, Kerala, India and analyse the effect of the building materials used and openings provided, on the indoor thermal comfort, and then derive neutral temperature for the selected low income housing in Trivandrum. And assess the enhancement of indoor thermal comfort with respect to the alternative building materials and openings. As the field study - thermal performance monitoring is carried out only for a period of 7 days,during only a single season, monsoon, in each type of housing, the time constraint is a limitation in getting accurate results. The study will be limited to conditions of the selected LIG housing project in Trivandrum, without considering all passive strategies, focusing more on opening size and material, because natural ventilation and envelope material is more concerned in warm-humid climates.

2. Methodology

This study is conducted using thermal comfort field study and software simulation. The thermal comfort field study was carried out to understand the current scenario by questionnaire survey and onsite measurements (following ASHRAE class II protocol) (Neto 2013). Questionnaire surveys give the subjective judgments of the perceived thermal sensation with respect to the thermal environment condition of the dwelling users (Indraganti 2009). Onsite measurements of parameters including air temperature, globe temperature, relative humidity profiles, and air movement, inside of each house of all typology - plastered and unplastered, were noted. This collected data is simulated and validated by the DesignBuilder, then analysis to be carried out based on the inference of the study.

Survey and field measurements are taken in 100 households - 70 numbers of row housing and 30 numbers of vertical stacking. Longitudinal field study, conforming to ASHRAE Class II protocol, was conducted for a period of 7 days to understand thermal comfort conditions and preferences of the occupants. The data collection method included a thermal comfort questionnaire survey and concurrent monitoring and measurement of environmental parameters such as air temperature, relative humidity and air velocity (Gameiro da Silva 2013). The questionnaire was prepared in English and then translated into Malayalam (local language). Each respondent was enquired thrice a day – during morning (8:00 am–12:00 noon), afternoon (12:00 noon –3:00 pm) and evening (3:00 pm–6:00 pm). These times were chosen based on the average temperature peaks of the city (Indraganti 2009, 867). Measurements of parameters - air temperature, globe temperature, relative humidity and air velocity were taken, within each space - the common hall, bedroom and kitchen. Measurements of parameters and questionnaire survey were taken accordingly. Measurements of parameters were noted within 15 to 30 minutes (Indraganti 2009, 867). This collected data is simulated and validated by design builder software, then analysis is carried out. The intention of thermal comfort simulation was to understand the existing condition of thermal comfort in houses and how it differs with changes in building materials and construction technology used. The building materials selected for final simulations will be based on the results from thermal performance of the existing case, as the study is limited to conditions of Chenkalchoola Housing Colony.

2.1 Site study

2.1.1 Site overview

Chenkalchoola Housing Colony (Figure 1), now known as Rajaji Nagar, is a 12-acre slum redevelopment project located near Trivandrum's city centre, near Trivandrum Central Railway Station, and Thycaud. This slum was redeveloped in the 1970s to accommodate approximately 700 families. Later, in 2005, Ar. Laurie Baker added 9 more units for a total of 90 families. The project comes under Thiruvananthapuram Municipal Corporation, an initiation by Jawaharlal Nehru National Urban Renewal Mission (JNNURM). The built-up area is about 23000 sq m, accommodating more than 900 families, with each household unit area 25 - 35 sq m. The 90 percent of the men are employed, some are government employees and the rest engaged in taxi or auto driving, loading and unloading works, building construction works, market merchants, vendors, etc., this contributes to the main income of the colony. The rest of the daily income is from the working women as home maids, sweepers, etc., also some working in higher income sectors. The population opted for surveying were homemaker women, elderly men and women, kids and men who stayed at home due to health issues or other home related activities, and the ones with small shops and service attached to their house.

Figure 1 : The site plan - Chenkalchoola housing

2.1.2 Housing typologies

Two typologies of low income housing were identified - a row housing constructed using conventional materials and a vertical stacking multi dwelling constructed using Laurie Baker's sustainable construction Technology. Type 1 : Row housing - plastered. These linear houses in 2 floors were constructed to accommodate about 750 families. Each unit is less than 25 sq m in floor area (Figure 2).

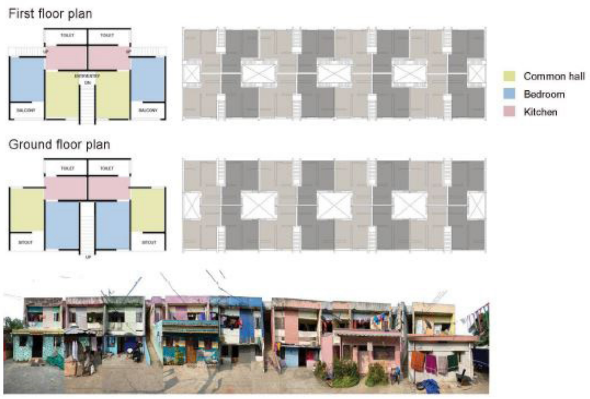


Figure 2 : Type 1 housing

Type 2 : Vertical stacking - unplastered and curvilinear. These are single units, through a vertical clustered stacking arrangement a single house can afford 10 families in 10 different units. 9 such houses are constructed for a total of 90 families. Units are vertically arranged as 5 units in the ground floor, 3 units in first floor with open terraces and 2 units are arranged in second and third floor with open terraces (Figure 3).

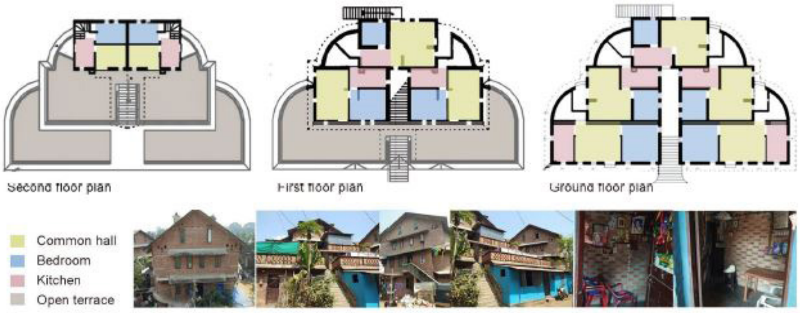
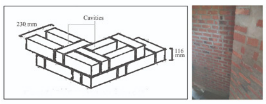
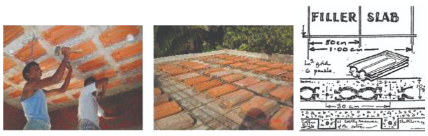
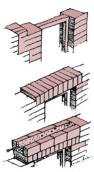


Figure 3 : Type 2 housing

2.2 Building materials and construction technologies used

The building materials and construction technologies used in this housing colony are shown in Table 1

Table 1: Building materials used in both type of housing

Components	Type 1 - Row housing	Type 2 - Vertical stacking
Wall	Walls are constructed of a type of cement brick, exported during an earlier stage of the project development. The wall thickness is 15 cm, including the plastering. The wall thickness is 15cm, including the plastering	*Rat-trap bond* This double-wall technique uses bricks on edge with a cross brick between each and produces a 9-inch thick wall with an insulating air cavity in between (Tewari 2015). Walls have been unplastered so as to expose the true characteristics of brick, thus reducing the cost of building by 10 percent. The wall thickness is 23 cm **(Figure 4)**.  **Figure 4** : *The Rat-trap bond*
Floor	The flooring was of plastered PCC	The flooring was of plastered PCC
Roof	Roofs are flat RCC slabs of 13 cm thickness.	Pitched or sloping roof sheds heavy rain, protecting walls from getting damp and from absorbing heat from sun and providing effective shading **(Figure 5)**.  **Figure 5** : *Roof - interior*
Slab	Flat RCC slabs of 13 cm thickness (**Figure 6**).  **Figure 7** : *Flat RCC slab - interior*	*Filler slab* Filler slabs are constructed instead of reinforced cement concrete slabs as they are very costly and use a lot of iron and cement. In filler slabs, rcc slabs replace some of the redundant concrete with mangalore tiles or other lightweight materials in order to reduce the overall cost of slab. This reduces the cost by about 30 or 35 % (Tewari 2015) (**Figure 7**).  **Figure 7** : *Filler slab* (12) (Tewari 2015)
Lintel		A hollow arrangement of brick-on-edge, filled with one or two steel rods in concrete carries the load of wall and roof above effectively. This type of lintel costs less than half the cost of an orthodox reinforced concrete lintel (Tewari 2015) **(Figure 8)**  **Figure 8** : *Lintels construction* (Tewari 2015)

3. Results

3.1 Thermal comfort field study

Measurement samples were taken in 100 houses, and the questionnaire surveyed more than 300 samples, with an average of 3 samples from each house. Out of this 48.8 percent of the population was within a group of 20 to 40 years, 27.9 percent was aged above 40 and 23.3 percent was aged below 20. And 53.5 percent of the surveyed population were male and 46.5 percent were female. The analysis began with compiling, coding and computing raw data obtained from different sources such as meteorological websites, questionnaires and field measurements. This data was sorted and summarised into a Microsoft Excel data set and also computed using CBE thermal comfort tool. Data from questionnaire forms which included personal identifiers, subjective comfort votes, personal variables were coded into excel spreadsheet at the end of each survey day. Outdoor environment data were then matched with the data obtained from the questionnaires using the date and time noted in the filled questionnaire forms.

Climatic parameters. Air temperature (Ta) and globe temperature (Tg) in row housing is greater than vertical stacking, by 2-3 deg C. Relative humidity (RH) is greater than the upper limit suggested in standards (70% IN SP.41 1987, ISHRAE 2019). Relative humidity in vertical stacking is higher than row housing throughout the day. Due to the lack of openings the velocity of air (Va) is almost zero throughout the day. Also kitchens are with zero daylighting (lux value likely to 0) in 90% of the units (Figure 9).

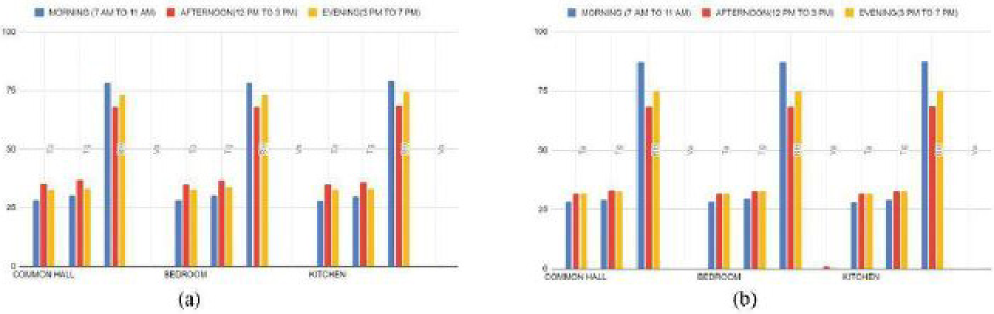


Figure 9: Climatic parameters - onsite measurement in (a) type 1 house and (b) type 2 house

Operative temperature (OT) and Mean radiant temperature (MRT). Operative temperature varies from 29.16 33 deg C in row housing and 28.7 - 32.7 deg C in vertical stacking. This is higher than the comfort limit suggested by NBC 2016 (lower limit 25 - 27.5 - 30 deg C upper limit) (Figure 10).

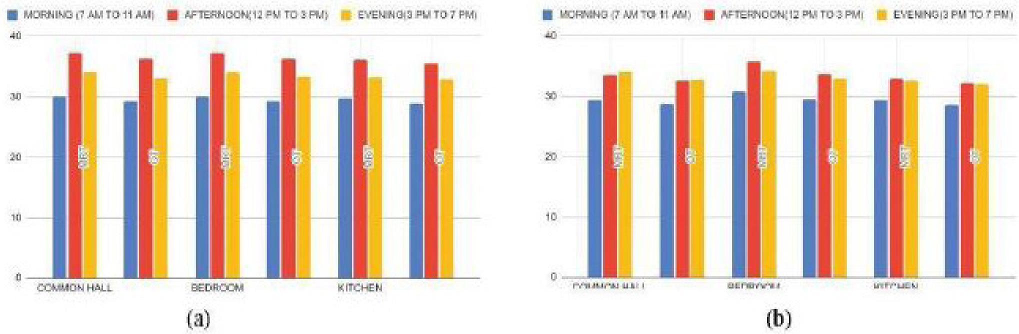


Figure 10: MRT and Operative temperature derived from onsite measurements in (a) type 1 house and (b) type 2 house

PMV. The Fanger's predicted mean vote model shows that the least value of TSV experienced is 1 (slightly warm) during morning, with 2 (warm) and 3 (hot) throughout the day in vertical stacking and row housing respectively (Figure 11).

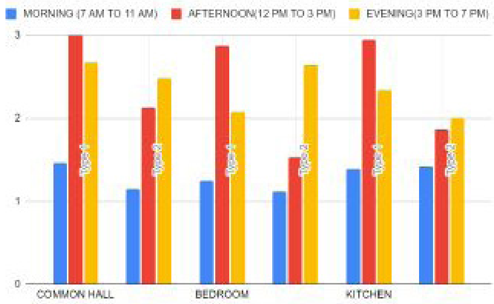


Figure 11: Comparison of mean PMV in Type 1 and Type 2 houses

Adaptive comfort temperature. When the monthly mean outdoor temperature is taken an 27.5 deg C, and air velocity up to 0.3 m/s, the acceptable operative temperature for naturally conditioned spaces ranges from 22.8 29.8 dec C (80% acceptability) and 23.8 - 28.8 deg C (90% acceptability). In both cases, the adaptive comfort zone is too warm than the acceptable ranges (Figure 12). The adaptive comfort chart shows that the comfort in type 1 houses lies closer to the comfort band than that of type 2 houses with cost effective and energy efficient construction techniques, this is caused due to the very low (nearly zero) air movement from less openings and lack of mutual shading in type 2 houses.

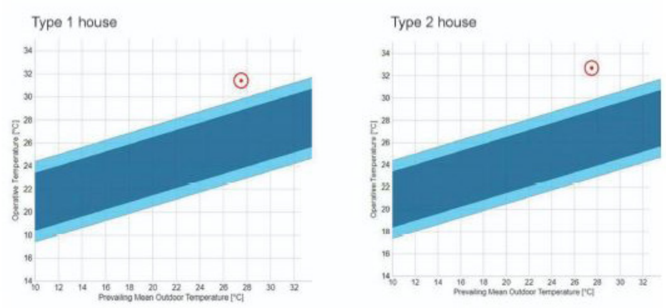


Figure 12: Adaptive comfort model

Calculation of Neutral temperature. Neutral temperature is obtained from the subjective thermal evaluation and calculated indoor thermal comfort indices (PMV). Neutral temperature in row housing is 28.8 deg C, and that of vertical stacking is 28 deg C, which is slightly greater than the neutral temperature obtained from TSV (28 deg C) (Figure 13).

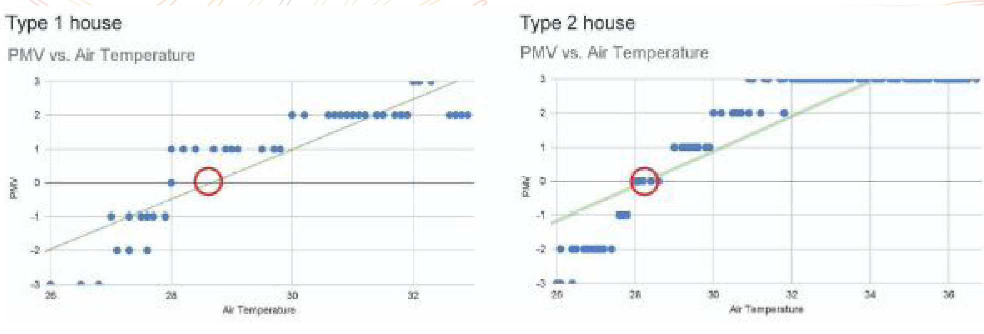


Figure 13: Neutral temperature

Thermal comfort - DesignBuilder simulation

Thermal comfort simulation is done with DesignBuilder software, to assess how the climatic parameters of thermal comfort changes with respect to the change of building material and construction technology. This is done as two cases of simulation:
Case 1 - thermal comfort simulation of the existing case of type 1 house (row housing), where the thermal monitoring study is conducted, with existing building materials, orientation and building density (Figure 14).

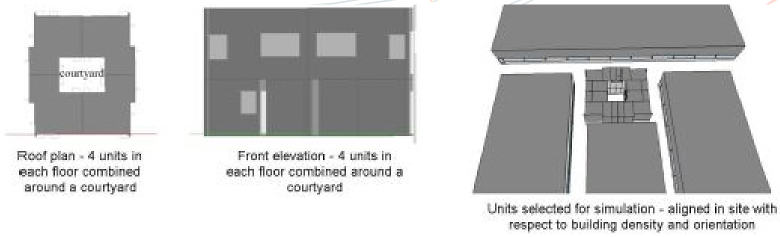


Figure 14: Model of type 1 house with existing conditions - prepared for indoor thermal comfort simulation in DesignBuilder

Case 2 - thermal comfort simulation of type 1 house (row housing), by applying the alternative building materials and construction technology used in type 2 house (vertical stacking) (Figure 15).

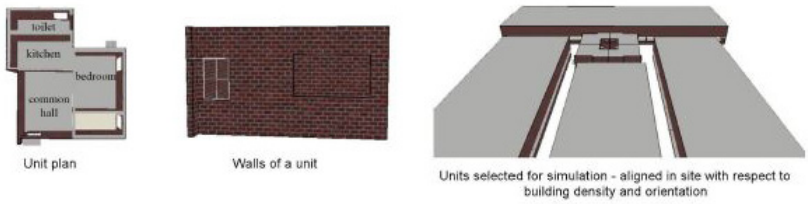


Figure 16: Model of type 1 house after changing the building materials used to that of type 2 house - prepared for indoor thermal comfort simulation in DesignBuilder

Case 3 - thermal comfort simulation of type 1 house with building materials as that used for case 2 simulation, with window wall ratio increased to 5% (in the existing case the window wall ratio is 3.3. - 3.6 %)

Case 4 - thermal comfort simulation of type 1 house with building materials as that used for case 2 simulation, with window wall ratio increased to 7.5%.

Case 5 - thermal comfort simulation of type 1 house with building materials as that used for case 2 simulation, with window wall ratio increased to 10 %.

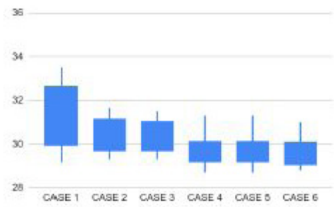
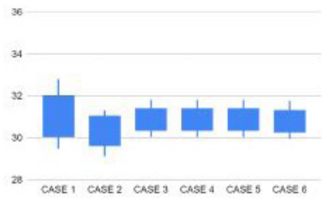
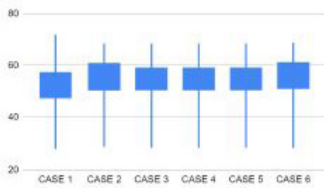
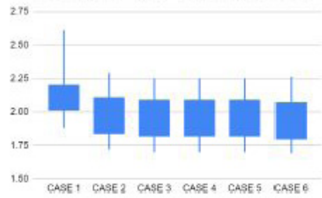
Case 6 - thermal comfort simulation of type 1 house with building materials as that used for case 2 simulation and window wall ratio increased to 10 % as used for case 5 simulation, with building oriented having openings towards the direction where maximum air movement is obtained - South-West (derived from the eco-chart prepared).

4. Discussion

Indoor thermal comfort with respect to envelope materials.

In this study when the wall material was changed from hollow brick plastered on both sides, overall thickness of 17 cm to unplastered brick wall construction (in flemish bond) with thickness of 23 cm, the roof material was changed from concrete slab of 13 cm to filler slab construction of 10 cm thickness, with terracotta roof tiles air cavity with (a total of 5 cm thickness) and reducing glazed windows by adding jali openings, a temperature drop of 3 deg C was attained, along with decrease in humidity range and PMV recorded. This can reduce the indoor air temperature by 10 %, indoor operative temperature 8.5% and relative humidity range by 7% during peak noon hours. The PMV obtained decreased by 17.5 % during peak noon hours.

Table 2: Table caption

Parameters	Results in graphical representation
Air temperature The effects of simulation cases on the indoor air temperature can be seen on the graph, from case 1 to case 6. Median value has decreased from 32.7 deg C to 29 deg C , minimum value has decreased from 29.16 deg C to 28.8 deg C and maximum value has decreased from 33.5 deg C to 31 deg C .	 **Figure 17**: *Air temperature improvement graph*
Operative temperature The effects of simulation cases on the operative temperature can be seen on the graph, from case 1 to case 6. Median value has decreased from 32 deg C to 30.3 deg C, minimum value has decreased from 29.6 deg C to 29.5 deg C and maximum value has decreased from 32.8 deg C to 31.77 deg C .	 **Figure 18** : *Operative temperature improvement graph*
Relative humidity The effects of simulation cases on the relative humidity can be seen on the graph, from case 1 to case 6. Median value has increased from 57.1 % to 60.1 % , minimum value has increased from 28.1 % to 28.55 % and maximum value has decreased from 71.85 % to 68.86% .	
PMV The effects of simulation cases on the PMV can be seen on the graph, from case 1 to case 6. Median value has decreased from 2.19 to 1.8, minimum value has decreased from 1.88 to 1.69 and maximum value has decreased from 2.61to 2.26	 **Figure 20** : *PMV improvement graph*

Indoor thermal comfort with respect to openings for natural ventilation.

Window to wall ratio : Window to wall ratio determines the required air flow towards the interior of a building. Providing a large percentage of openings on a single wall will not give enough air movement within the building.

But considering the characteristics of a warm humid climate, air movement is the best strategy to reduce the effect of high humidity, daylighting wasn't assessed before concluding the window to wall ratio due to limitations in the site. Optimum window to wall ratio identified from study is 7.5%. Increasing the window to wall ratio from 3.3% to 7.5% can decrease the indoor air temperature and operative temperature by 3%. Cross ventilation: Indoor thermal comfort is affected by the number of air exchange happenings in that space. Providing enough openings as per window to wall ratio on a single wall cannot cause much effect on the indoor thermal comfort. The number of air exchanges can only be improved by providing enough cross ventilation within the enclosed space. The study shows that the changes in the window to wall ratio in a single wall did not cause any change in the indoor thermal comfort condition.

Orientation of the building: Orienting the building with its openings towards the windward direction can cause a significant improvement in indoor thermal comfort of an enclosed space, even with less cross ventilation. Orienting the units within the site in such a way that the overall layout causes less wind shadow, can increase the air movement within the building thus improving thermal comfort. Also shading and over-hangings of the openings can reduce the internal heat gain, thus improving thermal comfort. Changing the orientation of the building with openings towards windward direction can decrease the indoor air temperature and operative temperature by a minimum of 3%, relative humidity by a minimum of 16% and PMV by 2.5%.

5. Conclusion

This study was to understand the condition of indoor thermal comfort in low income housing. And then develop passive design strategies to enhance the thermal comfort with respect to openings and envelope materials.

● The site selected for study consists of two types of housing units - type 1 row housing and type 2 vertical stacked multi dwelling units. Building materials study was done, type 1 house is of cement hollow block walls with RCC slab roof and plastered, whereas type 2 house is of brick walls in rat trap bond and filler slabs, with jali wall openings and unplastered.

After conducting thermal monitoring field study and questionnaire survey, a significant difference was noted in the measured parameters within both types of houses.

● The PMV values in row housing vary from warm to hot, while that in vertical stacking is slightly warm to warm, during evening and afternoon respectively.

● The adaptive comfort ranges obtained for both housing were too warm than the acceptable ranges, and are even greater than the 90 percent acceptable limits.

● The neutral temperature obtained in type 2 housing is 28.4 deg C, is within the acceptable range, whereas in type 1 housing it is 28.8 deg C.

As the second part of the study a thermal performance simulation was conducted to understand and analyse the role of building materials and openings in enhancing indoor thermal comfort.

● The results show that changing the building material to one with higher thermal mass and using openings with required window wall ratio in windward orientation can reduce the indoor temperature by 15.5 % and the PMV to slightly warm from hot by 20.5% reduction.

● The optimum WWR, with respect to air movement, required for the housing studied was derived, 7.5 %.

These design strategies developed with respect to building materials and openings for natural ventilation, can enhance the indoor thermal comfort of the housing units in Chengalchoola housing colony, Trivandrum.

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Perceptions of IEQ, well-being and work performance in work-from-home settings

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Abstract

In India, population growth, demand for housing, and rapid urbanisation have led to higher energy consumption in the building sector. According to the Government of India report, 80% of the buildings that will exist by 2050 are yet to be constructed and a larger percentage is contributed by the housing sector, the population using affordable housing is higher compared to other developed countries. The occupants tend to achieve the desired level of thermal comfort by personal adjustments and mechanical means. Using energy-intensive methods for comfort is not feasible for a country, like India, with a low-energy economy. This study analyses indoor thermal comfort in low income group housing with respect to the building materials and openings used. Two typologies of low income housing were identified - a row housing constructed using conventional materials and a vertical stacking multi-dwelling constructed using Laurie Baker's sustainable construction technology. The first section of the study explores the current scenario of housing based on a thermal comfort field study to understand the current scenario by questionnaire survey and onsite measurements (following ASHRAE class II protocol) and a detailed analysis of the results from the computed data. The second part of the study is software simulation of the existing case with different approaches to improve thermal comfort using design builder simulation. And analysing the results to understand the improvement in indoor thermal comfort with respect to the existing model. From the results, it can be concluded that building material with higher thermal mass can cause a significant reduction in indoor temperatures and PMV thus improving indoor thermal comfort. Passive design strategies to improve indoor thermal comfort with respect to envelope material and openings for future projects at the study area under the low-income housing category, without breaking the concern of cost-effectiveness in affordability, are developed.

Keywords - Indoor environmental quality (IEQ), Work-from-home (WFH), Subjective assessment, Well-being, Work performance, Productivity

1. Introduction

In recent years, a seismic shift has transformed the way we work. The rapid adoption of remote work, catalysed by technological advancements and global circumstances, has redefined the traditional office landscape. As a result, a significant portion of the workforce now finds themselves working from the comfort of their homes. This transformation, while promising newfound flexibility and convenience, has also presented a set of unique challenges and opportunities, particularly concerning the Indoor Environmental Quality (IEQ) within these domestic workspaces.

IEQ encompasses a spectrum of factors, including thermal comfort, indoor air quality, lighting, noise levels, and ergonomics, among others. Traditionally, IEQ has been a focal point in commercial office design, with its direct influence on occupant comfort, health, and productivity well-established. However, the rapid transition to work-from-home arrangements has blurred the lines between professional and personal spaces, making the assessment of IEQ in these domestic environments a pressing concern.

While research on work-from-home (WFH) settings has been conducted since the 1980s, with a focus on behavioral, psychological, and sociological perspectives [1], few studies have evaluated the IEQ of WFH settings [2]. With the rapid transition to work-from-home arrangements blurring the lines between professional and personal spaces, making the assessment of IEQ in these domestic environments a pressing concern. Several studies have explored the impact of IEQ factors, such as temperature, lighting, noise, air quality, and ergonomics, on work performance and overall health. However, most of the existing research has been conducted in traditional office environments rather than in WFH settings. Understanding the nuanced dynamics of IEQ in the domestic workspace is essential, as it directly influences the quality of life and productivity of a significant portion of the global workforce.

The importance of IEQ on occupant health and well-being has long been acknowledged. Poor IEQ can lead to a range of health issues, including respiratory problems, allergies, and stress-related disorders [3–5]. Conversely, a comfortable and healthy indoor environment can enhance well-being, reduce absenteeism, and increase job satisfaction [6]. Moreover, the link between IEQ and work performance is a topic of increasing interest. Numerous studies have shown that a conducive indoor environment can lead to improved cognitive function, enhanced focus, and increased productivity [7]. In contrast, poor IEQ can have the opposite effect, leading to reduced concentration and decreased job performance [8].

As work-from-home arrangements become more commonplace and are likely to continue even post-pandemic [9,10], understanding the relationship between IEQ and work performance and well-being in these settings becomes imperative. This study is a part of a larger research project that was initiated in March 2022 to systematically evaluate the indoor environmental quality (IEQ) and perceived well-being and productivity of at-home workers. While the project is ongoing, the objective of this study is to present a preliminary analysis of the workers' perception of their work-from-home (WFH) spaces and their impact on work performance and well-being.

2. Methods

Ninety-four study participants (or WFH sites) were recruited through convenience and snowball sampling from Metro Vancouver (Canada) and Seattle Metropolitan (U.S.) regions for a period of nearly two months in the summer of 2022. The inclusion criteria required that participants be working from home for at least two days a week, carrying out sedentary, computer-based work. Individuals planning to move houses, carry out home renovations, or change their working location during the study period were excluded from the study. Each participant was given an indoor, desktop IEQ monitor to be installed in their WFH offices. Results of the preliminary analysis of the monitoring data are published elsewhere [11,12]. A battery of survey items was assembled for subjective assessment of comfort, well-being, and productivity based on an extensive review of survey instruments[13]. The variables of interest being presented in this paper come from a bespoke long-term IEQ assessment questionnaire deployed towards the beginning of the study campaign.

The specific items included in the IEQ questionnaire for this study may be divided into two groups – the features available at WFH spaces and the problems encountered by the workers. Participants were offered a list of 21 features and 15 problems to select the ones relevant for them. These features and problems were related to the five IEQ domains of thermal environment, indoor air quality, visual environment, acoustic environment and physical environment. For this study, the physical environment refers to aspects related to the physicality of the WFH environments, such as furniture or workstation design, work-related equipment (laptop/ computer, monitors, keyboard, etc.), cleanliness, etc. The analysis presents the results based on the assessment of these items on four perception variables – availability (of features) or frequency (of problems), satisfaction (with features), impact on well-being and impact on work performance. A five-point Likert scale was used to rate satisfaction ('extremely satisfied' – 'extremely dissatisfied'), impact on well-being ('not at all' – 'very much') and impact on performance ('enhances a lot' – 'interferes a lot'). Lastly, questions related to overall perception of WFH in relation to satisfaction, well-being and work performance were also included. Data analysis was done in Python using Pandas to process the data and provide descriptive statistics; SciPy for correlation and Chi-square tests; and Matplotlib to create plots.

3. Results

3.1 Subjective assessment of IEQ

At least 50% (n = 47) of the workers had 14 of the 21 features available at WFH. Figure 1 shows the availability of features ordered by the number of participants who reported having access to these features. The most commonly available feature was views to outside (n = 85), followed by enough space to work, access to operable windows, extra monitor, daylight, a clean environment, and ambient light – at least 70% of the workers had access to these features. More than 60% had access to heating, aesthetically pleasing surroundings, and ergonomically designed furniture at WFH. Access to sound privacy, task light, fans, humidifier/dehumidifier was less common.

Figure 2 shows the % distribution of responses across the five satisfaction ratings for the 21 features ordered by the mean rating values. Mean satisfaction ratings were generally high, nearly 4 (corresponding to 'somewhat satisfied') across the features. Workers were most satisfied with the availability of extra monitor for work. In terms of counts, the highest number of 'extremely satisfied' votes were given to views to outside (n = 49), followed by operable windows (n = 40), amount of workspace (n = 37) and daylight (n = 35).

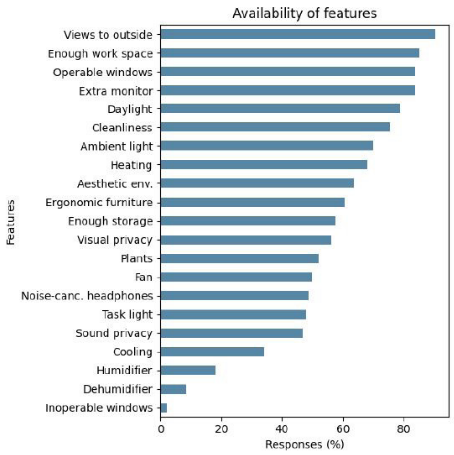

Figure 1: Distribution of responses across IEQ-related features in WFH settings

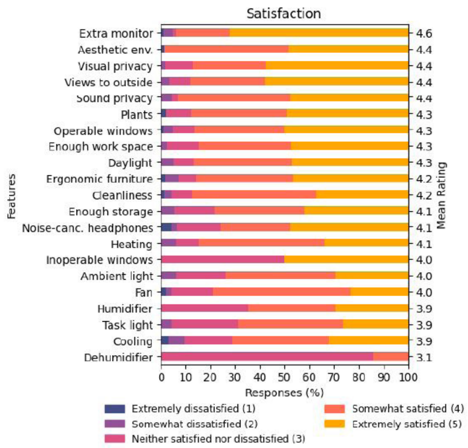

Figure 2: Distribution of responses across satisfaction categories for IEQ-related features in WFH settings

The most widely reported problems pertaining to IEQ in WFH settings were noise from the street (n = 39) and family members (n = 30) (Figure 3). These were followed by the workspaces being either too warm (n = 27) or too cold (n = 26) – interestingly, a majority of workers reported having both issues. Unwanted interruptions were also reported by several workers (n = 20). The occurrence of problems at WFH was rated on a five-point scale as well (always – never). Some of the more

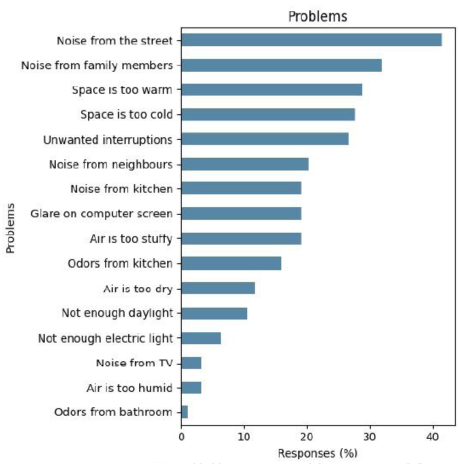

Figure 3: Distribution of responses across IEQ-related problems in WFH settings

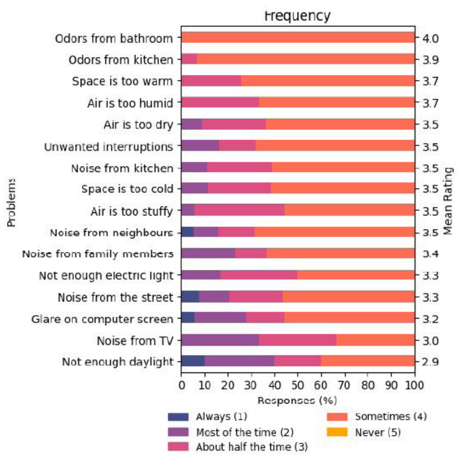

Figure 4: Distribution of responses across frequency categories for IEQ-related problems in WFH settings

frequently occurring problems (between 'always' to 'half the time') were related to disturbances, such as those due to noise from the street (n = 17) and family members (n = 11), or unwanted interruptions (n = 8). Workspace being too cold, too stuffy and glare on the screen (n = 8) were also reported to occur albeit with lesser frequency (Figure 4).

3.1.2 IEQ and work performance

Several features at WFH helped to enhance the work performance – views to outside (n = 76), access to operable windows (n = 72) and enough workspace (n = 73) were the most prominent, followed by availability of daylight (n = 68), clean (n = 65) and aesthetically pleasing (n = 59) environment, heating (n = 58), ergonomic furniture (n = 53), ambient lighting (n = 49) and visual privacy (n = 44). Features such as task light, fans and storage space were deemed less important (n < 40) for work performance (Figure 5).

The problems reported in WFH settings did not seem to affect work performance in general, with the mean ratings across the performance categories never going below 2.8, which is close to performance being affected 'somewhat'. While the number of samples were low, some of the problems most frequently reported to affect work performance were noise from the street (n = 9) and family members (n = 7), unwanted interruptions and the workspace being too warm (n = 7) (Figure 6).

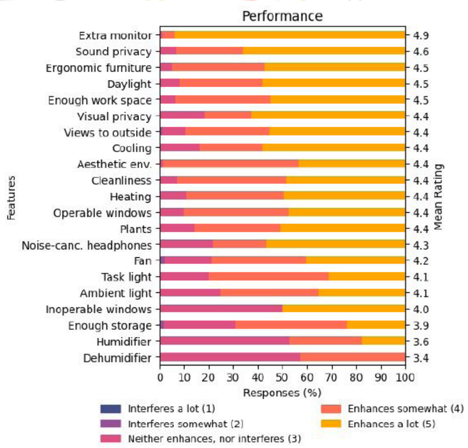

Figure 5: Distribution of responses across performance categories for IEQ-related features in WFH settings

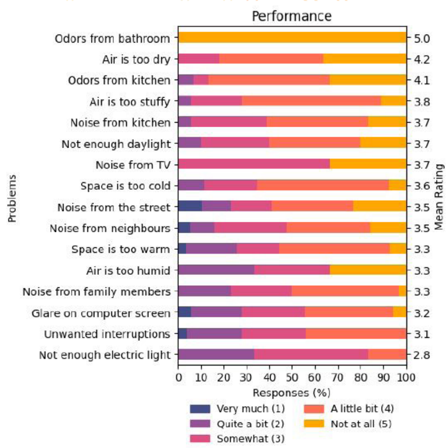

Figure 6: Distribution of responses across performance categories for IEQ-related problems in WFH settings

3.1.3 IEQ and well-being

A view to the outside was the most widely cited feature to affect well-being in WFH settings (n = 66) (Figure 7). The other important features were access to operable windows (n = 60), extra monitor (n = 60), daylight (n = 55), enough workspace (n = 53) and cleanliness (n = 49). For at least 12 features on the list, the mean rating on the well-being impact scale was at least 4, which indicates that these features affected well-being 'quite a bit'. The problems that most affected well-being were noise from the street (n = 27) and family members (n = 23), and unwanted interruptions (n = 15), followed by workspace being too warm (n = 15) and noise (n = 14) and odors (n = 13) from the kitchen. As in the case of performance, the effect of these problems on well-being ranged between 'somewhat' and 'a little bit' in terms of the mean ratings (Figure 8).

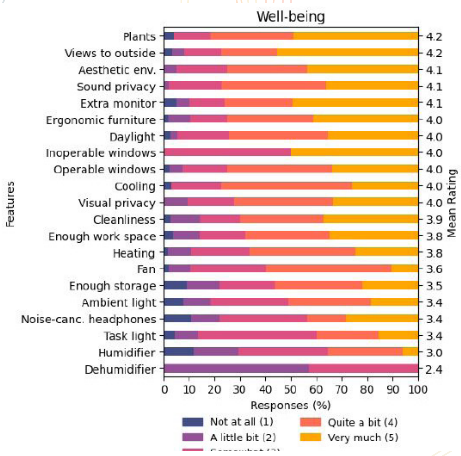

Figure 7: Distribution of responses across well-being categories for IEQ-related features in WFH settings

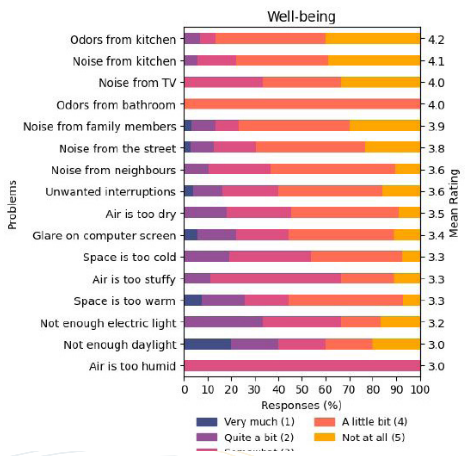

Figure 8: Distribution of responses across well-being categories for IEQ-related problems in WFH settings

3.2.4 Overall assessment of WFH

Nearly 80% of the workers felt their work performance was enhanced somewhat or a lot when they WFH while only than 9% said WFH interfered with their performance (M = 4.1). Satisfaction with overall workspace was also high with almost 89% being somewhat or extremely satisfied and less than 8% expressing dissatisfaction (M = 4.2). The scale used for the assessment of well-being indicated only if the workers were affected by the overall workspace and it did not show the direction of that impact in terms of whether it was positive or negative. Less than 52% said their overall workspace affected their well-being while nearly 23% did not report much difference in their well-being as a result of WFH (M = 3.4).

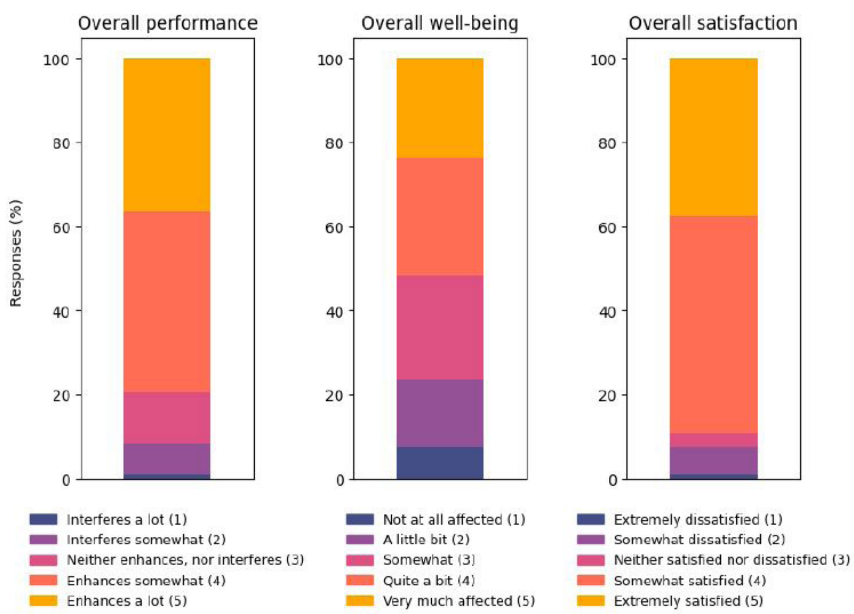

Figure 9: Distribution of responses across overall performance, well-being and satisfaction categories in WFH settings

Spearman's rank correlation was used to measure the strength and direction of the monotonic relationship between overall well-being, work performance and satisfaction (Table 1). Performance and satisfaction showed a strong positive correlation (rs (91) = .63, $p < .001$), indicating that as the performance at WFH increases, overall satisfaction with WFH also tends to increase. Performance and well-being showed a moderate positive correlation (rs (91) = .26, $p < .05$), suggesting that as

the performance at WFH increases, overall well-being while WFH also tends to increase. Well-being and satisfaction had a weak positive correlation (rs (91) = .20, p = .053), implying that there is some positive relationship between overall well-being and overall satisfaction with WFH, but it is not very strong.
A chi-square test of independence was also performed to examine the association between overall well-being, work performance and satisfaction (Table 1). The relation between overall performance and well-being was significant, $\chi 2$ (16, N = 93) = 50.45, $p < .01$. Similarly, the relationships between performance and satisfaction ($\chi 2$ (16, N = 93) = 146.42, $p < .01$), and well-being and satisfaction ($\chi 2$ (16, N = 93) = 28.78, $p < .05$) were significant as well although the latter was less strong.

Table 1: Outcomes of correlation and Chi-square tests between overall performance, well-being, and satisfaction

	Performance	Well-being	Satisfaction
Performance		50.45***	146.42***
Well-being	0.26*		28.78*
Satisfaction	0.63***	0.20	

Spearman's rho (r_s), chi-square (χ^2)
*p<.05, **p<.01, ***p<.001

4. Discussion

The preliminary analysis of subjective assessment of IEQ in WFH settings and its perceived impact on work performance and well-being revealed some interesting insights into the home-office environments of Canadian remote workers. The most prevalent features available to them in their workspaces were views to outside, operable windows, daylight and enough space to work. In addition to being the features with which most of the workers expressed satisfaction, they appear to affect workers' work performance and well-being. The problems most frequently experienced by workers were related to disturbances due to noise from the street and family members, and unwanted interruptions. Curiously, these problems seemed to affect workers' well-being more than they affected work performance.

The generally high ratings for satisfaction, work performance and well-being observed in this study also resonate with the new, albeit sparse, IEQ research in similar settings. These studies report medium to high satisfaction with the thermal environment [14–17], and high satisfaction with the air quality [14–20] and visual environment [21–24]. On the other hand, annoyance with noise was high in WFH settings and found to be detrimental to well-being [25] and work performance, especially compared to the pre-lockdown context [26,27] and compared to other IEQ domains [16,28,29]. This aligns with the noise complaints and their affect on well-being and work performance reported by the workers in this study.

There are two important themes to draw from these results. The first is the relatively understated role played by some of the otherwise significant factors from published research on IEQ – those related to the thermal environment. While this study underscores the significance of operable windows, which could potentially be related to thermal comfort, it is notable that it doesn't place as much emphasis on other factors directly associated with this domain. This suggests that operable windows might be serving a different purpose, possibly akin to the role played by outside views. It is rare to not have a heating system in Canadian residences and many existing and new buildings are being fitted with cooling as well. WFH also allows more personal control over the setpoint, potentially resulting in optimal thermal conditions, or at least, better acceptance to these conditions as a result of behavioural adaptation – clothing, metabolic rate and lifestyle habits.

This leads to the second prominent theme in the study's findings – the emergence of factors tied to the physical and acoustic environment. These factors encompass aspects such as the presence of scenic views, the available workspace area, aesthetics, cleanliness, on the one hand, and the challenges linked to noise and interruptions on the other. In the burgeoning field of research on IEQ in WFH settings, we observe a similar emphasis on the acoustic and physical surroundings. This emphasis may be attributed to the fact that workers have relatively less control over factors associated with these domains compared to others. For instance, mitigating noise originating from the street is primarily achieved by closing windows, a step that is likely to have a distinct impact on performance and well-being. Similarly, the containment of noise and unwanted interruptions stemming from family members can be a challenging task. Concerning the physical environment, there exist inherent limitations regarding the extent to which workspace improvements can be made, and in cases where space is insufficient, addressing such limitations becomes a formidable challenge.

5. Conclusion

This paper presented an analysis of the subjective assessment of indoor environmental conditions in WFH settings and the perceived impact of these conditions on work performance and well-being, based on a field study in the Pacific Northwest region involving 94 participants conducted during summer of 2022. The most prevalent features available to the workers in their workspaces were views to outside, operable windows, daylight and enough space to work. In addition to being the features with which most of the workers expressed satisfaction, they appear to affect workers' work performance and well-being. The problems most frequently experienced by workers were related to disturbances due to noise from the street and family members, and unwanted interruptions. These problems affected workers' well-being more than they affected work performance.

A majority of workers reported their work performance was enhanced while WFH (M = 4.1) and satisfaction with overall workspace was high (M = 4.2). Significant correlations were found between satisfaction and performance and between well-being and performance.

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Evaluation of the occupant perception of air quality within the indoor setting in the composite climate of Delhi

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1. Abstract

In India, the ill effects of a poor indoor environment are seen as the cause of about 2 million premature deaths per year, wherein 44% are due to pneumonia, 54% from chronic obstructive pulmonary disease(COPD), and 2% from lung cancer. Conventional studies typically take lesser consideration of indoor occupancy than would be found in real surroundings. These studies often evolve in artificial conditions, which lack authenticity. This work uses field research and a data-driven approach to assess contaminants in inhabited indoor spaces, such as carbon dioxide (CO2) and particulate matter (PM2.5) along with indoor climate measurements of Indoor Operative Temperature (IOT), Relative Humidity(RH), and air velocity. This paper reports the findings of a pilot field study carried out to understand the effect of CO2, IOT, PM2.5, RH, age, sex, general health condition, and perception of odours on occupant's perception of IAQ and perceived thermal comfort, during the summer monsoon season in the composite climate of Delhi. Participants were asked to rate their perceived thermal comfort on standardized scales and provide PIAQ votes based on their satisfaction with indoor air quality. Data analysis included correlation analyses and multiple regression modelling. Our findings reveal a statistically significant inverse relationship between perceived Indoor Air Quality (PIAQ) votes and perceived thermal comfort. Building occupants who rated the indoor air quality more favourably (higher PIAQ votes) tended to report lower levels of perceived thermal comfort, while those who expressed dissatisfaction with indoor air quality reported higher thermal comfort levels.

Keywords - Thermal Sensation, Perceived Indoor Air Quality, Correlation, CO2, PM2.5

2. Introduction

The World Health Organization (WHO) defines health as, "A state of complete physical, mental and social well being and not merely the absence of disease or infirmity."[1] Human health not only includes the physical state of individuals but also is a state of complete physical, psychological, and social well-being [2]. Exposure to environmental physical, chemical, biological, and radioactive toxins are some of the several factors that can have an impact on human health resulting in adverse effects such as chronic illness. People spend more than 80% of their time in indoor spaces, either in offices or at home. Compared to the air quality of outside surroundings, IAQ is more likely to have an impact on people's health, quality of life, and ability to work. People who spend a lot of time indoors, for instance, may experience uncomfortable symptoms like headaches, coughs, and exhaustion as well as be diagnosed with several serious conditions like respiratory, cardiovascular, and cerebrovascular disorders as well as an increased chance of developing cancer. As a result, indoor air quality has a significant impact on occupant health, perhaps even more so than outdoor air quality. According to the studies, those who have had underlying medical conditions including cancer, high blood pressure, diabetes, chronic respiratory disease, or even diabetes and cardiovascular disease are predicted to be more vulnerable to exposure to poor air quality.

SBS, tight building syndrome, and illnesses related to buildings, such as nausea, skin irritation, lethargy, etc., are some of the general terms used to describe the negative effects of poor IAQ on health. SBS symptoms are challenging to identify because they are predominantly characterized by sensory reactions, which are poorly understood even from a medical standpoint.[3] SBS is characterized as a collection of subclinical symptoms without a known explanation. Building inhabitants frequently respond to their surroundings in distinctly different ways, making it challenging to pinpoint the causes of specific issues. The symptoms seen in building occupants vary, and they are significantly influenced by thermal factors such as air and wall surface temperatures, air velocity, temperature variations, relative humidity, clothing, etc. pollutants, lighting, psychosocial workplace aspects, personal control, job happiness, relationships with coworkers, etc[4]

According to the findings of Wargocki et al., improvement of PIAQ, reducing the severity of some SBS symptoms, and increasing some aspects of occupant productivity can all be accomplished by reducing the pollution load on indoor air, as advised by CEN CR 1752 (1998).[5] In another study, thirty women took part, where each environmental condition was experienced for 4.6 hours. Throughout their presence in these conditions, the participants engaged in simulated office tasks while evaluating their perceived indoor air quality(PIAQ). The research reaffirmed prior observations regarding how temperature and humidity influence PIAQ.[6]

Moreover, Heudorf et al., found that the level of carbon dioxide (CO2) can be an indicator of adequacy of ventilation and a comfort parameter. Although it was assumed that CO2 concentration >1000 ppm may also indicate poor PIAQ, CO2 concentration <1000 ppm does not guarantee acceptable PIAQ[7].

The information summarized above shows that indoor air parameters like temperature, relative humidity, and CO2 concentration affect the PIAQ while the impact of general health conditions and pollutants like particulate matter require further elucidation. The present study aims to investigate whether PIAQ and its acceptability are influenced by these indoor air parameters and also investigate the relationship of parameters with each other. In the present study, we aimed to assess the relationship between indoor temperature, relative humidity, CO2, PM2.5 concentration, age, gender, general health condition, perceived odours, and perceived indoor air quality and thermal sensation for residences located in the South Delhi area of the National capital territory of Delhi.

Since the perception of IAQ in India is quite new, studies conducted on finding the linkage between indoor air parameters and PIAQ have been limited so far. Another novelty of this research is that it involves both, measurements of indoor environment parameters and concurrent questionnaire surveys over the summer-monsoon season, which has high levels of temperature and varying relative humidity levels, causing thermal discomfort in many instances as compared to other seasons. This research will also help in promoting public awareness to maintain a healthier indoor environment.

3. Materials and Methods

3.1 Setting

The study was carried out in Delhi, which falls under composite climate zone {Reference}, during the summer monsoon season. The study site is located in a residential locality in South Delhi that was developed in the 1950s. All the houses have 1 living room, 2 bedrooms, 1 study, 1 Kitchen, 1 Toilet and 1 Bathroom. All the houses have the same typical layout. The cooking fuel is the same for all houses (Piped Natural Gas, PNG). Every room has operable windows that open to an outdoor environment.

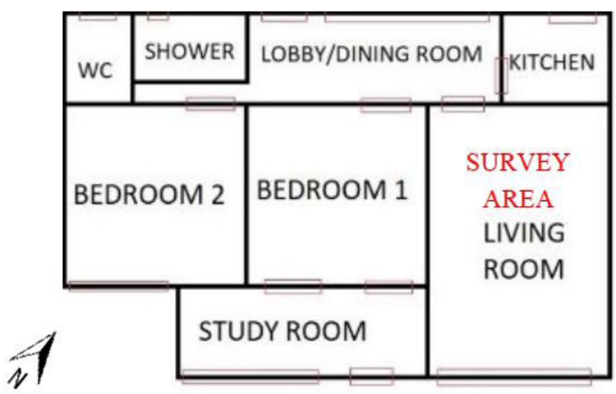


Figure 1: Typical Floor layout of study sites

The study site is close to a Ring Road with heavy traffic; a metro station located at 300 m distance and a fuel station at 350 m. The population density of the area is approximately 94 people per km2, and local public transportation consists mainly of cars and auto rickshaws.

Temperatures in Delhi usually range from 2 to 46 °C (35.6 to 114.8 °F), with the lowest and highest temperatures ever recorded being −2.2 and 49.2 °C (28.0 and 120.6 °F), respectively. The air quality index is generally moderate (101–200) level between January and September, and then it drastically deteriorates to Very Poor (301–400), Severe (401–500), or Hazardous (500+) levels in the three months between October and December.

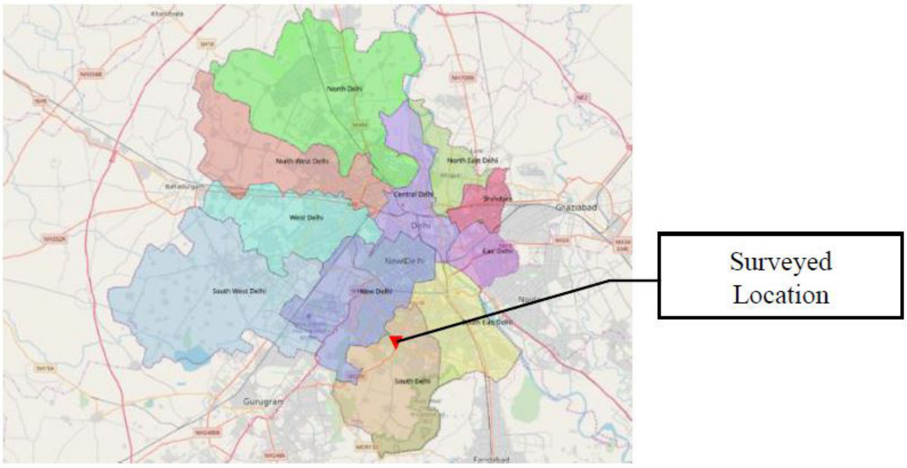


Figure 2: Map of the National Capital Territory (NCT) of Delhi

The study was conducted in July-August duration. Quantitative measurement of perceived indoor air quality and perceived thermal comfort is done using ASHRAE's psycho-physical scale[8] using a questionnaire-based survey of occupants' perceptions of indoor air quality. The indoor air parameters were sampled in 1-minute intervals for CO2, temperature, air velocity, and relative humidity and then were transformed into 5-minute averages, which were merged to generate a time-series matrix. The PM2.5 monitoring was sampled as 5 min averages. The indoor climate and air quality measurements were continuously obtained for a period of 2-h every day during the study period.

3.2. Participants

To begin with, 25 sampling sites were identified where 50 participants volunteered to be subjects for monitoring. Of them, only 30 were available for monitoring. Hence, the sample size of this study was 14 male and 16 female occupants. At each sampling site, a questionnaire was given to the occupants to assess the perception of indoor air quality in the space and related comfort levels. The occupants were asked to stay in their usual ventilation and environment conditions during the monitoring period, and normal activities were performed without any other interference. The indoor sensors were placed 1.5 m above the ground at each sampling point near the participant. Participants were asked to provide a PIAQ vote on a scale from 1 to 7 (1-breathable, 2-Very stuffy, 3-Slightly Stuffy, 4-Neutral, 5- Slightly Fresh, 6-Fresh, 7-Very Fresh) to indicate their satisfaction with indoor air quality. They were also asked to rate their perceived thermal comfort on a scale from 1 (very uncomfortable) to 7 (very comfortable).[9]. The general health condition of participants was also recorded and converted to a scale of 1(very good) to 5(poor).

3.3 Air Quality Monitors

To conduct on-site measurements, portable real-time air monitors were used to measure Temperature, RH, CO2, Air flow velocity, and PM2.5. Table 2 provides details of the devices used to measure respective air quality parameters in indoor environments. These monitors were placed inside the households for 24 hours in a room where residents spent most of their time, calculations. The monitors collected data on the concentration of PM2.5 once per minute. Output was in the form of an Excel spreadsheet with summary measures, and a time stamp.

Table 1: Instruments used for indoor measurements

IAQ Variable	Instrument Used	Model	Resolution	Range
Temperature, RH	IAQ monitor	Testo 400	0.1°C ±0 %RH	0 to +50 °C 5 to 95 %RH
$PM_{2.5}$	IAQ monitor	SPS 30	0 to 100 µg/m3 : ±10 µg/m3 100 to 1000 µg/m3 : ±10 % m.v.	0.3 to 2.5 µm
CO_2	IAQ monitor	Testo 440	1 ppm	0 to 10000 ppm
Air velocity	Hot wire probe	Testo 400	0.01 m/s	0-50 m/s

3.4 Data Analysis

Data were collected in Microsoft Excel and analyzed using Excel and MATLAB 2023. The contribution of monitored levels of IAQ parameters with the PIAQ vote among the participants was investigated. We examined the relationship between measured data and responses from the survey questions to provide further insights.

The study also excluded the impact of TVOCs on PIAQ as none of the spaces had any new furniture or any renovation done in the last year. In the current study, It is also assumed that the effect of socioeconomic background and physical habits on the subjective evaluation of IAQ is neutral.

4. Results

The number of subjects monitored was 30 with 16 female and 14 male participants. The average age of the participants was 34.6 years. The study was completed by collecting indoor air and climate measurements and questionnaires. The study site was visited at per convenience of the participants and hence 24-hour data measurement was not possible. The majority of the participants were indoor workers, children, and housewives. Of these, 30 participants included in the analysis, two had 1 min data (0.07%) missing and the rest had no missing data during the monitoring period. It was tried to maintain an equal proportion of age groups amongst both genders. There weren't any smokers among the participants. Additional information about the building was also recorded and the respondent's location was marked on the floor layout. Table 2 summarizes the indoor T, RH, CO2, and PM2.5 concentrations during the study period.

Table 2: Summary of indoor T, RH, CO2, and PM2.5 concentrations during the study period

Parameter	N#	Mean	Max
Indoor Measurements			
Temp (◦C)	402	30.46	32.7
RH (%)	402	70.57	77.1
CO2	402	521.4	721
$PM_{2.5}$	80	15.79	25.07

No. of data points

4.1 Correlation among different parameters and mean PIAQ votes per person

4.1.1 Mean PIAQ votes per person vs. Age

The questionnaire responses were used to set up a correlation between mean PIAQ votes per person and different measured parameters. The results of the overall PIAQ vote, as shown in Fig. 3, show that under studied indoor environment conditions, 50% of the occupants felt 'neutral' towards the environment they live in, 16% felt 'stuffy' or 'slightly stuffy', 33% felt that the indoor environment was 'fresh'. It was also found that the participants who felt that the environment had good indoor air quality were a mix of occupants who prefer thermal comfort over IAQ even when the CO_2 levels rose to a maximum recorded value of 721ppm and PM2.5 value exceeded the WHO prescribed limit of 12μg/m^3 within 24-h period,[10] as well as occupants who preferred more fresh air where CO_2 levels were as low as 422 ppm and temperatures as high as 31.7°C. The latter category of participants also voted that they were 'very satisfied' with the thermal comfort and that the thermal comfort conditions were 'acceptable' to them.

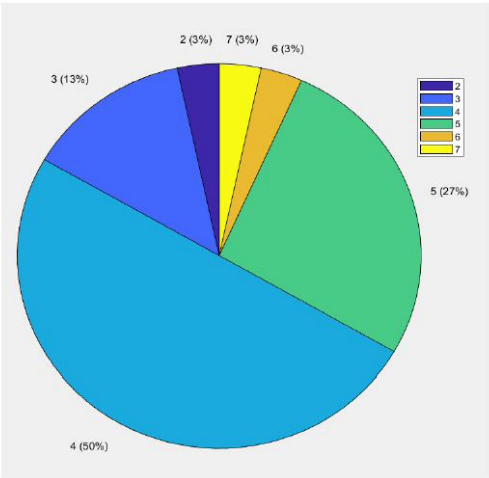


Figure 3: Overall PIAQ vote

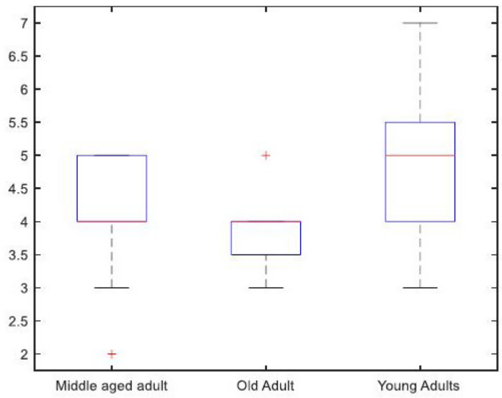


Figure 4: Distribution of mean PIAQ votes among studied age groups

Fig. 4, shows the distribution of overall PIAQ vote amongst different age groups that participated in the study. In the 'middle-aged adult' group, 25% of the respondents rated PIAQ as 4 or lower on the scale used in the graph. The interquartile range (IQR), spans from 4 to 5, indicating that the majority of respondents in the 'middle age' category fell within this range, with some perceiving indoor air quality as poor or suboptimal (25th percentile) and others perceiving it as moderately satisfactory (75th percentile). A significant portion of individuals within the 'old adult' group had relatively lower levels of satisfaction with indoor air quality, with the median and 25th percentile values both falling below the midpoint of the scale. This indicates that a substantial portion of respondents perceived the indoor air quality as less than satisfactory or neutral.

The interquartile range (IQR), in the 'young adult' age group, spans from 4 to 5.5, indicating the variability in satisfaction levels within this age group. For most individuals within this age group, PIAQ is moderately satisfactory, with a smaller subgroup expressing less satisfaction.

4.1.2. Mean PIAQ votes person vs. Occupant's Gender

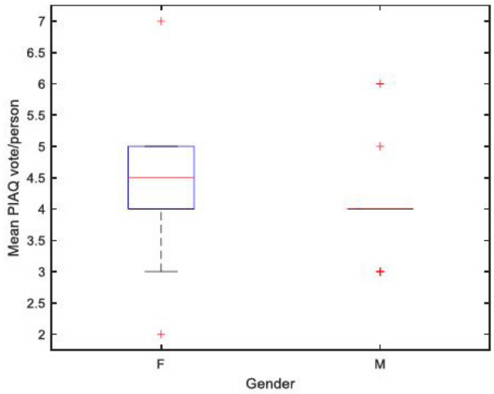


Figure 5: Distribution of mean PIAQ votes among male and female participants

90% of the females, who participated in the study, were housewives who spent more time in indoor surveyed environments as compared to surveyed males. Fig. 5, shows that the 50% quartile among females was 4.5 and among males was 4. Previous investigations carried out in different countries also reported that females were more susceptible to SBS symptoms than males.[11]

4.1.3. Mean PIAQ votes person vs. Perceived Odour

Occupants perceiving any type of odours in an indoor surveyed environment reported lower mean PIAQ rating, 4.06, and acceptability as compared to occupants, 4.43, who do not perceive any kind of odour indoors. (Fig. 6).

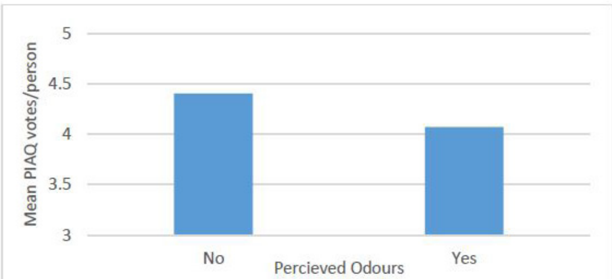
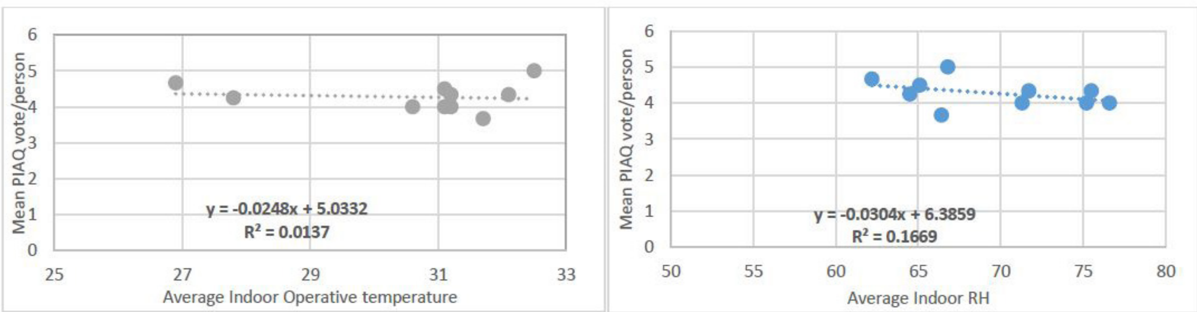


Figure 6: Mean PIAQ/person vs. perception of odour in the indoor environment

4.1.4. PM2.5, RH and CO2 as an indicator of IAQ



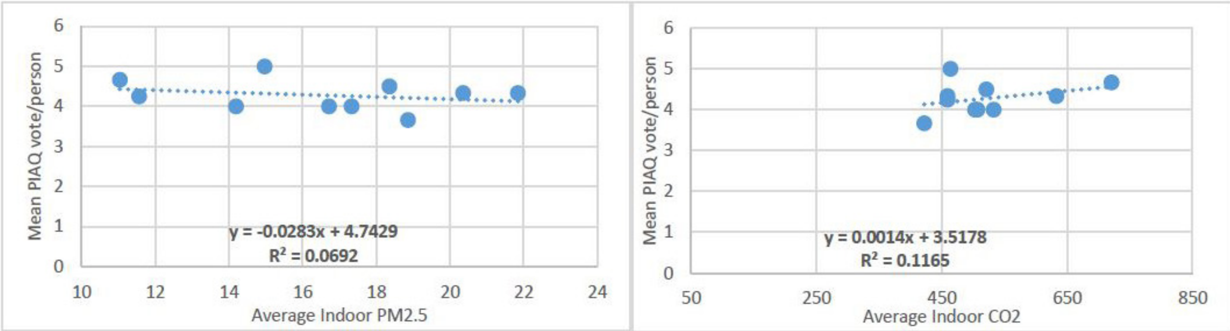


Figure 7: Variation of Mean PIAQ vote with (a) Average Indoor Operative Temperature, (b) Average RH, (c) Average Indoor PM2.5, (d)Average CO2

Fig. 7a-d, describes the relationship between measured values of Average Indoor Operative Temperature, Average RH, Average Indoor PM2.5, and Average CO2 with Mean PIAQ votes per person (at p>0.05). It can be observed from the above plots that PIAQ is 'less likely' to be dependent on Indoor Operative temperature and 'very likely' to be dependent on Relative humidity (R2=0.167) and Indoor CO2(R2= 0.12). Although the R2 values seem to be low, it provides a gateway to conduct more investigation in a controlled and/or real-time environment with a relatively large number of data points to calculate a more effective coefficient of correlation.

The above analysis also does not necessarily imply that PM2.5 (R2= 0.069) does not affect the perception of Indoor air quality. The above three parameters act as an 'indicator' or 'marker', indicating likely contamination of indoor air. The low R^2 value between the Mean PIAQ vote and Indoor operative temperature indicates that only 1.37% of the variance in the Mean PIAQ vote can be explained by changes in indoor operative temperature. In other words, temperature alone has very limited predictive power when it comes to assessing the acceptability or comfort of the thermal environment.

4.2. PM2.5, and CO2 as a function of Average Indoor Operative Temperature

The study attempted to also evaluate the possible effects of Average Indoor temperature on the concentration of CO2 and PM2.5 in indoor spaces. The negative slope in the linear relationship between Average Indoor temperature and Average CO2 (at p>0.05) indicates an inverse or negative correlation between two variables, meaning that as one variable increases, the other tends to decrease, whereas in the case of Average PM2.5, the correlation is positive.

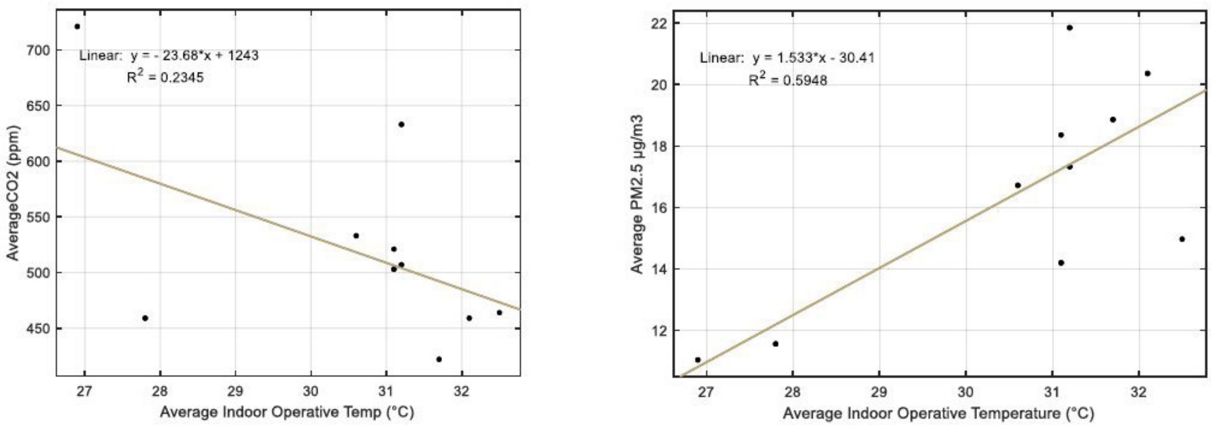


Figure 8: Relation of Average Indoor Operative Room Temperature with Average CO2 and Average PM2.5 in indoor spaces

4.3 PM2.5 as a function of Average relative Humidity

The non-zero slope and R2=0.261 between Average PM2.5 concentration and relative humidity, Fig, 9, in indoor space, expresses the probable relation of the thermal comfort equation with perceived indoor air quality. Their relationship can be complex and can be influenced by various factors. High humidity can contribute to the formation of secondary aerosols, which can increase PM2.5 concentrations.

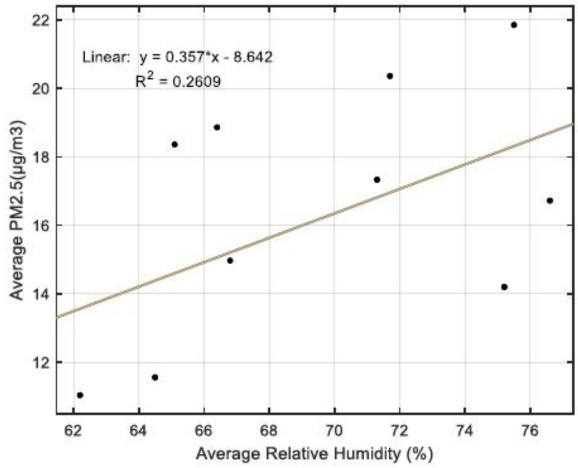


Figure 9: Relation of Average relative Humidity with Average PM2.5 in indoor spaces

4.4. PIAQ and Thermal Sensation

The concentration of the measured parameters in the indoor space may lie within ASHRAE standard limits but the occupants may still complain about sick building symptoms affecting the PIAQ..[12] The below graphs (Fig. 10), explain the above hypothesis. At a lower score of Mean thermal sensation (more thermal discomfort), the perception of IAQ is better with a median of 5, 6.5, and 5 at TSV 2, 3, and 4 respectively whereas the PIAQ vote is low (poor perceived IAQ) at a good score of TSV.

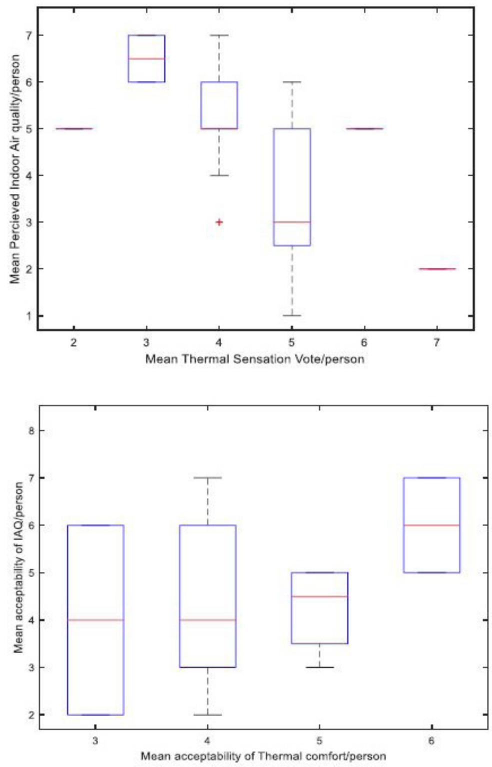


Figure 10: Relation of PIAQ with thermal sensation rating and their acceptability

However, when we surveyed the acceptability of the Thermal sensation and perceived IAQ, the occupants, despite being dissatisfied with either thermal comfort and/or IAQ, accepted the currently prevailing thermal and indoor air conditions. This shows that occupants were adaptive to the environment they lived in despite the discomfort. This could be due to other social, psychological, and physiological factors.[13]

4.5. General health conditions of the participants vs. PIAQ

General health conditions among the participants were recorded. Participants stated their general health condition on a scale of 1(very good) to 5(very bad). 27% reported their general health condition to be 'very good' whereas 30% reported 'good', 40% reported 'moderate' and 3% reported 'bad'. The results show that participants with 'very good' and 'good' health conditions felt 'neutral' to 'fresh' within the indoor setting. Participants with 'moderate' and 'bad' health conditions felt 'slightly stuffy' to 'neutral' in their indoor air quality (Fig.11).

In terms of the acceptability of the indoor environment, all the participants except those who had 'bad' health conditions felt that the indoor air quality could have been better and expressed their acceptability from 'unacceptable' to 'slightly unacceptable'.

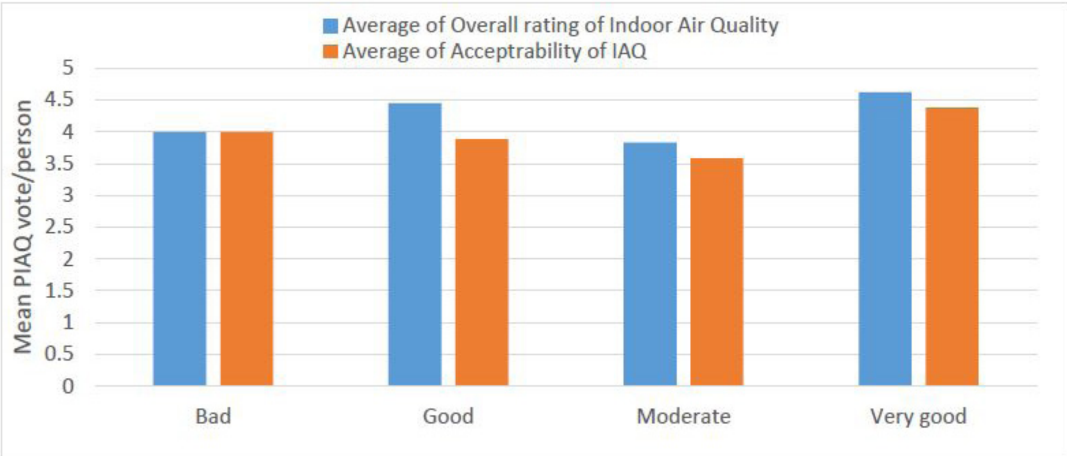


Figure 11: Distribution of mean PIAQ per person among participants according to their general health condition

4.6 Predicted response vs. Actual response

Unlike, in many earlier studies, both the PMV model and TSV model in the current study, have a non-zero slope, Fig. 12. This implies that PMV can be used here as a method to predict the thermal adaptability of the occupants. However, the PIAQ model has almost a zero slope with R^2=0.014, which indicates that Indoor Operative temperature may be 'less likely' to affect the perception of Indoor air quality in the presented study.

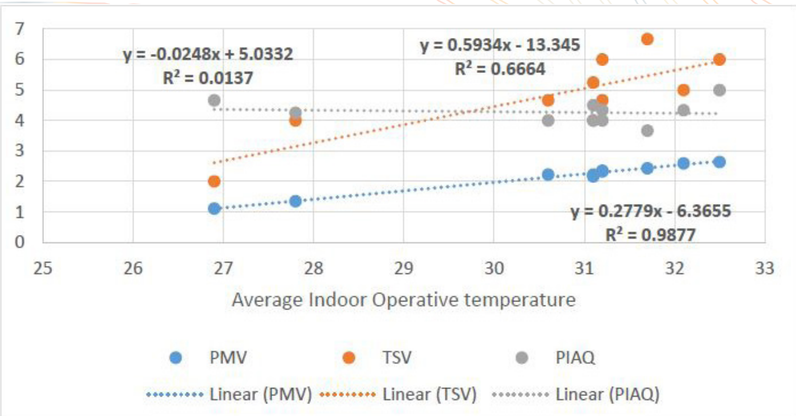


Figure 12: Correlation between calculated PMV, actual TSV, and PIAQ vote vs. Indoor Operative Temperature.

5. Discussion

In the present study, 77% of the spaces were naturally ventilated whereas 23% were mixed-mode. It is also worth mentioning that even though air conditioners were operating in some spaces, the doors were kept open to indoor connected spaces. While the low R^2 between Mean PIAQ vote/person and measured parameters suggests a weak linear relationship, it's possible that the relationship between them and Mean PIAQ vote is nonlinear. Exploring potential nonlinear relationships or interactions with other variables may reveal more insights into the PIAQ assessment.

Another noteworthy observation was that despite experiencing discomfort at some level due to indoor air quality in terms of respiratory and overall health issues, 83% of the overall participants were satisfied and/or felt better in the indoor environment. This could also be attributed to the possibility of their comparison of perception with poor Outdoor air quality. Thus, in further studies, it is also important to monitor Outdoor air quality in the studied region. of 12

This study also shares an insight that the perception of Indoor Air Quality is "unlikely" to be a function of Indoor Operative Temperature. This implies that people's responses were largely unaffected by the temperature settings they were in. The possible theory behind this is that the subjects/occupants were surveyed in the environment they usually live in for maximum time of the day.

The current study is a pilot experiment on quantitative and qualitative assessment of indoor air quality. However, it is limited to 30 participants. A clearer picture could be painted with more participants, 24-hour data monitoring, and conducting the study in an environment that is in the vicinity of more pollution sources. The study can also include variations in PIAQ over seasons to account for a wide range of climatic variations and ventilation conditions. Individual differences in perception and sensitivity to indoor environmental factors must also be acknowledged. E.g. the Differences due to Body Mass Index(BMI), health practices like yoga, meditation, etc. While our study reveals a general trend, it is essential to recognize that some individuals may be more resilient to variations in indoor air quality, while others may experience discomfort more acutely. Future research should explore these individual differences to tailor indoor environmental solutions effectively.

6. Conclusion

The questionnaire analysis indicated that occupants of the study site experienced a variety of illness symptoms that occurred 'often' or 'always'. The main symptoms prevailing were headache, lethargy, fatigue, shortness of breath, and dryness in mucous.
Results depicted that males were more susceptible to poor IAQ symptoms (50% more) as compared to females. Significant relationships between Mean PIAQ per person and age, gender, CO2 concentration, PM2.5 concentration, perceived odours, and relative humidity. Occupants in the 'middle-aged adult' and 'young adult' age group were less 'dissatisfied' as compared to occupants in the 'old adult' group. The general health condition also had a significant effect on the PIAQ as people with 'very good' health conditions also perceived that the IAQ was also towards a fresher side whereas participants with a 'bad' health condition perceived that IAQ was towards a 'stuffy' side.

CO2 concentration, PM2.5 concentration, perceived odours, and relative humidity varied linearly with the PIAQ vote, which shows that they may be categorized as an 'indicator' or 'marker' of IAQ.
A notable conclusion from the above study was that at lower values of mean TSV, the mean PIAQ vote per person was 'slightly fresh' to 'very fresh', The relationship between mean TSV per person and the mean PIAQ vote per person indicates that a good PIAQ does not necessarily indicate good Perceived thermal comfort. Thus, it is imperative to understand the optimal range of conditions that ensures occupant satisfaction both in terms of thermal comfort and indoor air quality for the overall health and wellness of the occupants.

In conclusion, the findings of this study provide compelling evidence of an inverse relationship between the PIAQ vote and TSV in indoor environments. Our research underscores the importance of considering not only thermal comfort but also indoor air quality as integral components of occupant satisfaction and well-being within indoor spaces.

In conclusion, the inverse relationship between PIAQ vote and perceived thermal comfort sheds light on the intricate dynamics within indoor spaces. Recognizing and acting upon this relationship can lead to improved indoor environmental quality, benefiting the health and satisfaction of building occupants. Further research and practical interventions are warranted to harness the full potential of this insight and create indoor environments that are truly conducive to human well-being.

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Study on WBGT for heat stroke evaluation during summer in Japanese living rooms

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Abstract

As the number of heat stroke cases in residential buildings has increased, countermeasures has to be taken. Although there are many studies on the relationship between heat stroke and outdoor environment, there are only a few studies which used Wet-Bulb Globe Temperature (WGBT) for the evaluation of heat stroke in the dwellings. The main objective of this study is to evaluate the risk of heatstroke occurrence using WBGT for the indoor environment during summer. A field measurement was conducted in summer of 2021 and 2022 in 33 dwellings to measure the indoor air temperature, relative humidity, and globe temperatures for every 10 minutes in the living room. Outdoor WBGT data were obtained from the Japan Meteorological Agency. The result suggests that indoor WBGT was 23~27°C in 2021 and 22~26°C in 2022, indicated that the risk of heatstroke occurrence is low in investigated dwellings. In both years, a correlation was observed between indoor air temperature and WBGT. The result showed that when indoor air temperature increased, WBGT is also increased.

Keywords - Living room, Summer, Field survey, WBGT, Heat stroke

1. Introduction

In 2022, Japan's annual average temperature deviated by +0.6 °C, indicating a rising trend in line with the average global temperature. With seasonal changes indicating a rise of 1.6 °C in spring, 1.2 °C in summer and winter, and 1.3 °C in autumn, the rate of increase is 1.3 °C per century. Focusing on urban areas, the average difference in annual average temperature exceeds 0.4~1.7°C among 15 locations (Global Warming Projection Information 2017).

The risk of heatstroke has increased in Japan due to the rising annual average temperature and high humidity levels. Heatstroke is not only affected by temperature, but also by humidity. The increase in the number of heatstroke patients in the summer is one of the issues in Japan (Climate Change Monitoring Report 2022).

The number of people who were transported by ambulance for heatstroke from June to September nationwide has increased significantly since 2010 (Fire and Disaster Management Agency). In 2018, there were 92,710 people, followed by 66,869 in 2019 and 64,869 in 2020. The proportion of people over the age of 65, which was about 40% of the total population in 2008-2009, increased to 40-50% in 2010-2017 and 48-58% in 2018-2021. In addition, heatstroke occurring in the home is also on the rise, and the need for countermeasures is increasing.

Most of the previous studies used WBGT for outdoors or semi-outdoors. There have been some studies on WBGT in indoor environments, but most of them have been done in the low income houses (Pradhan et al. 2013, Sudarsanam et al. 2023, and Adekunle et al. 2021). WBGT can be used to identify the risk of heatstroke at home. The objective of this study is to evaluate the relationship between the risk of heatstroke in Japanese dwellings during the summer by using WBGT.

2. Methods

2.1 Study area and climatic condition

The targeted dwellings for the case study are located in Tokyo, Yokohama, Chiba, and Yamanashi areas of Japan. The summer in Japan is characterized by high temperatures and high humidity.

Figure 1 shows the monthly mean outdoor air temperature and relative humidity obtained from the Tokyo Meteorological Station. The average annual temperature in Tokyo is 16 °C, with the highest and lowest temperature being 37 °C and -3 °C, respectively. The average relative humidity is 70%.

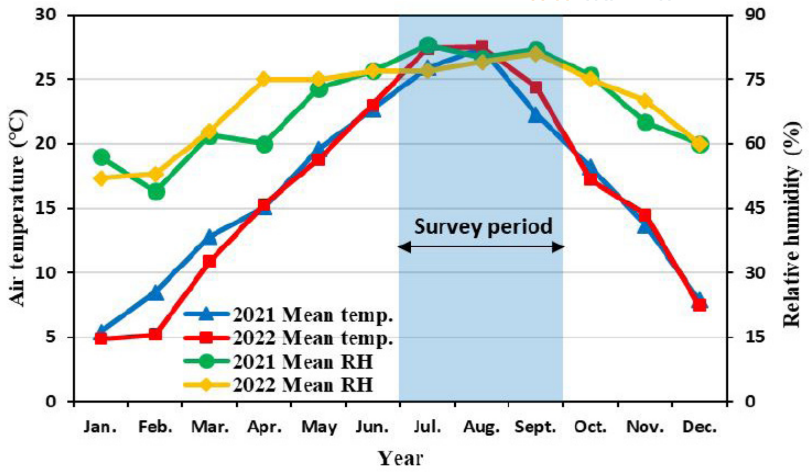

Figure 1: Outdoor air temperature and relative humidity in Tokyo

2.2 Investigated dwellings

Figure 2 shows the overview of one of the case study dwellings located in Tokyo. Table 1 shows the details of the targeted dwellings (33 houses, including 17 detached homes, 10 condominiums, and 6 apartments). The structure of the dwellings are wooden, reinforced concrete, and steel. The age of the dwellings ranged from 5 to 30 years. The floor of the living room is mostly on the first floor for single-family homes, and 2~10th floors for condominiums.

Figure 2: Overview of one of the case study dwellings

Table 1: Details of the investigated dwellings

Investigated year	Dwelling number	Location	Housing type	Housing structure	Age of building	Floor of living room	Window main directions	Distance to weather station (km)
2021	1	Yokohama	Condominium	RC	10	1	S	
	2	Chiba	Condominium	RC	10	1	S	
	3	Yokohama	Detached house	Wooden	15	2	E	
	4	Yokohama	Detached house	Wooden	20	1	S	
	5	Tokyo	Condominium	RC	10	2	S	
	6	Yokohama	Detached house	Wooden	20	1	E	
	7	Yokohama	Condominium	RC	30	3	E, S	
	8	Yokohama	Detached house	Wooden	30	1	S	
	9	Tokyo	Detached house	RC	15	1	S	24
	10	Yokohama	Detached house	Wooden	30	1	S	25
	11	Tokyo	Apartment	Wooden	20	1	S	28
	12	Tokyo	Detached house	RC	10	6	S	19
	13	Tokyo	Detached house	Wooden	5	4	E	37
	14	Yokohama	Detached house	Wooden	5	1	S	30
	15	Tokyo	Apartment	RC	10	1	W	35
	16	Yokohama	Apartment	Wooden	20	1	E	
	17	Yokohama	Condominium	RC	20	1	E	
2022	1	Yokohama	Apartment	RC	15	1	E	20
	2	Tokyo	Condominium	RC	20	9	S	17
	3	Yokohama	Detached house	Wooden	20	6	S	50
	4	Yokohama	Detached house	Wooden	5	10	SE	16
	5	Tokyo	Condominium	S	30	3	S	25
	6	Tokyo	Condominium	S	20	1	S	27
	7	Yamanashi	Detached house	Wooden	20	2	S	16
	8	Tokyo	Detached house	Wooden	30	1	S	28
	9	Tokyo	Detached house	RC	20	3	SE, SW, NW	24
	10	Yokohama	Apartment	Wooden	20	1	S	28
	11	Yokohama	Detached house	Wooden	30	1	S	25
	12	Tokyo	Condominium	RC	15	1	S	30
	13	Tokyo	Apartment	RC	10	1	W	35
	14	Yokohama	Detached house	RC	10	6	S	19
	15	Tokyo	Detached house	Wooden	5	4	E	37
	16	Yokohama	Condominium	RC	20	1	S	25

N: North, E: East, S: South, W: West, RC: Reinforced concrete

2.3 Thermal measurements

A field measurement was conducted from 1st July to 24th August 2021 and 1st August to 25th September 2022 in 33 dwellings where the indoor air temperature, relative humidity, and globe temperatures were recorded at every 10 minutes interval. Table 2 shows the detailed information about the instruments used for this survey. The sensors were placed at the height of 90 cm above floor level in the center of the living room. The outdoor WBGT data were obtained from the Japan Meteorological Agency.

Table 2: The information for the measuring instruments

Instrument	Air temp., Relative humidity and CO_2	Globe temp.
Model	TR-76Ui	Tr-52i
Range	0 to 55 °C, 10% to 95% RH, 0 to 130 klx	−60 to 155 °C Black painted 75 mm diameter globe
Accuracy	±0.5 °C, ±5%RH, ±5%	±0.3 °C
Photograph		

2.4 WBGT calculation method

The calculation formula for WBGT in the absence of direct solar radiation is shown below (International Standard Organization (ISO) 7243: 2017).

$$WBGT = 0.7T_{nw} + 0.3T_g \quad (1)$$

In this study, the WBGT in the residential building was calculated using equation (1). Tnw is the natural wet-bulb temperature (°C) and Tg is the globe temperature. Tnw was not measured, so it was estimated using the discomfort index. Discomfort index can be calculated by using equation (2) based on air temperature and relative humidity, and equation (3) based on air temperature and wet-bulb temperature. In order to estimate the wet-bulb temperature (Tw), equation (4) can be used. In this study, equation (5) from Saito & Sawada. (2022) was used to calculate the natural wet-bulb temperature (Tnw), and thus WBGT can be estimated.

$$DI = 0.18T_a + 0.01\mathrm{RH}\,(0.99T_a - 14.3) + 46.3 \quad (2)$$

$$DI = 0.72(T_a + T_w) + 40.6 \quad (3)$$

From equations (2) and (3),

$$T_w = \frac{0.09T_a + 0.0099T_a \times \mathrm{RH} - 0.143\mathrm{RH} + 5.7}{0.72} \quad (4)$$

$$T_{nw} = T_W + 0.05(T_g - T_a) \quad (5)$$

where; DI : Discomfort Index, Ta: Air temperature (°C), RH: Relative humidity (%), Tw: Wet-bulb temperature (°C) , Tnw: Natural wet bulb temperature (°C), Tg: Black bulb temperature (°C).

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2. Methods

3.1 Indoor air temperature in the living room

Figure 3 shows the indoor air temperature in the living room of this study. In 2021 and 2022, the indoor air temperature mostly ranged between 27 to 29 °C. A study conducted by Katsuno et al. (2015) found that the average indoor air temperature in summer was 28.9 °C, which is similar to the results of this study. A study conducted in the Terai region of Nepal found that the average indoor air temperature was 33 °C, which is higher than the results of this study (Pradhan et al., 2013). The large impact of housing performance is likely the reason for this.

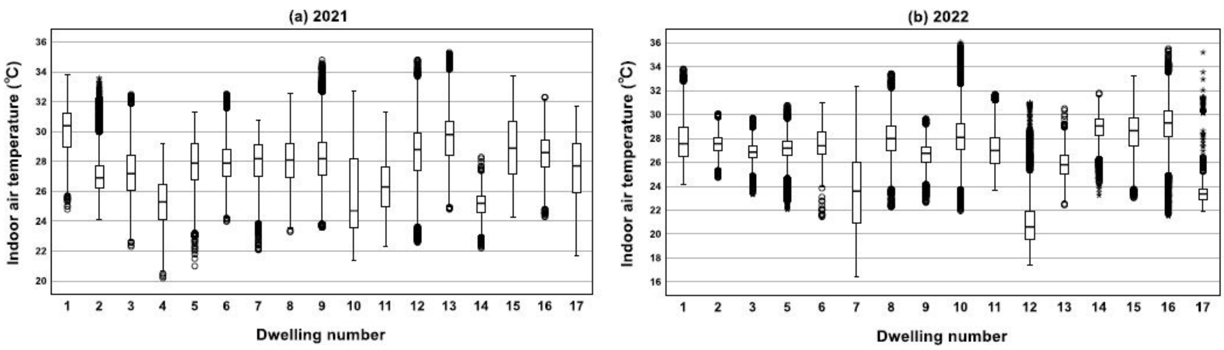

Figure 3: Indoor air temperature in the living room in (a) 2021 and (b) 2022

3.2 WBGT in living room

This section aims to clarify the trend of WBGT fluctuations in the living room. Figure 4 shows the trend of WBGT for the living room of all the targeted dwellings including the outdoor WBGT. It can be seen that the WBGT of most rooms in 2021 is distributed between the range of 23°C-27°C. Since the temperature standard range of WBGT in daily life is set below 25°C (Japan Society for Biometeorology: 2022). the risk of heat stroke indoors in most of the rooms is considered to be low. However, only dwelling 13 often exceed 28°C, and it is necessary to pay attention to the high indoor temperature. The WBGT of dwellings 4, 10, and 14 is low due to the use of the air conditioner in these houses. It is necessary to pay attention to health problems created by air conditioning use. In 2022, the WBGT of most living rooms is distributed between 22 to 26°C, and the difference between 2021 is small.

The WBGT of dwellings 7 and 12 is 13°C, and it is necessary to pay attention to health problems. The risk of heatstroke increases when WBGT exceeds 27°C. In this study, the WBGT of most rooms was below 27°C, and thus the risk of heat-related diseases might be low.

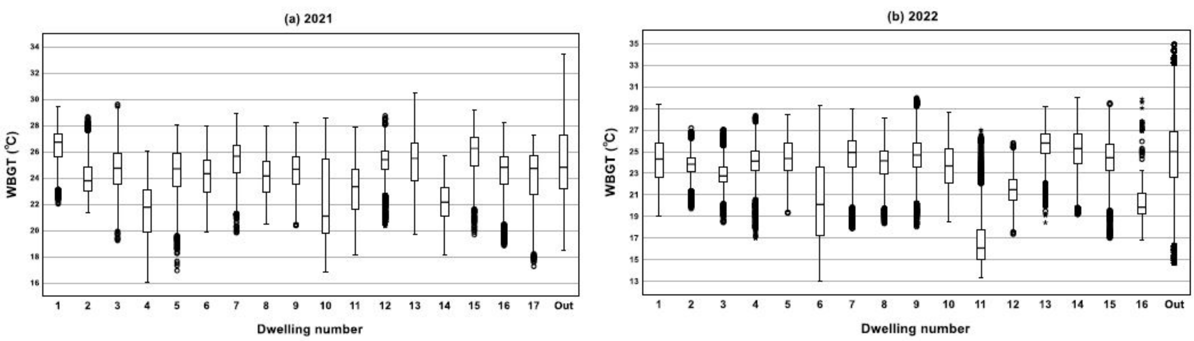

Figure 4: WBGT for each living room and outdoors

https://doi.org/10.62744/CATE.45273.1168-362-370

3.3 Distribution of WBGT in investigated dwelling

In this section, the WBGT were classified standards into four levels: "Low" (<25°C), "Moderate" (25~28°C), "High" (28~31°C), and "Extreme" (>31°C) based on the "Heatstroke Prevention Guidelines in Daily Life" of the (Japan Meteorological Society: 2021, 2022).

Figure 5 shows the WBGT percentage for each targeted dwelling in this study. In 2021, 20% of the living rooms of dwellings 1 and 15 were in the "severe alert" zone. This might be due to the lifestyle of the residents. Especially in dwelling 1, elderly people may not use air conditioners for the temperature control.

Eguchi & Hasegawa (2015) found that some elderly people do not improve their thermal environment despite the risk of heatstroke, as their ability to adapt to changes in temperature decreases with age. In dwelling 15, the natural ventilation is mainly used by opening many windows, and thus the indoor temperature is always high.

In 2022, the percentage of living rooms in dwellings 9 and 14 in the "severe alert" zone was 15%, which is about 5% lower than the 2021 living room data.

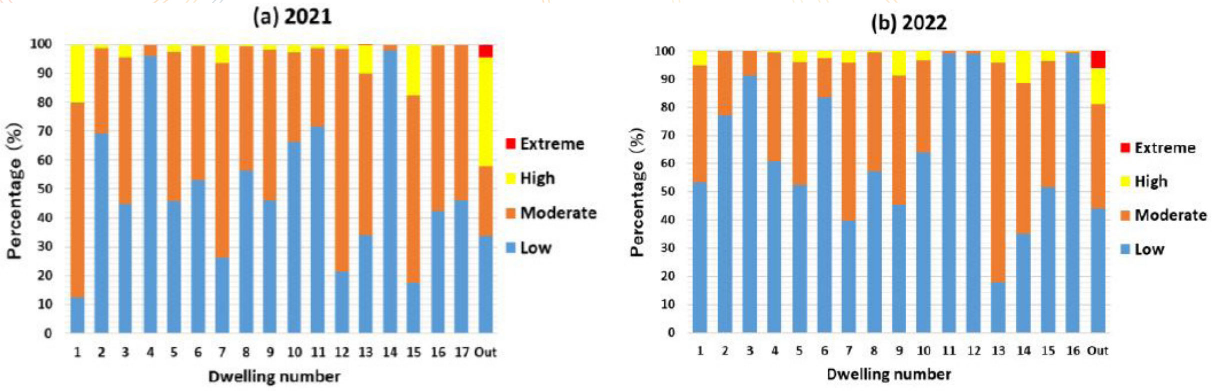

Figure 5: WBGT percentage in (a) 2021 and (b) 2022

3.4 Variation of WBGT

In this section, the daily variation of WBGT in the living room on the day when the outdoor WBGT was the highest during the measurement period was analysed to clarify the risk of heatstroke during the day and night.

Figure 6 shows the daily variation of indoor WBGT for all targeted dwellings during the highest outdoor WBGT of 2021 and 2022. In 2021, the outdoor WBGT was above 31°C for about 4 hours during the day. Dwellings 1, 7, 12, and 15 have a small WBGT variation throughout the day and fluctuate in the "Low" zone. This is because the houses are made of reinforced concrete, and the heat capacity of the house is larger than that of wooden houses. The WBGT of most of the houses decreased after 21:00, but dwelling 17 is increasing. The reason might be that this dwelling is turning off the air conditioner at night time.

In 2022, the outdoor temperature was above 31 °C for about 6 hours during the day time. It was found that dwellings 8 and 14 have a small WBGT variation throughout the day and fluctuate in the "Low" zone. The large WBGT variation in dwellings 1, 6, and 9 is due to the reason for ventilation by opening the window. Compared to 2021, the WBGT variation is lower in 2022.

The variation in WBGT in the room on a hot and humid day was 25 to 30 °C (Eguchi & Hasegawa., 2015). In this survey, the WBGT variation in 2021 was 19 to 27°C, and in 2022 it was 18 to 27°C. This might be because of elderly people want to avoid the cold by using the air conditioner, and they may use the fan. Most houses are in the "Moderate" zone and "Low" zone during the day time and nighttime, and the risk of heatstroke is low. However, some houses have significantly low WBGT throughout the day.

3.5 Variation of WBGT by housing structure

In this section, the variation of WBGT by the structure of the house is clarified. Figure 7 shows the variation in WBGT by wooden and RC houses. The RC houses show less variation in indoor WBGT than the wooden houses. It can be seen that the outdoor WBGT variation affects the indoor WBGT variation from around 1:00 to 8:00 for the wooden structure, whereas the RC structure is hardly affected by the outdoor WBGT at the same time. In addition, wooden houses show greater fluctuations in indoor WBGT than RC houses. This indicates that wooden houses need to be more resilient to mitigate the indoor WBGT than RC houses.

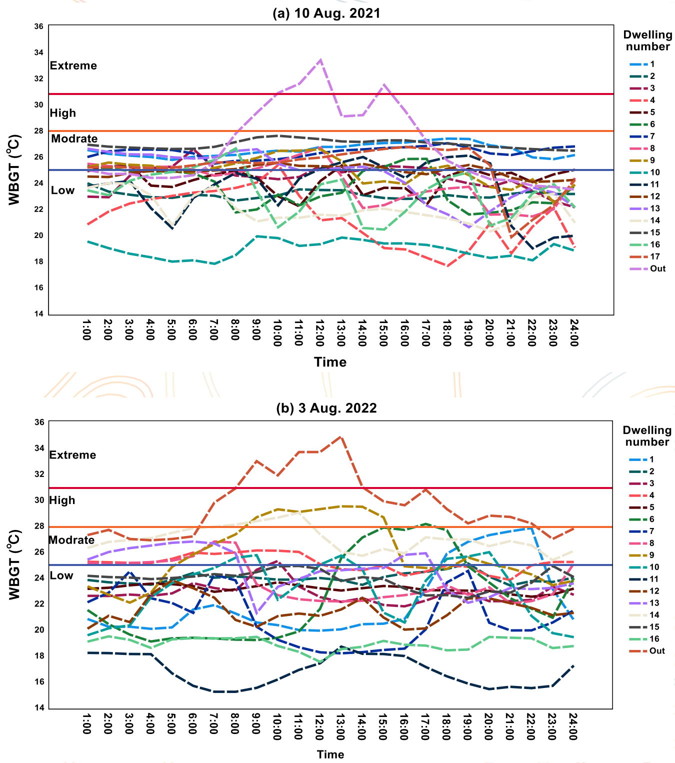

Figure 6: WBGT variation of all houses and outdoor during (a) 10 Aug. 2021 and (b) 3 Aug. 2022

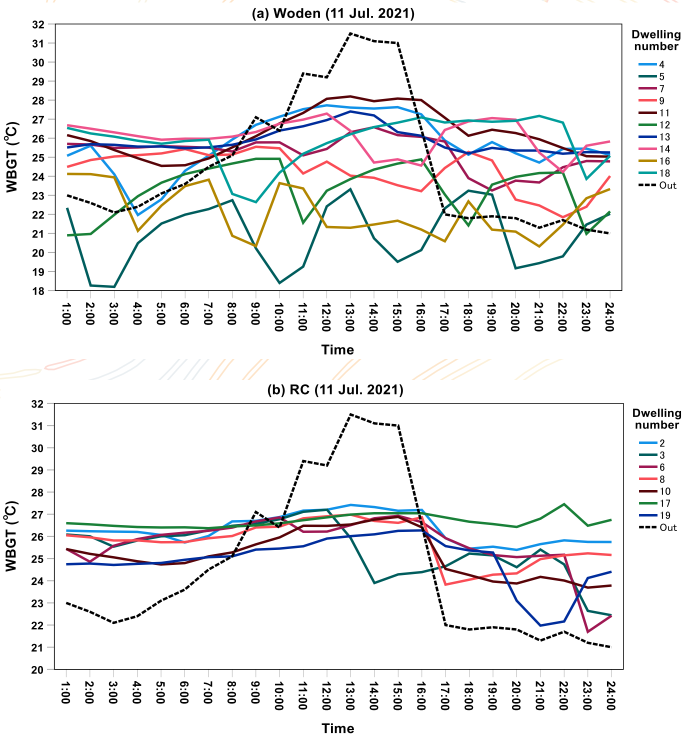

Figure 7: Variation in WBGT by housing structure

3.6 Relationship between indoor WBGT and indoor air temperature

In this section, the correlation between indoor WBGT and indoor temperature in the living room during the measurement period was analysed as shown in Figure 8. WBGT enters the warning zone when the indoor temperature is higher than 25°C. A strong correlation coefficient was observed for both years. When indoor temperature is 30 °C the WBGT is 26°C and 27°C in 2022.

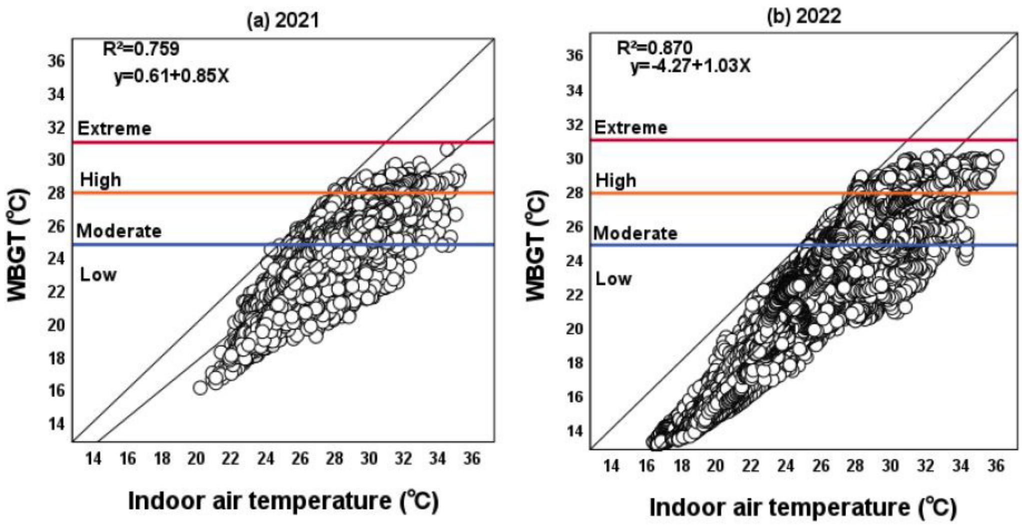

Figure 8: Relation between indoor WBGT and indoor air temperature

4. Conclusions

In this study, we measured the thermal environment and calculated the WBGT in the living rooms of 33 Japanese houses during summer. The conclusions are as follows:

1. The range of indoor WBGT was 23~27°C in 2021 and 22~26°C in 2022, and thus the risk of heatstroke indoors is low.

2. The "severe warning" zone of WBGT was 20% in dwellings 1 and 15 in 2021 and 15% in dwellings 9 and 14 in 2022. Although the risk of heatstroke is low, it was found that there are some dwellings where WBGT is significantly low, and thus air conditioning is not being used properly.

3. The variation of indoor WBGT on hot days in 2021 and 2022 was 19~27°C and 18~27°C, respectively. The risk of heatstroke was higher than the normal day.

4. There was a correlation between indoor air temperature and indoor WBGT. As the indoor temperature rises, WBGT also rises, and thus it is increasing the risk of heatstroke.

5. Acknowledgements

We would like to express our sincere gratitude to the residents for their cooperation for the thermal measurement.

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The climate spatial variability and its impact on the thermal energy simulation of buildings: a case study of São Paulo, Brazil

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1. Abstract

This study evaluated the impact of different weather stations on building energy simulations (BES) concerning local environmental factors. The investigation focused on eight distinct weather stations in São Paulo, Brazil, comparing their data's influence on thermal autonomy and cooling load in a low-income dwelling. Employing EnergyPlus for computational simulations, the outcomes were compared against the surrounding urban fabric and natural coverage indexes. The analysis revealed noteworthy differences between the weather stations with more natural vegetation and those densely urbanized. These disparities were particularly pronounced, with differences of up to fivefold observed in cooling degree hours (CDH) between these locations. Consequently, these discrepancies in weather inputs impacted cooling load predictions, portraying urbanized regions with markedly elevated cooling requirements relative to the more naturally covered areas. Regarding the correlation between the surrounding indexes, site coverage and vegetation cover were more impactful in predicting thermal autonomy and cooling load.

Keywords - Urban overheating, social housing, Brazilian climatic conditions, urban climate.

2. Introduction

Urban populations are particularly vulnerable to thermal risks due to rapid urbanization and increasing occurrences of extreme heat events. Understanding the factors that contribute to urban overheating and changing the urban-rural energy contrast is essential [1]. Social housing, often with lower thermal performance than the general housing stock, becomes especially exposed as weather patterns change and the urban heat island effect intensifies [2]. Vulnerable populations, such as those with low income or social isolation, bear a disproportionate mortality burden during extreme weather events [3].

Building Energy Simulation (BES) is a common approach for evaluating design alternatives and validating performance against regulatory and governmental requirements. The building performance depends on the building envelope (architectural choices, components and materials that define the relationships between the indoors and outdoors), the occupant behavior, and the weather. Therefore, weather data is a crucial input for BES tools [4]. Typically, the BES community relies on typical meteorological year (TMY) or test reference year (TRY) weather files to represent the weather of a location in a simulation process. However, TMY and TRY weather files are commonly developed from data recorded at distant airports, which may not accurately represent the urban region of interest. In this regard, BES tools usually adopt coefficient corrections to mitigate the presence of urbanity in the weather (especially on the wind speed); yet, it is still an approximation, and the urban landscape might be very heterogeneous.

Therefore, when using conventional weather data files, we may underestimate the effects of urban heat islands and other characteristics that would impose thermal penalties on the inhabitants of social housing in urbanized areas. When considering megacities like São Paulo, these effects can be even more pronounced due to the heterogeneity of an urban area of this magnitude.

In the case of São Paulo, some studies have already been conducted, but they consider surface temperatures in contrast to the internal thermal performance of buildings. Ferreira and Duarte [5] explored the relationship between land surface temperature, vegetation cover, and local climate zones. They found a strong negative correlation (>90%) between the land surface temperature of the local climate zone and its vegetation cover. Another study by the same authors [6] investigated the daytime and nighttime land surface temperatures over different urban forms in São Paulo. The compact local climate zone morphologies presented higher daytime land surface temperatures, with low-rise buildings being hotter than high-rise buildings by an average of 5°C. This higher temperature average suggests the difference can be even larger during extreme events.

Overall, this study contributes to the body of knowledge of the spatial variability of urban climate in a high-density city (São Paulo) and its ramifications for thermal performance in buildings. The findings can inform policymakers, practitioners, architects, and engineers on how different urban regions and urban design affect comfort and energy efficiency in the same metropolitan area.

Considering the above, this study aims to evaluate the spatial variability of the weather files in the urban zone of São Paulo, Brazil, and its impact on the thermal energy simulation of buildings.

3. Methods

The method of this study is composed of four main steps. Firstly, the weather data was obtained from eight weather stations (either getting existing weather files or creating weather files from weather stations). Then, the surroundings of each weather station location were characterized by considering urban indexes. A standard simulation model was simulated using the weather files on EnergyPlus, obtaining building performance indicators. Finally, the urban characteristics of each weather station location were compared to the simulation results and the weather data.

3.1 Weather data characterization

The metropolitan region of São Paulo measures around 1,600 km^2, with a population of 20 million [7]. It presents a Cfa classification (Humid subtropical climate) according to Köppen-Geiger and 2A (Hot humid) according to ASHRAE 169/2013 standard. The analyzed climatic stations are all located within the municipality of São Paulo, except for the station at Guarulhos International Airport, which is situated in the neighboring city of Guarulhos. Figure 1 presents general location and elevation data for all considered stations. The obtained climatic variables were Dry Bulb Temperature (°C), Relative Humidity (Pa), Atmospheric Pressure (Pa), Global Horizontal Irradiation (Wh/m^2), Wind Direction (°), and Wind Speed (m/s). The year 2021 was chosen because it had the highest number of available data.

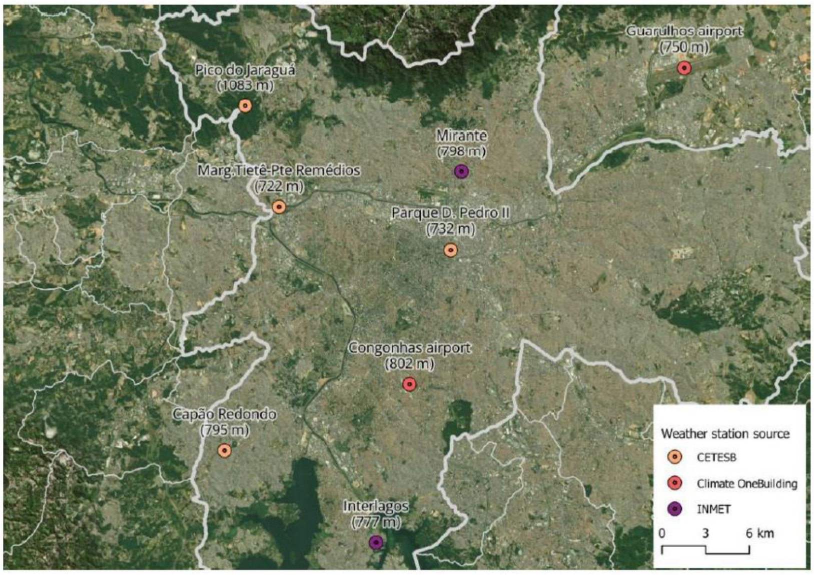

Figure 1: Weather station location, elevation, and data source.

CETESB is the state of São Paulo government agency responsible for controlling, inspecting, monitoring, and licensing activities generating pollution. The data is available for download on [8]. Regarding CETESB stations, the one in Pico do Jaraguá did not provide data for relative humidity, atmospheric pressure, and horizontal global irradiation. The other stations had a data completeness of around 90%. INMET, the Brazilian National Institute of Meteorology, offers access to data from all stations at [9]. For 2021, INMET stations' weather data were complete. Climate.OneBuilding [10] is a website with various weather files for building energy simulations maintained by Dru Crawley and Linda Lawrie. The website maintainers provided the historical time series used to develop the TMYx (Typical Meteorological Year) weather files. These files utilize data derived from hourly weather data in the ISD (US NOAA's Integrated Surface Database), supplemented with solar irradiation data from the ERA5 reanalysis dataset. The weather data is provided in the EPW (EnergyPlus Weather file) format, a simple ASCII format commonly used in EnergyPlus inputs. Therefore, these files were ready for use in the selected simulation tool for building performance analysis.

The other data sources require the development of EPW files to proceed with the building simulation phase. For this purpose, we utilized the Weather Converter program bundled with EnergyPlus to create the necessary weather files for building simulation. This tool converts and extends weather data into the EPW format. It performs calculations to fill in missing data and generates a statistical summary of the weather dataset during the processing [11]. The relative humidity and global horizontal irradiation values from the station located at Congonhas Airport were used to complete the missing values for the Pico do Jaraguá location.

In addition to using the EPW files for the simulation, we conducted an exploratory analysis of climate variables (specifically Dry Bulb Temperature, Wind Speed, Relative Humidity, and Global Horizontal Irradiation) to assess the overall behavior of the generated files. We also employed the Cooling Degree Hours (CDH) indicator to characterize different locations. CDH measures the accumulated amount (in degrees Celsius) and duration (in hours) that the dry-bulb temperature exceeds a specific base temperature. This study adopted a base temperature of 26°C for CDH calculations. From now on, we will use the abbreviation CDH26 for ease of understanding.

3.2 Surrounding indexes evaluation

The microclimates of each location are significantly influenced by their respective surroundings. To comprehensively characterize the weather station areas, a set of indices was employed. Natural coverage indexes included vegetation and water body cover, measured by the proportion of such coverages relative to the total site area.

The urban indexes comprised average building height, site coverage ratio, and façade-to-site ratio. The average height is derived from the mean of the building's height weighted by the building footprint. The site coverage ratio indicates the percentage of the total area taken up by the building's footprint. The relationship between façade areas (perimeter multiplied by height) and the site area determines the façade-to-site ratio.

The data collection consisted of a GIS (Geographical Information System)-based approach of a footprint area with a 500 m radius around the station. Table 1 presents the surrounding characterization for each weather station evaluated. The source of GIS information was OSM Buildings and the project SIG-SP [12].

Table 1: Weather station surrounding characterization.

Location (Weather station)	Average building height (m)	Site coverage	Façade-to-site ratio	Vegetation cover	Water body cover
Capão Redondo	5.73	0.21	0.42	0.32	0.01
Marg.Tietê-Pte Remédios	5.12	0.31	0.32	0.16	0.09
Parque D.Pedro II	9.40	0.31	0.74	0.14	0.03
Pico do Jaraguá	4.18	0	0.01	0.80	0
Interlagos	4.26	0.14	0.27	0.49	0.05
Mirante	7.50	0.36	0.16	0.13	0
Congonhas airport	6.16	0.09	0.16	0.33	0
Guarulhos airport	0	0	0	0.52	0

Figure 2 shows the evaluated areas, with marked natural elements (vegetation and water bodies) and buildings colored based on their respective heights. Each circle represents the area of 500 m around the weather station (the center).

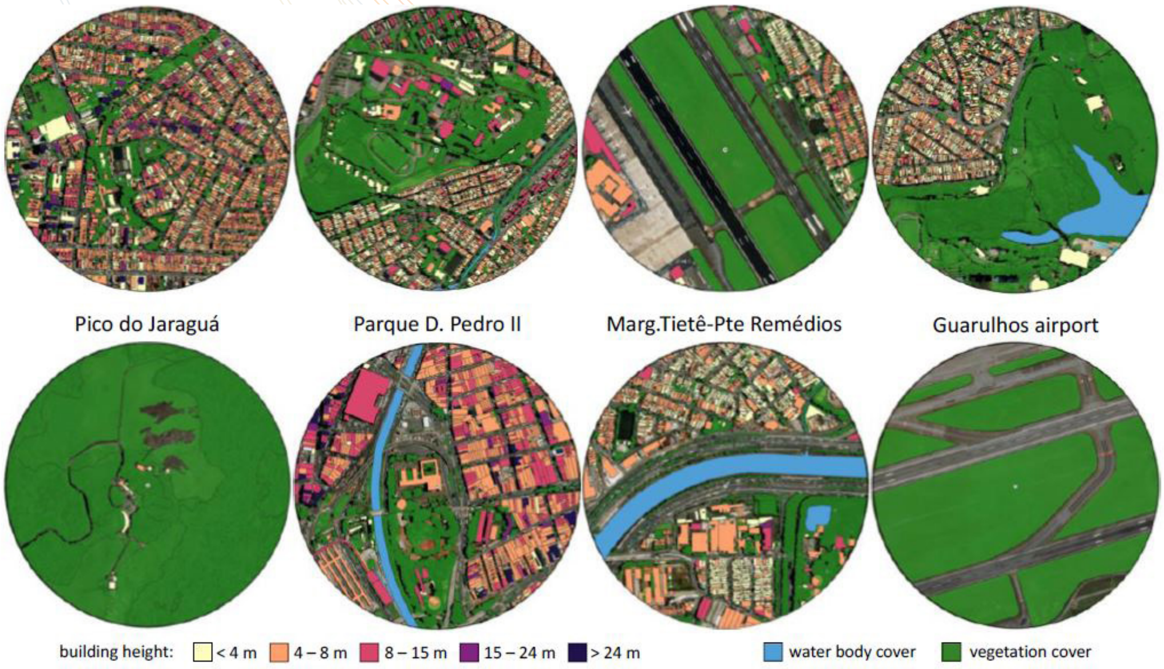

Figure 2: Process of GIS interpretation of the surroundings of each weather station.

3.3 Simulation method

A simulation model based on EnergyPlus version 22.2 was developed based on the requirements of the Brazilian Standard for the performance of residential buildings (NBR 15.575-1:2021) [13]. This way, the occupancy, lighting, and equipment loads were adopted per the standard (Figure 3). The thermal properties of the walls were chosen based on the reference model provided by the standard (equivalent to a 10 cm wall with a thermal conductivity of 1.75 W/m.K, specific heat of 1000 J/kg.K, solar absorptance of 0.58, and density of 2,200 kg/m^3). The GroundDomain:Slab object was used to model the contact with the ground, with the properties of the floor following the standard (equivalent to a 10 cm slab with a thermal conductivity of 1.75 W/m.K, specific heat of 1000 J/kg.K, solar absorptance of 0.65, and density of 2,200 kg/m^3).

The building model used in the simulations is a single-family house comprising two bedrooms, a living room with an integrated kitchen, and a bathroom, with a total area of 44.99 m^2 and a ceiling height of 2.50 m. Its geometric features were based on Triana et al.'s representative Brazilian building characterization [14].

Internal load	Living room	Bedroom
Number of people	Four people	Two people
Lights	5 W/m²	5 W/m²
Equipment	120 W	0 W
Activity Level	108 W	81 W
Occupation period	14h-18h: 2 people 18h-22h: 4 people	22h-8h: 2 people

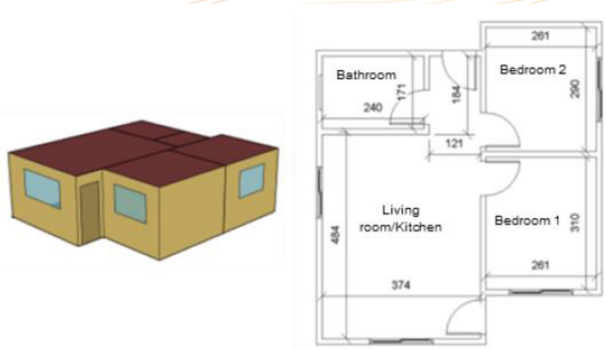

Figure 3: Simulation model and floor plan of the considered typology and Internal loads and schedules configuration.

The model was simulated in naturally ventilated and artificially conditioned states. The naturally ventilated model was designed with open windows and a ventilation factor of 45%, except for the bathroom window, which has an opening factor of 90%. The windows are allowed to be opened when the space is occupied for (1) indoor temperature higher than 19°C and (2) indoor temperature higher than the outdoor temperature. The artificially conditioned model was simulated with closed windows and utilized the HVACTemplate:

Zone:IdealLoadsAirSystem object. An infiltration rate of 0.5 air changes per hour was always considered. Two performance indicators for the naturally ventilated simulation were considered: (1) Thermal autonomy (%): it measures the percentage of occupied hours within an acceptable temperature range. We set an upper operative temperature limit of 26°C and a lower limit of 18°C for all locations; (2) Maximum and minimum operative temperatures (°C): these indicators represent the highest and lowest operative temperatures during occupied hours.

Two additional performance indicators were considered for the artificially conditioned mode: Cooling and Heating loads (kWh/year). In the artificially conditioned mode, the thermal load was considered only when the naturally ventilated mode's operative temperature fell outside the acceptable range during the same time frame.

3.4 Analysis of results

A first exploratory analysis of the simulation results (building performance indicators) and the characterization of the climatic variables were performed. Afterward, a dispersion analysis associated the simulation results with the surrounding indexes (Table 1). The linear general model was applied to obtain a statistical fit considering the association of Thermal Autonomy and Cooling thermal load to each surroundings index. In this sense, the coefficient of determination (R^2) expresses the level of association (influence) of each surroundings index on the simulation result and, consequently, on the building performance.

4. Results

Table 2 presents the maximum, mean, and minimum values of dry-bulb temperature, mean and maximum wind speed, mean relative humidity (RH), CDH26, and Global Horizontal Irradiation (GHI) for each weather station (location).

Table 2: Characterization of the climatic variables for each location.

Location (Weather station)	Dry-bulb temperature (°C)			Wind speed (m/s)		RH (%)	CDH_{26} (°C.h)	GHI (Wh/m². day)
	Max.	Mean	Min	Max.	Mean	Mean		
Capão Redondo	35.3	19.6	3.3	7.0	2.5	78.13	2593.3	*4045.7*
Marg.Tietê-Pte Remédios	35.3	20.6	**5.1**	5.9	2.1	*67.09*	4306.4	4685.8
Parque D.Pedro II	**35.5**	**21.0**	4.6	*4.0*	1.3	69.76	**5724.0**	4414.5
Pico do Jaraguá	*33.1*	*18.1*	1.7	7.0	1.8	73.58	*1082.6*	4762.8
Interlagos	34.1	19.0	3.7	6.4	2.0	**84.91**	1702.5	4443.9
Mirante	35.4	20.1	4.4	7.2	*1.2*	68.35	2495.6	**4892.8**
Congonhas airport	35.0	19.6	4.0	**14.9**	**3.4**	73.58	1848.3	4762.8
Guarulhos airport	35.0	19.6	*1.0*	12.4	2.7	77.95	2441.9	4790.0

* The highest values are highlighted in **red bold** and the lowest in *blue italic*.

The Pico do Jaraguá weather file exhibited the lowest maximum and mean temperatures, 33.1°C and 18.1°C, respectively, along with the lowest CDH26 value (1082.6°C.h). This location is within a large preservation area and is 300 meters higher than the others. It presents the highest vegetation cover index (0.80). On the other hand, the highest maximum and mean temperatures (35.5°C and 21.0°C, respectively) were found in the Parque D.Pedro II location, near the central region of São Paulo with the highest façade-to-site ratio of 0.74. Similarly, the highest CDH26 value was observed in this area (5724.0°C.h).

The weather stations located at Congonhas and Guarulhos airports showed intermediate values for the analyzed variables, except for mean and maximum wind speed, where these stations presented higher values compared to the others since these locations present more open spaces (site coverage index of 0.09 and 0, respectively).

Regarding relative humidity, the highest mean value was recorded for the Interlagos location, with 84.91%. The weather station is near large bodies of water (water body cover of 0.05) and is surrounded by a dense tree cover (vegetation cover of 0.49). Conversely, the lowest value occurred in the Marg.Tietê-Pte Remédios location with 67.09%. This area is adjacent to a major freeway in a highly urbanized part of São Paulo, presenting the second highest site coverage index of 0.31. It also presents the second-highest value of CDH26 (4306.4°C.h).

The simulation results are presented as performance indicators in Table 3 for each location.

Table 3: Building performance indicators for each location.

Location (Weather station)	Thermal autonomy (%)	Cooling load (kWh/year)	Heating load (kWh/year)	Max. op. temp. (°C)	Min. op. temp. (°C)
Capão Redondo	76.4	2110.2	167.1	34.8	13.6
Marg.Tietê-Pte Remédios	*62.7*	3852.3	188.1	38.2	*11.9*
Parque D.Pedro II	64.8	**3930.8**	48.6	**39.2**	15.3
Pico do Jaraguá	75.2	*1823.5*	**289.2**	*33.5*	12.7
Interlagos	76.3	2202.2	169.0	34.8	13.6
Mirante	65.7	3884.6	*30.2*	35.5	**15.4**
Congonhas airport	**77.4**	1994.2	142.1	34.0	12.4
Guarulhos airport	74.9	2453.9	146.9	34.0	12.0

* The highest values are highlighted in **red bold** and the lowest in *blue italic*.

The simulation using the weather file of Parque D.Pedro II again showed the highest cooling thermal load value (3930.8 kWh/year), while Pico do Jaraguá presented the lowest value (1823.5 kWh/year). As for the heating load, the simulation considering the Pico do Jaraguá location exhibited the highest value (289.2 kWh/year). The Mirante location presented the lowest value (30.2 kWh/year).

Parque D.Pedro II also showed the highest results for maximum operative temperature, reaching 39.2°C, 5.2°C hotter than the values simulated using the airport weather files – traditionally used for building energy simulation. The lowest value was found for Pico do Jaraguá at 33.5°C. Interestingly, the minimum operative temperature was found when considering the weather file of Marg.Tietê-Pte Remédios, with 11.9°C. The highest minimum operative temperature occurred in the Mirante location at 15.4°C. Regarding thermal autonomy, Congonhas Airport presented the highest value, 77.4%. Higher values of this indicator indicate that the building maintains mild temperatures for longer throughout the year. As for this indicator, the lowest value was found for Marg.TietêPte Remédios, with only 62.7%.

Figure 4 shows the association of the simulation results (Table 5) with the urban indexes (Table 3). The coefficient of determination (R^2) was higher for the association of site coverage with thermal autonomy (R^2=0.6634) and cooling load (R^2=0.7359). Also, the vegetation cover with the cooling load was relevant (R^2=0.6416). The other surrounding indexes were less meaningful. Despite testing other statistical models, the linear model represented the best fit. It is important to consider that the sample comprises a few cases (eight), making the correlations only indicative of a behavior.

5. Discussion

Several studies highlight the inadequacy of traditional weather station data, usually from airports, to assess the thermal energy of buildings, especially in urban contexts. In this context, relating the surrounding indexes and the weather data proved that the more densely built-up areas presented the warmest climates. Pico do Jaraguá was more naturally covered, with vegetation covering 0.8 of the 500 m radius area. This location showed the lowest mean and maximum air temperatures and CDH26. On the other hand, Parque D. Pedro II displayed the highest vertical density (façade-to-site ratio and average building height) and the second highest horizontal density (site coverage) between the locations, and CDH26 five times greater than Pico do Jaraguá.

The warmer climates consequently had a significant impact on the building simulation results. Much higher values of cooling loads and maximum operative temperatures were found for the more urbanized regions of the metropolis compared to the weather data from the airports in the region. Furthermore, if we consider that simulation users often utilize TMY files from a few years ago, there is a significant likelihood that overheating effects are underestimated in the performance analysis results.

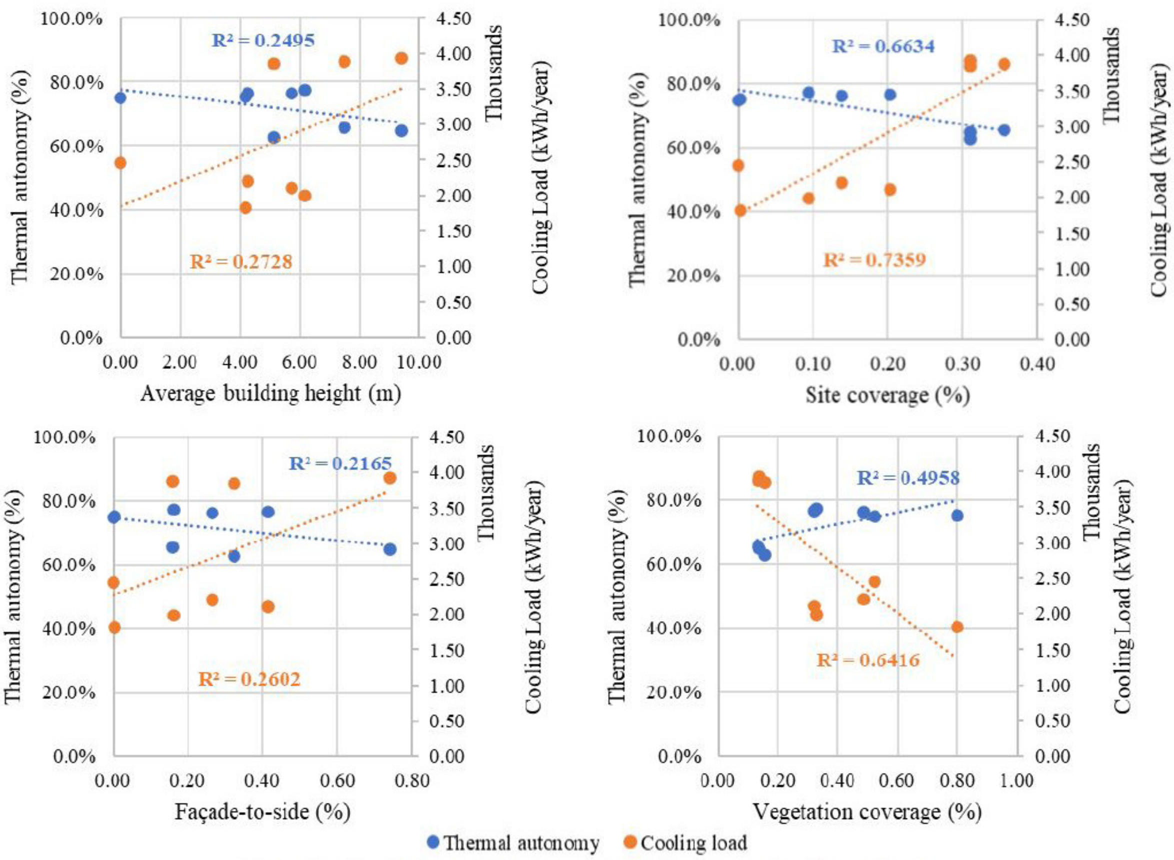

Figure 4: Simulation results associated with the surroundings indexes.

Salvati et al. [15] found that the three urban indexes exert a significant influence on the temperatures by parametric simulations on the Urban Weather Generator (UWG) model. Considering the cooling load and the thermal autonomy of the simulated building for each weather data, the relationship between the urban indexes was more significant for site coverage.

Regarding the vegetation's role in the climate, some studies assess their positive impact on decreasing air temperatures [16], [17]. Even though the linear correlation's R^2 value was not high (just 0.5 for thermal autonomy and 0.64 for cooling load), it showed the tendency of warmer air temperatures with less vegetation cover. Also, it is important to acknowledge that the specific vegetation types, like grass and trees, could have influenced the outcomes. This distinction should be considered in future research.

As limitations of this study, we address the following: assess monthly variations, determine the type of vegetation, explore filling missing data from weather files, expand the number of simulations for different typologies and building envelopes, consider surrounding shadows and explore future climate scenarios.

6. Conclusion

This study aimed to evaluate the spatial variability of the climate within the urban zone of São Paulo, Brazil, and its impact on the thermal energy simulation of buildings. To do so, eight weather data from different weather stations were used to run building performance simulations. Their surroundings indexes were evaluated, which were used to assess cause-effect inferences on building performance. In this sense, the following conclusions can be drawn:

- The different weather data locations considerably affect the simulation results. The maximum operative temperatures reach 5°C above the typical airport station data. In densely built-up areas, the cooling load was double that of the airports.

- Regarding the surrounding indexes, the site coverage presented a higher correlation with thermal autonomy and cooling load. Meanwhile, vegetation linear regression reasonably correlated to the building cooling load.

Future work will focus on expanding the cases considered for simulation and comparing tools like the UWG for developing weather data files considering the urban context.

7. Acknowledgements

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An assessment of the universal thermal climate index of urban outdoor spaces - a case study of Central Business District (CBD), Ahmedabad

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Abstract

This study is conducted to assess the transition in outdoor thermal comfort (OTC) due to the synergistic effects of high-density high-rise development in urban regions and increasing global temperature. The shifting climate of urban spaces impacts Outdoor thermal comfort(OTC), thus human behaviour and accessibility to outdoor spaces. Central Business District(CBD), located in the centre of a growing metro city, Ahmedabad, in a hot and dry climate, is the case study site. The on-site measurement and simulation method has been adopted to analyze the microclimate condition for current and future development scenarios of 2050 with increased Floor area ratio(FAR) and tree cover. To understand and quantify the heat stress on the human body produced by the surrounding meteorological circumstances, the Universal Thermal Climate Index (UTCI) has been used. The on-site collected data and simulation results provide a basis for studying the physiological and physical attributes related to OTC. The results suggest a significant impact of the sky view factor and the role of mean radiant temperature on OTC in all development scenarios. The shading due to the increased height of building stock imparts a favourable impact on thermal stress in outdoor urban areas.

Keywords - Outdoor Thermal comfort, Universal Thermal Climate Index, Urban Heat Island, Microclimate, ENVI-met.

1. Introduction

The rapid expansion of urban construction, accompanied by an increase in global temperature, is changing the environment of urban regions globally. In India, the urban population amounts to 461 million people, and due to rapid urbanization, it is growing by 2.3% each year. By 2050, it is projected that India will have added 416 million urban dwellers. This urban infrastructure growth demands a holistic urban development strategy and creates an opportunity to design human centric policies with the consideration of climate change. In the Indian urban setup, outdoor spaces are important to a sustainable city as they are the spaces that link the public with the urban built context while accommodating daily pedestrian traffic and various outdoor activities. When the outdoor thermal comfort is favourable, people are more inclined to use outdoor spaces. A comfortable outdoor environment reflects on indoor environments, reducing energy demand and pollutant concentration inside buildings (Kasun Perera, Marc Schnabel, 2015)[1].

Taleghani, Sailor, and Ban-Weiss (2016) have reviewed different heat mitigation strategies for OTC in which the authors have found out the use of vegetation (parks, street trees, green roofs, and green walls) and high albedo material (White reflective roofs, reflective ground pavements) as heat mitigation strategies for sustainable development. The assessment of increasing floor area ratio (FAR) allows an understanding of the influence of urban geometry and densification on outdoor thermal comfort and urban heat island effects. This study aims to evaluate the current outdoor thermal comfort of the central business district (CBD), Ahmedabad, with the help of the universal thermal climate index (UTCI) and assessment of future projections of the Universal thermal climate index (UTCI) in conjunction with the increasing built-up area and green cover with changing weather conditions.

The physical and physiological characteristics help to assess static and objective aspects of OTC. The physical level considers the interaction of the human body with the surrounding environment, which can be studied with field measurement and modelling the microclimate data like Air temperature, Relative humidity, wind speed, and solar radiation. The physiological level study focuses on the thermoregulatory response of the human body toward the surrounding thermal environment. Different thermal comfort indices like PMV, PET, SET, and UTCI help to understand this aspect of outdoor thermal comfort (Chng saun Fong, Nasrin Aghamohammadi, et al., 2019)[2]. In tropical climates like India, PET and UTCI are more suitable indices for evaluating OTC (Mahua Mukherjee, Shatabdi Mahanta, 2014)[3]. Compared to other thermal comfort indices, UTCI is very sensitive to variations in ambient stimuli like temperature, solar radiation, humidity, and especially wind speed and can represent the human body's response (Krzysztof Blazejczyk, Yoram Epstein. et al., 2011)[4], which makes UTCI suitable thermal comfort indices for OTC study.

In various studies related to OTC with the help of UTCI, researchers adopted several methods and tools: (a) using existing meteorological data to calculate and establish a trend in UTCI, (b) on-site microclimate monitoring for calculating and predicting UTCI based on the context (c) Modelling and simulating mean radiant temperature and other microclimate parameters for calculating UTCI for present and future prediction. Evola, G., Magri, C., et al., 2019[5] adopted a hybrid method combining on-site measurement with simulation tools. Where on-site data collection was used to validate and find the gap between simulated microclimate and UTCI data with actual data. As the mean radiant temperature is a crucial parameter while calculating UTCI and in the OTC study, it depends upon the context and the LoD of the model used for simulation. By comparing on-site data with the simulation results provides the accuracy of the model and allows calibration.

2. Methods

The methodology for this study has been divided into two parts: (a)Field Measurement and (b) Simulation– modelling. The steps followed: (1) Site selection (2) On-site field measurement and data collection (3) Development scenario and weather prediction (4) Modelling and simulation (5) Accuracy check of the model with the help of onsite collected data (6) UTCI assessment.

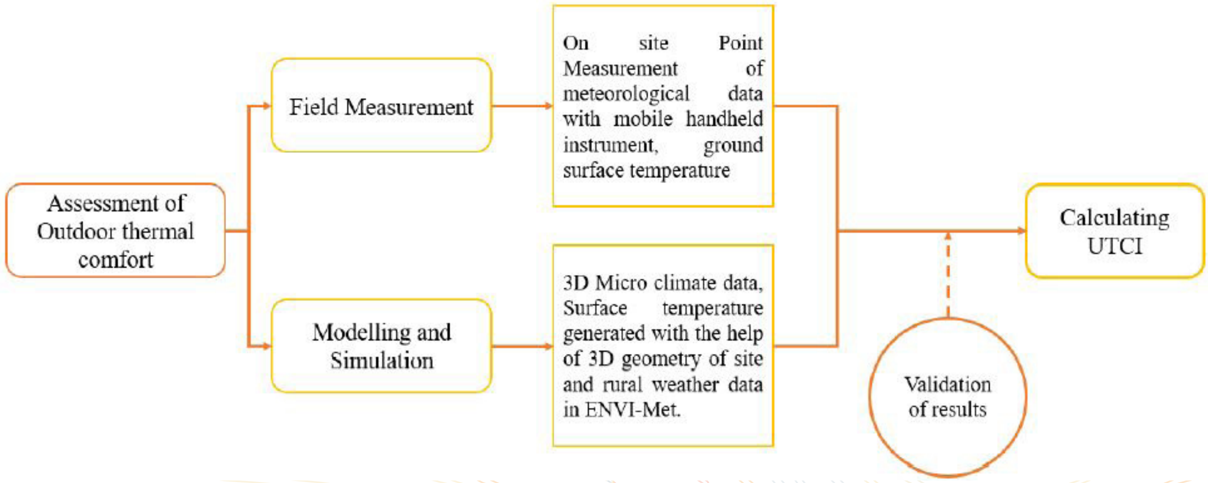


Figure 1: Basic framework of the workflow for the methodology

2.1 Site selection

Ahmedabad is one of the fastest-growing cities in the world (Forbes Magazine,2022), with innovative and progressive development strategies. The Ahmedabad Municipal Corporation (AMC) and the Ahmedabad Urban Development Authority (AUDA), along with HCP architects and planners, have been tackling rapid urbanization by transforming the city center into a vibrant Central business district (CBD), allowing an increase in the Floor Space Index (FSI) from the current 1.8 to 5.4 in the coming decades. Central Business District (CBD), located alongside the river Sabarmati, comprises 927 buildings with a 1.33 km^2 site area, including commercial, health care, institutional and residential buildings. This Scenario gives an ideal situation to study the impact of increasing urbanization on Outdoor thermal comfort in hot and dry climates.

To better understand the correlation between Urban geometry and OTC, eight spots have been selected within the site area. Each spot has distinct contexts, like tree cover, soft/hardscape, street-to-building height ratios, and water bodies. The selection of these eight spots has different sky view factors and represents various ambient conditions of any urban landscape. This spot will give a holistic scenario of CBD.

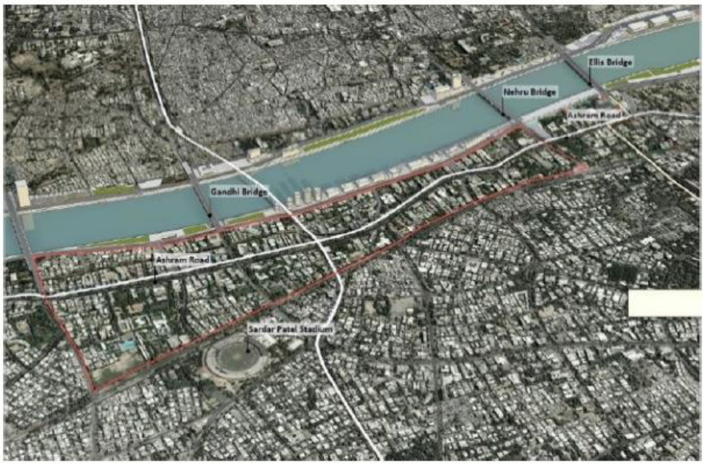


Figure 2: Central Business district, Ahmedabad with major landmarks

Table 1: Proposed urban development scheme for CBD

Parameter	Existing	Future
FAR (Plot)	1.8	5.4
FAR (Gross)	1	5
Total Built Up Area	1275000 m^2	5400000 m^2
Population	85000	200000
Street Coverage (Public Domain)	22%	40%
Number of blocks	31	76
Average block perimeter	743m	416m
Green Cover in Public Domain	6%	30%

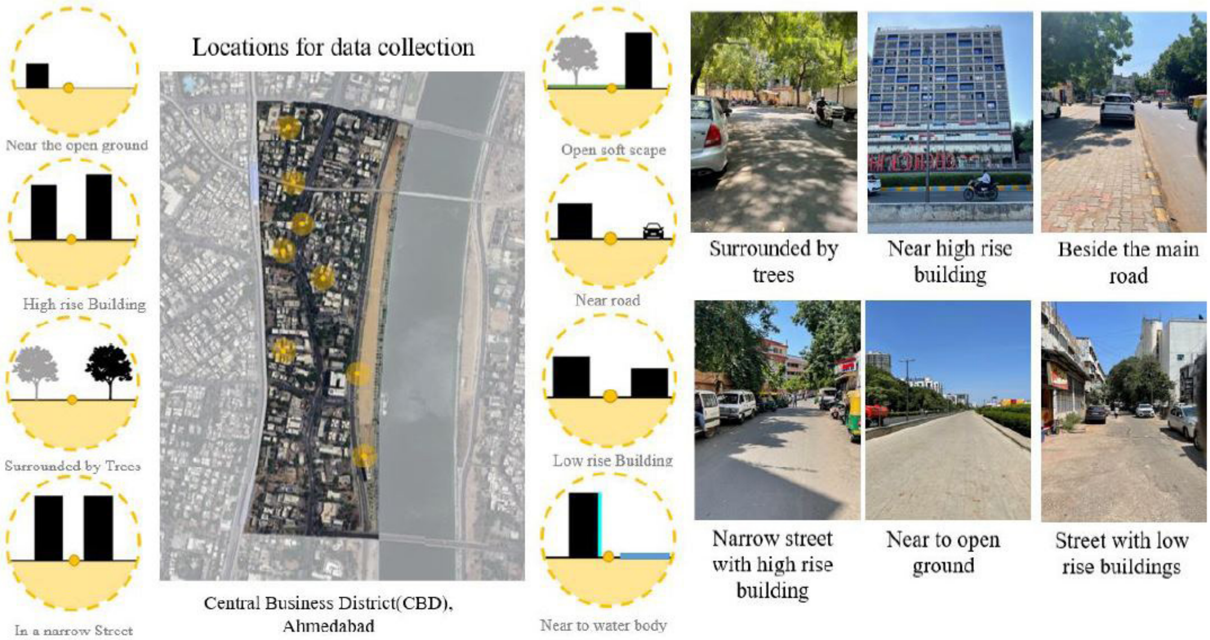


Figure 3: Different spot selected CBD area with various contextual attributes

2.2 Field Measurement

The on-site study aimed to create a database of meteorological factors like air temperature, relative humidity, mean radiant temperature, and wind speed at different times of day and various climatic conditions. Along with this, the surface temperature, On-site observations, sky view factor, and thermographic images have been documented. Weather data from major weather stations of Ahmedabad and weather data from the nearby weather station located on the CEPT University campus have been collected for the same duration to understand variations in the macro and micro climate of the site. This collected data set will help to determine the accuracy and computational sensitivity of microclimate data generated with the help of ENVI-met.

The data collection was conducted during four different time frames: morning at 8:00 am, afternoon at 12:00 am, evening at 4:00 pm, and night at 8:00 pm. These time-frames at the four-hour intervals will give data with different solar azimuth angles, changing the long-wave and short-wave radiation based on the sky view factor (SVF). This exercise has been repeated over a span of 6 months at 15-day intervals from October 2022 to March 2023. This period of the year covers the typical summer and winter seasons. A clear sky is expected and observed during this period of time as ENVI-met does not consider the cloud condition. For this same time frame weather, data has been collected from the nearby weather station, located in the CEPT University (2.5 km from the site), and the major weather station of the city located at the Ahmedabad International Airport (12 km from the site).

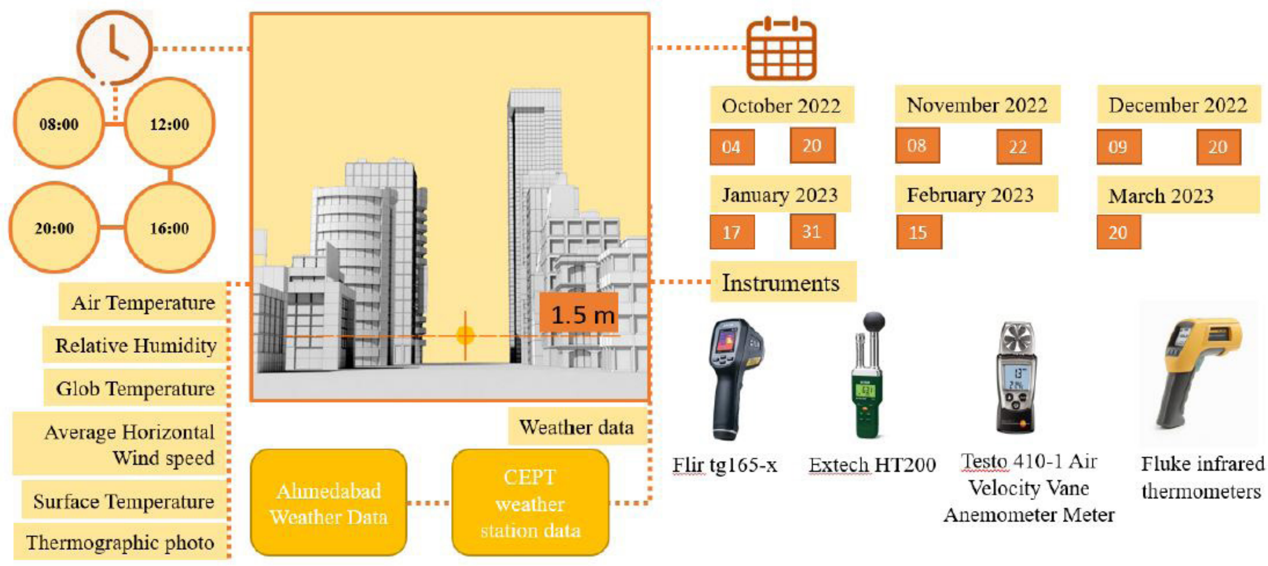


Figure 4: Time period and instruments used in On-site measurements

On-site Air temperature (°C), Mean radiant Temperature (°C), Relative Humidity (%), Surface Temperature (°C), and Wind speed were measured with different instruments at 1.5 m height from ground level. The overall study has been conducted at the pedestrian level, and the same working plane has been selected in the simulation module. Extech HT200 has been used to measure globe Temperature and further calculate mean radiant temperature, Relative humidity, and Air temperature. Wind speed has been measured with the Testo 410-1 Air velocity vane Anemometer in two directions to calculate average horizontal wind speed. 561 Fluke infrared thermometer for surface temperature and Flir TG165-x Thermal Camera for the thermographic image have been used.

2.3 Modelling and Simulation

ENVI-met-5 software has been used for continuous and multi-point data for different scenarios created to study OTC in the CBD area. By providing geometric and semantic data of the CBD area with the weather data file first, microclimate data have been extracted from ENVI-met. Further, with the postprocessing of that data in the Biomet engine of ENVI-met, the UTCI has been calculated. The Leonardo tool from ENVI-met-5 has been used for graphical representation and detailed data extraction from simulation.

2.3.1 Development Scenario

To analyze the change in OTC of CBD area with changing urban morphology, three scenarios have been studied,
(a) Current development scenario of the CBD area
(b) Extreme development scenario Of 2050
(c) Extreme development scenario with Native tree plantation

Table 2: Characteristics of different scenarios selected for the study

Cases	Building Geometry	Envelop	Weather Data	Tree	Land cover and water body
Current development	As per the current development scenario	ECBC baseline	Ahmedabad weather .epw file	As per the existing site Condition	As per the existing site condition
2050 Development	Extreme development scenario with 5.4 FSI proposed plan	ECBC baseline	Morphed .epw file based on IPCC RCP 8.5	As per the current site Condition	As per the existing site condition
2050 development + Native trees	Extreme development scenario with 5.4 FSI proposed plan	ECBC baseline	Morphed .epw file based on IPCC RCP 8.5	As per the GDCR and AUDA guidelines	As per the current site condition

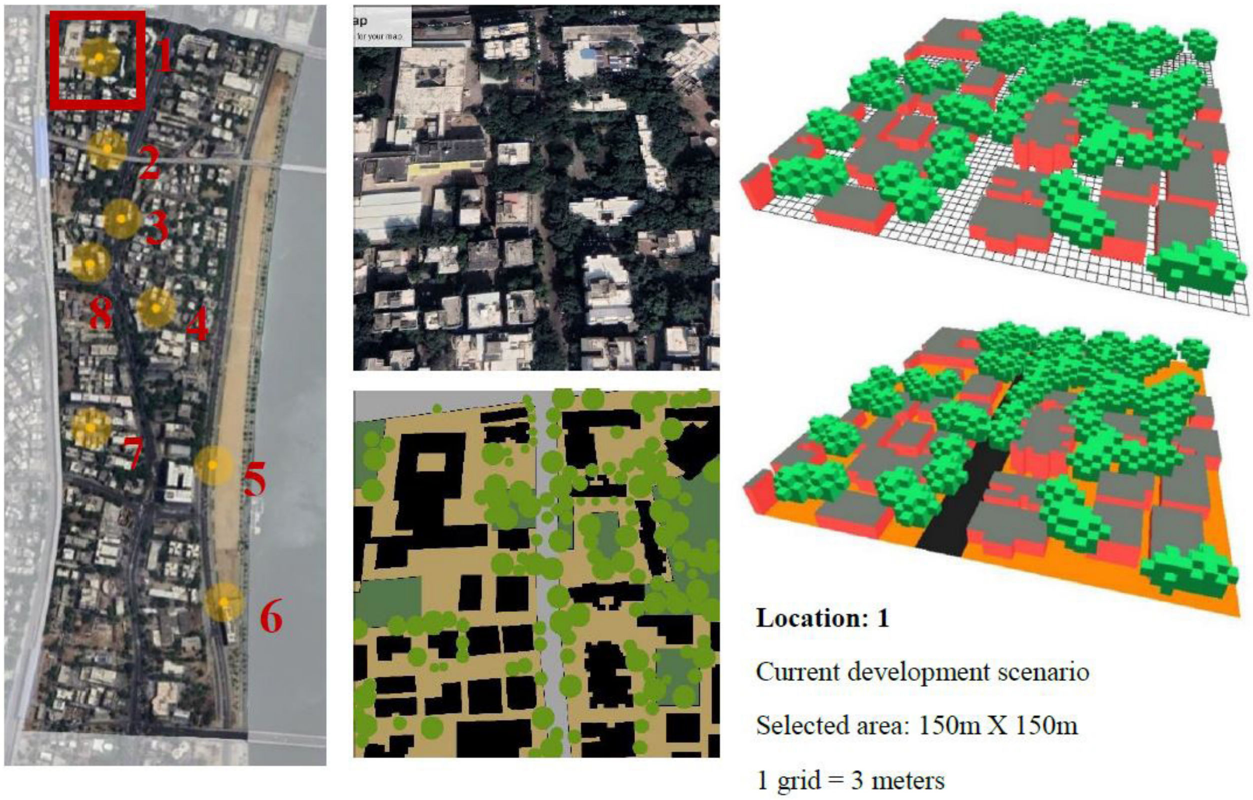


Figure 5: Modelling of location 1 in ENVI-met for current development scenario

2.3.2 Defining the Model Characteristics and Methodology

The site area of 1.33 km^2 with 927 commercial and residential building units (Appendix section 7.4 survey data) has been divided into eight parts based on the location selected for on-site measurements. The exact location of the on-site measurement 150m X 150m area has been selected for simulation.

For the current development scenario, the building geometry is taken from the on-site collected data, site survey data, and previously done research on the CBD area. The model has LoD1 (Level of Detail) with reference to site survey data. The envelope details of all the buildings are as per the ECBC baseline. The ground surface cover and trees are as per the site condition. The future development scenario is considered extreme development, where all the building blocks are considered to be developed with a full possible floor space index (FSI) of 5.4. Based on that, the geometrical and shape file has been prepared. The built environment has been modelled in ENVI-met- spaces with a 3-meter per grid ratio. Standard trees from the ENVI-met library have been used for modelling as per the on-site tree dimensions.

2.3.3 Weather Data

Ahmedabad's most relevant rural weather data file in the context of the case study site has been selected. This .epw file has been used in full forcing mode in ENVI-met for simulating microclimate data. The constant offset method is used to create the future hourly weather data. The Intergovernmental Panel on Climate Change (IPCC) has developed different representative concentration pathways (RCPs) for future climate modelling. The RCPs represent climate scenarios based on greenhouse gas (GHG) emissions in coming years. From that, the RCP8.5 has been used, representing the most carbon-intensive pathway with summer temperatures in high latitudes that will rise by at least 2° C by 2050. On this basis Future, rural TMY files will be generated. This file and the model of the extreme development scenario will be used to simulate the microclimate weather data of the Central Business District (CBD) of 2050.

2.3.4 UTCI Calculation

To analyze the outdoor thermal comfort for all three scenarios for different locations from the CBD area, UTCI has been calculated for two days of the year.

(1) Summer Design Day: 18th May
(2) Winter Design Day: 27th December

These two days will represent the two extreme weather cases in Ahmedabad. The simulation lasted 15 hours, from 6 AM to 8 PM. For the calculation of UTCI, air temperature, mean radiant temperature, relative humidity, and horizontal average wind speed data have been extracted from the ENVI-met simulated microclimate data, and for personal factors, the "Standard Human": ISO 7730 with age - 35, Weight – 75, Height – 1.75 m, Gender – Male, clo value – 0.90, and Met value – 1.48 has been taken. The UTCI value for all the locations and selected days have been calculated at the 1.5 m pedestrian level. The Leonardo tool of ENVI-met has been used for data interpretation and presentation.

2.3 Data Validation

To check the accuracy of the simulated data, data validation is required. Two days representing typical summer and winter days from the experiment dates have been selected to compare the simulation results with the onsite collected data set. For these two days, the weather data from a nearby weather station located at CEPT University have been used for simulating more accurate results. Simulations for 8 AM, 12 PM, 4 PM, and 8 PM have been conducted for 17th January 2023 and 20th October 2022. Microclimate data for the same location have been compared for the same time frame to check the model's accuracy. As the material used in the modelling is not as per the site, variations in the results are expected. With this exercise, the gap between the simulated data and actual data can be estimated. Further, this data can be used to calibrate the simulation model, but in this study, calibration is not part of the scope of the work.

3. Results

3.1 Simulation data validation

To check the accuracy of the simulation model, statistical analysis of on-site collected data and simulated data has been done. The linear regression method has been used. For the air temperature data degree of variation is less with R^2= 0.941 but in the case of mean radiant temperature, there is a gap between on-site data and simulated data as the simulation model has enveloped detail based on ECBC baseline but not similar to on-site condition. The data is from a nearby weather station, but the collected data might be influenced by the microclimate of the location thus, similar trends can be observed. For the UTCI values from the simulation and calculated UTCI value from on-site data, follow the same trend and in linear regression R^2= 0.7246. The data following the same trend while comparing two different scenarios still provide a relevant delta.

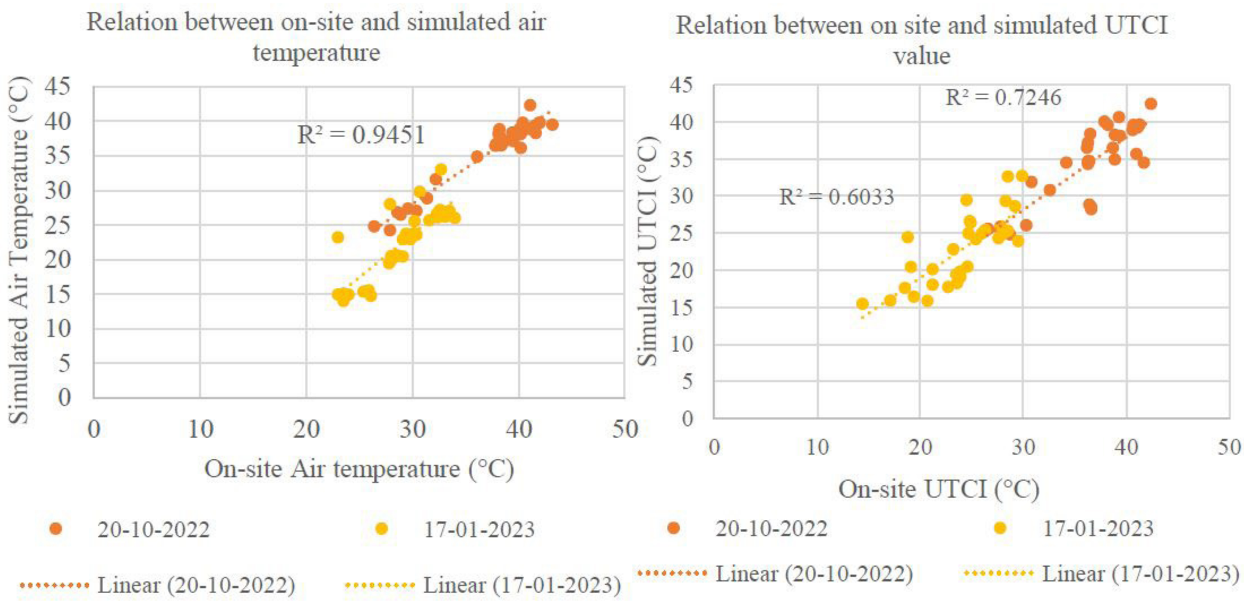
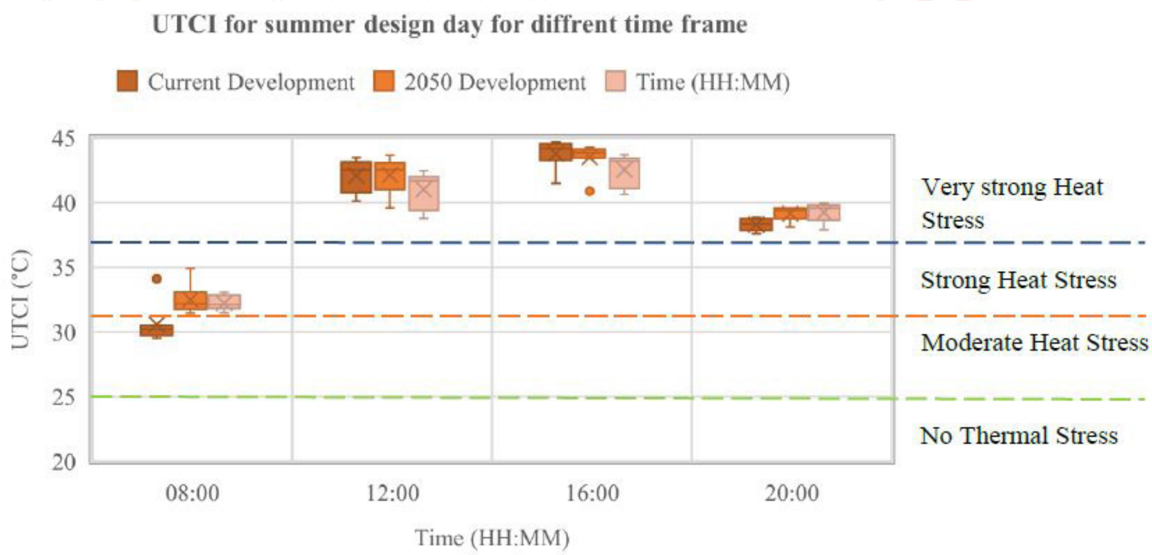


Figure 6: Comparative analysis of On-site collected data and simulated data for (a) Air Temperature (b) UTCI

3.2 Universal Thermal Climate Index (UTCI

In both summer and winter design days, the lower thermal stress level is achieved with more native tree plantation during the daytime. The shading effect of the trees reduces the increase in surface temperature and results in lower MRT. Though the Air temperature is higher for the 2050 development scenario, during the summer design day, less thermal stress can be observed at 12:00 and 16:00 hours. With increased FSI the building height is higher compared to the current development scenario, resulting in mode-shaded hours for the open outdoor space. But during the night time due to the urban heat island effect, the surface temperatures are higher than the current development scenario and give higher UTCI heat stress values. Due to the overall increase in temperature for future development scenarios, a smaller number of hours are falling under the no thermal stress category on winter design day. Even during the winter design day the majority of hours during the daytime fall under moderate heat stress levels.



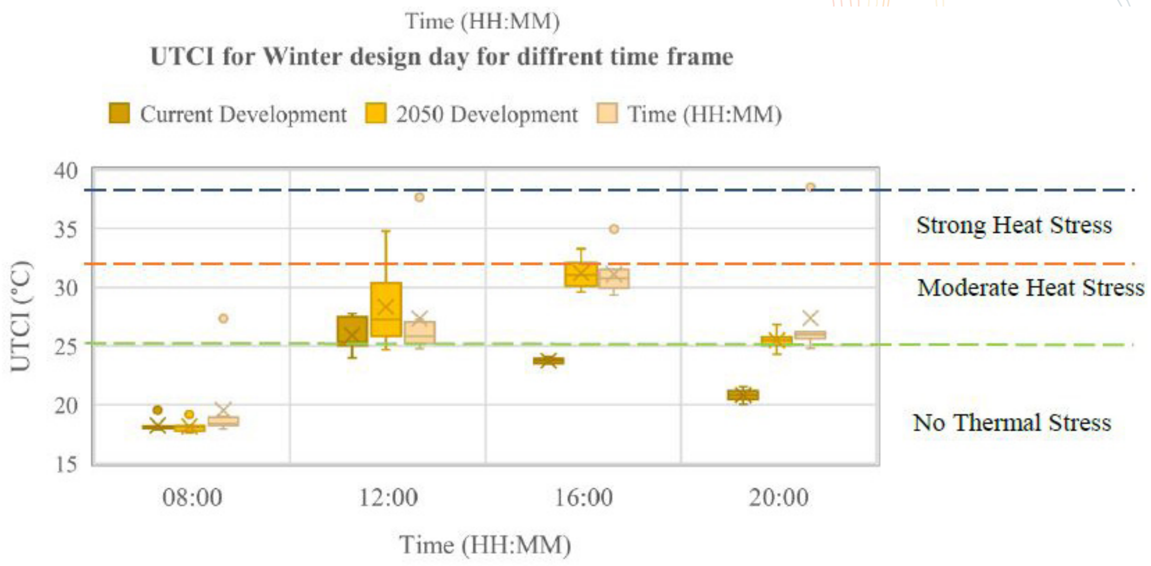


Figure 7: Comparative analysis of UTCI value for all three development scenarios at four time periods on (a) Summer design day (b) Winter design Day

In all three cases, a reduction in heat stress can be observed during the daytime in summer in cases with increased building height and more trees. In the case of location- 4, the reduction delta is lower because the existing site is already shaded with trees. The majority of land cover in location 3 is concrete, which is increasing the heat stress level for both the current development and 2050 development scenario. But when the native tree plantation has been introduced on the edges of roads and pathways, even during the daytime, comparatively less heat stress can be seen. After sunset hours when there is zero solar radiation, due to urban heat island effect (2050 development scenario) it takes more time to cool down resulting in higher heat stress.

4. Conclusion

The study of UTCI for outdoor thermal comfort shows the direct impact of change in contextual attributes as it is susceptible to minute changes in any microclimate stimuli. The predicted thermal conditions for the outdoor spaces of the CBD have a significant number of hours falling in higher thermal stress levels due to increased global temperature. While increased building heights are changing the sky view factor of any given observation point. The shading with increased height of building stock during the daytime plays a favourable role in the overall result of OTC. Tree cover acts as a more efficient factor by providing shading and increasing humidity in hot and dry contexts of the site.

With increasing global temperature, facing higher temperatures in outdoor spaces is inevitable but in this condition during the design process shadow analysis and study of the sky view factor of any outdoor space will help to articulate more thermally comfortable and accessible spaces. Following the minimum requirement of the plantation guidelines for new development and strategies for the green streets with native plants can help to reduce the effect of urban heat islands and achieve lower heat stress levels in urban outdoor places at the pedestrian level. This will improve the quality and accessibility of outdoor urban spaces for a more significant number of hours throughout the year.

Limitation: The envelope detail of the model used for simulation is constant as per ECBC baseline with LoD1 for all the buildings. The lack of surface albedo, surface roughness, and WWR as per the site creates a gap between the on-site microclimate data and simulated data. With a smaller grid size in ENVI-met, more accurate geometry of the building can be created which will give more accurate data for surrounding outdoor space.
Future Scope: In the case of OTC the sky view factor and shading hours play a significant role, further in-depth research for the effect of the sky view factor on different climates and geographical locations can be done.

5. Acknowledgements

I would also like to extend my appreciation to the Center for Advanced Research in Building Science and Energy (CARBSE) and staff members for their valuable assistance and cooperation in providing the necessary resources for this research.

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Study on the role of vegetation towards thermal comfort in outdoor urban areas

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Abstract

Urban heat islands have a direct impact on the areas where people are suffering from heat stress during the hot climatic conditions. In order to get relief from heat stress, many researchers have explored various strategies that have given more importance to green spaces i.e. vegetation. Urban greenery such as parks, gardens, and street trees helps to improve outdoor thermal comfort. Several research in different countries have given approaches to vegetation as improving methods for outdoor thermal comfort of urban open spaces. The main goal of this study is to analyze the human perceptions of outdoor conditions in Ratna-park, Kathmandu, Nepal through field survey and to establish the relationship between meteorological parameters. 78% of the visitors voted for neutral which shows that they are highly satisfied with the park. Additionally, the mean comfort temperature was found to be 29.1ºC. People are well adapted to the thermal environment of the urban park, and thus the comfort temperature was significantly high in summer.

Keywords - Outdoor thermal comfort, Field survey, Urban Park, Comfort temperature, Griffiths' method

1. Introduction

Thermal comfort is the state of mind that expresses satisfaction with the surrounding environment [1]. Occupants these days are more aware of urban issues due to the worsening urban climate. This compels the researcher to concentrate more on outdoor thermal comfort studies. Other than that, the effects of urbanization also contributed to the rise of studies that focus on outdoor thermal comfort. In the same way, open space can improve residents' social, environmental, and healthy lives [2]. However, comfort in urban space is governed by different factors, which include meteorological factors and personal factors.

With a focus on quality of life, people prioritize outdoor space thermal comfort levels. The topic of outdoor thermal comfort has gained significant attention in recent years, promoting a large number of studies to examine and explore the topic through field studies [3-5]. According to the IPCC assessment by 2100, the global surface temperatures are expected to have increased by 0.3-4.8 ºC [6]. According to research, being in a hot environment might make one feel exhausted and breathless, and increase in heart rate [7]. Comparably, green spaces improve mental health by lowering stress and raising satisfaction, which in turn raises comfort [2]. Additionally, it aids in air pollution filtering, which improves outdoor comfort and air quality.

Scientific evidence indicates that the impact of global warming is significantly high [8]. Up to 70,000 people died across Europe in 2003 as a result of heat waves [9]. Summertime research conducted in the Netherlands by Klemn et al. [10] found a 0.8K drop in air temperature between the city center and the park. Similar findings were made by Karimi et al. [11] who replaced the summertime vegetation in Iran with pine trees and found a 0.3K drop in air temperature. Furthermore, in Japan, it is found that people living in an urban area with green space extend their life expectancy [12]. Similarly, comparing a shady region to a sunny site in an open space, found a 6.9K drop in air temperature in Portugal [13]. In a 3.5 hectare park, Zoich et al. [14] measured a maximum air temperature of 32.1 ºC with a 1K air temperature drop in an area covered by trees.

Xu et al. [15] investigated the outdoor thermal benchmark of shaded spaces in an urban park in China by conducting field measurement and survey during winter and summer. Martinelli et al.

[16] investigated the impact of vegetation during the summer months in Italy. The prior study was limited to a specific country. More research is necessary because results from one city, country, or season may not be applicable to another. The main objective of this paper is to investigate the thermal sensation vote and thermal preference of the visitors in the urban park of Kathmandu, and to estimate the comfort temperature of the visitors.

2. Methodology

2.1. Study Area

The study area is located in Ratna-park, Kathmandu, Nepal. Kathmandu is approximately 1,400 meters above sea level, surrounded by the mountain to the north (Figure 1). Kathmandu lies in the temperate climate of Nepal. The mean outdoor air temperature in summer and winter are 20.5 °C and 9.2 °C [17,18]. The mean outdoor relative humidity was 73% and 79% in summer and winter [17,18].

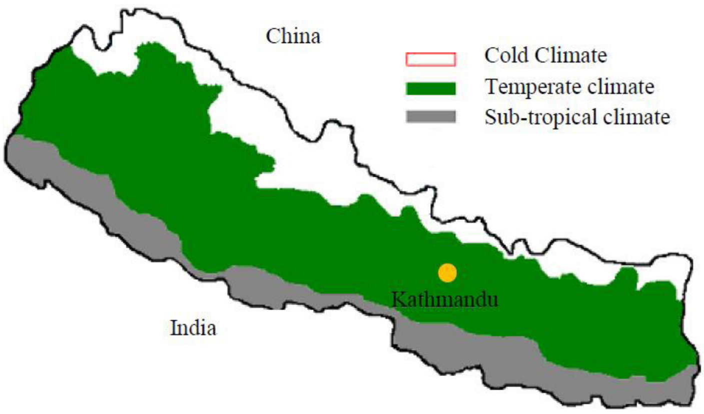

Figure 1: Location of the study area

2.2. Thermal Measurement

The field survey was conducted from 8th July to 12th August 2023 from 11:00 to 15:00. During the field survey period, the air temperature, relative humidity, wind speed, globe temperature, and radiant temperature were measured by instruments (Table 1). The instrument was set up at 1.5 m height from the ground level. If there was the presence of direct solar radiation, then the instrument was set up about 3 m away from the people. The data was recorded 15 minutes after the set up of the instruments.

Figure 2: Field survey in Ratna-park

Table 1: Details of instruments used

Measured variables	Instruments name	Accuracy
Air temperature, Relative humidity (RH)	TR-76Ui	±0.5°C, ±5%RH
Wind speed	TSI 9535-Anemometer	3% reading or ±3 ft/min whichever is greater
Globe temperature	Thermo Recorder TR-52i	±0.3 °C, (-20 to 80 °C)

2.3. *Thermal Comfort Survey*

The survey ensured that it included the majority of the park visitors, and the measuring time was chosen when people were using the park. First, a group of respondents was chosen in the study area. The questionnaire sheet consists of two sections. The first section contains the background of people like name, age, gender, etc. The second section consists of 16 questionnaires consisting of thermal sensation, thermal preference, clothing insulation, and park features. The seven-point thermal sensation scale, five-point thermal preference scale, and six-point overall comfort scale were used (Table 2). A total of 121 votes were gathered from 49 males and 72 females.

Table 2: Thermal sensation, thermal preference, and overall comfort scale

Scale	Thermal sensation scale	Thermal preference scale	Overall comfort
1	Very cold	Much warmer	Very discomfort
2	Cold	A bit warmer	Discomfort
3	Slightly cold	No change	Slightly discomfort
4	Neutral	A bit cooler	Slightly comfort
5	Slightly hot	Much cooler	Comfort
6	Hot	-	Very comfort
7	Very hot	-	-

3. Results and discussion

3.1. *Thermal environment during voting*

During the survey period, the physical parameters were measured to evaluate the thermal comfort of visitors. Table 3 presents the physical parameters of the investigated park. The mean air temperature, globe temperature, relative humidity, and wind speed were 28.4 °C, 29.3 °C, 61%, and 0.68 m/s respectively.

Table 3: Physical parameters during voting

Air temperature, T_a (°C)			Globe temperature, T_g (°C)			Relative humidity, *RH* (%)			Wind velocity, *V* (m/s)		
Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
28.4	31.8	26	29.3	32.7	24.1	61	72	48	0.68	1.5	0.1

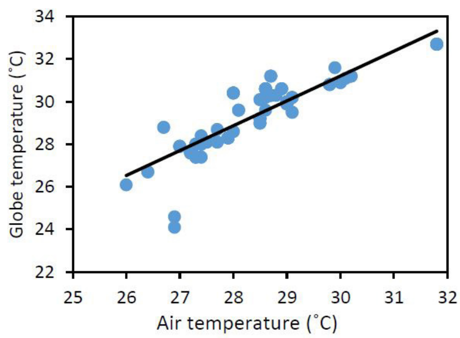

Figure 3: Relationship between globe temperature and air temperature

Figure 3 shows the relationship between globe temperature and air temperature. When air temperature increases the globe temperature also increases (R2 = 0.78). The regression equation obtained from Figure 3 is shown below. Due to the high correlation between air temperature and globe temperature, globe temperature is used for further analysis.

$$T_g = 1.1T_a - 3.8 \text{ (N = 121, } R^2 = 0.78) \quad (1)$$

Where T_g: Globe temperature (°C), T_a: Air temperature (°C), N: Number of samples, R^2: Coefficient of determination

3.2. Thermal Responses

Figure 4 shows the distribution of the thermal sensation and thermal preference vote from the visitors of the park. Most of the respondents (78%) voted for "4. Neutral". The second highest number of respondents (17%) reported feeling "5. Slightly hot". 5% of the respondents voted for "3. Slightly cold". This result was consistent with Zhang et al. [19] as they found that 60% of the respondents voted for "Neutral" during the field study which was conducted in Chengdu Park, China during the summer. The vegetation coverage of this park is high. On the other hand, from the thermal preference vote, 59% of respondents preferred "3. No change" as they are satisfied with the existing environment of the park, while 41% preferred "4. A bit cooler" in the investigated park. Canan et al. [20] also found that 43% of respondents preferred "No change" in the existing thermal environment in Turkey during summer.

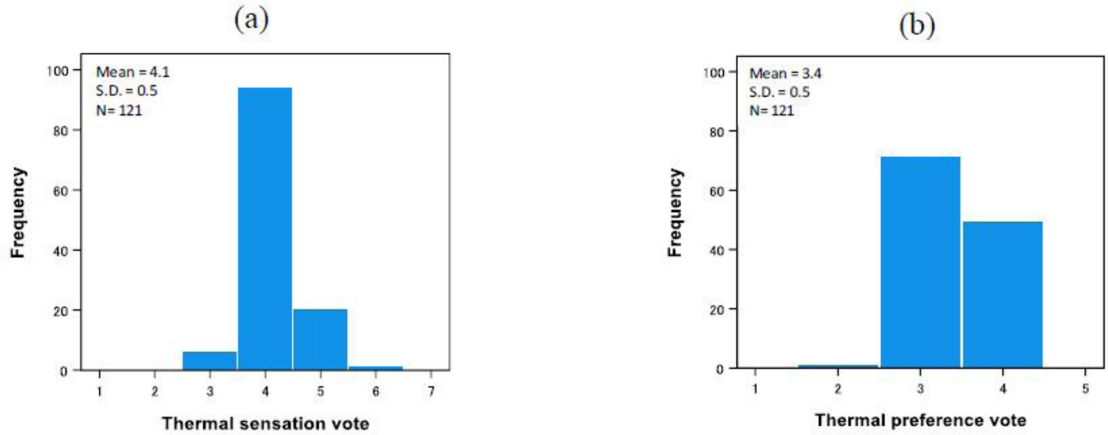

Figure 4: Distribution of thermal sensation and thermal preference vote

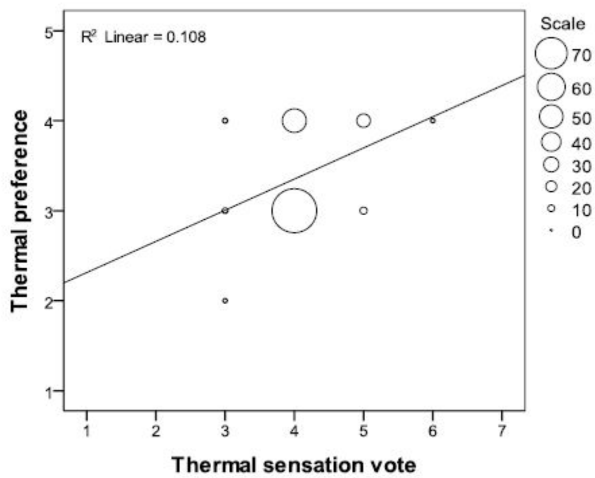

Figure 5: Relation between thermal preference vote and thermal sensation vote

Figure 5 shows that most of the respondents voted for "Neutral" thermal sensation and they preferred "No change" in thermal preference. Similarly, when occupants voted for a "Slightly hot" sensation, they preferred "4. A bit cooler" condition. The regression coefficient between thermal sensation and thermal preference is 0.34. The following regression equation from Figure 5 was obtained:

$$TP = 0.34TSV + 1.96 \text{ (N = 121, } R^2 = 0.11\text{, P} < 0.001) \quad (2)$$

Where TP: Thermal preference vote, TSV: Thermal sensation vote, N: number of the sample, P: significant level of regression coefficient.

The overall comfort of people in the park is shown in Figure 6. The majority of the respondents (65%) voted for "5. Comfort". 25% of the visitors voted for "4. Slightly comfort" and 9% of respondents voted for "6. Very comfort" in the park. The result shows that a high number of park visitors feel comfortable during the stay period at the park. This result was similar to Zhang et al. [19] that 82% of the respondents voted "Comfortable" in Chengdu Park during the summer season.

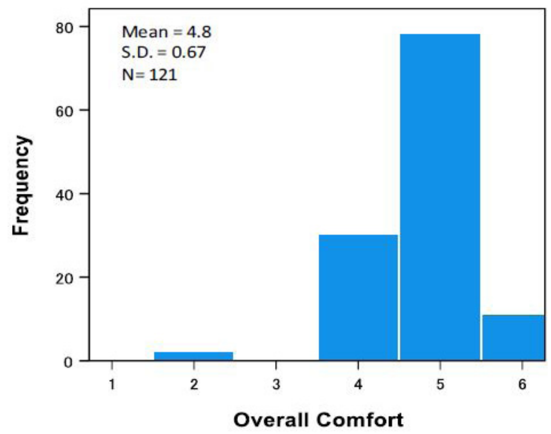

Figure 6: Distribution of overall comfort

3.3. *Prediction of Comfort Temperature*

Finding the comfort temperature is one of the objectives of this study. The linear relationship between thermal sensation votes and globe temperature was conducted to predict the comfort temperature as shown in Figure 7. The linear regression equation derived from Figure 7 is given below.

$$TSV = 0.075T_g + 1.9 \text{ (N = 121, } R^2 = 0.06) \quad (3)$$

Where, TSV: Thermal sensation vote, T_g: Globe temperature (°C), N: number of samples, R^2: Coefficient of determination

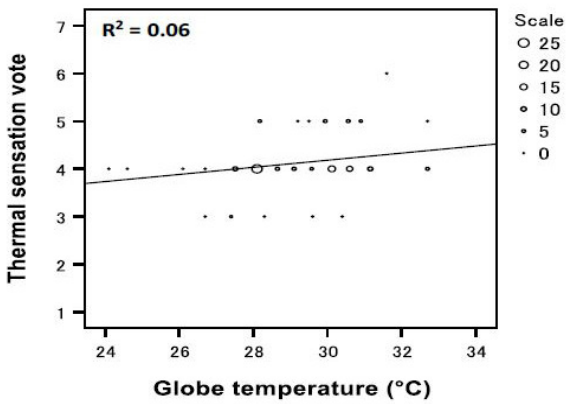

Figure 7: Relationship between thermal sensation vote and globe temperature

From equation 3 the regression coefficient is 0.075 i.e. 13.3 °C (= 1/0.075) is required to shift one thermal sensation vote. This seems to be unreliable. This could be because of insufficient data and a short period of survey. Therefore, Griffiths' method was applied to estimate the comfort temperature. This method is appropriate when there is a small number of data to calculate the comfort temperature. Griffiths' comfort temperature is calculated by the following equation.

$$T_c = T_g + (4\text{-}TSV)/a \qquad (4)$$

Where, T_c: Comfort temperature (°C), a: Griffiths' constant (0.5)

For each comfort vote, Griffiths' comfort temperature was calculated. The mean comfort temperature is 29.1 °C. The result of this study has been compared with other studies in outdoor spaces as shown in Table 4. Nikolopoulou and Nikolopoulou & Lykoudis [3] found a slightly lower value of comfort temperature in Europe. Givoni et al. [21] found a comfort temperature of 29.7 °C in Israel which is similar to our study.

Table 4: Comfort temperature found in various studies for outdoor spaces

References	Country	Comfort temperature (°C)
Nikolopoulou & Lykoudis [3]	Europe	26.7
Givoni et al. [21]	Israel	29.7
Lin & Matzarakis [22]	Taiwan	27.2

4. Conclusions

An outdoor thermal comfort survey was conducted and comfort temperatures were predicted by Griffiths' method. The following conclusions can be drawn from this study.

1. The occupants are highly satisfied with the park, as most of their thermal sensation votes (78%) were "Neutral". 65% of the occupants voted "Comfort" while staying in the park.

2. The mean comfort temperature is 29.1 °C. People are well adapted to the thermal environment of the urban park, and thus the comfort temperature was significantly high in summer.

5. Acknowledgements

We would like to acknowledge people for their kind cooperation during the field survey.

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Impact of extreme weather events on the thermal comfort of vulnerable populations in the city of Sao Paulo

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Abstract

In a context of global warming, heatwaves are predicted to become more frequent and intense over the next decades. The elderly are among the most vulnerable groups to extreme heat due to their dysfunctional thermoregulatory mechanisms and propensity to illnesses. This research aims to assess impacts of urban heating on this demographic group, using the ENVI-met V.5 model to simulate microclimatic conditions at a representative neighborhood in the city of Sao Paulo, adopting the PET Index as a comparative variable. Results obtained from historical climate data are compared to those of projections according to the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCP) 8.5 scenario. After the realization of impacts, urban surfaces albedo modifications were tested, in search for the most effective mitigating adaptations. Results obtained until now show that increasing the average albedo of built surfaces can help moderate rising temperatures, but would not be enough to compensate for the increase predicted for the coming decades.

Keywords - Heatwaves, Urban Adaptation, ENVI-met, PET Index, Outdoor Thermal Comfort.

1. Introduction

Climate change effects are already being felt worldwide, bringing significant increase in frequency, intensity, and duration of extreme weather events, such as heatwaves. People living in urban environments will be even more vulnerable to heat extreme events because of the Urban Heat Island (UHI) phenomenon and the high population density, with Asia, Africa, North America and parts of South America affected most [1]. According to the IPCC Sixth Assessment Report (AR6), published in 2021, global average temperature will probably rise by 1.5°C over the next decades, even if the emission of greenhouse gases were halt immediately. As they keep being emitted, global averages may rise up to 4°C until 2100. [2]

Since the elderly are more susceptible to heat, global population ageing trends will magnify risks from excess heat exposure. It is predicted that heat waves will cause higher mortality under conditions aggravated by greenhouse gas emissions [3,4]. In Brazil, maximum temperatures are expected to rise up to 5.8°C, while relative humidity may lower to about -11% until 2099, in case the IPCC RCP 8.5 scenario becomes true. A huge metropolis like Sao Paulo may experience a heatwave increase of around 1200% until the end of the century under that pessimistic scenario, causing mortality rates of the elderly to rise above 1000% if no adaptation measures are taken [5,6].

Therefore, without provision of structural adaptation of the current urban environment, outdoor comfort levels will be seriously degraded by the rising temperatures, and physiological stress will result in increased mortality during extreme events. Older people will be among the most severely affected groups, with additional risk from urban heat if already chronically ill, socially deprived or inner-city residents [1].

1.1 Context

Literature mentions the scarcity of studies on the impacts of climate change specific to cities in tropical climates, and the need for further investigation into the potential of planning measures to reduce thermal stress in outdoor environments, under constantly changing climatic conditions. A few recent works downscale projected climate data to assess microclimatic effects in urban outdoor areas. One of these articles compares measurements taken in loco with simulated projections in ENVI-met for an urban canyon in the city of Sydney, testing the effects of different measures of urban adaptation [7]. Guerreiro [8] used projected data, obtained from Meteonorm, to simulate the effect of future scenarios on thermal comfort using ENVI-met, in search of effective mitigation measures for the UHI in the city of Lisbon. Yoshida [9] uses climate data projections obtained in the Projeta Platform (Eta-HADGEM2), simulating with ENVI-met future conditions in the city of Sao Paulo, the same method and instruments of the present work, but with the objective of assessing effects of higher temperatures on the health of trees, not of human beings. Another important reference was the article [5] which estimates the evolution of the elderly population in Sao Paulo, its exposure and increased thermal risk over the next decades. The 2022 doctoral thesis by the same author [6] deepens that investigation by studying future climate scenarios for Brazilian capitals, associating them with exposure and health risks.

When the external environment is hot, the human body maintains core temperature by losing heat via radiant, convective, and evaporative heat loss, with vasodilatation and perspiration. When the surrounding temperature is the same or higher than the body, the effectiveness of this mechanism is remarkably reduced, leading to a clinical condition called heat stress, ranging from cramps to heat exhaustion. When the core temperature rises above 40.5°C, it can lead to heatstroke and multiple organ dysfunction. The hypothalamus is the region of the brain that coordinates physiological response to excessive heat. In extremely hot environments, irreversible brain damage can occur with neurological signs such as lack of coordination, consciousness and seizures. [1]

Diniz [6] elaborated tables identifying heatwave periods and its temperature thresholds in Brazilian capital cities. They show an average of maximum temperatures (°C) percentiles P90, P95 e P98 for the hot period in São Paulo, based on climate projections for the distant future (2079- 2099) of the Eta-HADGEM2-ES model. Table 1 was extracted from that study and summarizes these values for Sao Paulo.

Table 1: Heatwave threshold temperatures (°C)

RCP 4.5			RCP 8.5		
P90	P95	P98	P90	P95	P98
33.9	34.9	36.0	37.5	38.5	39.6

1.2 Objectives

The work presented here is part of a broader research, with the ultimate aim of proposing urban adaptation measures, in order to counterbalance the projected increase in environmental temperatures, and to mitigate physiological thermal stress that might lead to higher morbidity and mortality rates. The general objective of the research is to verify the impact of extreme climatic events on the thermal comfort of the vulnerable population in the city of São Paulo, especially the elderly. Its secondary objectives are: (1) Simulation of future scenarios, using the ENVI-met computational model, to assess the influence of high temperatures in representative areas of the city of São Paulo, on the elderly population (2) Analysis of thermal comfort based on thermal sensation calculations, using PET indices; (3) Contribution with practical proposals for urban adaptation for the Municipality's action plans.

The main hypothesis is that, without any structural adaptation of the current urban environment, outdoor comfort levels will be seriously degraded by increasing global temperatures, and during extreme events, physiological stress will result in increased morbidity and mortality.

1.3 Urban Adaptation

The main characteristics causing urban overheating are: thermal properties of building materials, urban canyons radiative distribution, urban greenhouse effect, diminished evaporative surfaces and turbulent transfer. Planned urban adaptation is an important strategy to control the negative effects of climate change on health. Passive solutions such as shading; waterbodies; increasing the surfaces albedo - can considerably reduce the air temperature [1]. Usual ranges of urban albedo vary between 0.1 and 0.7, with an average value close to 0.5. Cities with high levels of green infrastructure benefit from a higher temperature drop when reflective materials are implemented at the city scale. Correlations can be found between these variables, e.g., in average an increase of the albedo by 0.1 decreases in average the initial mortality by 1.8. This is a very serious contribution of reflective materials on urban public health. Increase in the vegetation fraction in cities offers serious benefits to the urban climate, pollution control and health [1].

Considering the whole of this research, a full set of simulations should include the following factors, based on the parameters suggested by the bibliography:

- Increase in surface albedo: with more reflective materials and coatings in lighter colors, causing buildings to absorb less energy, consequently reducing average radiant temperatures in the urban environment. [10, 11]

- Vegetation on the roofs and buildings facades: layers of vegetation applied to the envelope of buildings can absorb a significant part of the incident solar radiation, in addition to raising the humidity of the air in the immediate surroundings and providing cooling effects thanks to evapotranspiration in the leaves. [11 - 14]

- Vegetation cover on roads, squares and parks: it consists of several resources, from the traditional afforestation to the use of devices such as pergolas, shelters or shaded paths. In addition to the shading effect, the evapotranspiration of the leaves produces a cooling of the surrounding air. [15 - 18]

- Water bodies and sprinklers: while vegetation allows the reduction of air temperatures by increasing the moisture content in a natural way, artificial strategies can strongly increase the humidity in certain areas, providing localized relief from high temperatures. [7, 19, 20]

- Urban morphology: orientation of the road system along predominant wind direction; the adequate proportion between built and empty volumes regulate exposure to direct radiation. [21 - 24]

2. Methods

This research is based on a computational analytical method, using the ENVI-met model to simulate microclimatic conditions at a representative neighborhood in a central area of the city. The existing urban environment, under historical climatic data, is compared with projected scenarios, estimated with IPPC RCP 8.5. Among many variables, PET Index is used as a measure of the human body response, in several microclimatic conditions, ages and physiological variables.

The comparative analysis of physical, objective outputs with the physiological, subjective outputs allows us to distinguish how the variables will affect human comfort and eventually cause physiological stress conditions within the urban environment over the next decades.

ENVI-met is a three-dimensional model, designed to simulate complex surface-vegetation-atmosphere interactions for urban environments. It allows analyzing, on a microscale, the interaction between urban design and microclimate, using a high-resolution orthogonal mesh. It is a prognostic model based on the laws of fluid dynamics and thermodynamics, widely validated and used as a computer fluid dynamic (CFD) tool, able to simulate and evaluate the effectiveness of urban heat mitigation strategies including surface materials, greenery, water systems, and building geometry, with reasonable accuracy [25 - 27]

The ENVI-met model is widely used in urban outdoor simulations, with validation in different regions and climates. Studies using the ENVI-met with future projections data are rather scarce, though. Therefore, this work proposes bringing the mesoclimatic projections of the Eta-HADGEM2-ES model to feed microclimatic simulations, in the urban environment of the city of São Paulo.

Due to temporary unavailability and absence of intended sets of data, CORDEX was preferred over Plataforma Projeta as a source for climate data. Therefore, historical and projected climate data were obtained in the CORDEX platform . For the most accurate and recent data, the chosen Domain was the SAM 22 (South America, grid resolution around 25 x 25 km). For the sake of comparison with studies by local authors [4, 5, 8], the adopted Driving Model was the MOHC-HadGEM2-ES.

CORDEX is part of The World Climate Research Programme (WCRP) framework, intended to evaluate regional climate model performance through a set of experiments, by producing regional climate projections. Regional Climate Downscaling (RCD) has an important role to play by providing projections with much greater detail and more accurate representation of local extreme events. For the South America Domain, the Dynamical downscaling experiments and validation studies are led by Professor Rosmeri Porfirio da Rocha, from IAGUniversity of Sao Paulo [28 – 30].

Experiments used in the present work were: historical data from 1970 to 2005; projected data from 2006 to 2099, RCP 8.5. The highest available resolution was a time frequency of 3 hours, and the main variables were near-surface air temperature and near-surface air relative humidity, which are enough as inputs for ENVI-met Simple Forcing feature simulations, using the Indexed View Sphere – IVS tool. Extraction of the climate data was streamlined by the computer software CORDEX Data Extractor .

Simulations were performed using period average data (typical years for air temperature and relative humidity), as well as extreme events (heatwaves, with temperature above the 95th percentile, spanning at least 3 days). After the compilation of the simulation results, the base case scenario (under historical climatic data) was compared to projected scenarios, estimated with IPPC concentration path RCP 8.5.

The Bom Retiro neighbourhood (coordinates 23°53' S; 46°64' W) was chosen as a first object of simulation due to its historical relevance; geographical centrality as a metropolitan rail system hub; mixed use; walkability; high proportion of elderly population; high densification potential for the next decades.

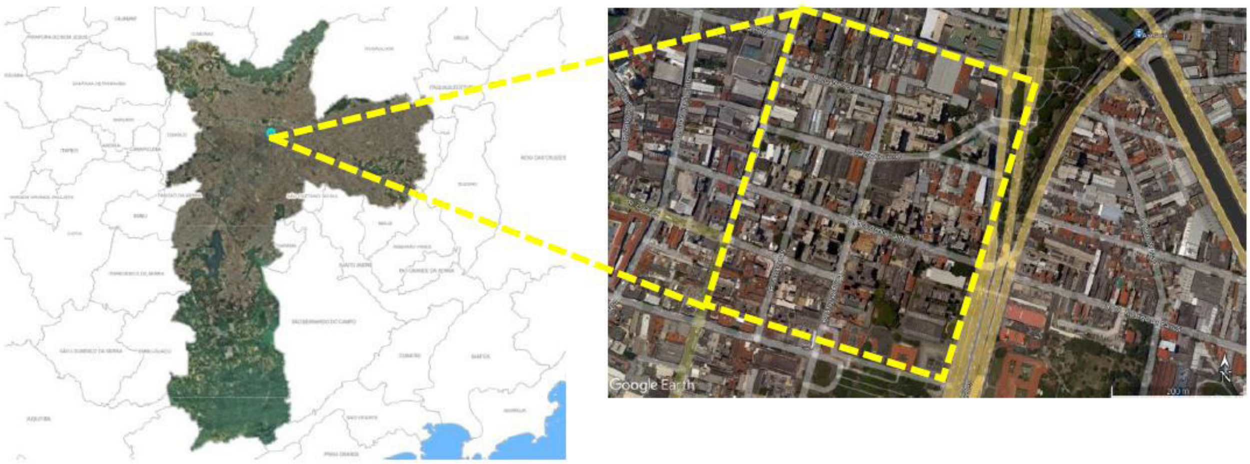

Figure 1: Area of study location in the map of Sao Paulo.

The base scenario consists of a rectangular section of the neighborhood with 558 x 426 m, covering 10 urban blocks. The 3D model was built with a 3x3 m grid resolution, reaching a 120 m height for simulation. Building materials properties data was extracted from local constructive usual practice sources [31].

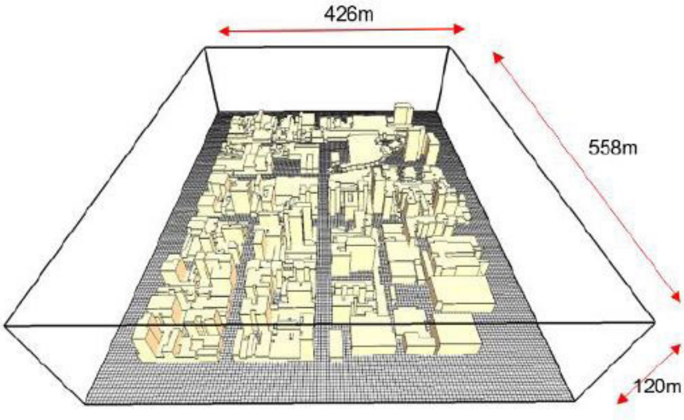

Figure 2: 3D model for the basecase

Among many output variables, PET Index was calculated using the BIO-met tool in ENVI-met, for 4 types of subjects: adult male and female, both 35 years old; 8 years old male child; and 80 years old male. All categories are supposed to wear light summer clothes (0.5 clo) and perform light levels of physical activity (walk at 0.9 to 1.34 m/s speed).

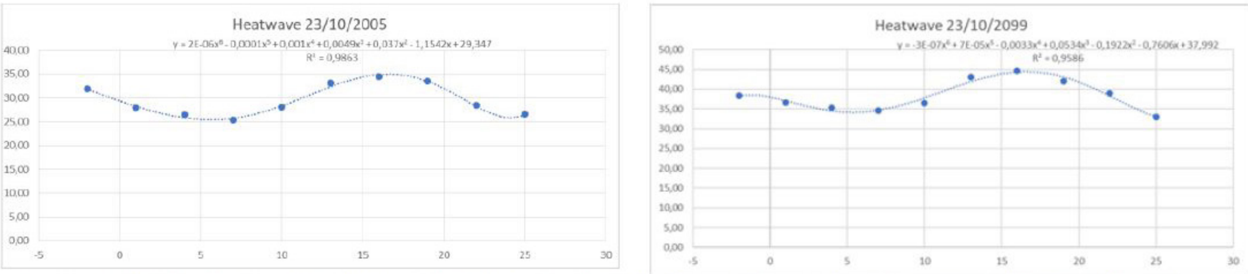

Figure 3: Graphics for air temperature extracted from CORDEX files, with intervals every 3 hours. Intermediary values for every hour were obtained by interpolation, using polynomial equations.

Analysis of climate data offers a preview of the projected climate changes. Fig. 3 shows a comparison between a heatwave (according to the definition adopted by [6]) occurring in 2005, and an equivalent event happening in 2099 under a RCP 8.5 scenario. Although the curves behave similarly, values are displaced from about 25 – 35°C to around 35 – 45°C. Therefore, in a pessimistic scenario, extreme heat events may elevate maximum temperatures to about 10°C within a single century. Another significant finding is that nighttime temperatures may reach above 30°C Celsius, which is absolutely unusual for the subtropical climate of Sao Paulo.

As for the average reflectivity of urban surfaces used for simulations, Table 2 shows the adopted values:

Table 2: Albedo values used in simulations

Material	Basecase	Future Adaptation
Asphalt Floor	0.10	0.40
Concrete Floor	0.20	0.50
Vertical Surfaces	0.20	0.70
Horizontal Surfaces	0.15	0.85

Sky View Factor used in the first simulations ranges from 2.00 to 3.50. For Sao Paulo conditions, PET values between 31- 43°C are considered hot, above 43°C are very hot, on the verge of thermal stress conditions [32].

3. Results

A sample of ENVI-met simulation outputs is shown below, with data from a heatwave occurring in 2005, compared to another in 2099 (RCP 8.5). Fig. 4 presents results for air temperature, comparing values at 3 p.m. Values on the right face of the rectangle tend to be higher, due to openness and proximity to a large avenue.

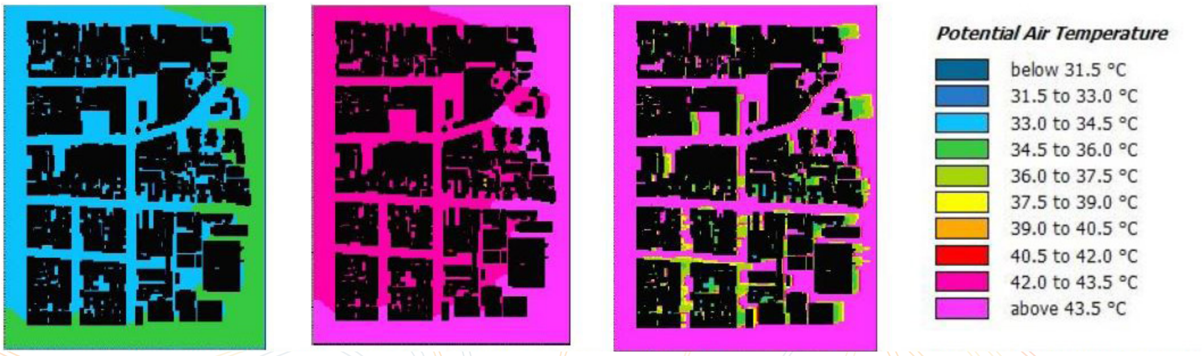

Figure 4: Results for Air Temperature at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

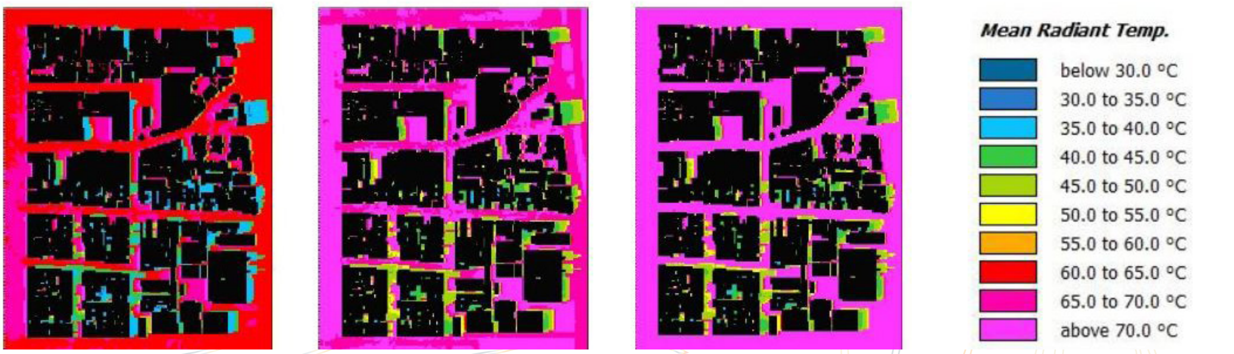

Figure 5: Results for MRT at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

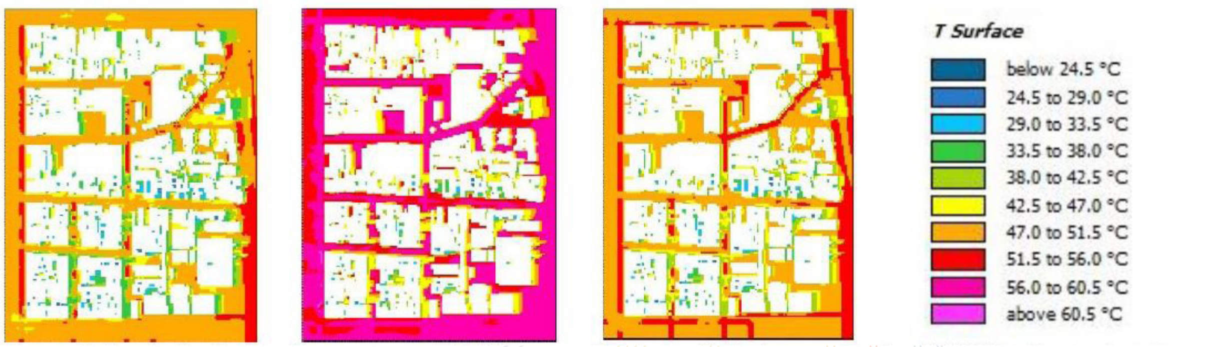

Figure 6: Results for Surface Temperature at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

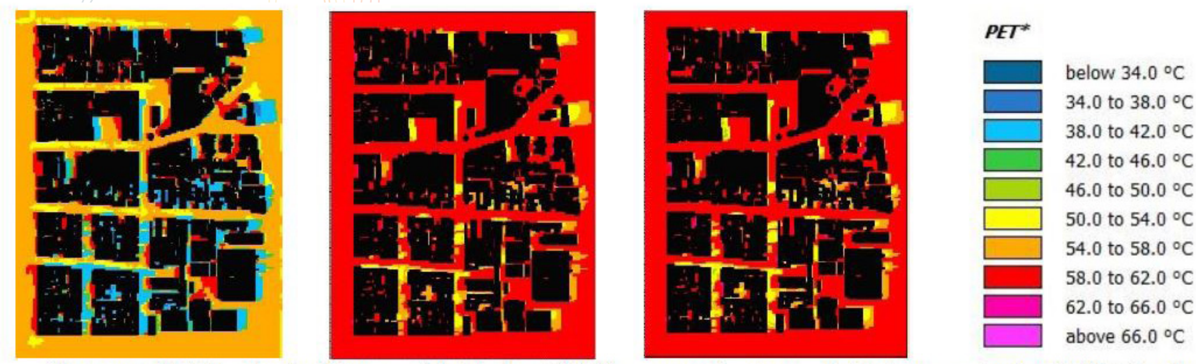

Figure 7: PET Results for 80 years old elderly at 3PM for current heatwave (left), future projection RCP 8.5 without adaptation (middle) and future projection RCP 8.5 with albedo adaptation (right).

4. Discussion

ENVI-met simulations allow a plethora of outputs. By comparing the different subjects in BIO-met calculations, it is possible to verify how sensitive to heat each group of the population is. Comparison among scenarios offer a notion of the evolution of urban heating over decades, allowing to test intervention hypotheses and its effects on each microclimatic variable. For the sake of concision of this article, only extreme results were shown, with the effects of heatwave events in a pessimistic RCP 8.5 scenario, comparing the business as usual with a general elevation of surfaces albedo.

The array of images show how the air temperatures would rise around 10°C in the whole area in the case of no mitigation, and how increasing albedo could benefit narrower streets with cooler pockets (Fig.4). As for the mean radiant temperatures, Fig. 5 shows that increasing albedo will make little difference in the future, but could have a very positive effect in reducing surface temperatures (Fig. 6), keeping them very close to the historical climate record.

PET results (Fig. 7) show that values are very uncomfortable for the elderly since the initial scenario, considering the heatwave data of 2005. That is worsened in the 2099 scenarios, and the change in urban surfaces albedo will have no noticeable mitigation effect.
The next round of simulations of this research will test the effect of increasing the Sky View Factor and offering shading devices on the sidewalks.

5. Conclusion

This is an ongoing research that is still exploring variables with the aim of proposing urban adaptation measures.

Results obtained until now confirm the hypothesis that increasing average albedo of built surfaces help mitigate rising temperatures, having a very favourable effect on superficial temperatures, and significant positive results on air temperatures. They also make clear that no single measure will be able to cope with the magnitude of the projected rising temperatures, but only a combination of factors will be effective in alleviating thermal discomfort. Increasing reflectivity of building surfaces, providing adequate urban morphology and wise inclusion of shading devices are some of the adaptation measures to be investigated.

Further developments of this research intend to contribute with effective guidelines for construction and urban planning for Sao Paulo, proposing urban adaptation measures for the Municipality's action plans.

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A reinterpretation of vernacular strategies for building envelopes in hot and arid climates: guidelines for façade design

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Abstract

In the context of various scenarios of global climate change and the imminent threats posed by escalating global temperatures, architects and urban planners must reflect on the lessons to be learned from the established model of vernacular architecture in arid climates. When closely examined and comprehended accurately, vernacular architecture offers a repository of readily applicable strategies that can be expanded upon and implemented in contemporary construction. This paper focuses on the benefits derived from incorporating height-to-width ratio (H/W) in urban settings, window-to-wall ratios and shading mechanisms inferred from vernacular architecture into envelope design for contemporary residential development. It employs the hot-arid climate of Cairo City, Egypt, as a reference context for this research proposed study. The paper elaborates on the methodologies and processes utilized to transform principles of vernacular strategies into quantifiable benchmark. This is accomplished through the integration of environmental performance simulations, including thermal and daylight conditions, which informed the exploration of potential architectural solutions. The outcome is a characterization of design elements inherent in vernacular architecture, leading to design recommendations for contemporary residential buildings in hot and arid climates, with emphasis on window-to-wall ratios and shading mechanisms.

Keywords - . Vernacular Architecture, Hot-arid climate, Adaptation, Passive strategies, Parametric Guidelines.

1. Introduction

1.1 Dry hot Climates: current distribution, future projections, and impact on global population

Climate exerts a great influence on both the choice of construction materials within a region and the design of buildings that provide essential shelter. Consequently, establishing a climatic framework is essential to understand the origins of vernacular architecture, its adaptations to challenging local conditions, and its potential applications in an era of climate change. This study specifically focuses on hot-arid climates following the Köppen-Geiger climate classification system. According to this classification, arid (B) climate zones dominate our planet, covering approximately 26% of its land area and extending roughly between 35° and 35° North and South of the equator [1]. Over recent decades, these arid climate zones have expanded at the expense of temperate and middle-latitude boreal climates, a trend predicted to persist throughout the 21st century [2]. To truly grasp the ramifications of climate change on urbanization and human well-being, it is essential to cross-reference current and projected climate scenarios with global population projections. As global temperatures are anticipated to rise by 1.5°C, 2°C, and 3°C, the severity of hot-dry climates is expected to intensify, particularly in regions such as southern Mediterranean Europe, Central and West Africa, Central America, the Amazon, and the west coast of South America. Consequently, due to 1.5°C, 2°C, and 3°C warming, the exposure of the population to hotter and drier climates is projected to increase by 93 million, 201 million, and 359 million, respectively [3].

1.2 Dry hot Climates: climatic conditions & vernacular passive strategies

Climate plays a pivotal role in shaping architectural design, with variables such as temperature, solar radiation, precipitation, and humidity being key determinants [4]. Regions within this climate are characterized by prolonged summers and brief winters, with daytime temperatures frequently surpassing 40 degrees Celsius and nighttime lows dipping below 25 degrees Celsius. Adding to

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these conditions, the average annual global radiation on a horizontal surface surpasses that of other climate zones, averaging approximately 1700-2000 kWh/m2 per year. Throughout the summer, sky illuminance levels soar from 75,000 lux to 10,500 lux, far exceeding the optimal indoor daylighting range of 300 to 2000 lx. In summary, arid climates present significant challenges, with excessive indoor lighting levels and occupants' discomfort stemming from intense solar heat gains being the foremost concerns. For arid climate regions grappling with escalating global temperatures and climate change, longstanding vernacular architecture stands as a pivotal model.

Density has an important impact on how much sunlight is absorbed, reflected, and stored in the fabric of a city, both in terms of incoming short-wave radiation and outgoing long-wave radiation. Common to cities in hot, dry climates is a combination of two main urban planning principles: the aspect ratio of the canyon, which is defined by factors such as its height-to-width ratio (H/W) and the building orientation. While it may have minimal impact on heat loss, precise orientation becomes crucial for harnessing optimal solar gains [5]. It is advisable to align buildings along the East-West axes to mitigate excessive solar heat accumulation and to facilitate shading of facades that are prone to direct sunlight, such as those facing East and West. Ideally, a slight eastward deviation from true south, typically around 15° east, proves to be more efficient, as it minimizes solar heat absorption on the western facade during the summer months [6]. To effectively manage sunlight absorption, it is imperative to reduce the number of windows in all directions and maintain a low window-to-wall ratio [7]. Additionally, incorporating external shading devices during the summer months is vital. These devices effectively obstruct excessive solar radiation from infiltrating building interiors while still permitting solar radiation to enter during the winter [8].

The materials, technologies, and architectural forms associated with vernacular architecture have long been acknowledged for their suitability to local climate conditions and their capacity to serve as a foundation for environmentally conscious design. It has long been understood that architectural needs within this climate zone typically revolve around offering shade and ensuring thermal comfort regardless of outdoor temperature fluctuations [1]. However, research projects that numerically demonstrate the benefits of embedding the described strategies within building envelopes are rare. Expanding on the classification of passive strategies by their response to one or more direct environmental stimuli [9],. this study attempts to convert the abstract definition of vernacular architecture features into measurable criteria.

2. Method

The study was conducted through a four-step research and methodology framework, with the first step dedicated to literature review, while the subsequent three steps centred on analytical exploration. Extensive research and literature review focused on raising knowledge on the benefits of vernacular architecture in hot, dry climates by using key phrases like Vernacular Architecture, Local Building Techniques, Arid Region Architecture, Climateresponsive Solutions, Traditional Building Methods, and Thermal Comfort (1). The next step (2) involved analyzing and reviewing the identified publications, categorizing passive strategies and architectural features based on their impacts on comfort and identifying those particularly relevant in the design of building envelopes, being: height to width ratio (H/W) of urban settings, window to wall Ratio (WWR) and shading devices.

Step (3) involved the establishment of an Analytical Base Case to facilitate comprehensive numerical investigations. Climate data from the Cairo International Airport weather station through EnergyPlus Weather files (.EPW) are available on the Ladybug tools website. Initially, a range of urban design configurations was set up, each consisting of a grid of residential blocks with diverse orientations and variable H/W (height-to-width) ratios. The different configurations were tested against their effect on the minimisation of cumulative solar radiation levels on vertical facades kWh/m2 and classified from optimal to less optimal. One, among the optimal scenarios, was selected as a base case to illustrate the steps for the subsequent phase of analytical work.

To perform essential indoor condition testing, the study selected one of the optimized urban configurations and carried out an analysis focusing on the annual cumulative solar radiation expressed in kWh/m2 on facades oriented in different directions. This approach was integral to investigating the impact of vernacular Window-toWall Ratios (WWR) on multi-story residential buildings as a passive design strategy. The assessment of WWR, rooted in vernacular architectural principles, was aligned with contemporary performance metrics, including Daylight Autonomy (DA) and Daylight Factor (DF). These metrics were subsequently calibrated to adhere to modern indoor lighting standards, and this iterative process yielded a comprehensive set of recommendations and design guidelines for optimizing WWR. Building upon the conclusions and guidelines derived from the Window-to-Wall ratios, traditional components of daylighting systems were subjected to a comprehensive evaluation and enhancement. This involved an examination of the type, orientation, and dimensions of vernacular shading devices, with the primary objective being to meet the minimum illuminance standards stipulated in the Egyptian Building Energy Efficiency Code (BEEC) [10]. To assess the daylighting requirements for units across all orientations and floors in the Base Case Study, point-in-time illuminance levels were tested over December 21st (a typical winter day) and June 21st (a typical summer day) at 9 AM, 12 PM, and 3 PM. These illuminance simulations played a pivotal role in identifying the specific daylighting needs. Furthermore, these simulations were juxtaposed with indoor thermal simulations to establish a correlation between window-to-wall ratios, illuminance conditions and the thermal performance of the units.

Step (4) consisted of consolidating this holistic strategy encompassing vernacular passive techniques into a comprehensive set of guidelines. These guidelines encompassed recommendations for building heights relative to street width, window-to-wall ratios, and shading devices for envelope design. The visual depiction of the methodological approach can be observed in Figure 1.

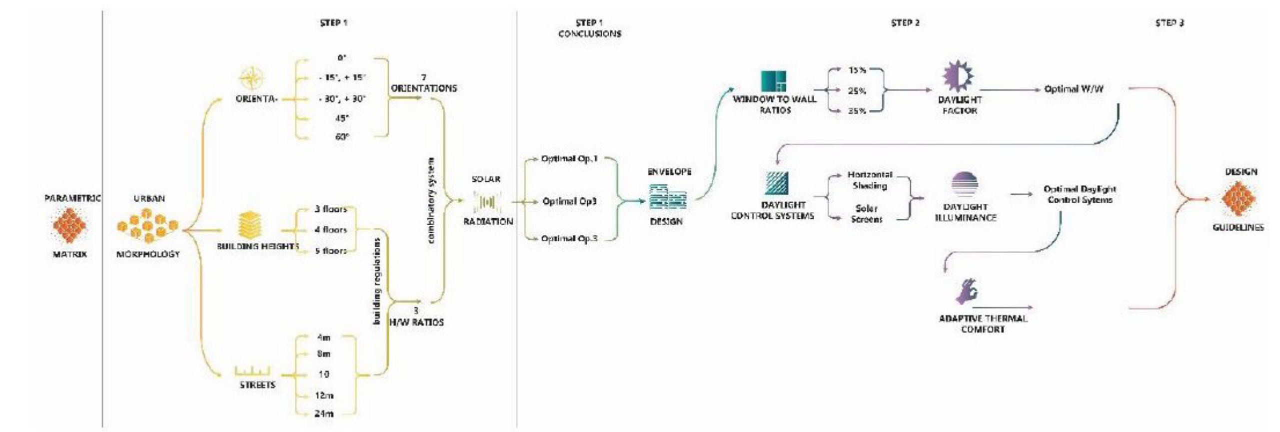

Figure 1: Research and methodology approach for the analytical work conducted on the Base Case Study.

2.1 Analytical Base Case: Urban Morphology

When comparing deep traditional urban canyons (H/W approximately 2.2) with modern urban canyons (H/W ratio approximately 0.46), it is evident that the second is related to urban surfaces' higher exposure to solar radiation and as a consequence of higher air temperature in [11]. The position of the sun must be considered when planning any building or cluster of buildings on-site, especially in the warmer months. In hot climates, the sun is the major source of heat; despite having little impact on heat loss, orientation is essential for receiving good solar gains [5]. The matrix of urban configurations presented in this study encompassed H/W ratios spanning from 1.6 (representative of traditional dense city layouts in hot, arid climates) to 1.25 (an intermediate ratio), down to 0.8 (reflecting shallow urban canyons more commonly found in contemporary urban development). These H/W ratios were systematically combined with different orientations, including 0°, 15°, 15°, 30°, -30°, and 45° from the north-south axis.

Subsequently, these combinations of H/W ratios and orientations underwent rigorous testing and classification using a multi-objective optimization approach focused on minimizing cumulative solar radiation in kWh/m2 (expressed as comparative solar factor) on building facades, particularly on the south and west orientation, so to reduce heat gains over the summer periods. This paved the way for formulating urban design recommendations to guide new developments, serving as the foundation for the subsequent phase of analytical work. One of the optimised urban configurations obtained by this process served as the foundation for our investigation into facade conditions, specifically focusing on aspects such as the Window-to-Wall ratio and the incorporation of shading devices. This configuration utilized a grid with a 25m x 25m footprint and urban blocks that reached a height of 13 meters, consisting of a 4-meter-high ground floor and additional 3-meter-high residential floors, maintaining a building height-to-street width ratio of 1.25 and an Orientation of 0 degrees to North South, as illustrated in Figure 2. These urban configurations served as the foundation for our investigation into facade conditions, specifically focusing on aspects such as the Window-to-Wall ratio and the incorporation of shading devices.

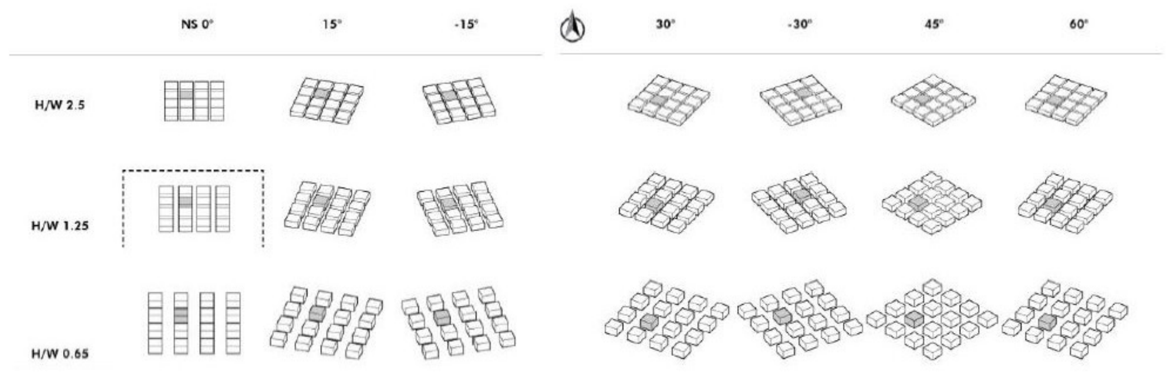

Figure 2: Visualizing tested orientations and H/W Ratios: Analytical Combinatory matrix for various urban configurations (Optimised Base Case Highlighted).

2.2 Analytical Base Case: Window-to-Wall ratio

In hot arid regions, the challenge lies in effectively integrating the primary functions of windows: good lighting, ventilation, and view. This often necessitates addressing each function separately due to their conflicting requirements. By conducting thorough literature reviews, the authors have discerned pertinent design principles imparted by vernacular architecture in hot-dry climates. Size: Instead of a few large openings, a series of small apertures is typically employed. This approach ensures privacy, security, uniform ventilation, and protection from direct sunlight. Overly large openings, while providing ample light and views, disrupt wind circulation and increase the risk of glare [12]. WWR: In arid climates, optimal sunlight control calls for low window-to-wall ratios. For various orientations, recommended ratios include approximately 0.16 for South-West facades, 0.09 for North-West facades, 0.18 for North-East facades, and 0.07 for South-East facades [13]. The literature review findings were quantified and implemented in the analytical Base Case for numerical assessment and testing of the WWR's impact in multi-story residential buildings. The WWR analysis spanned two steps.

The first step consisted of evaluating the daylight performance of WWR aligned with vernacular architecture (15%) against Daylight Factor (DF) and Daylight Autonomy (DA) benchmarks. The climate analysis of Cairo unveiled that, on average, the sky is covered 38% of the time. Consequently, the Daylight Factor (DF) was adopted as a dependable daylight metric, aligning with DGNB standards. According to these standards, when more than 50% of the usable area within a building achieves a DF > 3, it is considered "good"; > 2 is categorized as "medium"; > 1 falls under "slight"; and < 1 is labelled as "none." Furthermore, an illuminance threshold of 300 lux was utilized as the reference value for the Daylight Autonomy (DA) metric [14]. The second step revolved around the optimization of the WWR. Iterations with increased WWR (ranging from 25% to 35%) were conducted for daylighting optimization. Surface treatments and colours influencing daylight assumed external and internal wall reflectance of 30% and floor and ceiling reflectance of 30%.

2.3 Analytical Base Case: Systems for Daylight Control

The arid desert climate offers excellent opportunities for maximizing the use of natural light to illuminate indoor spaces in buildings during the daytime. However, the intense sunlight prevalent in desert regions like Egypt poses challenges. It leads to direct solar radiation entering indoor spaces, causing unwanted glare and resulting in discomfort, particularly during the summer months. A traditional solution employed to address this issue is the "Mashrabiya," a type of vernacular shading system. The Mashrabiya consists of cantilevered balconies enclosed with wooden lattices made of interconnected cylindrical elements held together by spherical joints [14]. Mashrabiyas come in various shapes and sizes with no fixed dimensions. However, the literature review has indicated that these structures typically extend about 60 cm into the street. Furthermore, considering the thickness of the exterior wall and the projection of the Mashrabiya, the width can range from 1.0 to 1.2 meters [15]. To achieve a geometric simplification and parameterization of its fundamental elements, the authors have classified the components of the Mashrabiya into the following two categories: horizontal cantilever ranging from 60 cm to 90 cm in length and solar screens with a degree of 50% 75%and 90% perforation, as seen in Figure 3.

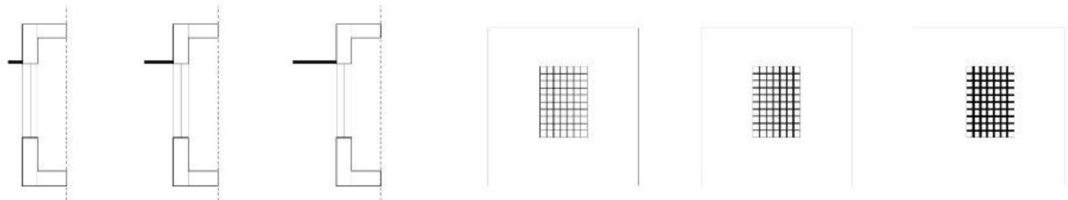

Figure 3: Visual Representation of Horizontal Shading Devices at 30cm, 60cm, and 90cm Projections (Left to Right) and Solar Screens with Opening Ratios: 50%, 75%, and 90% (Left to Right).

3. Results and Discussion

3.1 Urban Morphology

In the context of Cairo, it was concluded that, in accordance with what was found through the literature review, the urban canyon ratio (H/W) of urban fabric seems to have a bigger impact in reducing the total cumulative solar radiation on building facades compared to orientation in urban configurations. In this climatic context, the impinging solar radiation on faces (expressed in the comparative number of solar factors) is suggested as a reliable numerical indicator for defining urban development guidelines inferred from the vernacular. For urban configurations with comparable urban canyon (H/W) ratios, the Total Solar Factor did not change with the urban grid orientation changes. Deep vernacular urban canyon (H/W 2.5) has a recurring Total Solar Factor on building facades of TSF= 1 (compared to the base case). Intermediate urban canyons (H/W 1.25) resulted in a recurring Total Solar Factor on building facades of TSF= >1.6 - 1.7< when compared to the TSF =1 for the deep urban canyon, inferred from the vernacular. Shallow-contemporary urban canyons (H/W 0.60) resulted in a recurring Total Solar Factor on building facades of TSF= 2.2 when compared to vernacular urban canyons. Urban grid orientation can be used effectively to minimise impinging solar radiation on the South and West facades so as to reduce heat gains over the summer period. This led to the definition of optimised urban configurations and design recommendations for new developments summarised this way: H/W 0.65, Orientation 0° - H/W 1.25, Orientation 0° - H/W 2.5, Orientation -30°

3.2 Window-to-Wall ratio

Solar radiation analysis for the four differently oriented facades in the second optimised scenario (Orientation 0° - H/W 1.25, Orientation) was carried out to understand the vertical distributions of the cumulative solar radiation. South and East facades receive a comparable amount of direct solar radiation spanning from an average of 1000 kWh/m2 on the top third floor down to an average of 400 kWh/m2 on the bottom floor. The floors on the West went from av. 640 kWh/m2 (3rd F) to 300 kWh/m2 (GF), while the floors on the North went from av. 260 kWh/m2 (3rd F) to below 100 kWh/m2 (GF). Daylight Autonomy and Daylight Factor were tested for 10.0m wide and 7.5 m deep rectangular flats. When applying the WWR set at 15%, several notable patterns emerge, as illustrated in Figure 4. Ground floor apartments, regardless of orientation, exhibit a slight Daylight Factor exceeding 1%, while on the third floor, all four oriented apartments achieve a medium Daylight Factor surpassing 2%. In terms of Daylight Autonomy, the ground-floor apartments fall below the 50% threshold, reflecting limited autonomy. Similarly, the North and West-oriented apartments on the third floor also manifest a Daylight Autonomy below 50%. Therefore, the analysis unveils that the inferred WWR of 15% (drawn from vernacular architecture) fails to meet the standards.

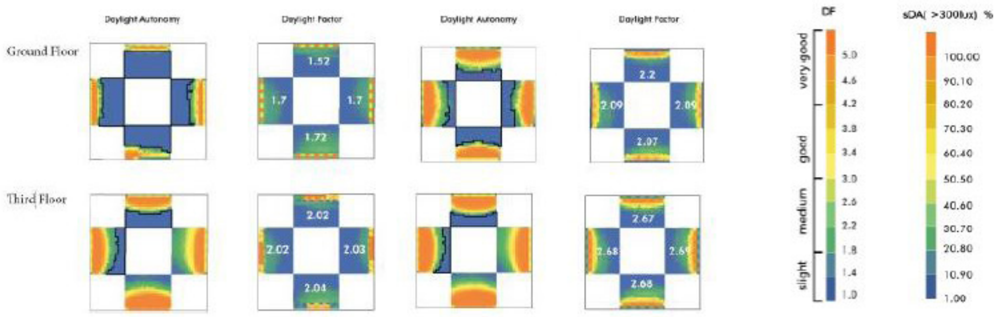

Figure 4: Daylight Autonomy and Daylight Factor analysis for ground floor and top floor apartments, WWR 15% (on the left) WWR .25% (on the right).

However, upon transitioning to a WWR of 25%, improvements become evident. On the ground floor, all four oriented apartments achieve a medium Daylight Factor exceeding 2%, a trend that continues on the third floor. Moreover, Daylight Autonomy experiences a positive shift, with ground-floor apartments achieving or exceeding the 50% threshold, indicating enhanced autonomy. Notably, three apartments on the third floor also achieve a Daylight Autonomy of 50% or higher, further underlining the benefits of the increased WWR. By adjusting the WWR to 35%, the medium illuminance standards are satisfied at the ground-floor level. Intermediate levels with a WWR ranging between 25% and 35% are deemed to meet the minimum illuminance standards adequately. The outcomes of the analytical work culminate in recommendations regarding the WWR, illustrated in Figure 5.

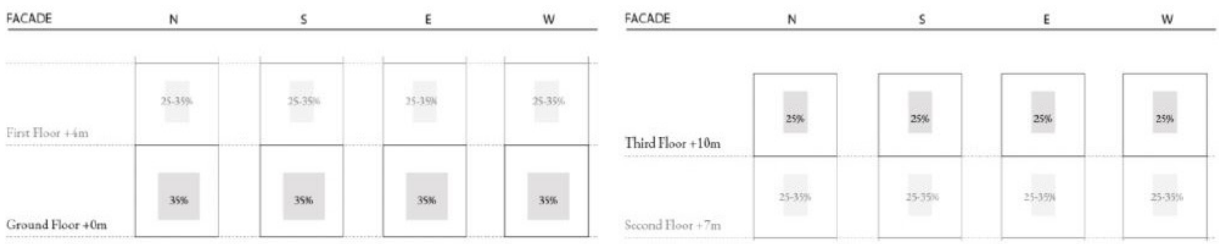

Figure 5: WWR guidelines for North, South, East and West oriented apartments.

3.3 Systems for Daylight Control

Testing was conducted on a standard summer day, revealing notable disparities in daylight levels between ground-floor and third-floor apartments in both the Base Case Study and the configuration adhering to the Window-to-Wall Ratio (WWR) guideline. These variations had the potential to cause discomfort for occupants. They correlated the average daily temperatures during these time intervals with the instances of pronounced daylight contrast. This is illustrated through graphs in Figure 6. The outcomes of the comparative analysis underscore the remarkable efficiency of horizontal shading elements in controlling high-altitude sunlight during the summer season, leading to a noteworthy average reduction of approximately 2.5 degrees Celsius in indoor operative temperatures within the apartments. The indoor operative temperatures of the North, West, and South apartments on the ground floor remain comfortably within the desired range. Meanwhile, the East apartment's operative temperature approaches the lower limit of the comfort band. This is illustrated in Figure 7.

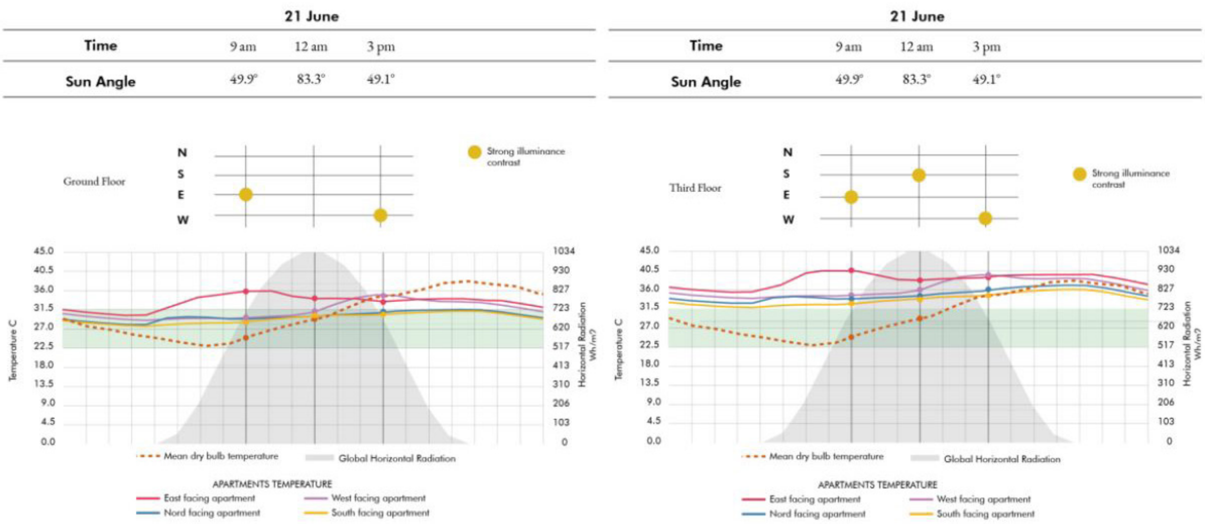

Figure 6: Comparing Excessive Daylight Conditions and Indoor Temperatures on a Typical Summer Day (June 21st) for Four Oriented Apartments in the Base Case Study, including Ground Floor and Top Floor Scenarios.

Using the same analytical approach, the authors extended their investigation to a typical winter day (December 21st) to assess the performance of solar screens. Their findings revealed that during the winter season, it's advisable to maximize the admission of solar radiation to harness heat gains, and effectively utilizing solar screen systems can aid in daylight distribution and mitigating excessive contrasts [14]. Additionally, findings indicate that solar screens can raise the indoor operative temperatures of the apartments by an average increase of around 1 degree Celsius and that solar screens lead to notably reduced fluctuations in operative temperatures across all apartments, both on the ground floor and the third floor. The outcomes of the analytical work culminate in recommendations regarding the application of WWR, horizontal shading devices and solar screen, as illustrated in Figure 8.

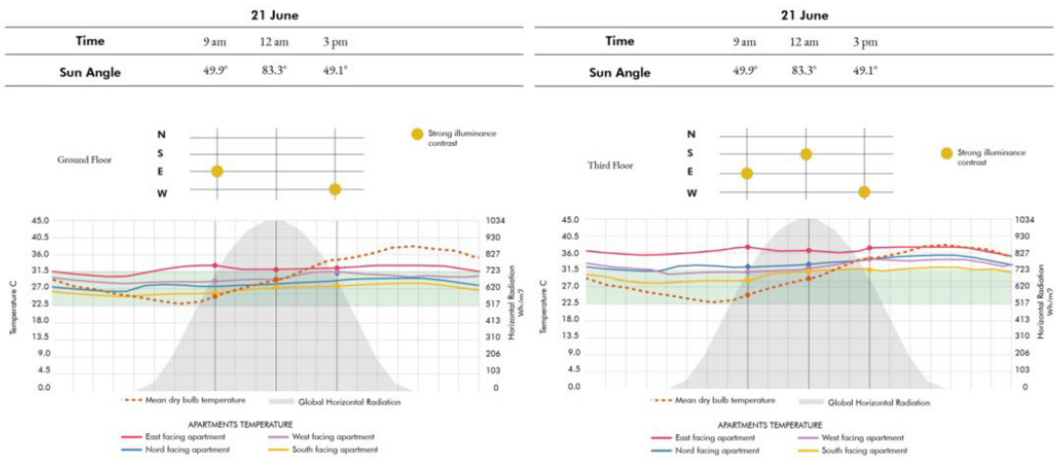

Figure 7: Comparing Indoor Temperatures on a Typical Summer Day (June 21st) for Four Oriented Apartments in the Base Case Study when added horizontal radiation, including Ground Floor and Top Floor Scenarios.

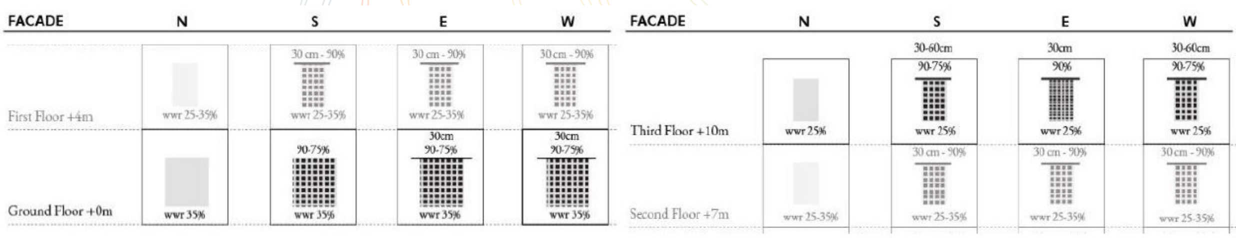

Figure 8: Guidelines for WWR, horizontal shading devices and solar screens for Base Case Study.

4. Discussion

This research aimed to illustrate methodologies and processes utilized to transform principles of vernacular strategies into quantifiable benchmarks by looking at the performance of vernacular urban canyons, window-towall ratios and shading devices on daylight and thermal comfort in hot-dry climates, where Cairo is taken as representative of the climatic conditions. As far as the result and discussions are concerned, deep vernacular urban canyons (H/W 2.5) consistently result in a Total Solar Factor of 1, while intermediate canyons (H/W 1.25) show a factor between 1.6 and 1.7, and shallow-contemporary canyons (H/W 0.60) result in a factor of 2.2, compared to vernacular canyons. Additionally, adjusting the urban grid orientation effectively proved to reduce solar radiation on South and West facades, thus playing a pivotal role in enhancing indoor lighting and thermal comfort within residential structures. As a result, the optimized urban configuration and design recommendations are H/W 0.65 with a 0° orientation, H/W 1.25 with a 0° orientation, and H/W 2.5 with a -30° orientation.

The vernacular architecture standard of 15% WWR revealed Daylight Autonomy (DA) and Daylight Factor (DF) levels insufficient to achieve the contemporary standards of comfort in both ground-floor and third-floor apartments. Transitioning to a 25% WWR significantly improved daylight metrics for both floors and a 35% WWR on the ground floor met minimum illuminance standards. The study's key finding is the recommendation for intermediate WWR levels, specifically between 25% and 35%, as they consistently achieved sufficient illuminance levels, indicating their effectiveness in optimizing daylight performance in residential buildings. Shading devices, encompassing both horizontal shading structures and solar screens, proved to be an efficient strategy for enhancing indoor comfort by effectively managing high levels of indoor illuminance and indoor temperatures. The efficacy of horizontal shading components in regulating high-altitude summer sunlight results in a substantial reduction in indoor operative temperatures, and solar screens emerge as valuable contributors to daylight distribution and heat retention during winter. Certain limitations ought to be considered when interpreting these results. Analytical Base Case, while providing a simplified representation of the average urban set-up and interior unit set-up, may not fully encapsulate the complexity and variability of new residential developments.

5. Conclusion

This study underscores the relevance of harnessing vernacular architectural wisdom to address the challenges presented by contemporary construction in arid climates. The outcomes derived from typical summer and winter days in a hot-dry climate, offer a comprehensive insight into the potential enhancements in thermal comfort achievable through the application of guidelines deduced from the assessment of vernacular urban features, WWR and shading devices. Although most of these recommendations can currently be applied to buildings in similar climate conditions, climate change projections suggest that hot-dry regions are expected to expand considerably in the coming decades. In this sense, lessons and methods from the vernacular are likely to be relevant and applied more extensively. Ultimately, this study offers a foundation for architects and urban planners to draw inspiration from the past and seamlessly integrate vernacular wisdom into the present, ensuring the sustainability and resilience of architecture in arid climates.

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Reducing extreme discomfort in the global South – A comparison of a calibrated model and locally measured data from informal housing in Peru

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Abstract

With most growth in urban population happening primarily through informal urbanisation, it is vital to identify cost effective measures for improving the often-poor housing conditions, which can have adverse health impacts on large parts of the population. The aim of this research is to investigate the indoor environmental conditions of self-constructed houses in low-income informal settlements in Lima, Peru, before and after implementing fabric retrofit strategies. Data loggers were placed in a family house in the informal settlement of José Carlos Mariátegui in Lima, measuring internal temperature and humidity at hourly intervals for two years. At the start of the second year the house underwent fabric improvement measures and particular roof insulation, following the recommendations of a calibrated dynamic thermal model. The results presented in the paper compare internal temperatures before and after retrofit as well as the modelling predictions. Overall, the measured data reveal the extreme indoor temperatures occupants are experiencing daily and the impact roof insulation has on these, with the modelling output predicting the reduction in daily peak internal temperature up to 3-5°C, and the measured data indicating an average of about 5°C on site, during warm months. The application of roof insulation on these self-constructed homes can be carried out by community members and was shown to be a cost effective measure, accounting between 5-10% of the total cost if it was to be implemented at the start of the construction process.

Keywords - extreme discomfort, internal temperature, retrofit, low-income, fabric insulation.

1. Introduction

For many decades urbanisation has been the main pattern of population growth globally, with the global South being at the centre of this growth, hosting 27 of the 33 biggest megacities around the world (Randolph & Storper, 2023), accommodating over 75% of the world's urban population (United Nations, 2022b). By 2050 the Global South may account for over 90% of the growth in urban population, reaching 7 billion inhabitants (United Nations, 2022a).

The primary mechanisms for housing urban dwellers and accommodating this rapid population growth in the global South, emerge primarily through the efforts of inhabitants themselves, building self-constructed homes and incrementally consolidating entire communities, in informal settlements. While the proportion of the global population residing in informal settlements is decreasing, their total population is increasing, with the number of people living in informal settlements exceeding 1 billion, according to the UN, (United Nations, 2022a).

Apart from the lack of basic services, and the difficulties in ensuring sustainable access to energy, the process of self-constructing homes comes with numerous other challenges. Acquiring land in hazard prone areas, sourcing materials, transporting these through often inhospitable terrain, weather-proofing various types of structures, are only some of the adversities settlers face in the pursuit of dignified living.

In most early formations, such self-construction practices result in the use of inadequate building materials, lack of sufficient living area, leaky building fabric, insufficient window areas for ventilation and daylight. Additionally, the often-dubious tenure status prevents early settlers from investing their already limited financial resources in improving the quality of their home, since the risk of eviction is always imminent. The result is poor housing conditions, which allow for extensive thermal discomfort and low indoor environmental quality, with adverse health impacts for the occupants. It is therefore vital to develop low-cost solutions for improving thermal comfort in low-income houses, which can be easily integrated in existing houses by community members.

This paper presents the output of such work, where roof insulation has been installed in a low-income self constructed home in the informal settlement of JCM in Lima, Peru, and the monitored as well as modelling results confirm the success in reducing thermal discomfort.

The following sections will present relevant important works, the methodology applied and the obtained results. A discussion of the implications of the work and the main messages for policy makers conclude the paper.

2. Background

Energy efficiency retrofits have been implemented and studied extensively in the global North across regions (Economidou et al., 2020; Fernandes et al., 2021), for residential (Saffari & Beagon, 2022), commercial (Lou et al., 2021; Ruparathna et al., 2016) as well as historical buildings (Webb, 2017). In the global South however, the subject of energy efficiency has seen less attention, especially in low-income areas where self-constructed homes are prevalent. In one of the earlier works, Mathews et. al. (1995) modelled the impact of cardboard on wintertime thermal discomfort, when applied as thermally insulating material on the envelope of self-constructed homes in South Africa (Mathews et al., 1995). The selection of cardboard, among other materials, was to accommodate the local communities' needs for accessibility, reusability, mobility and durability.

In more recent studies, more focus has been given to thermal discomfort due to high temperatures. In sub-Saharan Africa, surveys have indicated that over 65% of respondents described thermal conditions as uncomfortably warm. This has increased the need to explore ways of reducing internal temperatures by non-mechanical means, to avoid increasing energy demand for air conditioning (Adaji et al., 2019). In that perspective, studies making use of controlled experimental facilities in South Africa, showed that the use of reflective coatings on the roof and external walls of informal houses can reduce daily maximum temperatures as well as daily minimum temperatures by 4.3°C and 2.2°C respectively, in a warm and temperate climate near the city of Johannesburg.

Studies using empirical data to enrich the dynamic thermal modelling of informal dwellings in South Africa, calculated that the use of reflective paint on lightweight corrugated sheet roofing (cool roofs), can reduce excessive indoor heat stress by 42-63% (Hugo, 2023). Cool roofs were also the subject of a cross-city modelling study covering South Africa, India, Brazil, Kenya and Indonesia, assessing the impact of building design-related drivers on heat stress exposure. Their results showed that cool roofs, a rather universal solution, can reduce annual heat stress exposure by up to 91%, while by improving the building envelope to local building codes overall, the number of annual heat stress incidents in a city can drop by up to 98% (Nutkiewicz et al., 2022).

Contrary to these findings however, results of an experimental study making use of low-cost retrofit measures, showed that increasing the reflectance of the roof in a full-scale purposely built model of an unoccupied informal dwelling, was the least impactful measure, as it did not decrease the indoor temperature significantly. It was the application of thermal insulation which resulted in the reduction of internal temperature between 0.2-4.4°C (Bonaccorso et al., 2019). In further analysis, by using a validated dynamic thermal model, the researchers showed that an insulation board, made from recycled Tetra Packs, can effectively reduce indoor temperatures currently (2020s) and in the future (2050) by around 3°C, when combined with scheduled ventilation. This solution came at a cost of less than 1€/m2, making it relatively low-cost as well as easy to implement by local communities in South America and the Caribbean (Bonaccorso & Da Graça, 2022). Similar findings were drawn in an experimental study in Peru, using three full-scale purposely built unoccupied housing modules of different external wall construction (adobe, cement, wood), to investigate indoor thermal conditions under various roofing materials. The results showed that roof insulation can reduce indoor thermal discomfort, especially for the adobe and cement constructions (Wieser, 2016).

The presented work builds on these findings and by including empirical data from occupied homes as well as validated dynamic thermal building models, it reinforces the impact of insulating the roof of low-income self constructed homes in informal settlements can have, in reducing extreme discomfort.

3. Methods

3.1. Cases study house

This work is part of a larger project where internal temperatures were monitored in 45 houses in informal settlements in the city of Lima between 2021 and 2023. This study focuses on a rather representative house of lightweight construction in the José Carlos Mariátegui neighbourhood on the Andean hills, comprising a drywall construction for the external walls and a corrugated fibre cement sheet roof. This type of homes presents the worst thermal performance compared to other typical constructions (adobe, brick, cement), resulting in extreme thermal discomfort as found in previous work (Oraiopoulos et al., 2023). This was the main reason this house was selected to undergo roof insulation retrofit work, as well as the feasibility of performing works on the home and the obtained consent of the owner. The case study house, presented in Figure 1 below, has its four main sides fully exposed with one closely aligned next to the hill, leaving a small gap mainly due to earthquake risk structural considerations. One part of the house is made of drywall (living room, dining room and kitchen) and the other more precarious made with wooden boards (bedrooms).

Figure 1: Case study house. Onsite photo (left), 3D reality image from drone survey (right).

3.2 Data collection

Both outdoor and indoor environmental data were collected for a period 18 months between December 2021 and June 2023. The outdoor conditions were monitored hourly using a micro station data logger mounted on top of a concrete roof of one of the parish buildings, central to the informal settlement of José Carlos Mariátegui (see Figure 2 (left)). This was measuring: external air temperature (°C) relative humidity (%), solar radiation (W/m2), wind speed (m/s) and wind direction (°). The indoor conditions were also measured hourly, using a data logger placed in the main living space of the house (see Figure 2 (right)). This was measuring: internal air temperature (°C), relative humidity (%) and mean radiant temperature (°C). The pre-retrofit period was during the first 15 months of the monitoring (December 2021 – March 2022) and the post-retrofit period included the last three months of the presented data in this work (April 2023 – June2023).

Figure 2: Outdoor micro station data logger (left)

As the focus of this study is thermal comfort, the analysis will mainly concentrate on the temperature data and the differences between the pre-retrofit and post-retrofit periods.

3.3 Model calibration

A dynamic thermal simulation model of the case study house was developed to help the decision-making process with regards to the exact specifications of the roof insulation, which was to be applied, to avoid any unintended consequences as well as over-costing of the works. The model was constructed using DesignBuilder, a performance analysis tool and easy-to-use interface for the widely used EnergyPlus software (see Figure 3)

Figure 1: Case study house. Onsite photo (left), 3D reality image from drone survey (right).

The main inputs to the model, summarised in Table 1, concerned the geometry, the thermal (construction) and the behavioural (activity) aspects of the house and the occupants. These were captured by measurements, questionnaires and local building materials and standards.

Table 1: Main inputs to the dynamic thermal simulation model in DesignBuilder

Geometry	Construction	Activity
Drywall zone (D) Floor area: 30m² Average height: 2.7m Wood zone (W) Floor area: 30m² Average height: 2.4m Orientation (D): 37°	Ground: reinforced concrete slab on the ground, without insulation; e=100mm Walls: drywall construction system with exterior fibre cement sheet (e=6mm), air chamber (e=100mm) and interior plasterboard sheet (e=120mm). U-value = 1.997 W/m²-K Roof: fibre cement corrugated sheet; 0.4cm. U-value = 4.839 W/m²-K Windows: single clear glass (e=4mm), metal frame. U-value = 6.257 W/m²-K Door: opaque wooden door (e=35mm). U-value = 2.823 W/m²-K	Occupancy density: 4 occupants/60 m² = 0.07 ppl/m² Internal gains = 2.93 W/m² Hourly schedule, activity template, derived from household surveys: Until 07:00: 1 Until 08:00: 0.5 Until 14:00: 0.25 Until 20:00: 0.75 Until 24:00: 1

The external weather input data were given additional considerations since José Carlos Mariátegui is located at 18 kms from the international airport and at a 385m higher altitude on the Andean hills. Therefore, using the nearest official source for the .epw file was not regarded as representative of the local climate as it could add a significant source of potential error to the results. For this reason, the .epw file was edited using the onsite measured temperature, humidity, radiation, and wind data, to allow for increased confidence in the results.

The calibration of the model was centred around two main parameters, which are challenging to estimate and difficult to measure, the ventilation and infiltration rates. The infiltration rate calibrated value was based on a winter design week between 26th August and 1st September, for the ventilation to be kept at the minimum possible variation. Simulations were run at intervals between 2-8 ACH, with the best results given when infiltration was set to 8 ACH. The evaluation was based on statistical indicators as well as the visual inspection of the measured against the model data as seen in Figure 4 (left). Since a building calibration technique based on internal temperatures is not frequent in literature (Calama-González et al., 2021), the statistical indicators used were those often applied in energy-based calibration studies and given in the ASHRAE Guideline 14 (ASHRAE, 2002), namely CVRMSE and NMBE as also applied by (Petrou, 2023). This study also included the coefficient of determination (R2) to provide an indication of the overall fit of the data profiles. The ventilation rate calibrated value was based on a summer design week (12-18 March 2023) and was calculated to 40 ACH (for a window opening setpoint at 24°C) based again on the values of statistical indicators (R2, CVRMSE, NMBE). The results of the calibration can be seen in Table 2 below.

Table 2: Case study house model calibration statistics between measured and modelled internal temperature.

	R^2	CVRMSE (%)	NMBE (%)
Infiltration = 8ACH (calibrated during winter)	0.93	6.25	0.41
Ventilation = 40 ACH (calibrated during summer)	0.94	3.93	-0.83

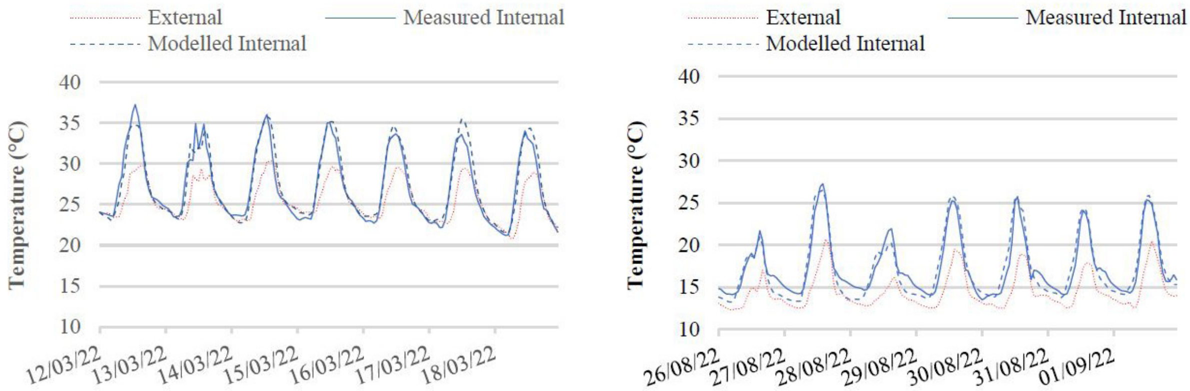

Figure 4: Measured against modelled internal temperature data for an infiltration rate at 8ACH (calibrated during wintertime, left) and ventilation rate of 40 ACH (calibrated during summertime, right)

The validated model was then used to assess the effectiveness of the different materials and thickness levels for the insulation of the roof. The results are presented in section 4.

4. Results and Discussion

This section presents the results from the roof insulation simulations as well as the measured data pre and post the retrofit works.

4.1 Roof simulation

The roof insulation material, which was selected for being economical, lightweight, easy to acquire and easy to install, is an insulating panel composed of two layers of fibre cement and 5cm of expanded polystyrene (EPS) with a U-value=0.656 W/m2-K. This was added to the roof layer in the model and the simulation results for both summer and wintertime are presented in Figure 5 below.

The results from the simulations indicate that there is a reduction of thermal discomfort during both summer and wintertime. During summer the modelled daily peak internal temperature decreases by up to 3-5°C, while the daily minimum internal temperature (during nighttime) only increases by less than 1°C. During winter, the modelled daily peak internal temperature reduces by no more than 1°C, while the hourly internal temperature during nighttime increases by 1-2°C.

Since informal houses in Lima do not incorporate any mechanical heating or cooling, the insulation had to be arranged such as to control both solar incidence during hot weather and prevent heat loss during cold weather. The simulations suggested the installation of the specified roof insulation can offer these conditions as it was shown to improve thermal comfort substantially during both summer and wintertime, without the addition of any significant unintended consequences.

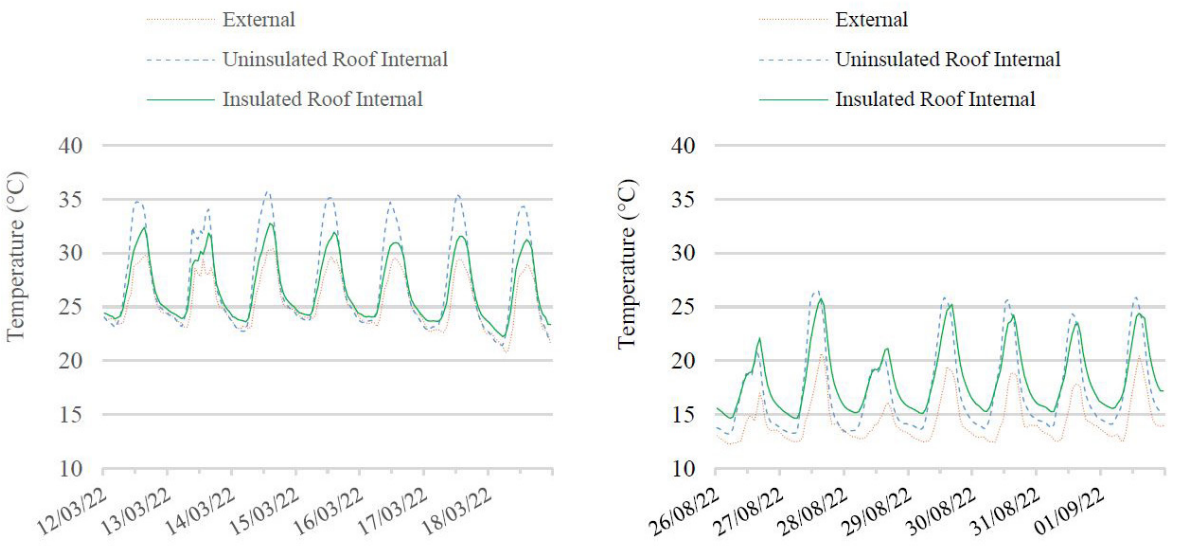

Figure 5: Simulation results of the calibrated model for the impact of insulation on internal temperatures during both summer (left) and wintertime (right).

4.2. Roof Insulation

Based on the modelling results, the installation of the roof insulation was carried out with the aid of a local NGO (CENCA). The installation of the insulated panels required structural reinforcement, hence the works lasted three days. The corrugated fibre cement sheets were placed again as an external layer to provide protection from the weather, as seen in Figure 6.

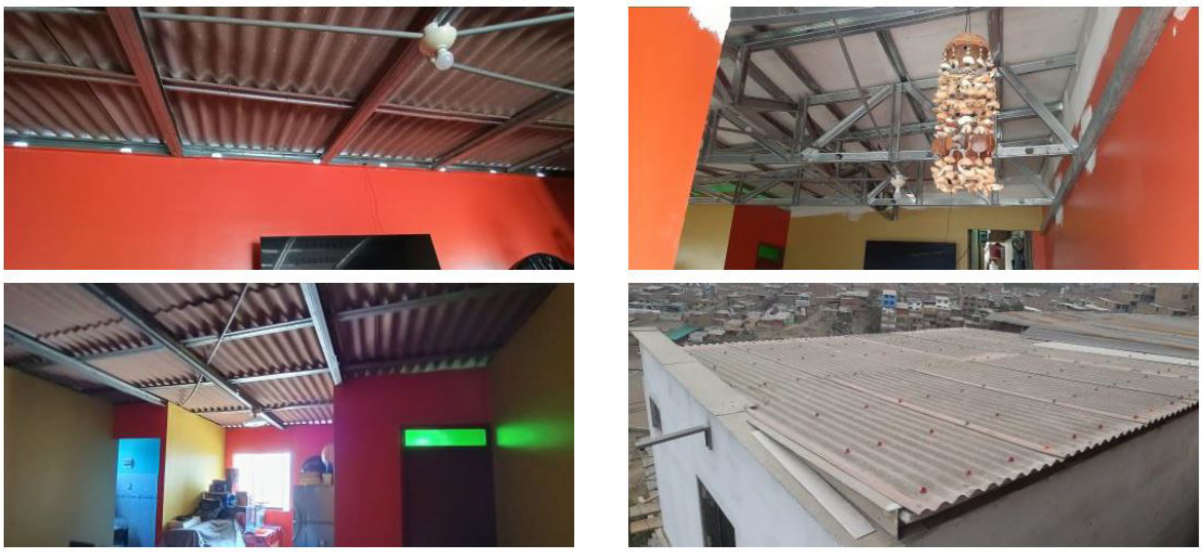

Figure 6: Roof details before retrofit (left) and after the installation of the insulation (right).

The total cost of the roof insulation for the 30m2 area was approximately US$1,200. This included material and labour, but also the removal and reinstallation of the existing roof, as well as the steel reinforcement structure, (approximately US$600 for labour and US$600 for materials). The local NGO CENCA is currently financing the construction of lightweight housing modules with uninsulated roofs, of similar floor area and materials, at an approximate cost of US$4,200 (approximately US$1000 for labour and US$3200 for materials), of which some US$600 are for the uninsulated corrugated sheet roof. Assuming the cost of labour will not change substantially, when constructing a new house with insulated roof, the increase in the overall cost should not exceed 5-10% compared to constructing a house with an uninsulated roof. It can also be noted that if the steel reinforcement structure is fully optimised for the appropriate load, the roof insulation cost could be further reduced to a value not exceeding 5% of the overall cost of the house, especially in the case of constructing more than one home.

4.3. Roof monitoring

Following the installation of the roof insulation, the hourly monitoring of the internal temperature continued for the following 3 months. This work presents the measured impact of the roof insulation on internal temperatures during warm external weather in April, in Lima. Due to the extremely warm weather during winter months of 2023 (June-August) in South America and specifically the region of Peru, it has not been possible to assess the impact of the roof insulation during colder external temperatures. However, the monitored data suggest the reduction in thermal discomfort is substantial. Figure 7 and Figure 8 present the external and internal temperature throughout the monitoring period in lower and higher temporal resolution, which includes pre- and post-retrofit periods.

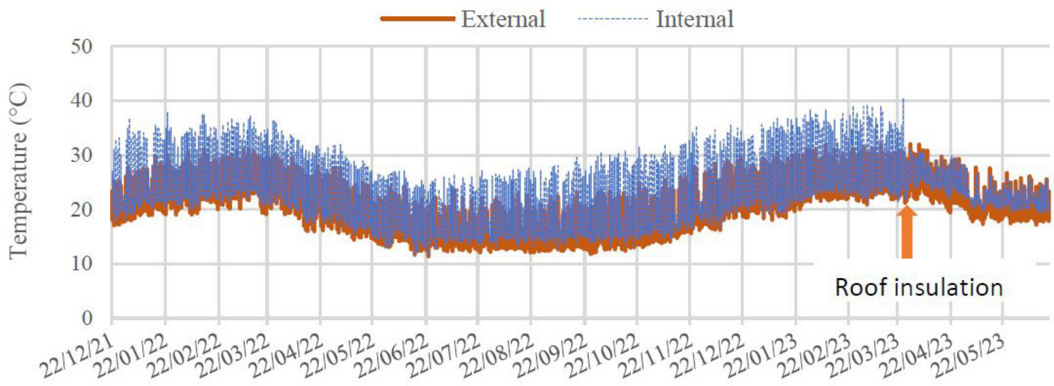

Figure 7: Monitoring period: External and internal temperatures pre and post roof insulation retrofit date (25-28/03/23).

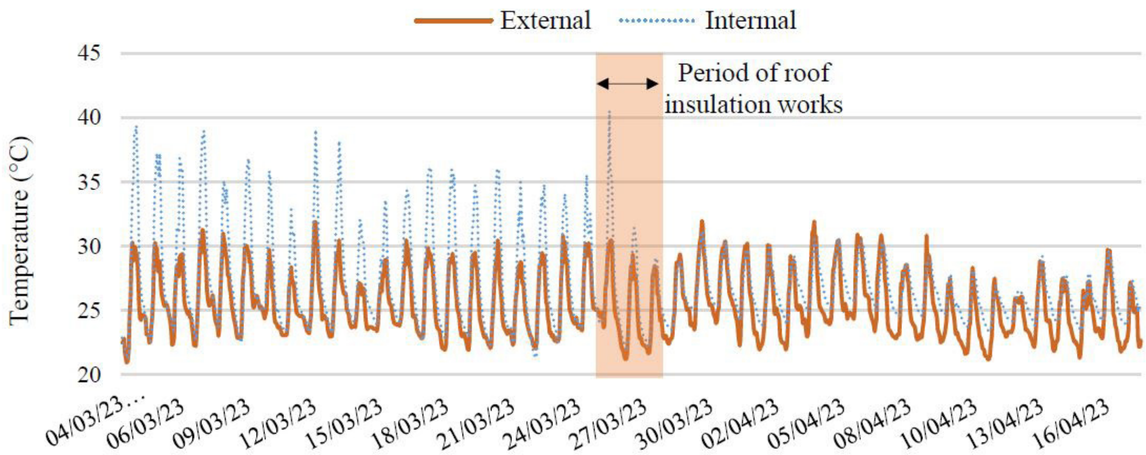

Figure 8: External and internal temperatures pre and post roof insulation retrofit date (25-28/03/23).

As it can be seen from Figure 7, the daily maximum internal temperature exceeds 30°C regularly from December up to April annually, often exceeding 35°C and reaching temperatures of almost 40°C, posing a significant health risk to occupants. In Figure 8 however, it is clearly indicated that the daily peak internal temperature post-retrofit was decreased by an average of about 5°C and in some cases up to 10°C, compared to pre-retrofit values. This is a significant reduction of the extreme discomfort the occupants experience on a daily basis during the warm months. The nighttime temperatures have also been affected, with the daily minimum shifted by 1-2°C. These findings are in line with the results from the calibrated model and confirm the impact of roof insulation in reducing extreme discomfort in low income, self-constructed homes in informal settlements.

5. Conclusions

This paper presented a study on the impact of roof insulation in low-income, self-constructed homes in informal settlements in Lima, Peru. Monitored data were used to calibrate a dynamic thermal model which was utilized in simulating the proposed retrofit design and test the impact ahead of the works. Overall, the results uncovered the large infiltration and ventilation rates possible in these houses, and the monitored data once more revealed the extreme thermal discomfort the occupants experience throughout the year. The findings show that roof insulation can reduce extreme thermal discomfort during warmer months, by lowering daily peak internal temperatures. Although during the period of monitoring, the region experienced an extreme lack of colder temperatures, the results from the calibrated model provide confidence of similar performance during colder weather. This was the first study of its kind in this informal settlement, suggesting the cost of future works can be reduced further, to maximum 5% of the total cost of a house, making this an affordable way to reduce extreme thermal discomfort.

6. Acknowledgments

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Urban oasis for adaptation to cClimate change: analysis of climate adaptation plans (CAP) around the world

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Abstract

Driven by climate change, especially the increase in the occurrence of heat waves around the world, this work has the objective of systematizing the municipal climate adaptation plans collected according to the criteria outlined in the document Measuring Benefits of Urban Heat Adaptation published in March 2021 by the C40 Group of Major Cities for Climate Leadership. The main results show that, out of 259 documents raised, only 154 effectively correspond to Climate Adaptation Plans, being that most of these documents are American. Among the actions proposed by C40, mention of mitigation is present in all documents, through the guideline aimed at reducing greenhouse gas emissions. The second most mentioned action refers to green infrastructure, 75%. However, it is important to highlight two other actions: heatwave response planning and development of cooling places, mentioned in only 44% and 34% of the analysed documents, respectively. In particular, actions related to cooling places, such as grey built-up structures and water features, appear only in more recent plans, mainly from 2015. Therefore, due to the current demand, it is urgent the readaptation of public spaces through the design of a network of refrigeration spaces distributed throughout the city.

Keywords - Climate Change, Climate Adaptation Plans, Heat Waves, Cooling Places.

1. Introduction

According to the United Nations Framework Convention on Climate Change (UNFCC), climate change is a phenomenon attributed directly and indirectly to human activity that modifies the global atmosphere composition that is beyond the natural climate variability which is already observed, creating changes in climatic pattern, rising global temperature average and extreme events attached to climate (IPCC, 2023).

Studies suggest that society will experience many impacts of climate change in the near future, over the next thirty years, and even more so in the second half of this century. Among these impacts, one that has significant implications for energy demand and the health of the population is the increase in the frequency and intensity of heat waves. Although there is no universally acceptable definition of heat waves (Perkins; Alexander, 2013) these are understood as periods of unusual hot and dry/humid weather lasting at least two to three days and having a noticeable impact on human activities. Over the duration of heat waves, not only daytime temperatures reach high values, but also night time temperatures, and humidity changes beyond the long-term average. Heat waves are relative to a climate location; the same weather conditions may constitute a heat wave in one place but not another (Stefanon et al., 2012).

Extreme heat conditions are becoming more frequent, increasing risks to human health and health systems. The main impacts have been recorded in places where extreme heat occurs in context with population aging, urbanization, urban heat island, and inequalities in health care (Fajersztajn et al., 2016). According to Zhao et al. (2019), climate change will increase the number of deaths linked to heat waves between 2031 and 2080, and Brazil is among the most affected countries.

As for extreme temperature events, these overload the human body by damaging the cardiovascular and respiratory systems, especially for the most fragile people such as the elderly, pregnant women, children up to 4 years old, and obese people, according to the World Health Organization (WHO, 2018). Cities are not the cause of heat waves; however, they potentiate their effects. Because of the large concentration of asphalt, concrete, stone, and other inert materials, cities end up absorbing and retaining more heat than rural areas (Stone, 2012), and are therefore more vulnerable to heat waves.

As for the vulnerable population, in 2018 about 220 million people under 65 years of age were exposed to heat waves, a higher figure compared to the period from 1986 to 2005 (WMO, 2020). It is worth noting, according to Diniz et al. (2020), that the projections made for the near future (2030 - 2050) and distant future (2059 - 2099) show that excess mortality of the elderly related to heat waves will increase, being higher when urban adaptation actions are not applied, especially for cardiovascular diseases in women (up to 587 deaths per 100,000 inhabitants/ year). In the Brazilian context, recent research indicates an increase in the frequency of heat waves over the years in different regions of the country under different climates. It is expected that by the end of the 21st century, with the increase in heat waves, the Brazilian Northeast region, due to its location and also affected by socioeconomic inequalities, will become the region most affected by intense heat (Geirinhas et al., 2017).

Importantly, urban areas have a dual role: besides housing much of the population, the present lifestyle is one of the main inducers of climate change, since cities are marked by excessive consumption, solid waste production, greenhouse gas emissions, intensive energy use, landscape fragmentation, soil sealing, predominance of inert and heat-absorbing materials, and other factors that intensify the effects of climate change. In this sense, the structuring of space, form of development and expansion of the urban fabric (Nobre, Young, 2011) added to the implementation of urban green infrastructure (Farrugia et al., 2013) are points to be considered. Urban green infrastructure can be interpreted as a hybrid of green spaces and built systems such as forests, wetlands, parks, green roofs and walls that together can contribute to ecosystem resilience and bring benefits to humans through ecosystem services (Naumann et al., 2021; European Environment Agency, 2022).

In view of the above, this work has the objective of systematizing the main national and subnational climate adaptation plans according to the criteria outlined in the document Measuring Benefits of Urban Heat Adaptation, published in March 2021 by the C40 Group of Major Cities for Climate Leadership (C40, 2021), highlighting the strategic role of urban planning and design in climate adaptation to the urban heat, looking mainly at the propositions for the creation of climate amenity spaces.

2. Methods

The analysis of the Climate Adaptation Plans was carried out in order to systematize them according to the criteria outlined in the document Measuring Benefits of Urban Heat Adaptation, published in March 2021 by the C40 Group of Major Cities for Climate Leadership (C40, 2021). Among the C40 criteria, this analysis was based on the temperature reduction potential of the proposed actions and feasibility of implementation, as follows:

- Cool surface: found on sidewalks and roofs, these are those that reduce energy absorption and capture as a result of the reflective capacity of the elements;
- Green infrastructure:

1. Urban parks: responsible for reducing the local urban temperature according to their size and canopy cover;
2. Green corridors: correspond to connected green spaces in order to direct the wind and promote biodiversity;
3. Vegetation, in general: corresponding to flowerbeds, bio-valets and green roofs.

- Urban form planning and design: according to the width of the streets, density, gauge, and materiality, it is possible to increase the albedo and consequently reduce the solar radiation stored on the urban surface.
- Heatwave response planning: corresponds to the policy of making the population aware of heat waves as well as action plans upon their occurrence in order to mitigate the effects generated by prolonged exposure to increased temperatures.
- Grey urban shading structures: corresponds to structures that provide shading, whose importance comes from the reduction of the amount of solar radiation captured and stored in the

urban surface and, therefore, reduction of air and surface temperature.

- Urban Water features: due to their greater ability to absorb solar radiation, when compared to inert materials, and to evaporative cooling, water bodies can reduce the air temperature of the surrounding area and promote greater thermal comfort.
- Wind corridors: through convection and evaporation, wind corridors can generate temperature reduction.

In addition to these criteria, this analysis included the search for the proposition and design of cooling places, as spaces of climate amenities distributed in a targeted manner throughout the city in order to assist the population during extreme heat.

It is worth noting the absence of conceptualization and specific literature on this topic, since the understanding about cooling places comes according to the local reality. The definition found is the one applied in Climate Adaptation Plans of developed countries such as the United States and Australia, in which the cooling places are mainly public or private air-conditioned buildings, able to receive the population, and where people are guided to go during extreme heat, besides some open spaces such as parks, public pools, squares with access to water, etc.

In total, 259 documents were analysed (Table 1). These documents encompass: i) municipal plans, ii) regional plans: preferably, administrative divisions corresponding to states and capitals; iii) documents available in official electronic portals; iv) cities mentioned in the consulted bibliographical references, so that there is a better understanding about the local conditions and possible similarities. This research was carried out based on municipal websites and specific websites related to climate change.

3. Results

Out of 259 of documents raised, 17 are from cities in Africa, 126 from America, 63 from Asia, 38 from Europe and 7 from Oceania; circa 68% correspond to Climate Adaptation Plans, as defined by Obermaier and Rosa (2013), with delimitation of the guidelines aimed at the local reality. Already 8% fit the pattern of booklets that, according to the IAUC (2020), are documents with education character that address the basic concepts on the subject and are not restricted to the existing local demands.

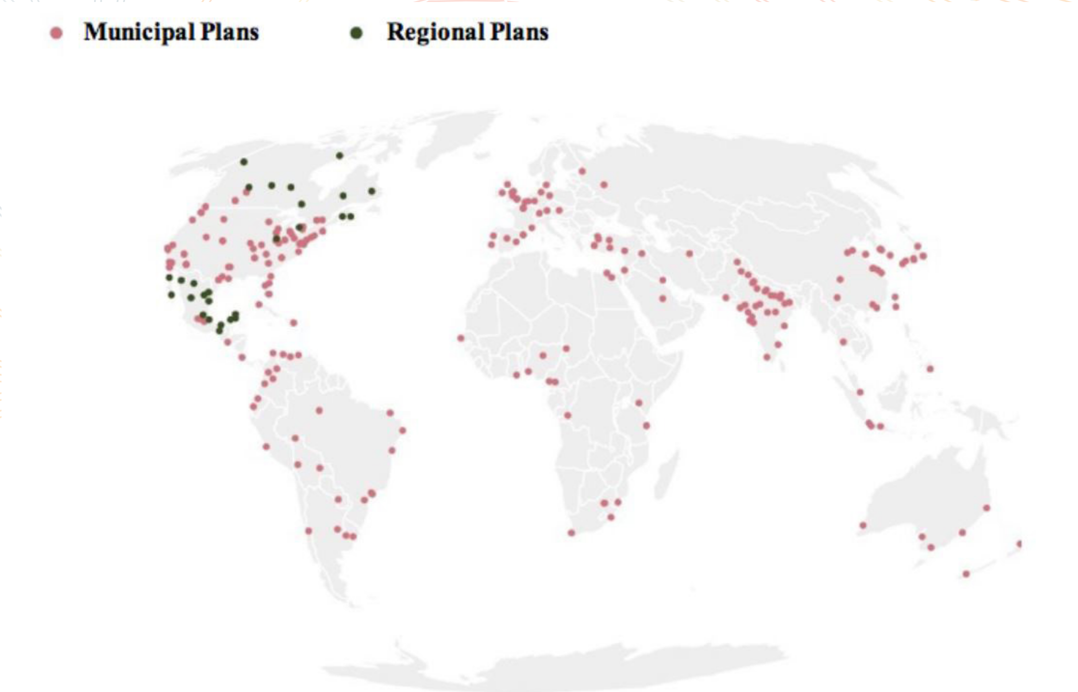

Figure 1: Spatialization of Climate Adaptation Plans: out of 259 of documents raised, 17 are from cities in Africa, 126 from America, 63 from Asia, 38 from Europe and 7 from Oceania (Authors, 2023; Infographics by Nicholas Pretto)

From the analysis of the above-mentioned plans, it was possible to understand the spatial distribution of the plans (Figure 1), which are more frequent in developed countries, especially in the USA. In addition, it was possible to draw an overview of the main issues dealt with in the Climate Adaptation Plans and similar documents (Figure 2 and 3). In Figure 2, through the bar graph, it is possible to understand the geographic Distribution of the analyzed documents as well as their publication period. Through Figure 3, it is possible to understand the mention of strategies.

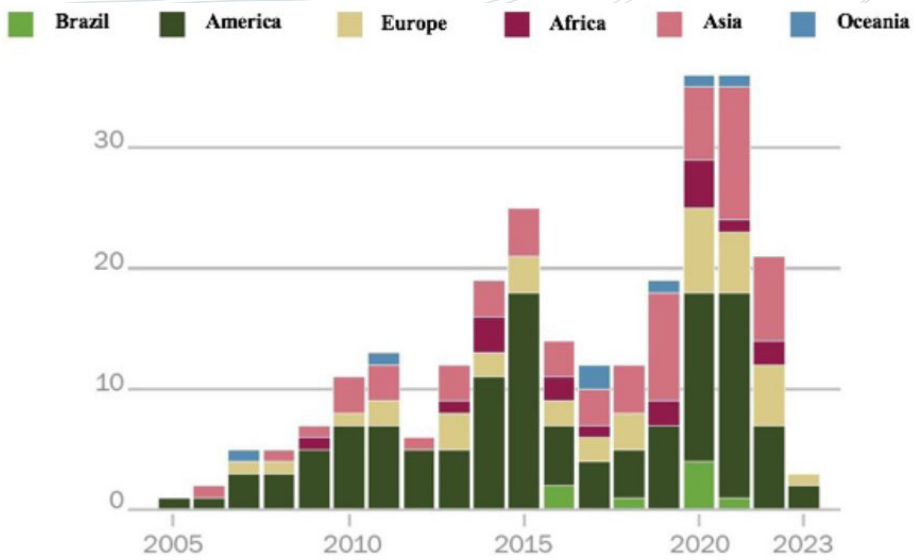

Figure 2: Geographic distribution of Climate Adaptation Plans (Authors, 2023; Infographics by Nicholas Pretto)

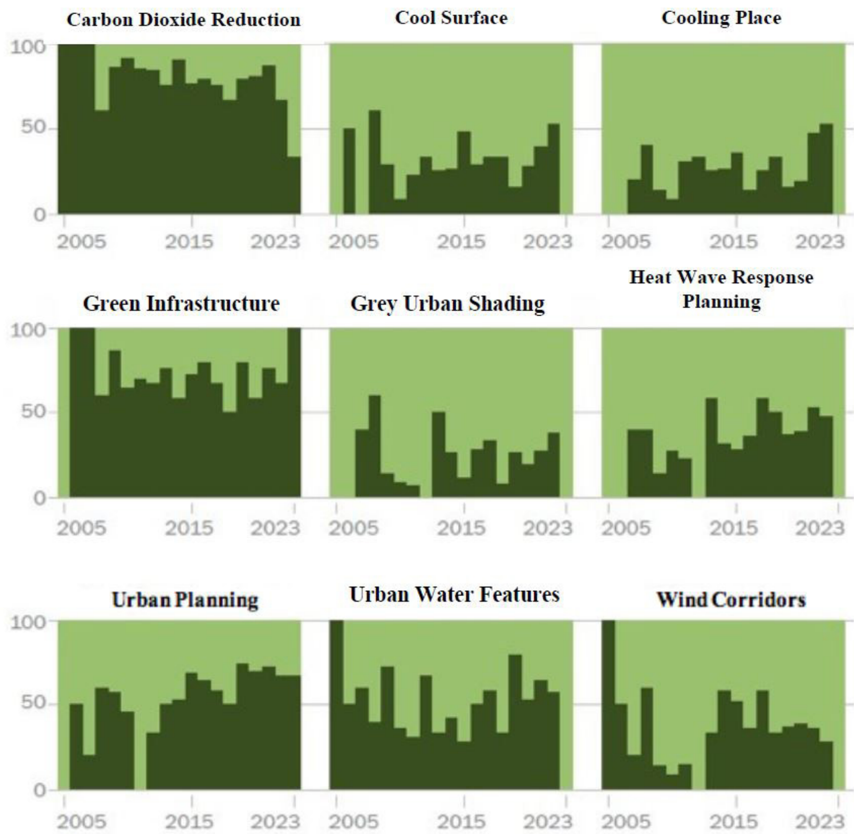

Figure 2: Geographic distribution of Climate Adaptation Plans (Authors, 2023; Infographics by Nicholas Pretto)

4. Discussion

Among the actions posed by the C40, the mention refers to reducing the emission of greenhouse gases, such as CO2, stands out. However, it is known that the concern with the urban environment should not be restricted to mitigation measures, but also address adaptive measures of cities in the face of climate change (Duarte, 2019).

The second most mentioned action is related to green infrastructure (75%). Despite predominant, the level of detail given to this action fluctuates too much and three different approach patterns were found: i) only mention the importance of the vegetation for alleviating thermal stress; ii) indication of guidelines for urban parks, urban vegetation and green corridors; iii) reference to green infrastructure plans based on the demand mentioned in the analysed documents.

For example: i) in the Strategic Focus Area Plan for the city of Charlotte, USA, the importance of planting trees as a strategy for maintaining community resources is highlighted, but guidelines for these plantations are not outlined; ii) in Guide to Urban Cooling Strategies referring to Australia, in addition to pointing out practical alternatives arising from green infrastructure, they show how vegetation can contribute to the reduction of thermal stress; iii) in Chicago Climate Action Plan, USA, other documents, such as the Urban Forest Agenda and the Chicago Trees Initiative, are mentioned. It was considered important to highlight two other actions: heatwave response planning and cooling places, mentioned in only 44% and 34% of the analysed documents, respectively. There is a relationship between these actions, for example, warning systems triggered in cases of heat waves as part of the Excessive Heat Plan (Philadelphia Hot Weather - Health Watch Warning System). In this program, municipal teams work together with the National Weather Service to determine the heat wave and the consequent alert when they are hit.

Thus, there is guidance for people to go to places determined as cooling places, which are located through an interactive map available on the internet, the Stay Cool Interactive Map. On this map there is an indication of places with milder microclimates for these become temporary refuges until there is recovery from the thermal stress caused by the constant above-average temperatures for prolonged periods. When analysing the existing climate adaptation plans, it can be noted that many of them recommend that people seek air-conditioned spaces as a way to recover from excessive and prolonged heat.

As for the actions related to urban planning and design strategies, 70% of the plans mention them, whose level of detail, as well as for green infrastructure, varies a lot. As an example, for this action, the Hong Kong's Climate Action Plan 2030+ is cited, which highlights the direct relationship between the reduction of air and surface temperature according to urban morphology and urban parameters, such as the minimum setback in urban lots and the shape of buildings.

5. Conclusion

Analysing the results of this research, it is possible to observe that there is a recent need - mainly in the last 10 years, with emphasis on the period after 2020 - for the development of climate adaptation plans, with most of the climate adaption documents found in developed countries. In the last 10 years, there has been a strong movement in the Asian continent. These plans aim to reduce the impacts generated by climate change and advance the understanding of the subject and the implementation of practical measures that minimize the expected impacts.

Despite this, part of the documents found can be classified as primers, as they approach the topic superficially and have an education rather than a performance or prescriptive nature. Most of these documents lack important details and may not be applicable to reality.

It is noted the prevalence of green infrastructure, actions related to urban morphology and reduction of greenhouse gas emissions, the first two aspects being climate adaptation actions, while the last one is aimed at mitigating climate change. The actions related to cooling places, grey urban built-up structures and urban water features, it was observed that these are less frequent in the survey and it appears only in more recent plans, being first mentioned in 2015.

Due to the current demand and the need for measures aimed at climate adaptation, the urgency needs to readapt public spaces through the design of a network of cooling places distributed throughout the city. Cooling places must be designed in accordance to local reality and might be interesting to be associated with green infrastructure and better developed with urban morphology actions in order to alleviate the thermal stress generated by heat waves.

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8. Appendix

8.1. Analyzed documents

Table 1: Table with list of analyzed documents – Part 1 (Authors, 2023)

CLIMATE ADAPTATION PLANS	YEAR OF PUBLICATION	CITY	COUNTRY
AMERICA			
Plan de Acción sobre el Cambio Climático 2021-25	2021	Buenos Aires	Argentina
Plano Municipal de Mitigação e Adaptação às Mudanças do Clima de Rio Branco	2020	Rio Branco	Brazil
Plano de Ação Climática	2020	Salvador	Brazil
Plano Local de Ação Climática da Cidade de Fortaleza	2020	Fortaleza	Brazil
Plano de Mitigação e Adaptação às Mudanças Climáticas	2020	Curitiba	Brazil
Goiânia Sustentável	2011	Goiânia	Brazil
Plano Local de Ação Climática	2022	Belo Horizonte	Brazil
Plano de Ação Climática	2023	João Pessoa	Brazil
Plano Local de Ação Climática da Cidade de Recife	2020	Recife	Brazil
Plano de Ação Climática da Cidade de Teresina	2023	Teresina	Brazil
Plano de Desenvolvimento Sustentável e Ação Climática	2021	Rio de Janeiro	Brazil
Plan Clima SP	2021	São Paulo	Brazil
Plano de Resiliência de Aracaju 2017-2024	2017	Aracaju	Brazil
Climate Change Strategy	2008	Alberta	Canada
Calgary Climate Strategy	2022	Calgary	Canada
Climate Resilient Edmonton	2018	Edmonton	Canada
Strategic Plan Mississauga	2009	Mississauga	Canada
Montreal_Management of the Climate Change Adaptation Plan	2017	Montréal	Canada
Climate Change Action Plan	2014	New Brunswick	Canada
The Way Forward on Climate Change	2019	oundland and Labr	Canada
Climate Change Impacts and Adaptation in Nunavut	2011	Nunavut	Canada
Climate Change Strategy	2015	Ontario	Canada
Climate Change Master Plan	2020	Ottawa	Canada
A Strategy for Reducing the Impacts of Global Warming	2008	rince Edward Islan	Canada
Climate Change Action Plan	2013	Quebec	Canada
TransformTO - City of Toronto	2021	Toronto	Canada
Climate Change Adaptation Strategy	2018	Vancouver	Canada
Community Climate Adaptation Plan for Waterloo Region	2020	Waterloo Region	Canada
A Sustainable Winnipeg	2011	Winnipeg	Canada
Climate Change Action Plan	2009	Yukon	Canada
Regional Climate Change Adaptation Plan	2019	Santiago	Chile
Mitigácion a La Variabilidad y El Cambio Climático	2013	Bogotá	Colombia
Climate Adaptation Plan for Medellín 2020-2050	2020	Medellín	Colombia
Green Vision	2008	San Jose	Costa Rica
Adaptation Plan for the Havana Coastal Zone	2019	Havana	Cuba
Planning-for-Climate-Adaptation	2018	Santo Domingo	Dominican Republic
Climate Action Plan	2021	Quito	Ecuador
Climate Action Plan	2020	San Salvador	El Salvador
Programa de Acción ante el Cambio Climático del Estado de Chiapas	2010	Chiapas	Mexico
Climate Action Program	2014	Mexico City	Mexico
Plan de Adaptacion del municipio de Puebla	2012	Puebla	Mexico
Climate Change Action Plan Overview	2009	Veracruz	Mexico
Recommendations of Actions for Resilience and Sustainability	2020	Asunción	Paraguay
Climate Action Plan	2015	Atlanta	United States of America
Climate Change Adaptation in Austin's Community Forest and Natural Areas	2014	Austin	United States of America
Baltimore County Climate Action Plan	2021	Baltimore	United States of America
Climate Ready Boston. Municipal Vulnerability to Climate Change	2019	Boston	United States of America
Bozeman Climate Plan	2021	Bozeman	United States of America
BGreen 2020 A Sustainability Plan for Bridgeport, Connecticut	2020	Bridgeport	United States of America

CLIMATE ADAPTATION PLANS	YEAR OF PUBLICATION	CITY	COUNTRY
Resilient-Buffalo-Niagara	2020	Buffalo	United States of America
Towards Resilience	2018	Charlotte	United States of America
Climate Action Plan	2022	Chicago	United States of America
Climate Action Plan	2013	Cleveland	United States of America
Climate Action Plan	2020	Columbus	United States of America
City Environmental & Climate	2019	Dallas	United States of America
Climate Action Plan	2021	Delaware	United States of America
Denver 2015 Climate Action Plan	2015	Denver	United States of America
Sustainability Action Agenda	2013	Detroit	United States of America
Fort Worth 2010 Sustainability Task Force Recommendations	2010	Fort Worth	United States of America
Climate Action Plan	2020	Houston	United States of America
Climate Change Roadmap	2020	Indiana	United States of America
Adaptation Action Area Workgroup Workgroup Recommendations	2019	Jacksonville	United States of America
Climate-Risk-and-Vulnerability-Assessment	2019	Kansas City	United States of America
Las Vegas Global Economic Alliance	2021	Las Vegas	United States of America
2045 Climate Action Plan	2023	Los Angeles	United States of America
Climate Action Plan	2020	Memphis	United States of America
Climate Action Strategy	2021	Miami	United States of America
ECO Presentation to Governor's Climate Task Force	2020	Milwaukee	United States of America
Minneapolis Climate Action Plan	2013	Minneapolis	United States of America
A General Plan for Nashville and Davidson County	2015	Nashville	United States of America
Climate Change at NYC	2021	New York City	United States of America
Community Action Plan	2018	Orlando	United States of America
Philadelphia Climate Action	2021	Philadelphia	United States of America
Climate Action Plan	2021	Phoenix	United States of America
Climate Action Plan 3.0	2017	Pittsburgh	United States of America
Bureau of Planning and Sustainability	2021	Portland	United States of America
Climate Adaptation and Resiliency	2019	Riverside	United States of America
Sacramento Climate Action & Adaptation Plan	2022	Sacramento	United States of America
Climate Adaptation Plan	2021	Salt Lake City	United States of America
Climate Ready. A Pathway for Climate Action and Adaptation	2019	San Antonio	United States of America
Climate Action Plan	2022	San Diego	United States of America
San Francisco's Action Plan	2021	San Francisco	United States of America
Coastal Adaptation and Resilience in Tampa Bay	2015	Tampa	United States of America
Virginia Coastal Resilience Master Plan	2021	Virginia Beach	United States of America
DNR's Plan for Climate Resilience	2020	Washington DC	United States of America
Wisconsin Climate and Health Adaptation Plan	2016	Wisconsin	United States of America

Table 2: Table with list of analyzed documents – Part 1 (Authors, 2023)

CLIMATE ADAPTATION PLANS	YEAR OF PUBLICATION	CITY	COUNTRY
AFRICA			
Resilience Strategy	2020	Accra	Ghana
Environmental Action Plan	2009	Alexandria	Egypt
Climate Change Policy	2017	Cape Town	South Africa
Territorial Climate Energy Plan of Dakar	2021	Dakar	Senegal
Dar es Salaam City Master Plan 2016-2036	2016	Dar es Salaam	Tanzania
Framework for Municipal Adaptation Plan. Case study of Douala V Municipality	2018	Douala	Cameroon
Durban Climate Change Strategy	2014	Durban	South Africa
Ekurhuleni Metropolitan Municipality. Corporate Disaster Management Plan	2013	Ekurhuleni	South Africa
Climate Change Adaptation. Plan for the City of Johannesburg	2021	Johannesburg	South Africa
Resilience Strategy	2020	Lagos	Nigeria
Voluntary Local Review	2020	Yaoundé	Cameroon
Nairobi Climate Action Plan 2020-2050	2020	Nairobi	Kenya
ASIA			
Climate Change and Environment Action Plan of Ahmedabad District	2022	Ahmadabad	India
Amman Green City Action Plan	2021	Amman	Jordan
Bangkok Assessment Report on Climate Change	2009	Bangkok	Thailand
Climate Change and Environment Action Plan of Bhopal District	2022	Bhopal	India
Resilience Chennai Strategy	2019	Chennai	India
Comprehensive Development Plan 2018-2022	2018	Davao	Philippines
Climate Action Plan 2030+	2020	Hong Kong	China
Climate Change and Environment Action Plan of Indore District	2022	Indore	India
Urban Challenges in a Changing Climate	2011	Jakarta	Indonesia
Karachi City Climate Change	2012	Karachi	Pakistan
City Lab Kochi	2020	Kochi	India
Implementation of the 2030 Agenda	2019	Kuwait City	Kuwait
Climate Action Plan	2022	Mumbai	India
Climate Change and Environment Action Plan of Nagpur District	2022	Nagpur	India
City Climate Action Plan	2021	New Delhi	India
Resilience Accelerator	2019	Pune	India
Ten Year Plan 2021-31	2021	Queenstown	Singapore
Climate Resilience City Action Plan	2018	Rajkot	India
Semarang Climate Change Resilience Strategy	2011	Semarang	Indonesia
A Guide for Sustainable Urban Development	2010	Shanghai	China
Preparing for a Climate Resilient Singapore	2021	Singapore	Singapore
Smart City Srinagar Report	2016	Srinagar	India
Surat Resilience Strategy. Resilient Cities Network	2017	Surat	India
Suwon Action Report	2020	Suwon	South Korea
Towards a Net Zero Future	2021	Taipei	Taiwan
Tokyo Climate Adaption Plan	2019	Tokyo	Japan
EUROPE			
Climate Emergency Action Plan	2022	London	United Kingdom
Paris Climate and Energy Action Plan_2012	2013	Paris	France
Copenhagen Climate Plan	2015	Copenhagen	Denmark
Ankara Climate Change Action Plan	2022	Ankara	Turkey

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CLIMATE ADAPTATION PLANS	YEAR OF PUBLICATION	CITY	COUNTRY
Plan Clima	2018	Barcelona	Spain
Climate Plan for the territory of the City of Brussels	2022	Bruxelles	Belgium
Bursa Sustainable Energy and Climate Change Adaptation Plan	2017	Bursa	Turkey
The perspectives of Cologne 2030+	2021	Cologne	Germany
Climate Change Action Plan of Gaziante	2023	Gaziantep	Turkey
Berlin's Climate Action and Adaptation Planning	2016	Berlin	Germany
Local Climate Change Governance	2011	Hamburg	Germany
Dublin City Council's Climate Change Action Plan 2019-2024	2019	Dublin	Ireland
Istanbul Climate Change Action Plan	2018	Istanbul	Turkey
Izmir Green City Action Plan	2020	Izmir	Turkey
Lille: action plan for a low carbon city	2014	Lille	France
European Green Capital	2020	Lisbon	Portugal
Roadmap to climate neutrality by 2050	2020	Madrid	Spain
Marseille's Path to a Greener Future	2021	Marseille	France
Climate Action Plan	2022	Moscow	Russia
Munich: Future Perspective	2013	Munich	Germany
Adapting to Climate Change in Vienna	2018	Vienna	Austria
Glasgow Climate Adaptation Plan 2022 - 2030	2022	Glasgow	United Kingdom
Climate Change Adaptation Action Plan 2012+	2011	Birmingham	United Kingdom
Valencia 2030 Climate Mission	2021	Valencia	Spain
Municipality Sustainable Energy and Climate Action Plan	2021	Karşıyaka	Turkey
OCEANIA			
City of Melbourne Climate ChangeAdaptation Strategy and Action Plan	2019	Melbourne	Australia
Adapting for Climate Change	2016	Sydney	Australia
Climate Change Adaptation Action Plan 2011-2013	2016	Adelaide	Australia

Energy usage in buildings for future climate: a case study of Concordia University Buildings in Montreal

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1. Abstract

. In light of escalating extreme events and climate change, this research focuses on understanding energy consumption in buildings, specifically under varied weather scenarios including past (2019-2022) and future projections (2061, 2099). Traditional building simulations stemming from representative, using typical year's weather data, doesn't capture the intricacies of long-term climate shifts especially for the future. To address this, this study incorporates detailed future climate data from combination of RCMs & GCMs. This data is used in combination with open-geospatial data to create a building geometry. Initial results highlight a shift to warmer temperatures in 2061 and 2099. When contrasted with a typical mean weather scenario (1960-1986), there's a noticeable increase in cooling energy and a decrease in heating energy consumption from 2019-2022. By 2099, overall energy use is predicted to decrease by 10%-30%, which when broken down constitutes to reduction in heating energy and increase in cooling energy. The research underscores the impending shift towards increased cooling demands and reduced heating needs. The findings emphasize the urgency for future building designs to be energy-efficient and resilient in the face of evolving climate conditions.

Keywords - Future energy use, extreme climate, extreme weather, future weather

2. Introduction

Climate change has amplified extreme weather events with catastrophic global impacts. Although there is growing global evidence of climate change consequences, a body of literature highlights mitigation measures across various sectors. [1], [2]. In the realm of infrastructure, buildings play a pivotal role, accounting for significant global energy consumption and emissions amounting to almost 1/3rd [3]. Buildings are also identified as susceptible to climate change impacts [4], [5], and for the province of Quebec in Canada [6], [7] but also as pivotal in mitigation efforts against such changes [8].

Incorporating insights from short-term weather and long-term climate data is crucial in building design and operations. The same has been widely used in building design regarding climate zones in buildings to incorporate predefined climatic strategies anchored on metrics like Heating/Cooling Degree Days (HDD/CDD). Additionally, modern building design frequently employs updated weather files [9], [10] for example, the CWEEDs dataset in Canada [11]. With increasing & updated data being available, numerous studies compare building energy performance using typical vs. historical/projected weather[12], [13]. The projected or future weather often relies on commonly employed General Circulation Models (GCMs). While these models incorporate multiple parameters and offer refined grids, they often need to be used in tandem with higher-resolution Regional Climate Models (RCMs). It's essential to account for biases in GCM/RCMs by aligning them with actual historical climate data, using statistical or dynamic downscaling methods. Gaur et al. [11] derived such weather data for 564 Canadian locations. But when the future scenarios are considered, very few studies integrate both future weather and its impact on building energy consumption [5], [14]. In one such study for Canada, Williams et al., [13] outline how an archetype-based building model for a multi-unit residential unit was used to modelled in future climate scenarios for typical mean weather conditions for 2040s, and interestingly, it was observed that the energy usage of buildings decreases in future climate. There is also an ongoing discussion about whether the typical meteorological year (TMY) is enough for building design or should the industry shift to XMY (extreme meteorological year) [15], [16], but only a few studies have been seen implementing the same. Thus, there is a lack of literature that uses such weather files for understanding the building energy consumption in future.

Understanding building energy consumption thus is pivotal, especially with the anticipated doubling of the global building floor area by 2060 [17]. Canada similarly foresees growth in its sectors and thus faces intensifying energy demands. To address this, a vast array of tools certified by the Canadian LEED body [18], codes [19], and certifications [20] are applied. A growing trend in urban energy modelling targets broader [21], [22] scales, like districts. The rise in open geospatial aids this cause [23], especially for the City of Montreal [24], and when such geospatial data is lacking, methods like UAV and photogrammetry offer precise city modelling solutions [25].

Given the intricate dynamics between urban buildings and the evident impacts of climate change, there's an urgency to study future building energy performance. Amidst mounting evidence of climate effects, this research introduces a Geospatial data driven approach, encompassing historical and projected climates. The adaptable downscaling method aligns with current workflows. Utilizing open-source data and energy simulation tools, the study's findings will guide future building policies, ensuring structures can endure long-term challenges.

This study operates under the assumption of limited data for future climate projections. Given the tie between building energy and weather variables, the unavailability of specific data from 2019-2022, such as direct and indirect solar radiation, necessitates the use of standard weather data. The research predominantly focuses on LOD1 blocks, widely used urban building energy modelling scenarios. Due to data constraints, the study only downscales the 'tas' or near-surface air temperature for future climate scenarios. The methodology encompasses workflows for generating weather files, energy modelling, and climate forecasts, as explained in section 2 of the paper. It utilizes data from past observations to future projections for 2099, including reference weather reference files from the Natural Resource Council of Canada. Based on diverse scenarios, results from climate data analysis and energy modelling are elaborated in section 4. Section 5 provides an outlook on the discussion, and section 6 highlights the conclusion, limitations, and prospective directions.

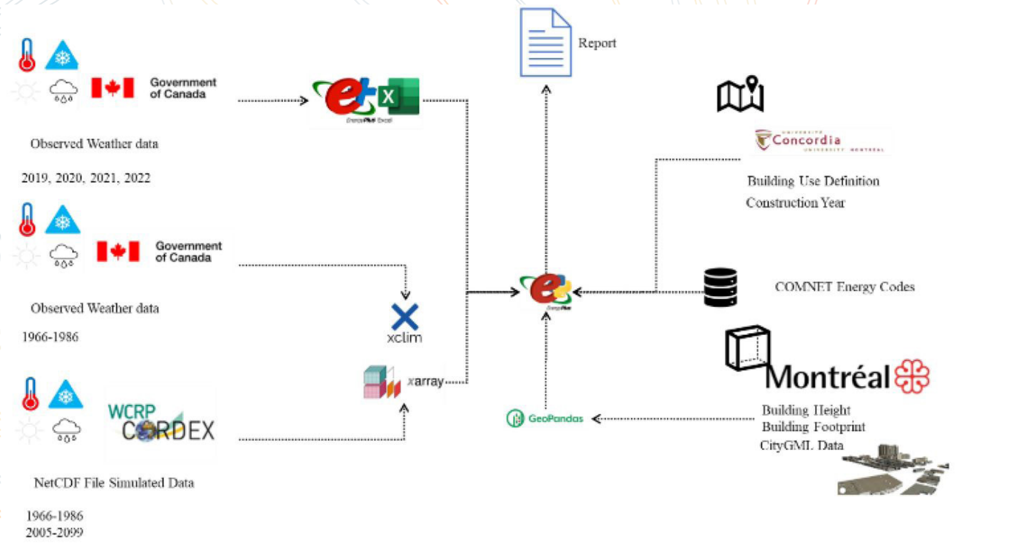

Figure 1: Methodology adopted for the study.

A LOD1 simplified building energy model for the EV and GM building at the Concordia Campus was developed, simplifying the roof to be flat. The geometry, refined using the GeoPandas[26] python module, was converted to the EnergyPlus format and detailed using the Geomeppy[27] module. After setting up the building, additional attributes like construction properties, window-wall ratio, and ideal air-load HVAC systems were incorporated. This ideal system ensures optimal heating/cooling for building comfort suitable for simplified scenarios, which was assigned to the model.
To analyze the impact of weather data on energy consumption patterns from 2019 to 2022, 2061 and 2099, we obtained weather data in the EnergyPlus format. Data was sourced from the hourly climate data extraction tool, capturing parameters like temperature, humidity, and wind speed. The other parameters, including solar radiation and winds-peed, were not included in the study. Missing

values were replaced with data from the nearest station. The collected data was processed using the EnergyPlus weather converter, converting Typical Meteorological Year (TMY) data into a CSV format. After integrating observed data from 2019-2022, the CSV data was converted back to EPW format. For accuracy, the EPW files underwent validation against the original datasets, ensuring error correction before further analysis.

For modeling future climate scenarios, the study followed a multi-step process. Initially, available GCM models focusing on 'tas' (surface air temperature) were identified. The 3Dimensional NetCDF files containing the climate data were parsed and extracted using Python modules, specifically X-arrays [28] and NetCDF4. By determining the nearest x and y grid for Montreal's location, specific data was sliced from these 3D files. Once extracted, the data was organized into a Pandas Dataframe formatted with date-time. The X-clim[29] Python library, particularly its quantile mapping module, was employed to downscale and bias-correct the obtained climate data. To ensure compatibility, the data was converted into X-arrays format. With the future data arranged, the study aimed to downscale it using a typical climate reference file. However, due to X-Clim's limitations, downscaling was performed for 2061-2080 and 2081-2099 using 1966-1986 as a reference.

Post-downscaling, the data was processed into the EnergyPlus weather file format, replicating the methodology from earlier steps. With the EnergyPlus weather files ready, simulations were executed using the EnergyPlus batch simulation option. No advanced building parameter modifications were needed. After simulation completion, various metrics like EPI, peak loads, and monthly consumptions were analyzed and visualized.

4. Case-study and Data

A Wide range of multi-disciplinary datasets are used for the different parts of the study. Table 1 summarises all the weatherrelated datasets used for the research.

Table 1: Overview of Climatic data used in the study.

Period	Source				
1966-86	https://energyplus.net/weather-location/north_and_central_america_wmo_region_4/CAN/PQ/CAN_PQ_Montreal.Intl.AP.716270_CWEC				
1966-86 2019-22	https://climate-change.canada.ca/climate-data/#/hourly-climate-data				
1966-86 2005-99	https://www.earthsystemgrid.org/search/cordexsearch.html	Model 1: GFDL-ESM2M.WRF RCP85	Model 2: HadGEM2-ES.WRF RCP85	Model 3: MPI-ESM-LR.RegCM4 RCP85	Model 4: MPI-ESM-LR.WRF RCP85

Using advanced climate data tools from Environment Canada, historical climate data for Montreal was extracted from the St Hubert A weather station (Station ID: 716270), with its comprehensive data for 1966-1986 and 2019-2022. A typical meteorological year weather file was also obtained, representing 30-year typical scenarios. The study also incorporated reference extreme weather files for Canada [11] for the extreme temperature RCP8.5 scenarios. Four GCM scenarios with hourly temperature variables were selected from the NA-CORDEX dataset for the NAM domain, with the RCP 8.5 scenario indicating the peak future greenhouse gas concentration. The building energy model utilized 2D building footprint data from the City of Montreal [24], extracted from a high-fidelity LoD3 model derived from oblique imagery and LiDAR. Natural Resources Canada offers similar 2D datasets [30] for other Canadian provinces.

The building's function, primarily an office/education mix, was predetermined. Construction material data, vital for thermophysical interactions, was obtained from Concordia University's management team. Key values include wall R-value at 11.9 (ft2·°F·h/BTU), roof at 17.2 (ft2·°F·h/BTU), glazing at 2.7 (ft2·°F·h/BTU), a 0.44 shading coefficient, and a 33% window/wall ratio.

5. Results

This section discusses the results obtained for downscaling to obtain the future weather files and subsequently used for building energy modelling scenarios.

5.1 Downscaling Results

The results of downscaling the future weather data are plotted in the QQ and CDF plots for all four scenarios in Figure 2 for 20 years for hourly values, along with ridge plots showing the monthly distribution of hourly scenarios for the selected scenarios. From the results it is observed that after the downscaling the values are shifted towards the right side, which means the climate is shifting more towards a warmer side. For the M1 and M2 model, the shift intensity is greater than the M3 and M4 models. Similarly, the QQ plots show that that data is left-skewed, i.e., negatively skewed.

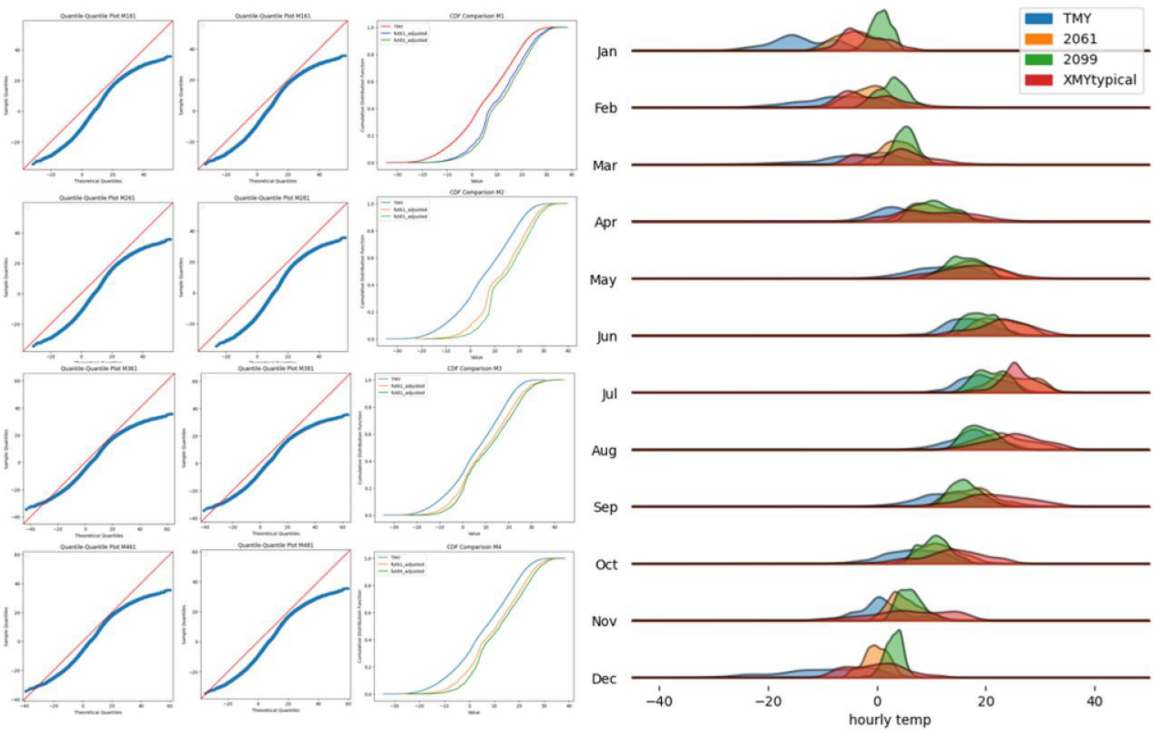

Figure 2: QQ plots and CDF plots for downscaled weather (Left) and Joy plots for extracted weather scenarios (Right)

To better understand the overarching comparison of the extracted weather data for the future, a ridge plot was plotted for different weather scenarios considered in the studies. From the ridge plots, it was observed that there is a noticeable shift in climate in all months towards warmer scenarios. Colder months also see a considerable shift towards warmer temperatures for all scenarios, especially for the 2099 scenario year. The Heating/cooling degree days extracted for each scenario are tabulated in Table 2.

Scenario	TMY	2019	2020	2021	2022	2061	2099	XMY Max	XMY Min	XMY typical	XMY Fstat
HDD	4949	4384	3900	3774	4050	3199	2807	1996	4485	3217	3286
CDD	26	102	145	131	105	201	18	886	82	260	279

Table 2: HDD/CDD for all scenarios

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The figure 3 presents the annual heating/cooling consumption in kWh for a base case, three different years (2019-2022), and two extreme weather years (2061 and 2099), as well as for four different climate scenarios (Extreme Warm, Extreme Cold, Typical downscaled year, and TMY FSTAT).

The energy consumption is broken down by end-use: Room electricity, lighting, heating (gas), cooling (electricity), and domestic hot water (electricity). Since the room electricity and lighting scenarios will remain the same and are not affected by weather-related scenarios, they are not considered in the plot. The base case (i.e., Typical mean year) shows that heating is the largest end-use, accounting for 42% of the total energy consumption (57 kWh/m²). Whereas heating accounts for almost 20% (26 kWh/m²). Between 2019 and 2022, there's a notable trend in energy consumption. Heating energy consumption decreased from 57 kWh/m² in 2019 to 51 kWh/m2 in 2022. However, cooling energy consumption increased from 26 kWh/m² in 2019 to 31 kWh/m2 by 2021, before slightly decreasing in 2022. For the year of 2061, a 33% decrease is observed. At the same time, cooling energy consumption remains similar. For 2099, a 60% drop in heating observation and a 26% decrease in cooling energy consumption are observed.

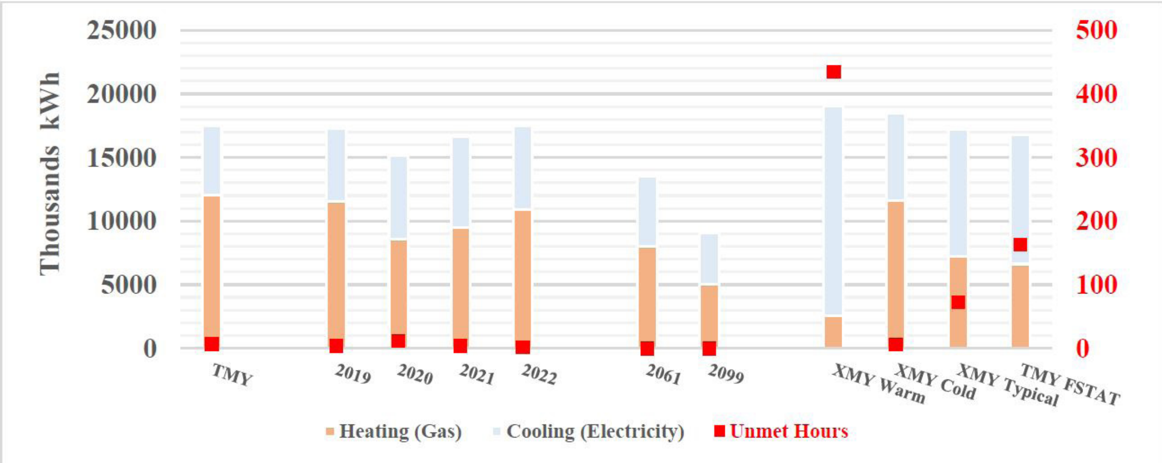

Figure 3: Heating and cooling energy consumption for all scenarios (Unmet hours are highlighted on the secondary axis)

When contrasted with the reference weather file obtained from Climate Canada for the four different climate scenarios, it shows that the energy consumption for heating and cooling varies greatly depending on the scenario. XMY Warm has the highest energy consumption for cooling, i.e., 78 kWh/m2, compared to 26 kWh/m2 in the TMY scenario. XMY Cold has the higher energy consumption amongst the four reference scenarios (i.e., 55 kWh/m2), but it is still lower than the base TMY scenario. Finally, both XMY typical and XMY F-stat (i.e., meteorological) observe a decrease in heating energy and an increase in cooling energy.

6. Discussion

The downscaling results and energy consumption analysis highlight the effects of climate change on future building performance. Both the NRC study [18] and a study on Canadian prairies [31] show a trend towards warmer temperatures. While different attributes and scenarios were used in these studies, the consistent shift to warmer temperatures across models used in the relevant studies highlights the need for mitigation strategies. Even though RCP85, the highest forcing scenario, was selected, the combined insights from all four models present a comprehensive view of potential future scenarios.

While the overall energy consumption saw an increase of 8.5% in 2020 compared to TMY, the observed weather data indicates that when the building's hourly values exceeded those of the Typical Meteorological Year (TMY), the energy consumption was higher. Similar observations are observed for 2021 and 2022. However, in 2022, it is observed that while the heating energy consumption increases, the decrease in cooling energy negates the overall increase. Thus, results remain like the Typical year. A study in Catania [32] and Canada [12] highlighted the uncertainties when using TMYs in energy modelling, noting significant discrepancies in some years. Additionally, while the current study considered parameters like Temp, RH, and Dewpoint temperatures for the 2019-2022 files, the relationship with solar irradiation remains, and other parameters remain unexplored. Solar irradiation is pivotal in energy consumption, especially in regions experiencing significant climate variations. While many studies use statistics-based methods to create custom weather files based on combinations of extreme climatic events, this study took a unique approach by considering the actual weather year, reflecting real-world conditions buildings encounter. Energy efficiency initiatives can influence a decline in heating energy consumption over time. Still, it depends highly on evolving weather trends, notably the observed reduction in cooling degree days, as seen in Table 2. Research indicates that fewer Heating Degree Days (HDD) correlate with reduced energy consumption [33], [34]. For instance, a study on Toronto's climate forecasted decreased energy consumption in 2040 due to fewer HDDs [13]. Although this study hasn't explicitly calculated HDDs, the linear relationship between HDD and heating energy consumption suggests that the decrease in HDDs likely results in reduced heating energy consumption. This challenges the notion that climate change will invariably lead to increased building energy consumption. While this analysis focuses on Montreal's cold and humid climate (ASHRAE classification 5A), the impact of HDD variations might differ in other Canadian cities with distinct climatic classifications. Moreover, the implications of these shifts could be significant for cities in predominantly climates, where changes in heating and cooling degree days have profound future implications [35], [36].

The energy consumption breakdown emphasizes the dominance of heating and cooling systems in total energy use, while lighting and room electricity play a lesser role. Given that buildings are designed with a lifespan of 80-100 years, or even longer, evaluating their performance in future climate scenarios is crucial. In extreme weather conditions, such as intense warmth or cold, heating and cooling energy demands can vary by 58% to 70%. For instance, during exceptionally warm periods, cooling energy requirements may double beyond the building's designed capacity, stressing the comfort systems. Conversely, in reduced cooling energy needs scenarios, high-capacity systems designed today might become redundant, leading to underutilized resources and capital losses as equipment deteriorates without reaching its full potential.

The rising cooling energy consumption underscores the necessity for research into efficient cooling systems and passive strategies. Although passive cooling methods offer limited potential in extreme conditions, they often need pairing with active systems to achieve thermal comfort and reduce energy usage. This variation in energy demands across climate scenarios highlights the importance of customized building designs and energy management. Even with an ideal air load system, the notable unmet heating and cooling hours suggest that these systems may fall short in providing the desired comfort. While there's no global standard for acceptable unmet hours, their frequency impacts equipment sizing, making it a critical factor for future climate resilience and cost-efficiency.

7. Conclusion and further remarks

The study offered a data-driven approach for cities to gauge climate change's effect on building energy use. Key findings indicated an increased cooling energy need and decreased heating consumption from 2019-2022 compared to typical weather. Up to 2099, a decrease of up to 30% was anticipated in the long term. Extreme weather, especially in NRC study scenarios, highlighted potential unmet heating and cooling demands. The study underscored the need to factor in climate change when designing HVAC systems, with peak load variations between winter and summer weeks as a significant indicator. Given the rise in extreme weather, integrating climate insights into HVAC design is crucial.

The study employed statistical climatic downscaling for future climate projections, a method scalable for other cities. With advancements in machine learning, transitioning to dynamic downscaling could yield more precise future climate representations.A primary limitation was the study's focus on only temperature, relative humidity, and dewpoint, excluding variables like wind speed and solar radiation. Future research should broaden the scope to include these for a fuller understanding. Additionally, weather files for 2061 and 2099 lacked relative humidity and dewpoint considerations, restricting insights to near-surface air temperature impacts only.

Finally, the study highlighted the importance of considering the impact of climate change on building energy consumption in the context of sustainable building design and energy management practices. With the increase in extreme weather events, it is imperative to incorporate climate change considerations in building design and operation. Sustainable building design and energy management practices can help reduce the impact of climate change on building energy consumption and contribute to a more sustainable built environment.

In conclusion, the study provided a data-driven method for cities to inform climate adaptation decisions by understanding the impact of climate change on building energy consumption. The study found that climate change has the potential to significantly impact building energy use and performance, emphasizing the need for adaptive and sustainable building design and energy management practices. While the study had limitations, including the need to consider variables other than temperature, relative humidity, and dewpoint in future studies, it demonstrated the importance of incorporating climate change considerations in building design and operation. With the increase in extreme weather events, sustainable building design and energy management practices can help reduce the impact of climate change on building energy consumption and contribute to a more sustainable built environment.

An immediate future scope of study that can be endeavoured are the implementation of climate files developed in the NRC, for all 564 locations. With the NRC data available for all these locations and the availability of urban building modelling tools, this is a very required study that can be undertaken. This study can help inform the building industry and the federal government in identifying which cities are the greatest target for climate change in terms of energy consumption in buildings.

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Paper Presentation - Session 13

Session 13A - Climate Resilience Buildings and Communities

- Balancing Carbon Emissions and Comfort: A Comparative Study of Envelope Materials in Affordable Housing Projects
- Improved burnt clay brick masonry: Lowering upfront embodied carbon, improving thermal comfort and climate resilience of new housing in the Indo-Gangetic Plains
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Note: The Presenting Author has been marked with an asterisk (*)

Balancing carbon emissions and comfort: a comparative study of envelope materials in affordable housing projects

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Abstract

This study presents a comparative analysis of carbon emissions and thermal comfort in an Indian affordable housing project, employing two envelope materials: EPS core technology and brick-and-mortar construction. The study quantifies embodied and operational emissions through life cycle analysis to establish an emissions thermal comfort trade-off. Focused on the Bureau of Energy Efficiency design under the Pradhan Mantri Awas Yojana 2022 scheme in Bhubaneswar, Odisha, the study addresses the pressing need to track carbon emissions in this sector. Buildings contribute 39% of energy-related carbon emissions, gaining significance due to urbanisation and affordable housing projects. The study highlights a significant 10.16% reduction in operational carbon for EPS (Expanded Polystyrene) core technology compared to a brick wall assembly construction, driven by its superior thermal performance. But this comes at a cost of a much higher embodied carbon value. Despite higher embodied carbon, EPS achieves heightened comfort with fewer operational emissions over 50 years. Findings underscore the relationship between environmental impact, comfort congruence, and emissions. Results hold location-specific importance for informed decisions in diverse urban contexts across India.

Keywords - Carbon emissions, thermal comfort, life cycle analysis, embodied carbon, discomfort hours

1. Introduction

1.1. Background

Urban areas worldwide face multifaceted challenges, especially in developing countries like India. The challenges include population growth, increased informal settlements, limited urban services, concerns regarding climate change, and many others. India's economic growth and urbanisation are intertwined deeply. Indian cities create a pull factor for the human resources from rural areas towards urban areas in search of economic opportunities. This involuntarily creates a need to accommodate this workforce, which, if not catered to, results in the generation of informal settlements in the form of slums. Currently, the housing shortage in India is around 76.3 million units, of which 26.3 million are urban. [10]. The Government of India recently launched a campaign to provide housing for all citizens by 2022. The scheme known as Pradhan Mantri Awas Yojana (PMAY) 2022 aims to provide access to sustainable and affordable housing for every citizen. The Bureau of Energy Efficiency, under the Ministry of Power, has developed a set of designs for affordable housing units specific to the different climate zones of India. These designs are replicable and modular and have been designed in response to the climate [8]. The future of the affordable housing sector is thus expected to grow according to this roadmap. The government has also developed a set of construction typologies for different climate zones across India, which have been used worldwide to construct affordable housing units with relatively quicker construction time and minimal environmental impact. This has been done under the Global Housing Technology Challenge (GHTC), a sub-mission under the PMAY 2022. This study compares a business-as-usual construction scenario with an approved GHTC construction technology regarding environmental impact and thermal comfort.

1.2. Approach

The environmental impact of any product can be studied by conducting a life cycle analysis for both construction scenarios. A life cycle analysis is a tool to evaluate the environmental impact of any product during its whole life. Life cycle Analysis gives a cumulative numerical value of the emissions associated with that product. As per ISO14044 and 14040, a predefined functional unit should quantify the impact [14,15]. For the scope of this study, a functional unit of kgCO2eq has been used throughout [14,15]. This metric can account for all greenhouse gas (GHG) emissions regarding carbon dioxide equivalence. The study's second aspect is related to evaluating the state of thermal comfort inside the houses. For this, the range of operative temperatures is checked against the IMAC(Indian model for adaptive comfort) band of the city in India [23]. This results in estimating the discomfort hours of that space for the given set of conditions. This has been carried out with the help of energy simulations.

1.3. Scope

The scope of the study is limited to investigating and assessing one affordable housing project in Bhubaneswar, Orissa, India. The city falls under the warm and humid climate region of India. As per the GHTC, EPS core technology is proposed for the city of Bhubaneswar to construct affordable housing units. Therefore, the study's scope is based on comparing a business-as-usual case with the proposed solution. The emissions associated with the building are calculated for two different construction sets: A brick wall assembly construction and Expanded Polystyrene core technology. Following a similar order of business, thermal comfort has been evaluated for both scenarios. The U-value for Brick wall assembly is calculated to be 2.41 W/m²K; for EPS core technology, it is 0.5 W/m²K. This is based on the material study database prepared by CARBSE [22]. Figure 1 shows the typical floor plan selected for the study. The building is a four-storey structure with both sides open, as shown [8]. Figure 2 shows the proposed site plan for constructing these affordable housing units per the GHTC under the PMAY. Figure 3 and Figure 4 show the typical wall illustrative sections for both scenarios.

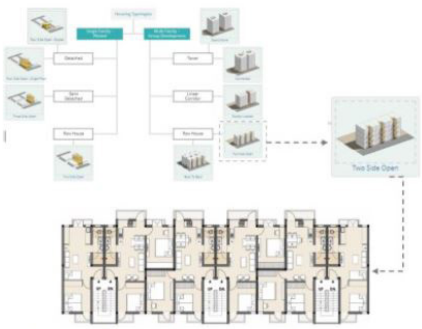

Figure 1: Building typical floor layout

Figure 2: Affordable housing site in Bhubaneshwar

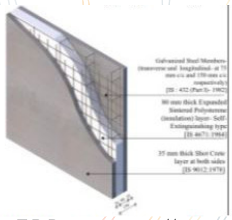

Figure 3: EPD core wall section

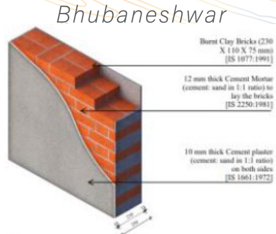

Figure 4: Brick wall section

2. Methods

2.1. Data collection

The outcomes of the study are mainly dependent on the quality of the Data. For the scope of this study, data collection has mainly two components, i.e., gathering data for conducting life cycle analysis and assessing thermal comfort. Most studies in the Indian context have gathered data from academic research papers and published reports [2,3], [17-21]. Some studies have also utilised EPDs(Environmental product declarations) of products in case it is relevant and available [19]. The studies conducted for the building sector in India use international data sources for performing the Life Cycle Analysis.

Further, embodied energy values are dynamic and region-specific, which may change according to the technology and transportation distances involved. Thus, to ensure the reliability of the results, the embodied carbon coefficient has been taken from various sources [1-3], [7,9,11,12], [16-21]. The architectural layout has been downloaded from the ENS replicable design tool on the ENS website [8]. For thermal comfort assessment, which requires energy simulations, the nearest weather station data is obtained with the help of a typical meteorological year weather file available online.

2.2. Data Analysis

As mentioned earlier, wherever possible, data is collected based on secondary sources such as academic research papers, technical reports and EPDs of products. This calls for a data quality check since each source brings a certain amount of uncertainty, and no single best value can be utilised to produce results [5,6,24]. Hence, a range of final carbon emissions has been produced to understand the possible emissions. All data sources have been scored based on a scoring system, as shown in Table 1 [14,15]. This clarifies the nature of each data source based on specific rules, as per ISO 14040.

Table 1: Pedigree matrix

Rule/score	1	2	3	4	5
Data Source	EPD of product	LCA database	Research paper/report	Other sources	-
Data Age	0-3yrs	3-5yrs	5-10yrs	10-15yrs	>20yrs
Technological completeness	A specific way of production	General industry methods	Innovation (pilot)	-	-
Geographical aspect	Sate specific value	Country-specific value	Continents specific	Globally used values	-
Functional unit	$kgCO_2/kg$	MJ/kg	kWh/kg	MJ/m^3	MJ/unit of material

Another layer of data quality check is usually done in a life cycle analysis to present a quantitative outlook. Uncertainty analysis is one such critical method of scientific research. It involves evaluating and quantifying the potential sources of uncertainty in data, models, and calculations used in a particular analysis. In life cycle analysis, uncertainty analysis plays a crucial role in assessing the environmental impacts of a product or process throughout its life cycle. It helps evaluate the robustness and accuracy of the results and enhances the credibility of the findings. Existing literature [16,19] used the classical statistical model to quantify uncertainty. In this, the uncertainty is expressed in terms of the standard deviation. The following equation has been used to quantify the uncertainty:

$$Uncertainty\ (u) = \sqrt{\frac{\Sigma[x_i - \mu]^2}{n(n-1)}}$$

Where,
x_i= i^{th} reading in the dataset
μ= Mean of the dataset
n= number of readings in the dataset
From the equation above, the percentage uncertainty is evaluated as follows:

$$Percentage\ Uncertainty\ (Pu)\ (\%) = \frac{u}{selected\ data\ point}\ x\ 100$$

2.3. Procedures

The procedure has been structured as per the required output from the study. The life cycle analysis of the selected stages has been conducted based on the data collected from various sources. This process helps give a range of possible embodied carbon values possible. The energy simulations help give the operational carbon emissions and state of the thermal comfort for the considered building. These results are then correlated and plotted against each other to understand the comparison between both construction scenarios for Bhubaneswar.

2.4. Life Cycle Analysis

As per ISO 14044 and ISO 14040, a life cycle analysis is conducted in a four-phase manner. First, the goal and scope of the study have been defined. The goal of conducting the LCA is to quantify the amount of CO2 emissions in the embodied and operational phases of a residential building. The System Boundary of the LCA is limited to the embodied and operational stages. The scope of the LCA is limited to one design typology (as per the ENS design tool for affordable housing [8]) for Bhubaneswar but for brick wall construction and EPS core technology. The inventory analysis is conducted where each product, in this case, each building material, is identified along with the quantities used. Each item is assigned its respective embodied carbon coefficient based on the data collection and analysis [16-21]. The quantity of the materials is calculated by creating a building information model based on the architectural layouts available. The impact assessment and interpretation of results are the last two phases of a life cycle analysis, discussed in Results and Discussion.

2.5. Thermal comfort assessment

The two different construction technologies in consideration have different thermal properties. Both envelopes have different materials with different physical and thermal properties. Therefore, both construction scenarios are expected to have different internal operative temperatures, resulting in different discomfort hours. An energy model is created based on the available drawings with all the necessary details to assess the situation. Data input in the energy model, such as schedules and internal loads, is based on assumptions and kept the same for both cases. Each flat in the building has at least one bedroom inside, modelled as a separate thermal zone, with the remaining other spaces as a different thermal zone. The model has been simulated for Bhubaneswar's four different available weather files. The results from the latest weather file are carried forward. The thermal zones assigned have been simulated as a naturally ventilated space to calculate discomfort hours.

The natural ventilation logic provided is based on the set points provided as per the IMAC-R (Indian model for adaptive comfort-residential) model. The model is also simulated by inputting a packaged terminal air conditioning system with mixed-mode operation, meaning operating only when windows are closed. This is done by assigning the model a range of set points throughout the year. These set points have been calculated weekly for 52 weeks based on the IMAC-R. The AC operation is limited to inside the bedroom zones in all the flats. This is done to estimate the difference in energy consumption of the building and, hence, annual operational emissions for both construction scenarios considered.

3. Results

3.1. Uncertainty analysis and Embodied stage carbon calculations

Table 2 summarises the quantity and embodied carbon calculations for all the building materials based on the architectural drawings and various data points for embodied carbon factors. The quantity of each material has been estimated in kg. The embodied carbon factors have a unit of kgCO2/kg of material. Therefore, the quantities obtained are multiplied to obtain the embodied carbon emissions.

Table 2: Construction materials quantities as per drawings

S.No.	Product	Qty.(m^3)	Components	Qty.(m^3)	Total(kg)
1	Concrete	296.41	Cement	29.26	**42,127.61**
			Sand	89.05	**1,29,122.84**
			Aggregate	178.10	**5,27,177.41**
2	Reinforcement	2.96	Steel	2.96	**23,267.87**
3	Windows	45.72	Glass	45.72	**685.8**
4	Brick wall	363.91	Brick	301.26	**4,52,793.78**
			Cement	34.81	**50,123.8**
			Sand	27.84	**40,377.51**
5	EPS core wall	337.85	EPS	121.82	**1,827.43**
			Cement	25.32	**36,453.68**
			Sand	37.97	**55,060.24**
			Aggregate	75.94	**2,24,797.7**
			Steel	76.78	**6,02,789.7**

As mentioned earlier, the embodied carbon values for each material are obtained from multiple sources. At least six sources of data points were used for each material to calculate the uncertainty. Based on the uncertainty analysis, three scenarios have been created for reporting the total embodied emissions. Scenario 1 relates to total emissions when the data points with the slightest uncertainty have been multiplied by respective quantities of materials for total emissions. Scenario 2 is when the data points with median uncertainty have been multiplied with respective quantities of materials for total emissions. Scenario 3 relates to total emissions when the data points with maximum uncertainty have been multiplied with respective quantities of materials for total emissions. These scenarios make the emissions range possible within the maximum and minimum limits of correctness. Figure 5 shows the evaluation of embodied carbon values for both construction assemblies. The EPS core assembly has a significantly high embodied carbon value, with steel contributing to 96.7%, cement with 2.6% and EPS with 0.3%, respectively, of the total value.

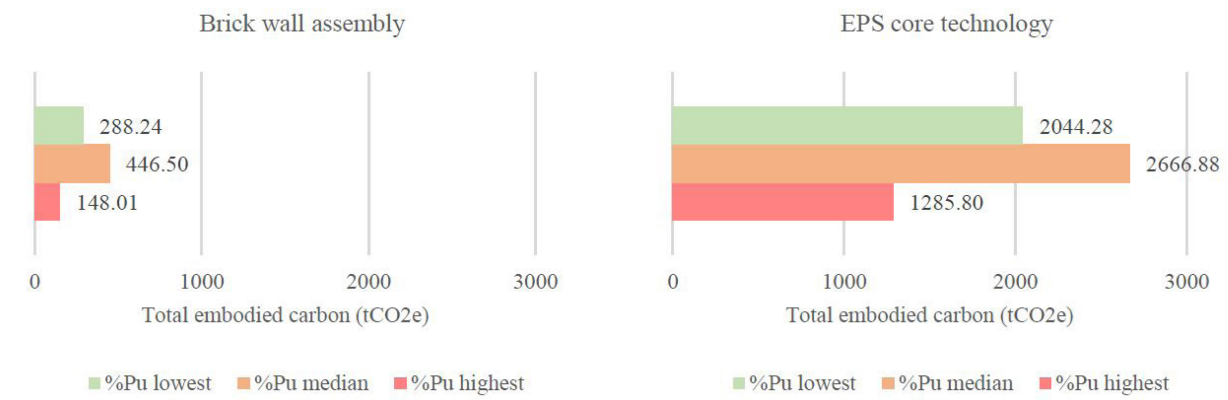

Figure 5: Brick wall assembly and EPS core technology embodied carbon

3.2. Thermal comfort and operational phase calculations

Figure 6 shows the degree of discomfort hours inside a single naturally ventilated zone in brick wall construction considered for the case. The upper and lower limits of the comfort band represent 90% acceptability rates for thermal comfort. The model has been provided with a set-point-based window operation logic based on the nature of outdoor ambient air temperature. From the graph, 2238 hours are uncomfortable throughout 8760 hours for the brick wall construction. Figure 7 shows the results of discomfort in the case of EPS core technology. For this case, a total of 1780 hours are uncomfortable throughout the year. The number of discomfort hours in EPS core technology is lesser due to better thermal performance. The additional insulation helps cut off heat gains and losses; therefore, internal temperatures are less frequently higher than Brick wall assembly. This also reduces the air conditioning load inside the space.

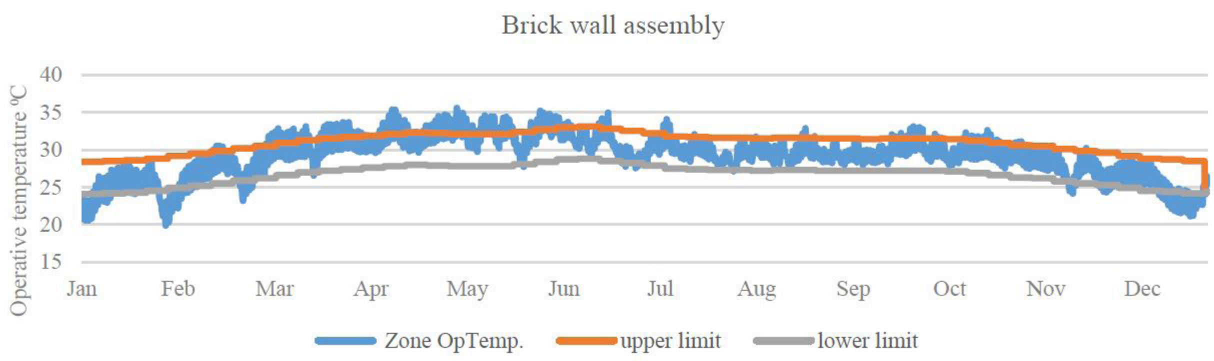

Figure 6: Operative temperatures for naturally ventilated space-Brick wall assembly

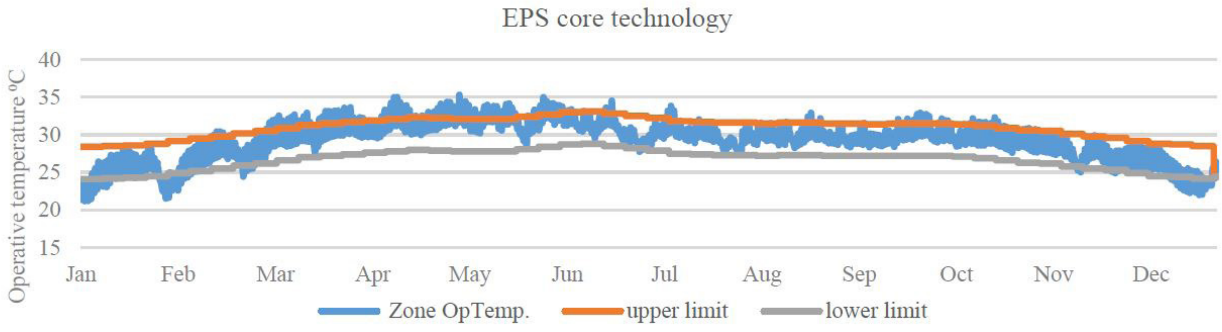

Figure 7: Operative temperatures for naturally ventilated space-EPS core technology

As discussed in section 2.5, the operational emissions are based on the operational electricity simulated based on the latest weather file selected for simulations. In India, electricity is majorly produced by burning fossil fuels such as coal. Coal-based electricity generation significantly contributes to building operational carbon emissions [4]. Therefore, to quantify the carbon emissions as part of the life cycle analysis, a characterisation factor denoted by kgCO2/kWh is required [4]. This factor varies geographically and technologically across the world. Central Electricity Authority of India (CEA) has compiled a database containing the necessary data on CO2 emissions for all grid-connected power stations in India [4]. As per the CEA, the national grid emissions are 0.91 kgCO2/kWh. However, this value might change in the future and might be an underestimation of the future emission scenarios, given that only coal-based power sources are used. Figure 8 shows the comparison of operational emissions between the two construction technologies. Brick wall construction has 11.32% higher emissions than EPS core technology. This is due to a lower thermal performance of the former envelope, resulting in higher cooling electricity consumption than the latter. As per the IPCC AR 6 report and India's commitment to achieve net-zero status, the years 2030, 2050 and 2070 are crucial [13]. Hence, the operational emissions have also been extrapolated for these three points.

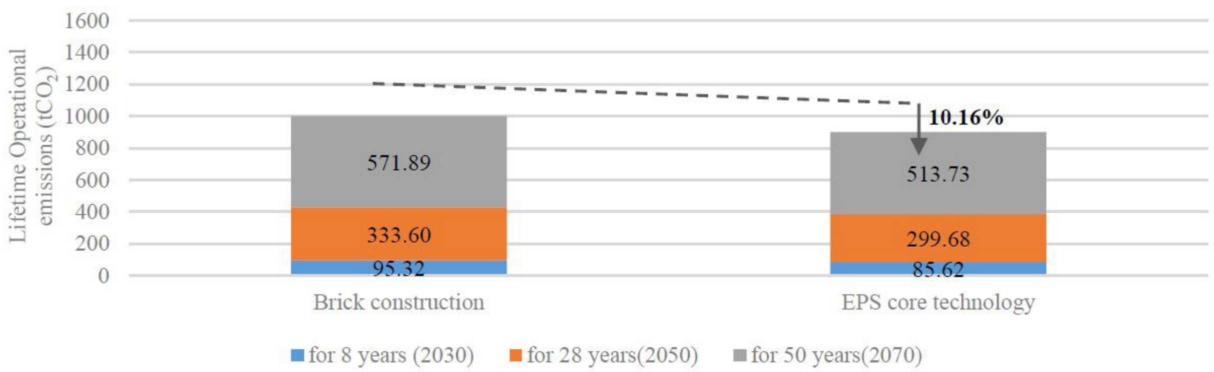

Figure 8: Lifetime operational emissions

4. Discussion

This section talks about the learning and findings of the study conducted by adopting a structured methodology and secondary data sources. The relation between thermal comfort and carbon emissions has been tried to understand from the results obtained. Figure 9 shows the obtained results from the simulation and life cycle analysis. At the cost of extra embodied carbon, the operational energy of the EPS core technology is less than a business-as-usual brick wall assembly. The discomfort hours have been calculated for a naturally ventilated space. The operational energy represents lighting cooling consumption with the air conditioner only in the bedroom in mixed-mode operation, with set points from IMAC-R. EPS core technology has a higher embodied carbon contribution, as compared to the embodied carbon of Brick, mainly due to the extensive amount of steel usage. The operational carbon emissions are lower for EPS core tech than Brick, owing to a better thermal performance of the envelope. The operational carbon for 50 years in the case of Brick is 98.8% more than its embodied carbon, indicating the necessity of using renewable energy sources for electricity generation for carbon offset purposes. The operational carbon has been calculated with the present emission factor available in the literature and data, which is projected to be a different value in the coming years based on technological changes.The discomfort hours are 25.73% less in the case of EPS core tech than in Brick, with 10.16% less operational carbon emission over 50 years. At the cost of almost seven times higher embodied carbon, EPS core tech is more thermally comfortable with less operational emissions than Brick Wall. The built-up area normalised embodied carbon for brick wall construction is 247.19 kgCO2/m², whereas, for EPS core construction, it is 1755.99 kgCO2/m². Similarly, the operational carbon for brick wall construction is 674.84 kgCO2/m², whereas, for EPS core construction, it is 606.21 kgCO2/m². These results are specific to Bhubaneswar since all the results are based on the climate profile of the city. The operational emissions and discomfort hours are expected to change for different locations across India.

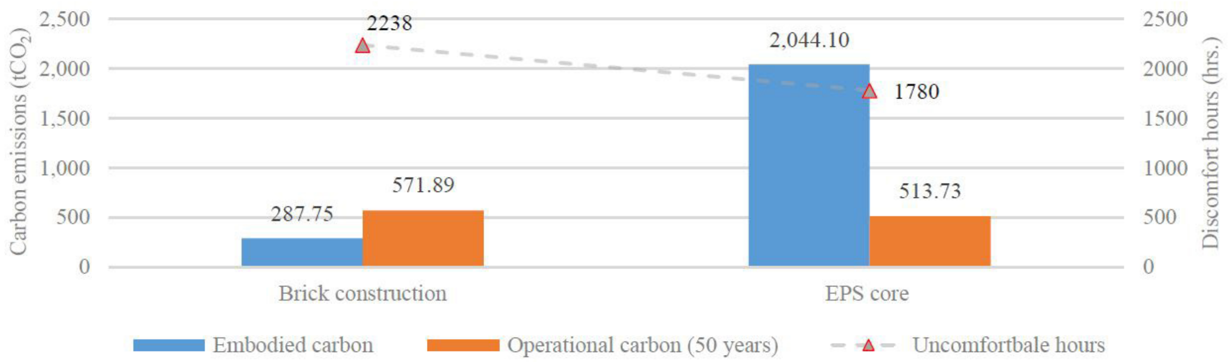

Figure 9: Relation between carbon emissions and thermal comfort

5. Conclusion

The findings of this study highlight the significance of considering multiple data sources with varying values to comprehensively present the results and understand the potential range of scenarios related to the outcome. Analysing data on embodied carbon values and operational emissions has provided a clear and valuable understanding of the situation within defined limits. However, it should be noted that life cycle analysis is susceptible to the quality of data used, and the results are critical in informing decision-making by stakeholders. This study's wide range of data sources has allowed for a more comprehensive analysis, considering potential inconsistencies. This approach has facilitated a more robust understanding of the research outcomes and their implications. Including data from diverse sources has ensured a more holistic assessment of the research problem and contributed to a more nuanced understanding of the complex relationships between different variables. These findings can serve as a valuable reference for policymakers, practitioners, and other stakeholders in making informed decisions about managing carbon emissions and sustainability efforts. This research study fills a critical gap in the existing literature by investigating the relationship between thermal comfort and carbon emissions in building materials, considering both embodied and operational emissions and showcasing a comparison between two different construction scenarios. The findings highlight the need to further study various materials and their thermal performance and carbon emissions to establish a direct correlation, if any, between thermal comfort and carbon emissions. Further research on studying more materials and considering other climate zones will help advance the understanding of carbon emissions and their link with comfort.

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Improved burnt clay brick masonry: lowering upfront embodied carbon, improving thermal comfort and climate resilience of new housing in the Indo-Gangetic Plains

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Abstract

The urban residential building footprint is expected to increase four-fold during 2020-2050 in the Indo-Gangetic Plains region of India. The business-as-usual construction technology of RCC frame with solid burnt clay brick as the walling material uses large quantities of steel, concrete and solid brick and is highly resource and carbon intensive. The region produces 110-140 billion solid burnt clay bricks per year. Brick production is associated with large energy consumption, carbon dioxide emission, air pollution and degradation of agricultural land. The study presents an innovative new burnt clay product – vertically cored interlocking burnt clay block- being manufactured by a brick manufacturer in the region. The study presents the results of the life cycle analysis (as per EN 15804) and quantifies reductions in carbon and resource consumption for the product and the building element (wall). The analysis is based on the data collected from the industry. The cradle to gate analysis shows a reduction of 31% in the CO^2 emissions ($kgCO^2/m^3$ of burnt product) and 58% in soil consumption (m^3 of soil/m^3 of burnt product) for the vertically cored hollow block. A 150 mm thick wall made of vertically cored hollow block results in 55% reduction in the CO^2 emissions ($kgCO^2/m^2$ of wall) when compared to a 230 mm thick wall of solid brick. In addition, the cement consumption in mortar reduces by 66% and sand consumption by 62% per m^2 of wall area. The study further indicates a significant reduction in concrete and steel consumption by extending the analysis to the building level.

Keywords - Low-carbon housing, hollow burnt clay block, life cycle analysis, Indo-Gangetic plains, resource efficient clay brick industry

1. Introduction

The Indo-Gangetic Plains (IGP) region covering the states/Union Territories of Punjab, Haryana, Chandigarh, NCT of Delhi, Uttar Pradesh, Bihar, West Bengal and Assam, has high population density and accounts for 42% of the total population of the country [1]. Several major states of the region have low rates of urbanisation e.g. Uttar Pradesh (22.3%), Bihar (11.3%) [2]. A large growth in

Table 1 Percentage of census housing reporting burnt clay brick as walling material in Indo-Gangetic Plains [4]

	% of census houses reporting burnt clay brick as walling material		
	Rural (%)	Urban(%)	Total (%)
Punjab	86.97	88.31	87.5
Haryana	87.83	86.52	87.36
Chandigarh	84.36	88.78	88.65
NCT of Delhi	84.82	86.27	86.24
Uttar Pradesh	63.57	83.04	67.87
Bihar	44.52	71.15	47.46
West Bengal	33.09	72.22	45.72
Indo-Gangetic Plains	51.53	78.80	58.68
India	40.47	64.00	48.06

urban population and housing is expected in the coming decades. The total urban residential built-up area in the region is expected to increase four-fold from 1.88 billion m^2 in 2020 to 7.35 billion m^2 by 2050 [3].

As per Census 2011, burnt clay brick is the main walling material for housing construction in the region. In 2011, 78.8% of the urban census houses in the IGP region reported burnt clay brick as the walling material [4]. In several of the states the percentage was more than 85% (refer Table 1).

The IGP region is rich in alluvial soil deposited by the major rivers, Indus, Ganges and Brahmaputra originating from the Himalayas. The bricks made from the alluvial soil in the region are of good quality and continue to remain the most widely available and preferred walling material for residential housing construction [5]. Reinforced Cement Concrete (RCC) frame, RCC slab and solid burnt brick infill is the dominant construction technology despite the introduction of several new building materials and construction technologies. For multi-storey housing projects in the National Capital Region (NCR) and other metropolitan cities, there is an increase in the use of Autoclaved Aerated Concrete (AAC) block masonry. Recently, some of the mass-housing, particularly high-rise residential projects have been constructed using monolithic concrete construction technology. The use of fly-ash bricks is limited to a few pockets, particularly in housing constructed by the government agencies.

The annual production of burnt clay bricks in the IGP region is estimated to be 110 -140 billion bricks per year, which is around 60% of the national production [6,7]. The number of manufacturing units is estimated to be around 60,000. Except for around 20 manufacturing units equipped to manufacture perforated or hollow bricks, almost all the other manufacturing units are producing only solid bricks. The brick making involves baking the brick at high temperature (~1000 ºC) in a kiln. The brick kilns in the region employ either Fixed Chimney Bull's Trench Kiln Technology (FCBTK) or an efficient version of FCBTK known as zig zag kiln technology. Large quantities of Coal and biomass fuels are used in brick kilns making them an important source of both carbon-dioxide emissions as well as local air pollution (particulate matter). To reduce particulate matter emission from brick kilns, the new environment standards issued by the Ministry of Environment, Forests and Climate Change (MoEFCC) for brick kilns in February 2022, mandate that all the FCBTK must shift to zigzag kiln technology or other cleaner technology/fuels in two years' time, i.e. by early 2024 [8]. As per information collected from the industry, around 30,000 or 50% brick kilns of the IGP region have converted to zig-zag kiln technology by June 2023. The brick kilns in the region use topsoil from the agricultural fields and degradation of agricultural fields is another area of concern.

Given this background, it is critically important to find new scalable low carbon and resource efficient building materials and construction technologies for the construction of housing in the IGP region. In this context, recently a brick manufacturer located at Varanasi has started manufacturing an innovative vertically cored interlocking hollow burnt clay block, which potentially can have large application in new residential construction. In this paper we apply the Life Cycle Analysis (LCA) approach and quantify the upfront carbon and resource savings at the product stage, at the building element (wall) stage and at the full building stage due to use of this new type of block.

2. Methods

2.1. Cradle to gate (A1-A3) carbon emissions for solid burnt clay brick & vertically cored interlocking hollow blocks

Following the standard EN 15804 [9], the project life cycle is shown in Figure 1. The analysis of cradle to gate (A1A3) carbon emissions for the vertically cored interlocking hollow blocks and solid burnt clay brick manufactured in the IGP region was carried out. As shown in Figure 1, A1 is raw materials extraction and supply; A2 is transport of raw material to the manufacturing plant and A3 is the manufacturing. The declared unit for the analysis is 1 m^3 of the burnt clay product. Based on the analysis, the results are presented in $kgCO^2/m^3$ of burnt clay product.

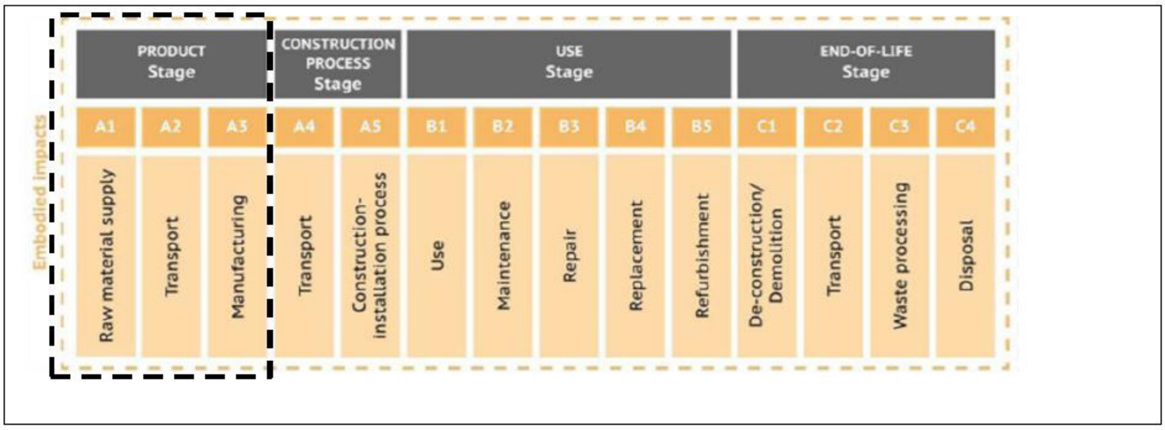

Figure 1: Project Life Cycle

2.1.1 Solid Burnt Clay Brick

The process flow diagram of solid brick manufacturing process in the IGP region is shown in Figure 2

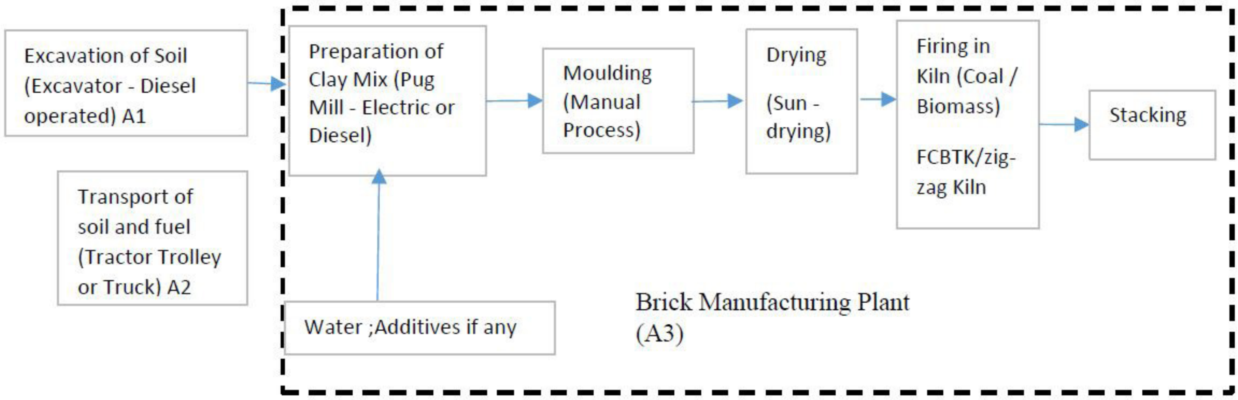

Figure 2: Process of solid burnt clay brick manufacturing in the Indo-Gangetic Plains

The data on energy used during A1-A3 was collected from the industry and literature. While there are many similarities in terms of the brick production across the IGP region, there is also some diversity in terms of size of brick, fuel, etc. Based on the industry data an average energy use pattern for solid clay brick production in the IGP region was developed.

For the analysis, the average size of the solid burnt clay brick is taken as 230mm x 110 mm x 70 mm and the weight of single fired brick is taken as 3.0 kg, which translates into the bulk density of 1694 kg/m^3. A typical brick kiln was assumed to fire 50,000 bricks per day (150 tons of burnt clay brick/day or 88.55 m^3 of burnt clay brick/day).

The process and energy data used for LCA is presented in Table 2.

Product life cycle stage	Description
A1	The soil for manufacturing bricks is surface soil excavated from nearby agricultural fields. A JCB excavator is used for excavating the clay. The typical diesel consumption in excavation is taken as 7 l/h and the excavation rate as 45 m^3 of soil/h. The specific diesel consumption of excavation is 0.225 l of diesel/m^3 of burnt clay product. The carbon emission factor for diesel is taken as 2.68 $kgCO_2$/l [10]
A2	a) Both trucks and tractor trolleys are used for transporting the soil from the agricultural fields to the brick manufacturing unit. For the analysis, the transportation is considered by 10-wheeler truck, which transports 20 tons of soil/trip. As soil is mostly procured from nearby agricultural fields, the distance of the place of excavating the soil to the brick kiln is taken as 10 km. b) The coal is assumed to be transported using trucks from the coal mine to the brick kiln. For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of coal/trip. It is assumed that all the coal which is being used is indigenous and the average distance from the place of mining to the brick kiln is taken as 500 km. The total travel distance taken for the analysis consists of both to-and-fro travel of the truck. The emission factor for the 10-wheeler truck is taken as 0.7375 $kgCO_2$/km [11]
A3	a) The soil mix is prepared in a machine known as pug-mill, which is mostly operated using the tractor (diesel operated). During the soil-mix preparation, water is added to the soil. In some cases, additives like fly ash are also added, but for the analysis no additives are assumed. It is assumed that on average the pug-mill per hour produces soil-mix sufficient to mould 12,000 15,000 bricks. The specific diesel consumption of pug-mill is 0.225 l of diesel/m^3 of solid burnt clay brick. The carbon emission factor for diesel is taken as 2.68 kgCO2/l [10] b) The moulding of brick is done manually. c) The bricks are dried in the open under the sun. d) The bricks are fired in a kiln. Both FCBTK and zig-zag kilns are used in the IGP region. The major fuel used is coal, with biomass fuels like mustard stalk, saw dust, and firewood used in small quantities. For the analysis, the base-line Specific Energy Consumption for FCBTK is taken as 1.34 MJ/kg-brick and 1.06 MJ/kg-brick for zig-zag kiln [12]. As the two types of kilns are present in almost equal numbers in the IGP region, an average SEC of 1.2 MJ/kg-brick or 2033 MJ/m^3 of burnt clay product is used for further calculations. For estimating the carbon emission, it is assumed that all the energy comes from burning coal. The carbon dioxide emission factor for bituminous coal is taken as 94.6 tCO_2/TJ [14]

2.1.2 Vertically Cored Interlocking Hollow Clay Block

The product vertically cored interlocking hollow clay block (Figure 3) is manufactured in a brick manufacturing plant located at Varanasi, Uttar Pradesh. The size of the vertically cored hollow block is 300mm x 150 mm x 200 mm and the weight of single block is 8.6 kg, which translates into the bulk density of of 956 kg/m^3. The product is fired in a zig-zag brick kiln which has capacity to fire 150 tons of burnt clay product/day.

Figure 3: Vertically Cored Interlocking Hollow Clay Block

The process flow diagram showing energy/fuel used in various stages of the production of vertically cored interlocking hollow clay blocks is shown in Figure 4.

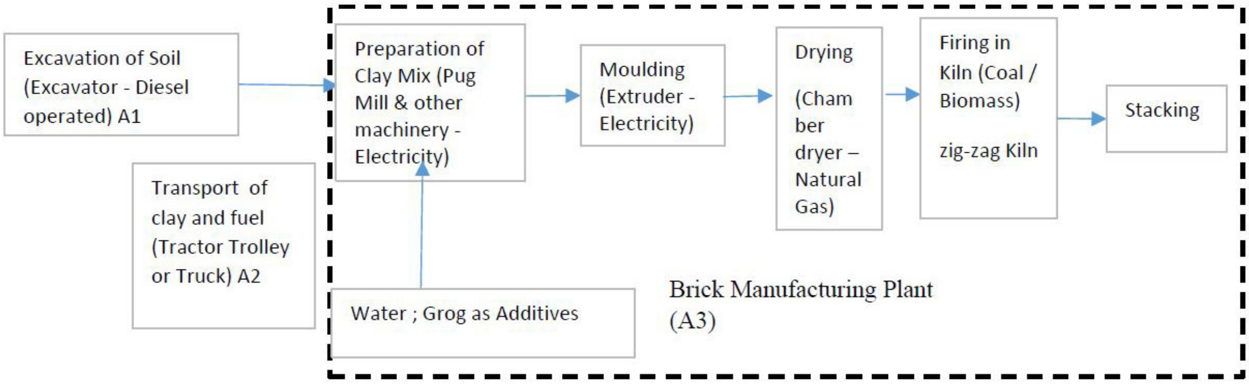

Figure 4: Manufacturing process of Vertically Cored Interlocking Hollow Clay Block

The process and energy data used for LCA is presented in Table 3.

Table 3: The process and energy data used for cradle to grate analysis of Vertically Cored Interlocking Hollow Clay Block

Product life stage	Description
A1	The soil for manufacturing bricks is surface soil excavated from nearby agricultural fields. A JCB excavator is used for excavating the clay. The typical diesel consumption in excavation is taken as 7 l/h and the excavation rate is 45 m^3 of soil/h. The specific fuel consumption of excavation is 0.095 l of diesel/m^3 of burnt clay product. The carbon emission factor for diesel is taken as 2.68 $kgCO_2$/l [10]
A2	a) Both trucks and tractor trolleys are used for transporting the soil from the agricultural fields to the brick manufacturing unit. For the analysis, the transportation is considered by 10-wheeler truck, which transports 20 tons of clay/trip. The distance of the place of excavating the soil to the brick kiln is taken as 10 km. b) The coal is assumed to be transported using trucks. For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of coal/trip. It is assumed that all the coal which is being used is indigenous and the average distance from the place of mining to the brick kiln is taken as 500 km. The total travel distance taken for the analysis consists of both to-and-fro travel of the truck. The emission factor for the 10-wheeler truck is taken as 0.7375 $kgCO_2$/km [11]
A3	a) The soil-mix is prepared in a series of electricity operated machinery including pug-mill and mixers. The specific electricity consumption of various machinery together is 4.03 kWh/m^3 of burnt clay product. b) The moulding of the block is done using an electricity operated extruder. The specific electricity consumption of the extruder is 5.04 kWh/m^3 of burnt clay product. c) The bricks are dried in a chamber dryer. The chamber dryer has multiple chambers. One chamber having capacity to dry 1848 blocks, has a cycle time of 14 hours and consumes 380 scm of piped natural gas. Taking 10,000 kcal/scm as the gross calorific value of the piped natural gas, the specific energy consumption for drying is 955 MJ/m^3 of burnt clay product. d) The blocks are fired in a zig-zag kiln. The kiln has a capacity to produce 150 tons of burnt clay product every day. The kiln uses mainly bituminous coal (4 tons/day), along with sawdust (1 ton/day) and dry cow dung (1 ton/day). Taking GCV of 5500 kcal/kg for the bituminous coal, 4000 kcal/kg for saw dust and dry cow dung, the specific energy for firing is calculated as 794.20 MJ/m^3 of burnt clay product. Weighted grid emission factor for electricity is taken as 0.71 $kgCO_2$/kWh [13]. The emission factor for natural gas is taken as 56.1 tCO_2/TJ [14]. For the carbon analysis, it is assumed that all the energy in the kiln comes from burning coal. The emission factor for bituminous coal is taken as 94.6 tCO_2/TJ [14].

2.2 Embodied carbon assessment of walls constructed using solid burnt clay brick & vertically cored interlocking hollow blocks

Referring to project life cycle (figure 1), this analysis covers product (A1-A3) and construction process stage (A4 -A5). A4 accounts for transportation of the materials from the manufacturing plant to the construction site and A5 accounts for construction and installation. The functional unit chosen is one square meter of wall and the results are presented in kgCO2/m² of wall area.

The analysis compares two walls a) 230 mm thick wall (unplastered) made from the solid burnt clay brick (230mmx 110 mm x 70 mm size) and b) 150 mm thick wall (unplastered) made from the vertically cored interlocking burnt clay blocks (300 mm x 150 mm x 200 mm). The average thermal conductivity of the manually moulded solid burnt clay brick produced in the IGP region is 0.6 W/m.K [15], which results in a computed Uvalue of 230 mm thick solid brick wall (un-plastered) as 2.6 W/m².K The U-value of the 150 mm wall constructed using vertically cored interlocking burnt clay blocks is 1.4 W/m².K as per the product specifications provided by the brick manufacturer. Thus, it can be observed that even with lower thickness, the U-value of the vertically cored block is expected to have lower U-value.

The quantity of bricks/blocks, cement and sand were determined by constructing two walls, each having an area of 38 ft2 (3.53 m²), one using the solid burnt clay brick and the other using the vertically cored interlocking hollow burnt clay blocks. The construction of the two walls was carried out at the site of a multi-family residential housing project at Varanasi. The quantity data used for the analysis is given in Table 4.

Table 4: Quantities of materials required for the construction of wall

		Wall with solid burnt clay brick (un-plastered)	Wall with vertically cored interlocking hollow burnt clay block (un-plastered)
Size of the brick/block		230 mm x 110 mm x 70 mm	300 mm x 150 mm x 200 mm
Thickness of the wall (mm)		230	150
Area of the wall (m²)		3.53	3.53
Brick/blocks	Number	370	54
	Weight (kg)	1110	464.2
	Volume (m³)	0.655	0.486
Cement in mortar	Volume (m³)	0.050	0.017
	Density (kg/m³)	1440	1440
	Weight (kg)	71.78	24.47
Sand in mortar	Volume (m³)	0.241	0.092
	Density (kg/m³)	1600	1600
	Weight (kg)	385.2	147.3

Table 5: The data used for carrying out life cycle carbon analysis (A1-A5) for walls

Product life cycle stage	**Description**
A4	Transport of building materials from the manufacturing plant to the construction site a) Brick and Block: For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of brick/trip. The distance of the brick manufacturing plant to the construction site is taken as 50 km. b) Cement: For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of cement/trip. The distance of the cement manufacturing plant to the construction site is taken as 250 km. c) Sand: For the analysis, the transportation is considered by 10-wheeler truck, which transports 18 tons of sand/trip. The distance from the sand mining location to the construction site is taken as 100 km. The total travel distance taken for the analysis consists of both to-and-fro travel of the truck. The emission factor for the 10-wheeler truck is taken as 0.7375 kgCO_2/km [11]

Product life cycle stage	Description
A5	Construction and installation. The carbon emission factors considered for the analysis are: a) Solid burnt clay brick: 198.9 $kgCO_2/m^3$ of burnt product as computed in this study. b) Vertically cored interlocking hollow clay block: 137.3 $kgCO_2/m^3$ of burnt product as computed in this study. c) OPC cement: 0.996 $kgCO_2/kg$ [15] d) Sand: 0.009 $kgCO_2/kg$ [16]

3. Results

3.1 Cradle to gate (A1-A3) carbon emissions for solid burnt clay brick & vertically cored hollow block

The results of the cradle to gate carbon emissions for solid burnt clay brick manufactured in the IGP rgion is estimated as 198.87 $kgCO^2/m^3$ of burnt product, while that for the vertically cored interlocking hollow burnt clay blocks is 31% lower at 137.27 $kgCO^2/m^3$ (refer Table 6 for details).

Table 6: Results of Cradle to gate (A1-A3) carbon emissions for solid burnt clay brick and vertically cored hollow block

		CO_2 Emissions ($kgCO_2/m^3$ of burnt product)	
		Solid Burnt Clay Brick	Vertically Cored Interlocking Hollow Burnt Clay Block
A1	Excavation of Soil	0.60	0.25
A2	Transportation of soil	1.38	0.45
	Transport of coal	3.98	1.42
A3	Soil-mix preparation	0.61	2.86
	Moulding/Extruder	0	3.58
	Drying	0	53.58
	Firing of brick/block in the kiln	192.30	75.13
	A1-A3	**198.87**	**137.27**

It is interesting to note that in the case of the 230 mm solid brick wall, while the brick contributes to around 60% of the carbon emissions, almost 34% of the emissions are contributed by the cement used in the mortar. This points out to the fact that for low-carbon masonry, apart from attention on using bricks with lower carbon emissions, due attention needs to be paid to the quantity and carbon emission characteristics of mortar also.

3.2. Upfront embodied carbon (A1-A5) assessment of walls constructed using solid burnt clay brick & vertically cored interlocking hollow blocks

The upfront embodied carbon emissions (A1-A5) for a 230 mm unplastered solid burnt clay brick wall is calculated as 59.81 $kgCO^2/m^2$ of wall, while that for a 150 mm unplastered wall made from vertically cored interlocking hollow burnt clay block is 55% lower at 27 $kgCO^2/m^2$ of wall (refer Table 7 for details)

For the vertically cored hollow block, firing and drying operations contribute to 55% and 39% of the carbon emissions respectively. For the solid burnt clay brick the firing operation alone contributes to around 97% of the carbon emissions, there are no emissions from drying as bricks are dried in the open under the sun.

Table 7: Upfront embodied carbon (A1-A5) assessment of walls constructed using solid burnt clay brick & vertically cored interlocking hollow blocks

		CO_2 emissions ($kgCO_2/m^2$ of wall)	
		Solid burnt clay brick (wall thickness 230 mm)	Vertically cored interlocking hollow burnt clay block (wall thickness 150 mm)
A4 (Transportation)	Brick/Block	1.29	0.54
	Cement	0.42	0.14
	Sand	0.86	0.34
A5 (Construction & Installation)	Brick/Block	36.16	18.76
	Cement	20.24	6.90
	Sand	0.85	0.33
A1-A5	**Total**	**59.81**	**27.00**

4. Discussion

The housing in the IGP region is dominated by solid burnt clay brick masonry. The analysis shows that if the conventional solid burnt clay brick (230mm x 110 mm x 70 mm) is replaced with the vertically cored interlocking hollow burnt clay blocks (300 mm x 150 mm x 200 mm), then significant reduction in carbon dioxide emissions and resources is possible. The analysis shows that at the product level (cradle-to-gate), the CO^2 emissions ($kgCO^2/m^3$ of burnt product) for vertically cored interlocking hollow burnt clay blocks is 31% lower than that of solid burnt clay brick. In addition, it also results in savings of 58% in the consumption of soil which reduces from 1.44 m^3 of soil/m^3 of burnt product for solid brick to 0.61 m^3 of soil/m^3 of burnt product for the vertically cored blocks.

The savings at the product level are further enhanced when the bricks/blocks are used to construct a wall. A 150 mm thick wall made of vertically cored hollow block results in 55% savings in the CO^2 emissions ($kgCO^2/m^2$ of wall) when compared to a wall of 230 mm thickness made from solid burntclay brick. It is to be noted that the thermal transmission or U-value of the vertically cored hollow block wall is lower, thus improving the thermal comfort and reduction in operation energy. In addition to the CO^2 savings, there are additional savings in materials used in the mortar. The cement consumption in mortar reduces by 66% from 20.3 kg of cement/m^2 of wall for solid brick wall to 6.9 kg of cement/m^2 of wall for vertically cored hollow brick wall. The sand consumption reduces by 62% from 109.1 kg of sand/m^2 of wall for solid brick wall to 41.7 kg of sand/m^2 of wall for vertically cored hollow block wall.

As the scope of the study was limited to the product and building element level, the study has not analysed the impact on CO^2 emissions and other resources for the construction of a full residential building using the two types of bricks. Such an analysis will help in quantifying additional large savings in steel and concrete. An indication of the scale of savings is available in a recent study [17] that has compared the steel and concrete consumption in a four-storey residential building (built-up area of 500 m2 located at Kolkata). The study has compared three construction systems:

a) RCC framed structure, RCC slab, with solid brick masonry (brick size: 250 mm x 125 mm x 75 mm)

b) RCC framed structure, RCC slab with horizontally cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)

c) Constrained masonry, waffle slab using vertically cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)

The savings obtained in steel and concrete is shown in Table 8. It is seen that just by replacing the solid burnt clay brick with hollow burnt clay blocks, 32% reduction in steel and 20% reduction in concrete can be achieved. However, if the construction system is changed to constrained masonry using vertically cored burnt clay block and waffle slab, then 66% reduction in steel and 48% reduction in concrete is possible.

Table 8: Savings obtained in steel and concrete for three construction systems [17]

Construction system	Steel (kg/m² of built-up area)	M 30 Concrete (m³/m² of built-up area)	Savings (%)
RCC framed structure, RCC slab (150 mm), with solid brick masonry (brick size: 250 mm x 125 mm x 75 mm)	48.1	0.393	Nil
RCC framed structure, RCC slab (150 mm) with horizontally cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)	32.9	0.315	32 % in steel and 20% in concrete
Constrained masonry, waffle slab (200 mm) using vertically cored hollow burnt clay blocks (block size:300 mm x 200 mm x 200 mm)	16.4	0.204	66% in steel and 48% in concrete

Overall, the study results show the large potential of carbon and resource saving by shifting from solid burnt clay brick to vertically cored interlocking hollow clay blocks. Further work can focus on:

b) Extending the analysis to full building level for various types of residential buildings

c) Exploring further the possibility of confined masonry and waffle slab construction system and other innovative low-carbon construction systems using the vertically cored blocks

d) Experimentally determining the U-value of the 150 mm wall made from the vertically cored blocks and studying the improvement in thermal comfort and reduction in operational energy through simulations.

e) Studying in detail the techno-economics of the vertically cored blocks and examining its scaling-up prospects in the IGP region.

5. Conclusion

The study presents an innovative new burnt clay product – vertically cored interlocking burnt clay block- being manufactured by a brick manufacturer in the IGP region. The study presents the results of the life cycle analysis (as per EN 15804) and quantifies reductions in carbon and resource consumption for the product and the building element (wall). The analysis is based on the data collected from the industry. The cradle to gate analysis shows a reduction of 31% in the CO^2 emissions ($kgCO^2/m^3$ of burnt product) and 58% in soil consumption (m^3 of soil/m^3 of burnt product) for the vertically cored hollow block. A 150 mm thick wall made of vertically cored hollow block results in 55% reduction in the CO^2 emissions ($kgCO^2/m^2$ of wall) when compared to a 230 mm thick wall of solid brick. In addition, the cement consumption in mortar reduces by 66% and sand consumption by 62% per m^2 of wall area. The study further indicates a significant reduction in concrete and steel consumption if the analysis is extended to the building level.

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Integrated evaluation for energy and comfort quantification of windows in a residential apartment of Mumbai

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Abstract

This paper aims to understand the energy and comfort performance of glazings for residential apartments in Mumbai. Firstly, an integrated workflow was developed on Ladybug tools to conduct thermal, energy and daylight simulations using a single model. Secondly, the developed workflow was deployed to simulate multi- comfort (visual & thermal & energy performance) for a 2 Bedroom, Hall and Kitchen (BHK) apartment as case study. Two glazing types, clear (U-value 5.6, SHGC 0.85, VLT 0.85) and high performing (U-value 2.5, SHGC 0.27, VLT 0.34) were analysed. The results demonstrated that high performance glazing reduces the energy consumption by 37%, improves the thermally comfortable area from 34% to 85% and also provides better visual comfort (DGP <30%).

Lastly, the research was extended to analyse 8 different types of glazings with incremental variation of SHGC and VLT to generate an integrated metric. This metric compares the performance of all glass options in terms of cooling consumption, thermally comfortable area and glare probability in the space, enabling the stakeholders to select an optimal window configuration for their project. The results demonstrate that use of ideal option (G8) is is providing highest thermally area comfortable (80%) and lowest DGP (27%) with reduced energy consumption (47 kWh/m2).

Keywords - integrated metric, energy efficiency, thermal comfort, visual comfort, ladybug tools, residential apartment

1. Introduction

The world we live in is changing, and so are our lifestyles. People spend about 80–90% of their time indoors and research has clearly established that problems with indoor environmental quality (IEQ-thermal, acoustic, visual, air quality) of buildings has a direct effect on comfort, health, productivity of the occupants. IEQ is affected by multiple parameters and just looking at one in isolation might not be enough to understand its impact on other parameters. (ASHRAE, 2013) Thus, a holistic & integrated approach is required to understand, correlate & analyse the complex & conflicting relationship between IEQ parameters in conjunction. (Yang & Moon, 2019)

Thermal and Visual comfort are the key parameters of occupant well being affected by indoor air-velocity, radiant temperatures, and illuminance & luminance levels in a space respectively. With respect to glazing properties, these are conflicting comfort parameters which need to be evaluated in conjunction with energy efficiency to find optimal glazing specification & envelope design. Which means that higher daylight availability will also bring higher direct solar gains thereby increasing the energy consumption. (Jakubiec et al., 2017)

Impact of radiant temperature (short- wave & long wave radiation) across spatial-temporal range is important to understand thermal comfort. (Arens et al., 2015) Similarly, glare, quality views,and daylight availability holistically represent visual comfort. (Mardaljevic et al., 2012)

Thus, a workflow has been developed that can generate spatial thermal comfort (Christopher Mackey, 2017) & conduct view based radiance renderings indicating visual comfort. This paper proposes an integrated workflow to understand multi-comfort performance of indoor spaces based upon which the optimal specifications can be proposed for improved IEQ and thereby, wellbeing. The workflow is developed on Ladybug tools (LBT) which is capable of conducting thermal, energy & daylight simulations using a single geometric model. (Roudsari & Pak, 2013)

The paper also demonstrates a case study example of 2 BHK apartments in Mumbai. The developed workflow was deployed to optimize glass specification (SHGC, U-Value & VLT) for conflicting multi-comfort parameters with lowest cooling consumption. The scope of the study was to develop a single model which can be linked to various simulation engines to conduct thermal, energy & visual simulations in an iterative loop. (Mathur et al., 2021)

2. Methods

2.1 Developing integrated simulation workflows (single model across energy, comfort, daylight

The workflow should be capable of using single model across thermal & daylight simulation and should be able to generate the 3 following parameters-

1. **Cooling EPI**- It indicates total cooling energy consumed in a building over a year per square meter of the floor area. This is affected by many factors including the envelope materials (windows, walls etc.). In windows, the SHGC and U-Value of the glass determines the heat gains against which the cooling energy is required to be offset.

2. **Thermal Comfort**- Is indicated by operative temperature (T_{op}). Top is calculated as the resultant of air temperature (T_{air}), and radiant temperature (T_{mrt}) caused by both direct solar radiation through glazing (shortwave) and temperature of all internal surfaces (long wave). (ANSI/ASHRAE, 2017) For windows, these parameters are a resultant of U-Value and SHGC of glass. Typically, Top is computed using the following formula:

$$t_{op} = \frac{(T_{mrt} + (T_{air} \times \sqrt{10v_{air}})}{1 + \sqrt{10v_{air}}}$$

▪ Expression below is used to calculate mean radiant temperature, where F is the fraction of the spherical view occupied by a given indoor surface and T is the temperature of the surface. N refers to the number of surfaces within the room, indicating that the equation above is summed for all surfaces surrounding an occupant.

$$mrt = [\sum_{i=1}^{N} F_i T_i{}^4]$$

Further to compute solar adjusted mean radiant temperature, methodology has been developed and validated (Mackie, 2015) which is based on the SolarCal method proposed by (Arens et al., 2015). Traditionally, to determine this solar adjusted MRT, a radiation study of human geometry is performed, and this is then used to produce an Effective Radiant Field (ERF) through the following formula:

$$\alpha LW\ ERFsolar = \alpha SW\ Esolar$$

▪ Where Esolar is the short wave solar radiant flux on the body surface (W/m2), αSW is shortwave absorptivity, and αLW is the long-wave absorptivity (typically around 0.95). The ERF can then be related to an MRT through the following formula:

$$ERF_{solar} = (0.5\, f_{eff}\, f_{svv}\, (I_{diff} + I_{TH}\, R_{floor}) + A_p\, f_{bes}\, I_{dir}/A_D)\, (\alpha_{sw} sw/\alpha_{lw})$$

I_{dir}, I_{diff}, I_{TH}:	Direct normal, diffuse horizontal & total horizontal radiation
A_D:	Geometry coefficients of the human body
R_{floor}:	Ground reflectivity
f_{svv} and f_{bes}:	sky view factor & fraction of the body visible to direct radiation

3. **Visual Comfort-** Daylight Glare Probability (DGP), which predicts the likelihood that an observer at a given view position and orientation will experience discomfort glare, is used as a metric to analyse visual comfort. (Naber et al., 2017)(Wienold & Christoffersen, 2006) It is a resultant of glass's visual light transmittance (VLT) that governs the quantity of light that enters the space determining overall visual contrast. (P. CHAUVEL, J. B. COLLINS & LONGMORE, n.d.)

$$DGP = c_1 . E_v + c_2 . \log\left(1 + \sum_i \frac{L_{s,i}^2 . \omega_{s,i}}{E_v^{a1} . P_i^2}\right) + c_3$$

Where,

E_v : *vertical eye illuminance (lux)*	$c_1 = 5.87 * 10^{-5}$
L_s : *Luminance of source (cd/m2)*	$c_2 = 9.18 * 10^{-2}$
ω_s : *Solid angle of source*	$c_3 = 0.16$
P : *Position index*	$a_1 = 1.87$

To cumulatively analyse the above parameters, an integrated workflow has been developed on the ladybug tools (v1.6) which allows linking a single geometric model across energy, thermal & daylight simulations. The backend engines used are Energyplus to conduct thermal & energy simulation and radiance to conduct DGP analysis. (Soi et al., 2022) LBT has been used due to its visual programming capabilities which allows us to conduct parametric simulation across multiple & conflicting parameters. Each comfort module (thermal, visual etc.) can also be simulated independently on the LBT platform, however, it has been interconnected with all components for faster computation and outputs. The following steps are undertaken to set the modelling process:

1. **Defining the geometry and internal parameters:** The workflow picks up model geometry from polylines and window to wall area ratio can be defined for each face. Specifications for both the comparative cases can be defined and rest all the parameters like internal gains, infiltration, activity templates & space programs can be directly applied with existing pre- defined templates as per ASHRAE 90.1 standards. Also, these analyses are spatial in nature, hence grid planes need to be defined along with spatial resolution for the analysis along with temporal range of analysis.

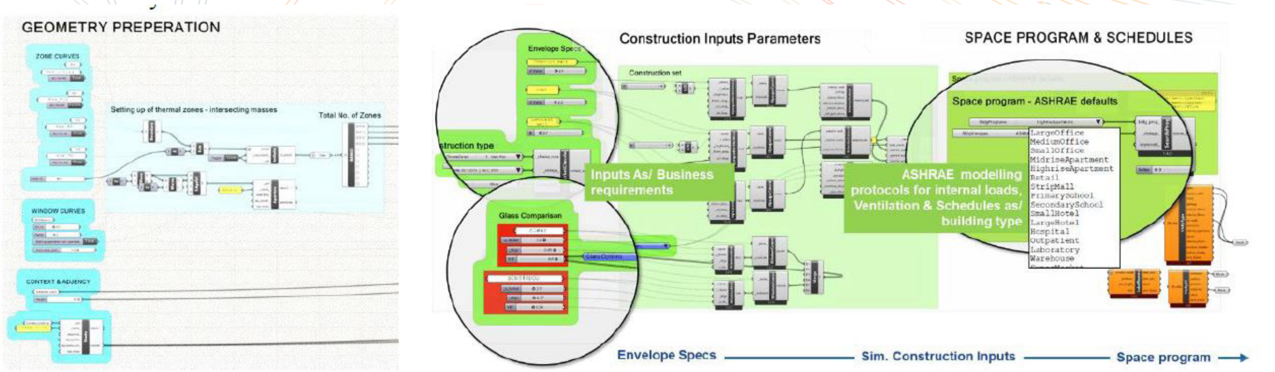


Figure 1: Geometry & construction inputs

2. **Result Visualization:** Once the script is set up the simulation can be run one by one or all at once for thermal, Energy & Daylight. Under thermal comfort- Spatial Operative temperature plots can be generated for point- in- time and cumulative across temporal range. Thermal comfort analytics have also been added to the script to precisely calculate metrics like '% area comfortable', average operative temperature etc. Under Energy Simulation, the workflow currently simulates EPI & Cooling load. Under daylight the script currently can simulate illuminance maps and annual metrics like sDA, DA & UDI along with DGP through view-based renderings.

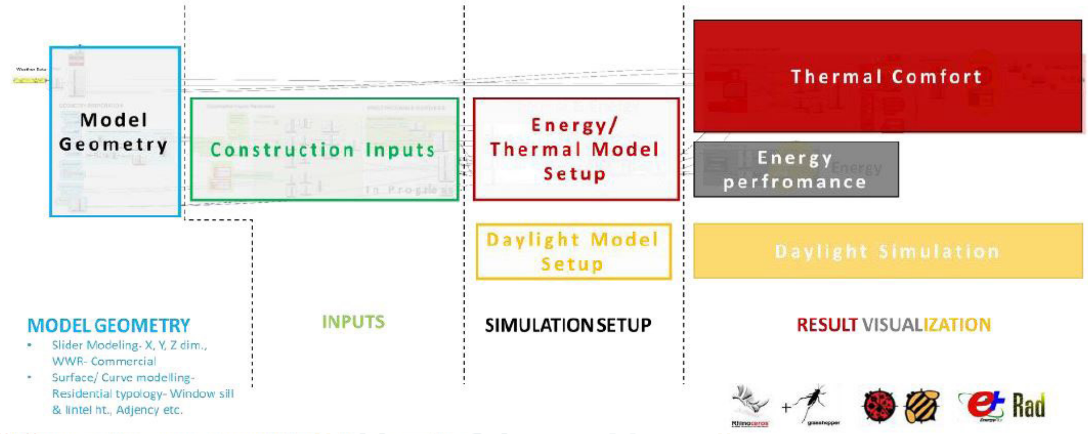


Figure 2: Integrated wor kflow Process flow

2.2 Case-study for a 2bhk apartment in Mumbai

As a case study example a typical high- rise residential unit in Mumbai has been modelled in Rhinoceros as per the floor plans shown in Figure 3.

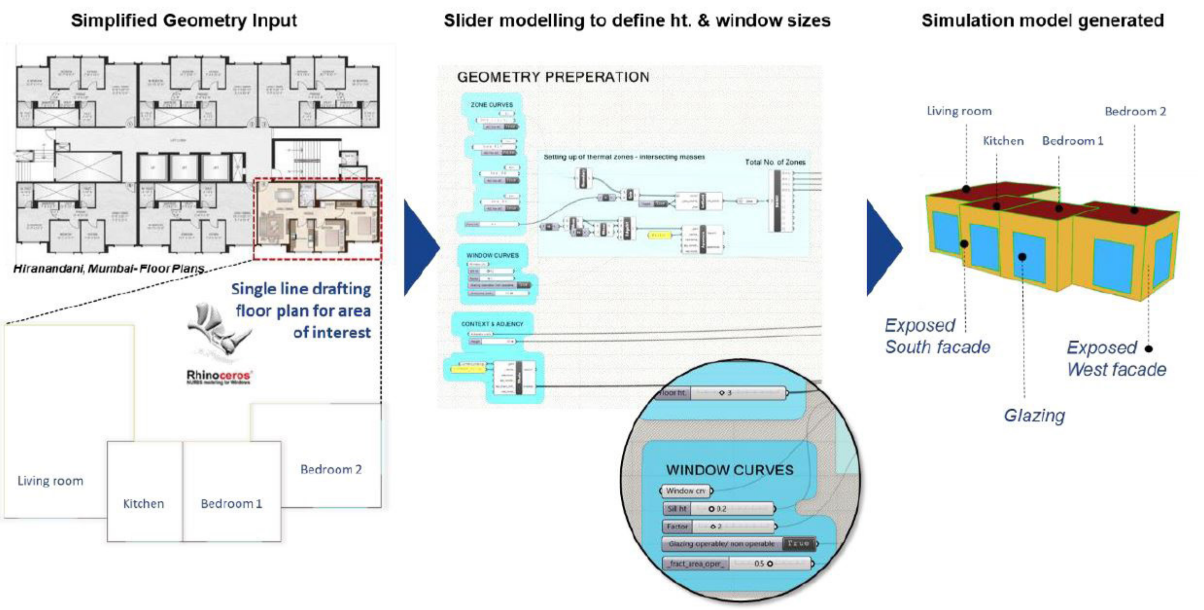


Figure 3: Model details for the residential apartment

The dwelling unit is oriented towards the South having a 70% window to wall area ratio. The building geometry is then linked to Ladybug tools daylight & thermal simulation components via grasshopper.

- Thermal Simulation Inputs: Since the residential buildings predominantly function as mixed-mode state in India, the indoor conditions are analysed for both air-conditioned and naturally ventilated state to get a holistic picture of the thermal conditions. ASHRAE 90.1 simulation protocols have been applied for space programs and schedules and the HVAC system is set up as Ideal air loads systems. Envelope specification has been defined as per business as usual considering 250mm AAC with U-Value of 1 W/m2K and 6mm clear glass. Adjacency of both walls & roof is set as adiabatic since; we are considering a middle floor of a typical high- rise building.

- Daylight Simulation Inputs: Interior wall surfaces reflectance have been defined as per IES standards for the following surfaces- Walls- 50%, Floor- 30%, Ceiling- 80% and 85% visual Light transmittance of clear glass. Daylight simulation has been conducted using Climate based sky for a typical weather file of Mumbai. The scene for DGP rendering was set up for the living room facing towards the window. Parallelly, the workflow was also tested by conducting a comparative case study between 2 glass types with following specification.

Parameters	Clear *(SGU)*	Comparative case
U Value *(W/m2K)*	5.60	2.5
SHGC *(%)*	0.85	0.27
Visual Light Transmittance *(%)*	85%	34%

2.3 Parametric analysis for glazings

The advantage of a combined workflow is the ability to conduct parametric analysis for multiple specifications of U-Value, SHGC & VLT across thermal, energy & daylight performance, on the same geometry as above. For the parametric analysis, there were a total of 4 SGU & 4 DGU glass types with SHGC varying incrementally in the multiples of 0.1. Similarly, for DGP analysis, VLT varied in the interval of 10%. The specifications of glass type in the parametric analysis can be refined for any thresholds of SHGC, VLT & U-Value or can be even made product specific. The intent of this workflow is to develop an informed glass selection workflow based upon thermal comfort, energy consumption & visual comfort. Further, a combined metric visualization is proposed to analyse the results from the parametric analysis and base decision on glazing performance.

Table 1: Glazing properties for the parametric analysis

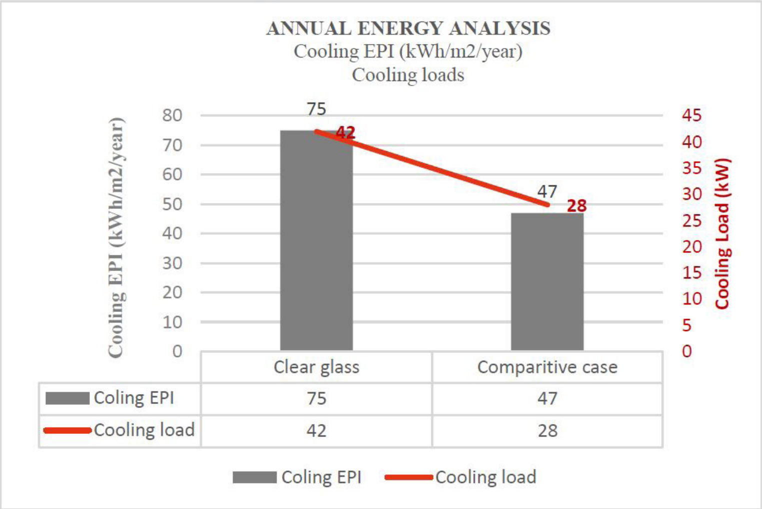
Glass no.	Glass Type	U Value *(W/m2K)*	SHGC	VLT *(%)*
1	Single glazed	5.6	0.7	65%
2	Single glazed	5.6	0.55	55%
3	Single glazed	5.6	0.45	45%
4	Single glazed	4.9	0.35	35%
5	Double glazed	2.8	0.55	55%
6	Double glazed	2.8	0.45	45%
7	Double glazed	2.8	0.35	35%
8	Double glazed	2.8	0.25	25%

3. Results

3.1 Case study for a 2bhk apartment in Mumbai

In addition to energy efficiency, it is also critical to look at the ability of the glass product to improve thermal and visual comfort in space. The thermal comfort was analysed by plotting spatial-temporal contours of operative temperature for both air-conditioned and naturally ventilated conditions during the hottest week 21st- 27th May between 12pm- 4pm.

The analysis for residential apartment case study has been conducted in three parts: 1. energy efficiency 2. thermal comfort and 3. visual comfort inside the rooms. Firstly, the energy analysis (Figure 4) was conducted to understand the impact of glass selection on cooling EPI & Cooling load. Compared to a clear glass, a reduction of 10% in cooling EPI and 30% in peak cooling load can be observed due to high performing glass. The difference between the 2 cases is due to lower U-Value & SHGC of the high performing glass, which results in lower conductive and radiative gains.



	Clear glass	Comparitive case
Coling EPI	75	47
Cooling load	42	28

Figure 4: Annual Cooling consumption

For air-conditioned scenario, even with the set point of 24°C, the clear glass case exhibits average operative temperature of 27.7°C with only 34% area falling within thermal comfort limits, Also, uneven distribution of Top across the floor is observed, especially near windows is almost 30°C due the high glass surface temperature and direct solar radiation. With the use of high-performing glass the average temperature is observed to be reduced to 25.6°C with a significant increase in the thermally comfortable area as 85%. This is due to the better specifications of the glazing resulting in reduced solar heat gains.

For naturally ventilated scenarios, the conditions are worst case. Even though there are no ACs or fans in the space, the use of high-performing glass is resulting in a 5°C drop in average operative temperature in the space and improved thermal distribution across the floor plate (Figure 5).

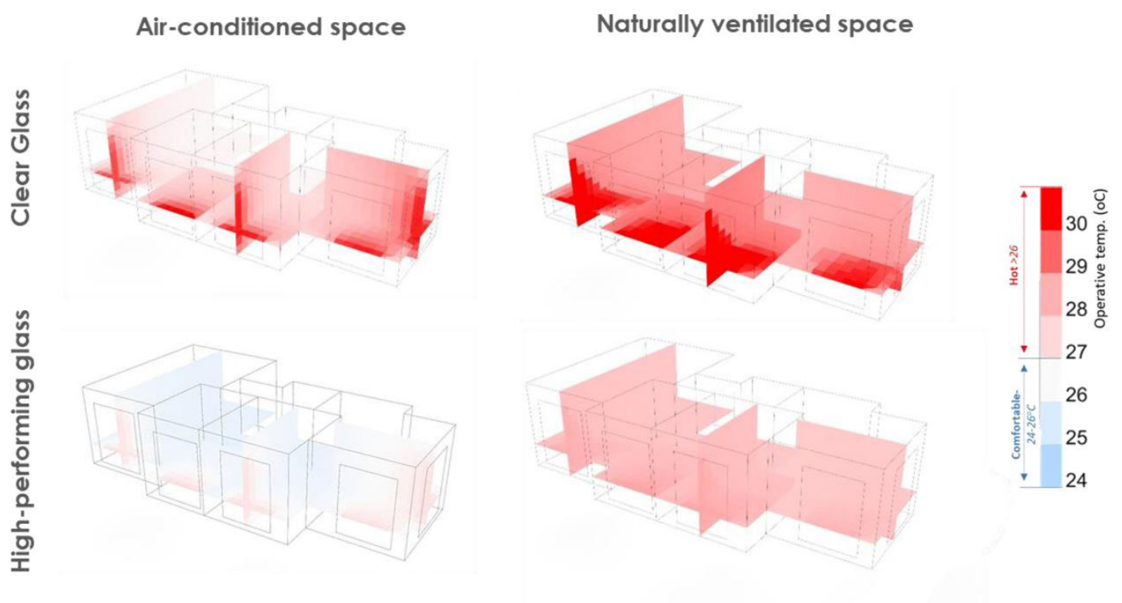


Figure 5: Thermal comfort contours for air conditioned and naturally ventilated scenario

Daylight analysis (Error! Reference source not found.) indicates good daylight availability and distribution across the dwelling unit but also excessively lit perimeter. Hence, the tendency of occupants will be to put on curtains which defeats the entire purpose of large windows and compromises views. In conjunction, DGP analysis indicated sky component towards south was

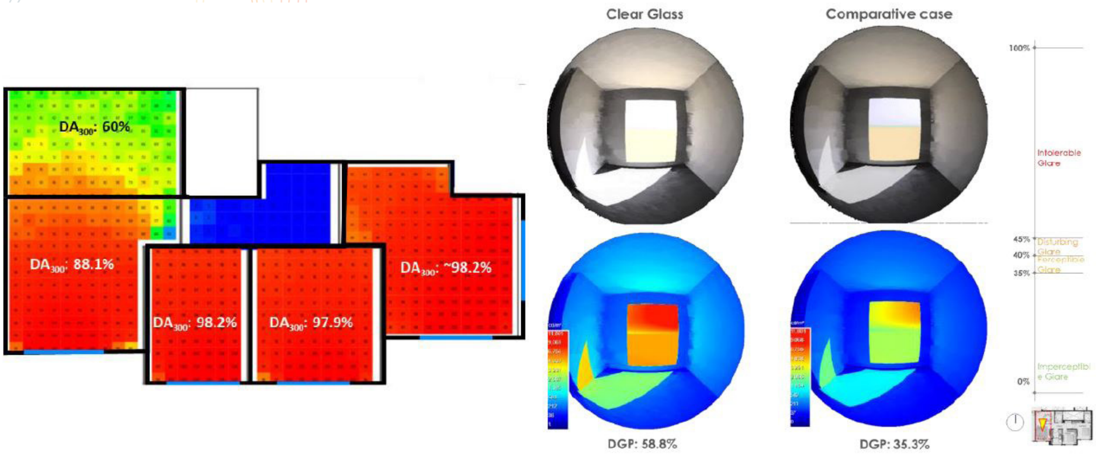


Figure 6: Illuminance & View Based Daylight Renderings (DGP)

significantly brighter than room interiors and hence, occupants will experience 'intolerable glare' (DGP58.8%) with baseline specification on 21st Dec, 2pm. Upon comparing with comparative cases, the DGP reduces to 35% i.e., imperceptible glare.

3.2 Parametric analysis for glazings

To analyse different glazing types, it is important to holistically look at its performance for both energy efficiency & comfort. For the parametric study, there are 8 types of glazing analysed for 3 conflicting parameters. The results are then converted into a 'combined metric' which is both visual and analytical. This enables better decision-making during product selection as it displays the overall efficiency of all product ranges in a single dashboard.

For thermal comfort quantification, the spatial operative temperature distribution across floors is translated into a metric 'percentage area thermally comfortable'. This is calculated using analytics which is pre- defined in the workflow, where upper and lower limits of thermal comfort are defined and the area falling under the same is computed. The energy consumption is expressed in annual EPI's and the Visual comfort is translated as DGP%, depicting the glare experienced by an occupant at a given point in time.

Hence, to be able to compare three different metrics a 'Combined or Integrated Metric' has been proposed in a form of X-Y scatter plot. The x-axis depicts 'Daylight Glare Probability (DGP%)' and the y-axis depicts 'Thermally Comfortable Area (%)'. The colour of each circle indicates EPI, and the shade becomes darker for higher EPI's.

The visualization dashboard helps correlate visual & thermal comfort parallelly while the combined metrics graph helps understand how that glazing type is ranked. For example, glazing type 3 (G3) has a DGP of 37 and 40% area thermally comfortable with 50 kWh/m2 EPI. As the SHGC of glass reduces the 'percentage thermally comfortable area' increases and reduction of annual EPI is observed due to lower SHGC. Similarly, with the reduction in VLT of glass the DGP reduces towards imperceptible glare.

Hence, glazing type (G8) is the most optimal specification based upon the highest thermal area comfortable (80%), lowest DGP (27) and energy consumption (45 kWh/m2).

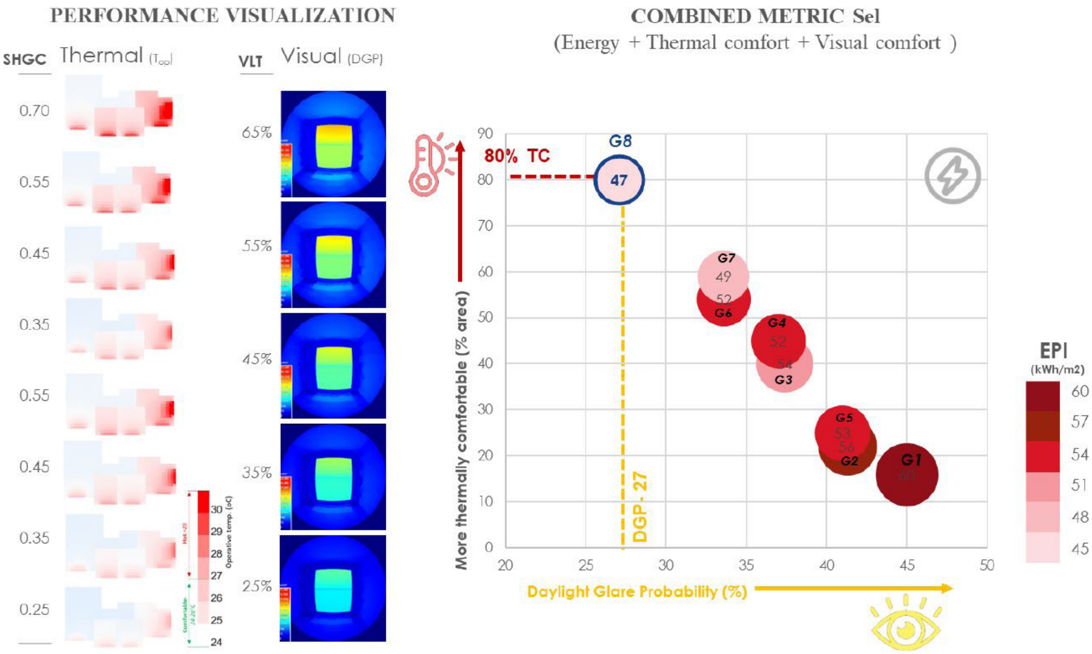


Figure 6 - I llumin ance & View Based Daylight Renderings (DGP)

4. Discussion

The paper attempts to mainstream and utilize technical metrics of thermal & visual comfort in conjunction withEPI to enable informed glass selection which will help stakeholder understand the impact of multi-comfort. Until now, such decisions have been mostly steered by energy savings but intangible benefits like thermal comfort, use of blinds/ curtains were not demonstrated or considered. Currently, workflow has been developed for 4 metrics- Thermally comfortable area (%), Energy Performance Index (EPI), Daylight Glare Probability (DGP) and Daylight availability (sDA, DA, UDI). These metrics should ideally be decided based upon the type of building, for example this typical dwelling unit has 80% WWR for spaces which aren't deeper beyond 4-5m hence, daylight availability is not the challenge. Rather, the perimeter spaces are prone to glare. Also, due to direct solar gains and limited shading on the façade the direct solar gains will cause radiant asymmetry. This analysis led to selection of these 3 metrics of this case.

But there might be future studies where the daylight availability might be more critical than glare. Energy Performance Index for each glass type can also be translated in terms of cooling energy cost and Carbon Emission Intensity as a part of future research.

The workflow allows to conduct parametric analysis for any specification of glass type. In case an analysis is needed to optimally select SHGC & VLT between 0.4-0.5 the number of simulation runs can be adjusted to an increment of 0.1. Thus, the input specification of glass can be refined to any threshold based upon the intent of the study.

5. Conclusion

This paper aims to understand the energy and comfort performance of glazing in typical high rise residential apartments in Mumbai using an integrated workflow developed on Ladybug tools capable of conducting thermal, energy & daylight simulations using a single model. The purpose of this study is to deploy an integrated workflow to optimize glass specification (SHGC, U-Value & VLT) based upon conflicting multi- comfort parameters with lowest cooling consumption. Thermal comfort is indicated by Spatial operative temperature and visual comfort is indicated by Daylight Glare Probability. In parallel to comfort the paper proposes energy performance as the third metric for glass selection optimization. Cooling EPI indicates total cooling energy consumed in a building over a year which is a resultant of envelope gains. The SHGC & U-Value of the glass determines the heat gains against which the cooling energy is required to offset.

Hence, an integrated workflow has been developed (single geometric model across energy, thermal & daylight simulations) on the ladybug tools (v1.6) which allows linking a single geometric model across energyplus to conduct thermal & energy simulation and radiance to conduct DGP analysis. LBT has been used due to its visual programming capabilities which allows us to conduct parametric simulation across multiple & conflicting parameters.

The workflow developed was first used to understand visual & thermal performance of a comparative case between clear glass and a high-performance glass. Two glazing types, clear (U-value 5.6, SHGC 0.85, VLT 0.85) and high performing (U-value 2.5, SHGC 0.27, VLT 0.34) were analysed. The results demonstrated that high performance glazing reduces the energy consumption by 37%, improves the thermally comfortable area from 34% to 85% and also provides better visual comfort (DGP <30%). Lastly, the research was extended to analyse 8 different types of glazings with incremental variation of SHGC and VLT to generate an integrated metric. This metric compares the performance of all glass options in terms of cooling consumption, thermally comfortable area and glare probability in the space, enabling the stakeholders to select an optimal window configuration for their project. The results demonstrate that use of ideal option (G8) is providing highest thermally area comfortable (80%) and lowest DGP (27%) with reduced energy consumption (47 kWh/m^2).

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Roadmap to implementation of thermal comfort policies in affordable housing.

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Abstract

The residential sector contributes to 24% of India's annual Green House Gas emissions within which 50% comes from heating and cooling needs. India's thermal comfort demands need to be energy-efficient and affordable to meet the 18 million low-income urban housing deficit. Here, we discuss the implementation of thermal comfort policies in affordable housing in India. We cross-examine the current implementation mechanism of thermal comfort and affordable housing policies and identify gaps in (a) clarity of roles and responsibilities of actors, (b) communication channels between actors, and (c) policy support instruments. We hypothesize that the gap between policies and their implementation comes from a lack of standardization and convergence between the two types of policies. We propose a roadmap to implementation via a 4-step approach: 1) outlining redefined roles and responsibilities of actors, 2) establishing a participatory planning process, 3) supplementing policies with implementation support, and 4) providing a framework for capacity building. The proposed roadmap can act as a guide to policy makers at the Union and State level, and impementation actors at the Urban Local Body level.

Keywords - Affordable Housing, Implementation Mechanism, Policy Implementation, Energy-efficient Construction, Thermal Comfort Policies

1. Introduction

The residential sector contributes 24% to India's annual GreenHouse Gas (GHG) emissions. 50% of this comes from heating and cooling needs for thermal comfort (Ozone Cell, 2019). The Intergovernmental Panel on Climate Change (IPCC, 2018) projects a global temperature rise of 1.5^{0}C above pre-industrial levels over the next three decades, with the number already a reality for many regions (Masson-Delmotte et al., 2019). Indian cities are already at risk and inaction may lead to further heat waves similar to the one in 2015 that killed 2,300 people (National Weather Forecasting Centre, 2020).

An exponential rise in building footprint in the coming decades exacerbates this situation. As per the latest available information, the urban housing deficit in India was projected to be at 18.78 million homes for the period 2012-2017. 96% of this demand belongs to the low-income housing category (Roy & ML, 2020). The Pradhan Mantri Awas Yojna (PMAY) committed to construct 11.2 million affordable housing units across India, of which 7.6 million have been completed so far (Mission Dashboard, n.d.). This massive increase in building stock will result in 6-13 times increase in energy consumption, under a business-as-usual scenario (MoEFCC, 2021). The rise in energy demand, coupled with extreme heat events, will have widespread environmental, economic, and social implications, especially for the urban poor.

Heating, ventilation, and air conditioning (HVAC) systems are energy and carbon intensive, and unaffordable for low-income households (Dong et al., 2021). Studies show that poorly insulated affordable housing units pose a higher risk of exposing inhabitants to energy poverty (Chen & Feng, 2022). Higher indoor temperatures due to poor insulation and ventilation further lead to disproportionately higher mortality in the urban poor (Reducing Heat Stress in India's Informal Settlements, n.d.). Adaptive thermal comfort using low-cost, energy efficient means is thus the need of the hour.

There are efforts being made to address this in the policy sphere. The India Cooling Action Plan

(ICAP) was drafted by the Ministry of Environment, Forest, and Climate Change (MoEFCC) to address sectoral cooling requirements. It provides recommendations for thermal comfort in residential housing, but lacks tailored recommendations for affordable housing. Building codes such as the Eco Niwas Samhita (ENS) are similarly not integrated with affordable housing policies, and not mandated in all states (Bureau of Energy Efficiency, n.d.).

The consequences can be seen in Telangana's affordable housing program, wherein 60% of the blocks in the state led affordable housing projects have compromised thermal comfort standards - being either too windy or in wind shadow areas compromising ventilation (Roychowdhury et al., 2021). An array of policy support instruments for thermal comfort such as the Bureau of Energy Efficiency (BEE) Design Guidelines for Energy-Efficient MultiStorey Residential Buildings, and the Building Materials and Technology Promotion Council (BMTPC) Compendium of Prospective Emerging Technologies for Mass Housing, which promotes innovative materials and construction techniques for thermal comfort in housing, exist. However, evidence on the adoption and implementation of these policies in the context of affordable housing is limited.

In this paper, we hypothesize that the gap between policies pertaining to thermal comfort in affordable housing and their implementation on ground stem from a lack of standardization and convergence between the two. We discuss the implementation framework of these policies to identify gaps through a threefold lens – (a) mapping roles and responsibilities of relevant actors, (b) mapping existing communication channels for implementation and monitoring, and (c) analysing the existing technical/ knowledge support instruments required for policy implementation. Finally, we recommend a roadmap to policy implementation based on the identified gaps.

2. Methods

This paper cross-examines policy implementation mechanisms across two paradigms – thermal comfort in the residential sector, and affordable housing. We conduct a literature review in the context of affordable housing in India to understand the implementation of existing policies on energy-efficiency and thermal comfort.

Table 1: Description of policy instruments reviewed

Instrument category	Description of instrument	Name of policy instrument
Regulatory instrument	Building codes and standards	Eco Niwas Samhita (Energy Conservation Building Code - Residential (ECBC-R)) part 1 and 2; National Building Code (NBC); American National Standards Institute/ American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) Standard 55; Central Public Works Department (CPWD) Schedule of Rate for New and Innovative Technologies
Policy support	Design guidelines	Handbook of Climate Smart Cities: Thermal Comfort in Affordable Housing; BEE Design Guidelines For Energy-Efficient Multi-Storey Residential Buildings
Research, development, and deployment (RD&D)	Compendium of material and construction technologies	BMTPC Compendium of Prospective Emerging Technologies for Mass Housing
Climate Strategy	Perspective plans outlining climate targets and strategies	ICAP

In addition, we reviewed the individual implementation mechanisms of affordable housing policies under the PMAY mission, and state affordable housing policies of Karnataka, Rajasthan, and Tamil Nadu to create a comprehensive framework across both sectors.

Fig. 1 describes the framework for implementation of policies on thermal comfort and affordable housing. The framework comprises of five core actor groups – 1) Union level, 2) State level, 3) Urban Local Bodies (ULBs) 4) implementation experts – developers, contractors, designers, and 5) end users – Self-Help Groups (SHGs) and affordable housing consumers. The roles and responsibilitiesof each actor are outlined.

We then reviewed the implementation mechanism to identify gaps through two methods: 1) literature review on gaps in implementation, and 2) industry expertise on implementation process requisites for infrastructure-based policies.

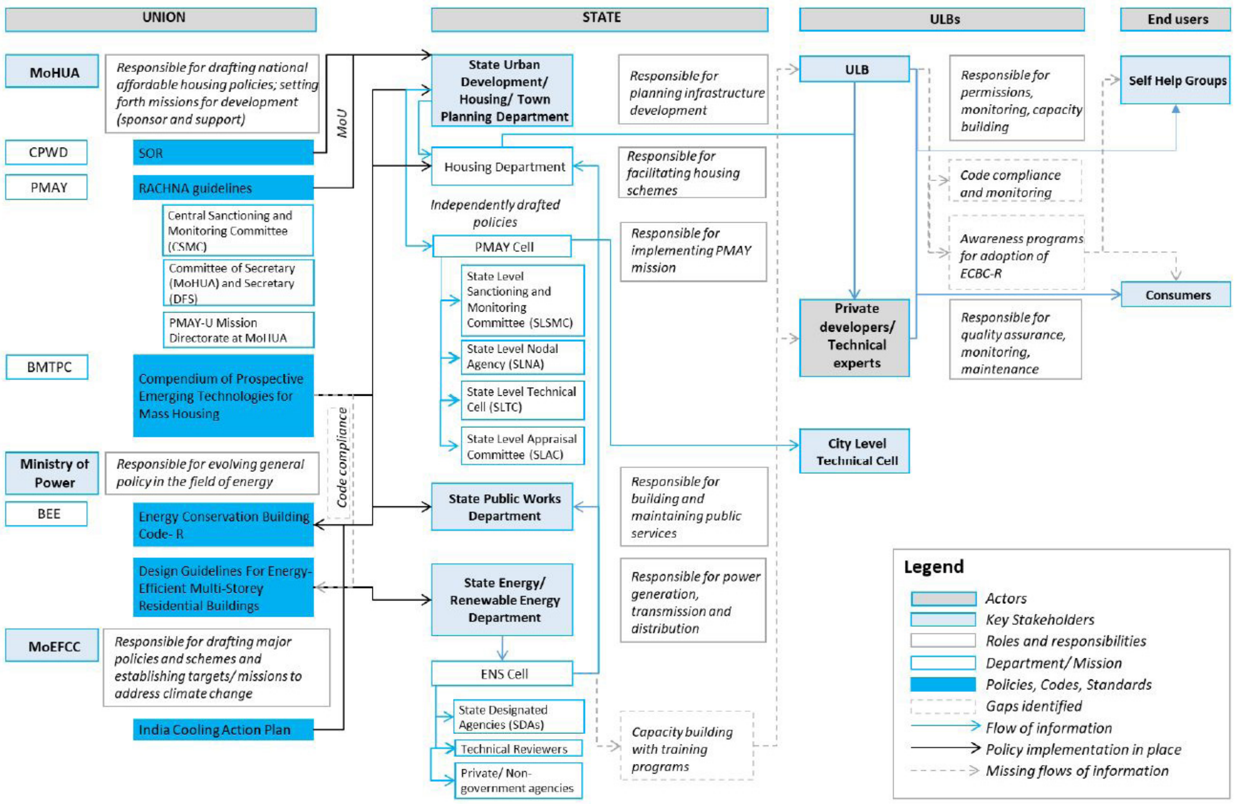

Figure 1: Implementation mechanism for thermal comfort and affordable housing policies

2.1 Implementation process requisites for infrastructure-based policies

Policies pertaining to infrastructure development require a comprehensive approach – from design to maintenance, including regular monitoring and evaluation to feed back into respective policies (see Fig. 2). We developed this process based on our expertise of implementing policy-based projects on ground, and through stakeholder consultations with municipal engineers, developers, and end users. Overlaying the findings from the literature review and the implementation process flow onto the existing implementation mechanism (Fig. 1) helped us identify the gaps in the current process. The next section presents the findings from the gap analysis, and provides recommendations to the current implementation mechanism to arrive at a comprehensive roadmap to implementing thermal comfort policies for affordable housing.

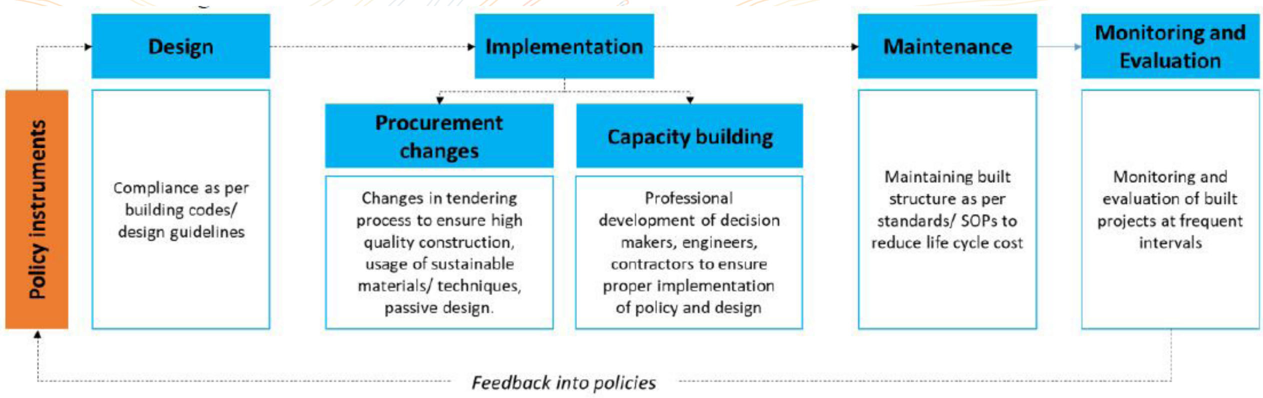

Figure 2: Implementation process for infrastructure-based policies

3. Results

3.1 Gaps in current implementation mechanism

3.1.1. Lack of a robust regulatory mechanism

Thermal comfort policies are not regulated across all affordable housing policies. The ENS policy is mandated in 10 states and amended and adopted for 10 more states (BEE & AEEE, 2022). However, its scope is not tailored to affordable housing policies. The PMAY has drafted the RACHNA guidelines through its technology sub-mission. However, there is limited evidence on its application, currently implemented in 6 lighthouse projects (Welcome To Global Housing Technology Challenge, n.d.) and demonstration projects across 14 cities (BMTPC, n.d.).

Fig. 1 demonstrates the regulatory framework of ENS, wherein dissemination from the Union is done through the State Energy Department, with the CPWD, State Public Works Department (PWD), and State Urban Development Authority as implementation partners. An ENS cell is sought in all states and Union Territories (UTs); however, there is limited evidence on their establishment (Bureau of Energy Efficiency, n.d.). The role of ULBs in the implementation scheme is currently not defined. Additionally, the State Energy Department engages with the Housing Department for ground implementation of thermal comfort standards, which has a limited role under the PMAY scheme. This demonstrates challenges in implementation stemming from a lack of inter-agency coordination and a robust regulatory mechanism.

3.1.2. Lack in participatory planning process

The BMTPC compendium on innovative materials is a comprehensive document comprising 24 materials and technologies identified for strength, stability, fire resistance, thermal comfort, water tightness, constructability and economic viability. Roychowdhury et al. (2021) finds that these materials and technologies have a higher cost implication and face market hurdles in mass housing schemes. This indicates a lack of feedback from consumers on the affordability of materials for thermal comfort.

Interviews with engineers conducted to measure the penetration of policies under the PMAY scheme show that there is considerable gap in the understanding of policies at the ULB level (WRI India Ross Center for Sustainable Cities, 2019). A lack of awareness of codes and policies at the end-user level leads to sale of affordable housing units that are not thermally comfortable (Suman & Kumari, 2022).

3.1.3. Lack in implementation support

Analysing the current implementation mechanism against the process for infrastructure-based policies (see Fig. 2) highlights the gap in implementation support. Existing policy support instruments such as design guidelines drafted by BEE and India Infoline Finance Limited (IIFL), and the BMTPC compendium proposes passive design techniques, innovative materials and construction techniques for thermal comfort. They are, however, not sufficiently supplemented by implementation manuals and capacity building programs for implementing actors at the ULB level such as engineers, contractors, developers, and self-help groups.

While PMAY has a dedicated capacity building program, this does not hold true for most state sponsored affordable housing programs (WRI India Ross Center for Sustainable Cities, 2019). Additionally, even for the PMAY program, the capacity building program has limited focus on thermal comfort.

3.2 Roadmap to implementation

In order to address the gaps identified, there needs to be a standardized approach integrating thermal comfort in affordable housing that ensure the following:

(a) An integrated thermal comfort policy tailored to the Indian context and attuned to the 5 broad climatic zones, building codes addressing thermal comfort needs at the district/city level, notified design guidelines supplemented with implementation support toolkits, and a regulatory system enabling amendments of policy support instruments such as the Schedule of Rates at regular intervals.

(b) Convergence of thermal comfort policies with affordable housing policies at the Union and State level, to ensure all affordable housing units are thermally comfortable and energy-efficient. This should be compounded with a mandate for all states to have an integrated affordable housing policy.

A roadmap to implement this approach is further outlined.

3.2.1. Outlining redefined roles and responsibilities

An analysis of the current implementation mechanism (see Fig. 1) highlights the need for redefined roles and responsibilities for all actors, to ensure stronger penetration of policies at/ beyond the ULB level.

Table 2: Redefined roles and responsibilities in the implementation mechanism

Actor	Current role	Additional roles and responsibilities
Union	Formulation of policies and standards; Specialist committees to ensure policy implementation; Monitoring policy implementation at the State/ ULB level; Development of effective regulatory systems	Enable inter-ministerial coordination for better integration of thermal comfort and affordable housing policies; mandate integrated thermal comfort and affordable housing policies for all states; develop database for housing deficit (data coordination with ULBs); convergence between existing guidelines and compendiums to consolidate into one guideline that is standardized/ notified into building codes; coordinating lab/ ground testing of materials to be incorporated into CPWD Schedule of Rates (SoR) and State SoR
State	Adoption, compliance and enforcement; Approval of incentives; Consultation of policy revisions to union government	Mandate thermal comfort standards in all affordable housing policies; develop database of district/ city level climate conditions;
ULB	Building construction approvals; Policy compliance through document verification; Monitoring of projects on ground; Capacity building for Self-Help Groups (SHGs) under PMAY mission	Collection of data on district/ city level climatic conditions; data collection on housing deficit and demand; feedback on contextual challenges in policy implementation; education and awareness of end users on thermal comfort standards; capacity building of engineers, contractors, developers, SHGs on thermal comfort, energy-efficient material and construction techniques; monitoring and compliance of thermal comfort standards
Developers/ contractors/ Designers	Design and building construction; quality assurance; ensuring code compliance	Ensuring compliance of thermal comfort standards; capacity building in energy-efficient materials/ construction techniques; collect and communicate feedback on administrative compliance process
End users	SHGs – housing construction; consumers – buying housing	Provide feedback on implementation challenges; comply with thermal comfort standard for buying affordable homes

3.2.2. Establishing a participatory planning process

Robust feedback mechanisms to understand implementation side challenges can only be enabled through a strong participatory planning process. Such a process enables a bottom-up approach in the policy implementation process, with dedicated communication channels across all actors, as outlined in Table 3.

Table 3: Participatory planning process

Communication Channel	Feedback parameters
Union - State	Revisions to code as per suggestions; Capacity building for decision makers to augment policy implementation; Suggested changes in SoR from BMTPC studies
State - Union	Communicating data on housing deficit; Providing policy feedback received from ULB and Developers; Communicating district/ city level climatic requirements for incorporation in national policies
State - ULB	Changes in policy compliances; Incentives for adoption of policies; Information on data collection for district/ city level climate requirements; Information on data collection for housing deficit; Implementation support through manuals/ job aids; Amendments in SoR
ULB - State	Data on housing deficit; Data on city/ district level climate requirements; Implementation challenges faced by developers/ contractors/ end users; Project monitoring and evaluation on thermal comfort evaluation of completed projects
State - Developers/ contractors/ designers	Incentives on adoption of policies; Training/ capacity building for alternate materials/ const. techniques
Developers/ contractors/designers - State	Feedback on ease of compliance of policies and codes; Feedback on incentives for policy implementation
ULB - Developers/ contractors/ designers	Code compliance and monitoring systems; Capacity building and training for alternate materials/ const. techniques
Developers/ contractors/ designers - ULB	Feedback on ease of compliance of policies and codes; Implementation and verification of code compliance; Design and planning documents; Code compliance verification
ULB - End user	Education and awareness regarding thermal comfort policies and standards
Developers/ contractors/ designers - End user	Stages of design development; Materials and construction techniques; Maintenance standards
End user - Developers/ contractors/ designers	Suggestions and feedback on design; Affordability of materials; Feedback on ease of maintenance post completion; Feedback on thermal comfort post completion

3.2.3. Supplementing policies with implementation support

In addition to building a robust feedback system between all actors in the ecosystem, it is imperative to augment policy implementation at/beyond the ULB level with additional policy support instruments, as outlined below.

1. **Design guidelines** – A design guideline provides unit, block, and site level spatial standards on the practical application of thermal comfort policies. This includes the usage specifications of passive design techniques, alternate materials and construction techniques pertaining to thermal comfort. A comprehensive design guideline should also account for housing affordability through the choice of materials, construction techniques, and design recommendations.

2. **Implementation manuals** – An implementation manual provides support to the design guideline by detailing out procurement changes in the form of contractor agreements/guidelines for contractor selection pertaining to thermal comfort design implementation. It also provides material specifications, templates of standard Good for Construction (GFC) drawings, Bill of Quantities (BoQ) and other relevant tender documents. A comprehensive implementation manual also incorporates project monitoring tools such as Job Aids including site visit checklists, documentation methodology, survey methodology to ensure standardization in measuring policy compliance on ground.

3. **Maintenance manuals** – This document provides a step-by-step detail on maintenance of all components of the affordable housing unit and community facility, for developers/contractors responsible for maintenance, and for housing occupants. This also includes specific maintenance for special materials and equipment, along with the frequency of maintenance.

4. **Green Schedule of Rates (SoR)** – BMTPC is currently the nodal agency for testing alternate materials/techniques pertaining to thermal comfort, and suggesting amendments to the CPWD SoR. We recommend a new Schedule of Rates manual called the Green SoR which comprehensively covers all materials/techniques pertaining to thermal comfort and energy efficiency. Such a document should incorporate local material/techniques vetted by the BMTPC. It should also contain construction manuals to ease knowledge transfer for contractors/ engineers/developers etc. The

BEE is developing an online database of alternate materials (BMDI, n.d.), which can be incorporated into the Green SoR.

3.2.4. Providing a framework for capacity building

A sound capacity building program that caters to all relevant stakeholders is crucial for successful policy implementation. We recommend the development of a Centre of Excellence in each district/ city to deliver capacity building/ training on innovative construction. This can be incorporated within the ENS cell planned in each state. Multiple forms of training are recommended, as outlined.

a) Training on thermal comfort, energy-efficient building codes and regulations compliance for all stakeholders responsible for and affected by policy implementation

b) Knowledge/Awareness training for decision makers, junior to senior municipal engineers, energy officials responsible for policy implementation and recommendation on amendments.

c) Knowledge training for engineers/developers/contractors on passive design, material innovation and construction techniques, by subject matter/industry experts such as Indian Green Building Council (IGBC), Leadership in Energy and Environmental Design (LEED) professionals, and Architects. This should incorporate sessions on preparation of BoQs, integrating the Green SoR with rates from various departments, methods on writing contract agreements for implementation, operation and maintenance, and efficient integration of Public-Private Partnership (PPP) models.

d) Field training for actors responsible for project implementation on site monitoring, interagency coordination, sequencing of constructions, and post occupancy surveys and evaluation.

e) Design workshops for decision makers and implementing actors on thermal comfort and energy-efficient buildings. This should incorporate sessions with all utility agencies, energy departments and technical cells. Accountability for the capacity building program should be maintained through skill certifications which can be integrated with existing courses under the National Skill Development Council (NSDC).

4. Discussion

4.1 Convergence of thermal comfort and affordable housing policies for efficient policy implementation

Thermal comfort policies in India are drafted for the residential sector in general, with no specific consideration to affordable housing requirements. The implementation mechanisms have limited convergence between actors (see Fig. 1). Two affordable housing policies (PMAY and state led programs) further complicate the roles and interactions of actors. Suggett, (2011) captures the requisites for successful implementation of program-based policies: (a) leadership and role clarity, (b) focus on skills: program design, administration etc., (c) governance and project management regimes, (d) risk management and audit, (e) communication: internal and external, and (f) monitoring, transparency and accountability. Aspects such as leadership and role clarity can only persist in the presence of a clear institutional framework with clearly defined roles. In this paper, we attempt to understand the ambiguity and potential duplication of roles between actors at the State and ULB level, and identify redefined roles and responsibilities that converge the implementation of thermal comfort and affordable housing policies.

4.2 Participatory planning in public policy

Participatory planning and stakeholder involvement is essential to policy implementation. The United Nations Industrial Development Organization, (2022) report on participatory policy making demonstrates how involving local actors in various stages of decision making lead to a higher willingness for policy adoption. Conversely, a failure to involve stakeholders in the policymaking can lead to difficulties during implementation. A study by the World Resources Institute (2019) captures how a communication gap between Union, State, and ground-level implementation actors lead to reduced acceptance of the policy. In this paper, we address the need for robust communication that enables a mix of top-down and bottom-up approaches of policy implementation, and ensures a constant feedback of ground realities to further refine the policies or the implementation mechanism.

4.3 Program support at the implementation level

Successful implementation of policies is contingent to tactical support for implementing actors. Most regulatory instruments focus on a top-down policy implementation approach, relying on statutory language and administrative processes that ignore a supporting framework to translate policies on ground. In this paper, we discuss the need for supplementary policy instruments and capacity building at the implementation level.

4.4 Limitations of the study and future work

The scope of this paper is limited to understanding the roles, responsibilities of actors, feedback channels, and implementation support at the ULB level. However, this can be broadened to understand policy leverages and regulatory instruments such as mandating thermal comfort compliances in Environmental Impact Assessments, and amendment of building byelaws to incorporate thermal comfort guidelines and standards. Additionally, the research provided here is assimilated from secondary sources. Cross-examining the suggestions made here through stakeholder interviews on ground will lead to a more robust implementation framework.

5. Conclusion

In this paper, we discuss the implementation framework of thermal comfort policies in affordable housing. Through categorical exploration and thermal comfort and affordable housing policies and related instruments, it is evident that there exist sufficient resources for the implementation of thermally comfortable, energy-efficient affordable housing. However, the gap in implementation comes from a lack of standardization and convergence of the two policies, leading to duplication of roles, gaps in communication between implementing actors, and a lack of focus on strengthening implementation capacity on ground through relevant policy support instruments and a robust capacity building framework. To address this, we propose a new roadmap that builds onto an existing frame of resources, primarily advocating for a standardization and convergence of resources and information under the two types of policy in question. The roadmap outlines – (i) redefined roles and responsibilities for implementing actors, (ii) framework for a participatory planning process, (iii) policy support instruments such as implementation and maintenance manual, and a green SoR to ensure ease of construction, and (iv) a robust capacity building framework. The proposed roadmap has a two-fold intent – (i) ensuring affordable housing is thermally comfortable and energy-efficient, safeguarding consumers from extreme weather events and energy poverty, and (ii) developing a robust framework to ensure 100% penetration of infrastructure-based policies on ground.

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Study on thermal comfort zone in MM and HVAC office buildings in Aichi prefecture based on daily survey

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Abstract

Thermal comfort has been a subject discussed since 1930. Researchers are into understanding the thermal comfort of the occupant's whether at home, offices, educational institutions because the occupants have significant effects on their indoor environment. In this study we aim to understand the comfort temperature ranges in Mixed-mode (MM) and Heating, Ventilation, and Air Conditioning (HVAC) types of office buildings in Japan. The field data is collected in six office buildings located in Aichi prefecture from July 2021 to October 2022, where 16,411 responses were collected from 46 occupants. The environmental parameters such as air temperature, relative humidity, and so on were measured along with the responses. The result suggests that the office workers are highly satisfied and they are adapted to the indoor environment, as in the MM office buildings 80 % of the occupants were comfortable at the temperature range of 19~29 °C whereas in HVAC office building this range was 22~27 °C. MM office buildings had wider range of thermal comfort zone even under HT and CL mode as compared to HVAC buildings which suggests that the MM type of buildings are better than HVAC.

Keywords - Office buildings, Field survey, Thermal sensation vote, Globe temperature, Probit analysis, Thermal comfort zone.

1. Introduction

The energy consumption of the office building plays a significant role in terms of the country's overall energy consumption. In 2019, the commercial sector's buildings accounted for 30% of Japan's final energy consumption, according to the report given by the International Energy Agency [1]. The fact that fully air-conditioned office buildings with fixed windows are becoming increasingly fascinating and trendy [2]. However, the pandemic 2019 has focused on the idea of having mixed mode (MM) operated office buildings even if the office buildings are in HVAC operation mode as stated by Hayashi et al. [3]. Concurrent MM building operations are the office building having both natural ventilation and the air-condition system strategies whenever required [4]. MM buildings have the potential to offer higher degree of thermal comfort as the occupants can prefer to choose the environment according to their desire [5] and are reported to use less energy [6]. Japanese government recommend an indoor temperature of 28 °C for cooling and 20 °C for heating [7] which requires an evidence from the field survey [8] as Takasu et al. [9] mentions that this recommendation was considered focusing on making it easier for the office occupants to be comfortable based on the outdoor thermal environment. The author also adds that just by shifting the temperature and changing occupants' clothing may not achieve the improvement towards improving comfort and reducing the energy consumption [9].

According to ASHRAE 55, thermal comfort is achieved when the indoor environmental conditions can satisfy 80 % of the occupants [10]. Understanding the range of temperature to which these occupants are mostly satisfied can be considered as the thermal comfort zone. Aghniaey et al. [11] stated that it will be possible to reduce energy consumption through correct adjustment of the temperature range. Kim et al. [12] emphasized the importance of understanding the thermal sensation and the comfort zones to maximize the energy saving. In HVAC office buildings of China [13], the thermal comfort zone was obtained as 24.6-28.6 °C from 442 occupants whereas in a study conducted in the temperate climate of Romania [14], it was 22.6-26 °C in HVAC types of office buildings. These previous studies suggest that the thermal comfort zone can be obtained differently for different climatic zones.

With the above view, this study aims to determine thermal comfort zones through comparative analysis between MM and HVAC types of Japanese offices by use of probit analysis method.

2. Methods

Thermal comfort field survey was applied in MM and HVAC types of office buildings located in Aichi prefecture which lies in the central part of Japan having the climate characterized by hot and humid summers and relatively mild winters (Köppen climate classification Cfa, i.e. humid subtropical climate).

2.1 Investigated buildings and measurement period

Field studies were conducted within five MM and one HVAC office buildings located in Ichinomiya and Nagoya city of Aichi prefecture in Japan from July 2021 until October 2022. The chosen office buildings were of changeover mixed-mode type having operable windows and the HVAC systems depending on the seasons or the time of the day [4]. Table 1 summarizes the general information about the buildings, its locations and mode of operation along with their occupants. All the office buildings were equipped with HVAC systems; however, in five MM office buildings use was according to the seasons and time of the day, and one HVAC building has AC use throughout the year. Figure 1 shows the pictures of the investigated office buildings [15].

For the outdoor environmental data, it consists of daily mean, maximum and minimum temperature and the relative humidity values for the fifteen months from July 2021 until September 2022 that was collected from the meteorological station of Aichi prefecture. Figure 2 shows the monthly mean outdoor air temperature with relative humidity for the surveyed period. In case of the indoor environmental parameters, it was recorded by using the data loggers instrument set up which is placed 1.1 m above the floor level which was placed away from direct sunlight. The measurement of the indoor and the outdoor air temperature with relative humidity were collected at continuous ten-minute intervals.

Table 1: Summary of investigated office buildings and subjects

Building mode	Building code	Area	Building structure	Air-conditioning adjustment methods	No. of occupants	
					Male	Female
MM	N1	Ichinomiya City	SRC	Distributed	2	2
	N2	Nagoya City	RC	Distributed	3	5
	N4	Nagoya City	SRC	Distributed	5	3
	N5	Nagoya City	SRC	Distributed	9	1
	N7	Nagoya City	RC	Distributed	3	2
HVAC	N6	Nagoya City	SRC	Central	6	4
Total					28	17

MM: Mixed-mode, HVAC: Heating, Ventilation and Air-conditioning, SRC: Steel reinforced concrete, RC: Reinforced concrete construction

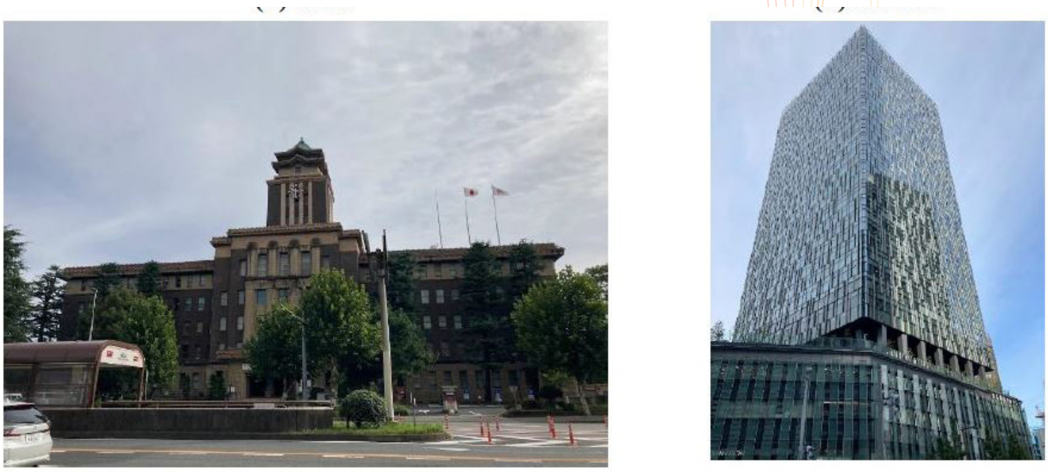


Figure 1: Overview of investigated office buildings [15]

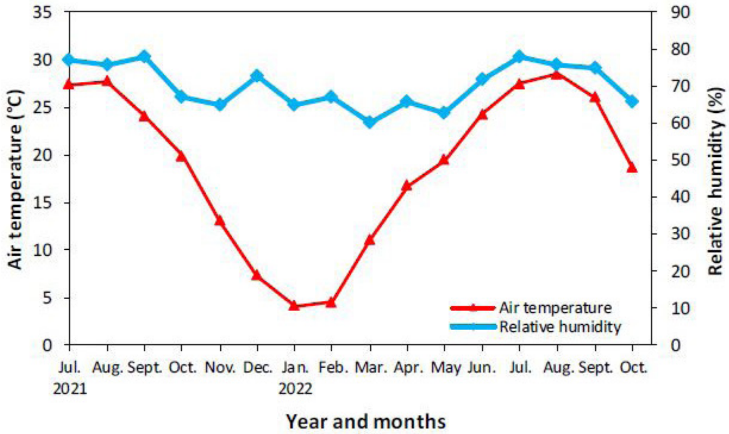


Figure 2: Monthly outdoor air temperature and relative humidity of the investigated area during survey period

2.2 Thermal comfort survey

Thermal comfort survey is a questionnaire that is used to assess the thermal comfort perceptions of the occupants' in the office buildings. The questionnaire was designed based on the work of previous researchers on the field of thermal comfort survey questionnaire which was divided into three sections. The initial section of this survey was collecting the personal information of the participants, second section was the occupants' thermal perceptions, satisfactions and the preferences. The final sections are the questions regarding the perceived level of the environmental control and its use. This survey uses the modified thermal comfort ASHRAE scale (Table 2). The questionnaire sheets were distributed to the office workers and the purpose of the survey and how to fill out the questionnaire were explained briefly in the first month of the survey started period. However, two office buildings carried out the survey using a PC. The occupants were asked to fill the questionnaire four times a day. The questionnaire was replaced every two months. The survey was conducted in the Japanese language.

Table 2: Scale of thermal sensation vote survey scale

No.	Scale
1	Very cold
2	Cold
3	Slightly cold
4	Neutral (Neither cold or hot)
5	Slightly hot
6	Hot
7	Very hot

3. Results and discussion

This research applies various analyses in the process to understand the thermal comfort of the occupants in the office buildings. The first approach is to investigate the overall environmental conditions during the survey periods following the comfort zone for the MM and HVAC office buildings with the help of probit analysis.

3.1 Thermal environment during voting

The mean outdoor air temperature and mean globe temperature for MM and HVAC office buildings are shown in Table 3 enlisting different modes (i.e. free running mode (FR), heating mode (HT), cooling mode (CL)) respectively.

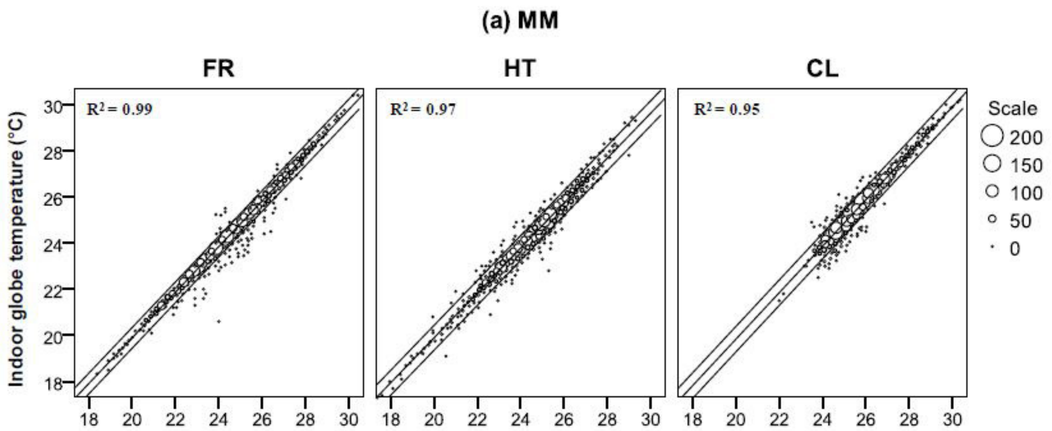
In the present study, Figure 3 indicated indoor air temperature is strongly correlated with the indoor globe temperature which is clear that these indices were similar (i.e. difference <0.5 °C) [8, 16, 17]. This result showed that any one of these temperature indexes was suitable for the later analysis process. In this study globe temperature is considered as it measures the combined effects of radiant heat, air temperature, and wind speed.

Distribution of the globe temperature is shown in Figure 4 for MM and HVAC office buildings. Most of the indoor globe temperature is obtained between 22~28 °C in MM and 22~26 °C in HVAC. The mean globe temperature of MM office buildings for HT and CL were 24.4 °C, 25.5 °C whereas in terms of HVAC buildings, they were 24.6 °C and 24.5 °C respectively. However, in consideration, with the Japanese government recommended indoor temperature of 20 °C in winter and 28 °C in summer in terms of energy savings. In this case, mean indoor temperatures during HT and CL modes were 3~4 °C different from the recommended values for both MM and HVAC office buildings. These results are similar to the previous study in Japanese office buildings [8, 16].

Table 3: Environmental parameters during voting period

Building type	Mode	N	T_{out} (°C)	T_g (°C)
MM	FR	3,943	19.4	24.6
	HT	4,592	9.8	24.4
	CL	3,984	29.0	25.5
HVAC	HT	2,685	15.1	24.6
	CL	992	25.9	24.5

MM: Mixed-mode, HVAC: Heating, Ventilation and Air-conditioning, FR: Free running mode, CL: Cooling mode, HT: Heating mode, N: Number of sample, T_{out}: Outdoor air temperature, T_g: Indoor globe temperature



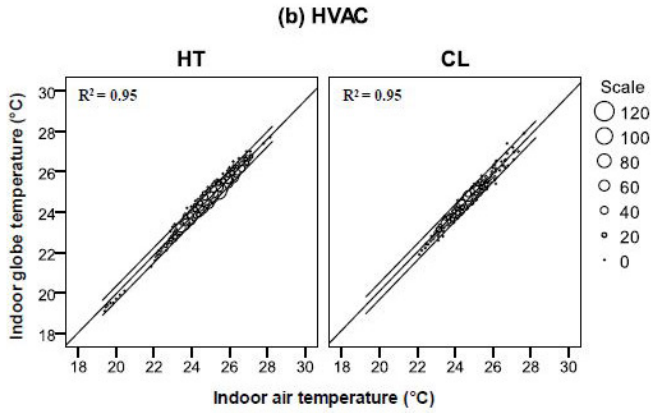


Figure 3: Relationship between indoor globe and air temperature

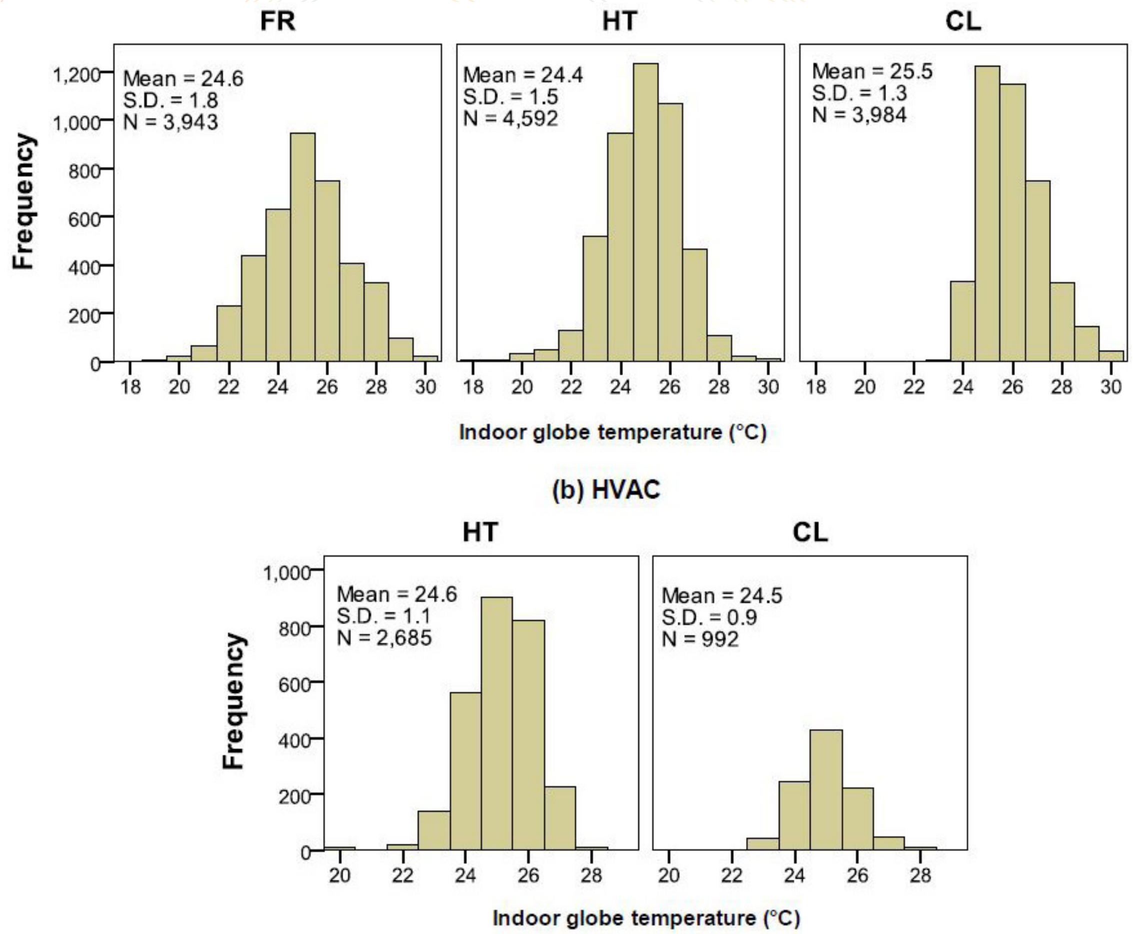


Figure 4: Distribution of globe temperature of MM and HVAC office buildings

3.2 Distribution of thermal sensation vote

Figure 5 shows the distribution of thermal sensation votes of the occupants in MM and HVAC office buildings. The highest number of votes were "4. Neutral". The mean thermal sensation vote in Figure 5 suggests that the occupants of both MM and HVAC office buildings were highly satisfied with the thermal environment of the offices as most of the votes are in comfort zones (i.e. "3. Slightly cold" "4. Neutral" and "5. Slightly hot").

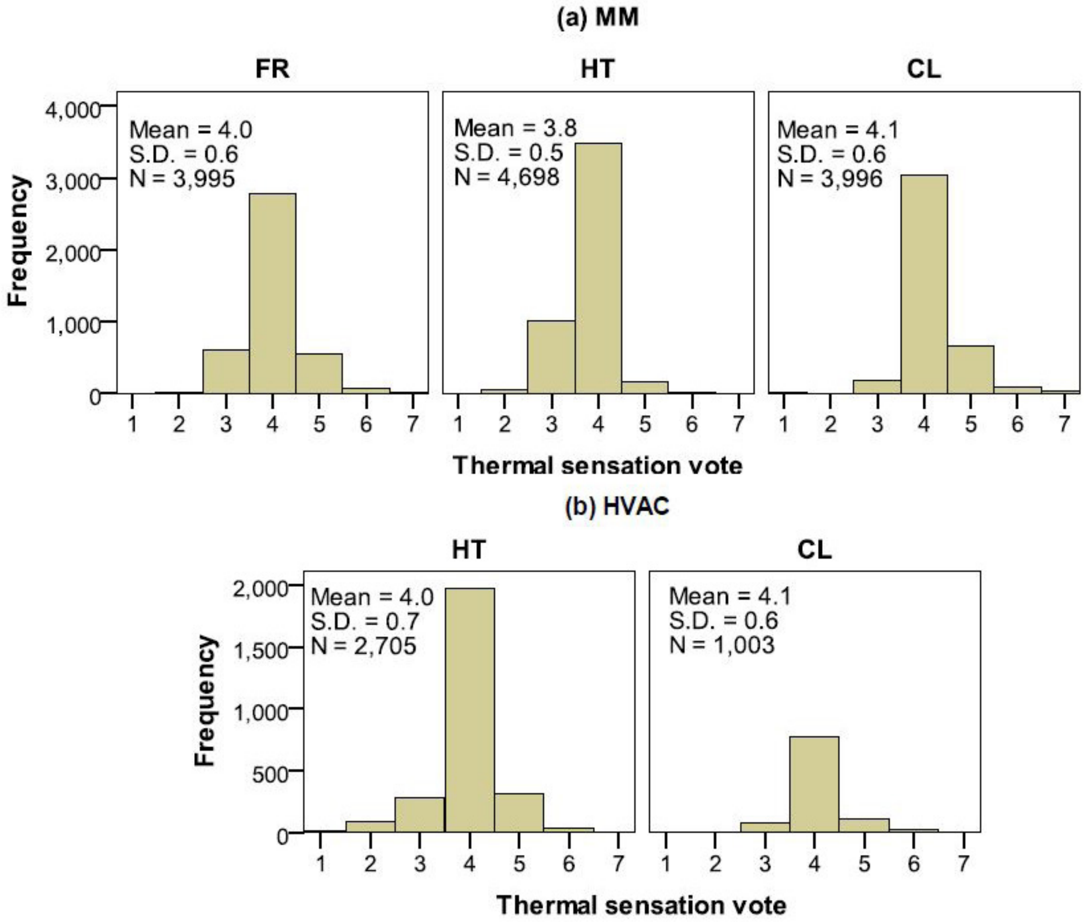


Figure 5: Distribution of thermal sensation votes

3.3 Thermal comfort zone

According to ASHRAE, thermal comfort is achieved when the indoor environmental conditions can satisfy 80 % of the occupants. Understanding the range of temperature to which these occupants are mostly satisfied can be considered as the thermal comfort zone. In this section, the thermal comfort zone is considered to be 3-5 on the subjective thermal sensation scale.

To locate the thermal comfort zone, probit regression analysis was conducted for the thermal sensation votes categories and temperature for MM and HVAC buildings. The analysis method is ordinal regression method using probit as the link function and the temperature as the covariate as done by Rijal et al. [18]. Probit analysis results are shown in Table 4. The temperature corresponding to the mean response (probit = 0) is calculated by the regression coefficient (for e.g. the mean temperature for the first equation will be 5.564/0. 0.354 = 15.7 °C). The inverse of the probit regression coefficient is considered as the standard deviation of the cumulative normal distribution (i.e. 1/0.354 = 2.8 under FR mode in MM buildings). All these calculations are calculated and shown in Table 4. After getting the equations and all the required variables, we transformed the probits using the following function into proportions which gave the curves for all the values as shown in Figure 6. The vertical axis is the proportion of the votes and comfortable.

$$Probability = CDF.NORMAL\,(quant, mean, S.D.) \qquad (1)$$

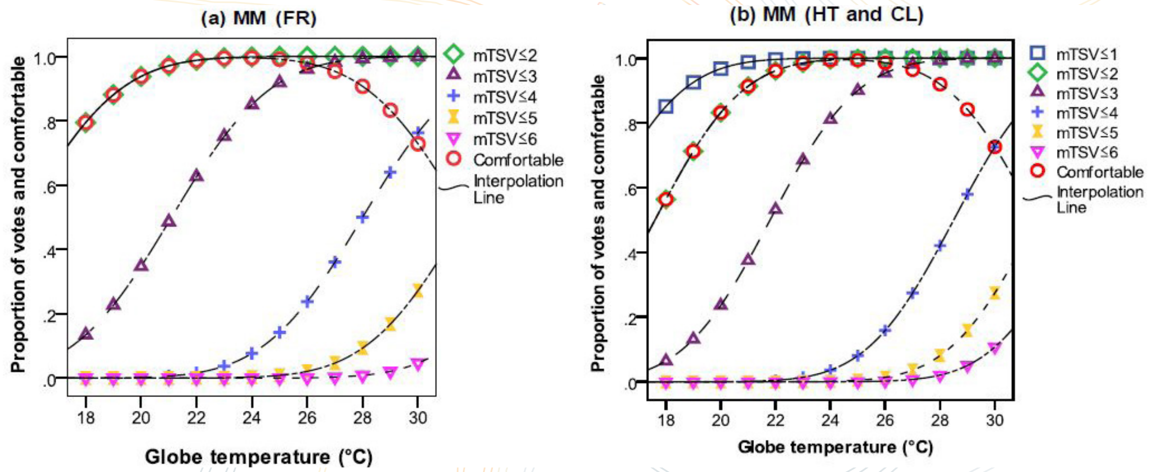
Where, CDF.NORMAL is the cumulative distribution function for the normal distribution; quant is the indoor globe temperature (°C); mean and S.D. are given in Table 4. Considering to take an example, the highest line with square markers in Figure 6 (a) defines the proportional area for TSV 1 (Very cold) and TSV 2 (Cold) and so on until the lowest line of inverted triangle 6 (Hot) and TSV 7 (Very hot) below it. As the globe temperature increased, the proportion of people who voted for TSV 2 increased, and the proportion of the occupant who voted for hot sensation increased.

Using TSV 3, 4, and 5 as the comfortable range, the probits were transformed into proportions which resulted in a bell-curve as illustrated by Rijal et al. [18]. In all meaning whether that be MM, FR mode and HT or CL mode of MM and HVAC office buildings proportion of comfort was obtained at higher level. In the MM office buildings 80 % of the occupants were comfortable at the temperature range of 19~29 °C whereas in HVAC office buildings this range was 22~27 °C. MM is further analyzed by FR category as well as HT or CL combined. The FR mode in MM office buildings showed that the range for comfort zone is 18~29 °C. HT and CL mode for MM office buildings had the comfort zone of 20~29 °C. The results suggest that MM office buildings have a wider range of comfort zones as compared to HVAC buildings. Even if we analyzed the HT and CL mode, the range of comfort zone is wider than the HVAC which means that the occupant had adaptive opportunities in the HT and CL mode in the MM office buildings. This proves that MM is better than HVAC as HVAC occupants are compelled to be comfortable in a narrow range of comfort zones.

Table 4: Probit analysis

Bldg.	Mode	Equations*	Mean	S.D.	N	R^2	S.E.
MM	FR	$TSV\ (\leq 2)$=0.354 T_g-5.564	15.7	2.8	3,941	0.23	0.012
		$TSV\ (\leq 3)$=0.354 T_g-7.481	21.1				
		$TSV\ (\leq 4)$=0.354 T_g-9.917	28.0				
		$TSV\ (\leq 5)$=0.354 T_g-11.222	31.7				
		$TSV\ (\leq 6)$=0.354 T_g-12.290	34.7				
	HT and CL	$TSV\ (\leq 1)$=0.397 T_g-6.117	15.4	2.5	8,575	0.19	0.010
		$TSV\ (\leq 2)$=0.397 T_g-7.004	17.6				
		$TSV\ (\leq 3)$=0.397 T_g-8.638	21.8				
		$TSV\ (\leq 4)$=0.397 T_g-11.319	28.5				
		$TSV\ (\leq 5)$=0.397 T_g-12.491	31.5				
		$TSV\ (\leq 6)$=0.397 T_g-13.147	33.1				
	All	$TSV\ (\leq 1)$=0.373 T_g-5.360	14.4	2.7	12,516	0.20	0.007
		$TSV\ (\leq 2)$=0.373 T_g-6.314	16.9				
		$TSV\ (\leq 3)$=0.373 T_g-8.030	21.5				
		$TSV\ (\leq 4)$=0.373 T_g-10.617	28.5				
		$TSV\ (\leq 5)$=0.373 T_g-11.828	31.7				
		$TSV\ (\leq 6)$=0.373 T_g-12.586	33.7				
HVAC	HT and CL	$TSV\ (\leq 1)$=0.534 T_g-9.928	18.6	1.9	3,687	0.17	0.021
		$TSV\ (\leq 2)$=0.534 T_g-10.946	20.5				
		$TSV\ (\leq 3)$=0.534 T_g-11.821	22.1				
		$TSV\ (\leq 4)$=0.534 T_g-14.361	26.9				
		$TSV\ (\leq 5)$=0.534 T_g-15.517	29.1				
		$TSV\ (\leq 6)$=0.534 T_g-16.569	31.0				

Notes: *All regression coefficient are significant ($p<0.001$).
$TSV(\leq 1)$: Probit of the proportion of vote that is for 1, $TSV(\leq 1)$: Probit of the proportion of vote 2 and so on, S.D.: Standard deviation, N: Number of sample, R^2: Coefficient of determination and S.E.: Standard error of the regression coefficient



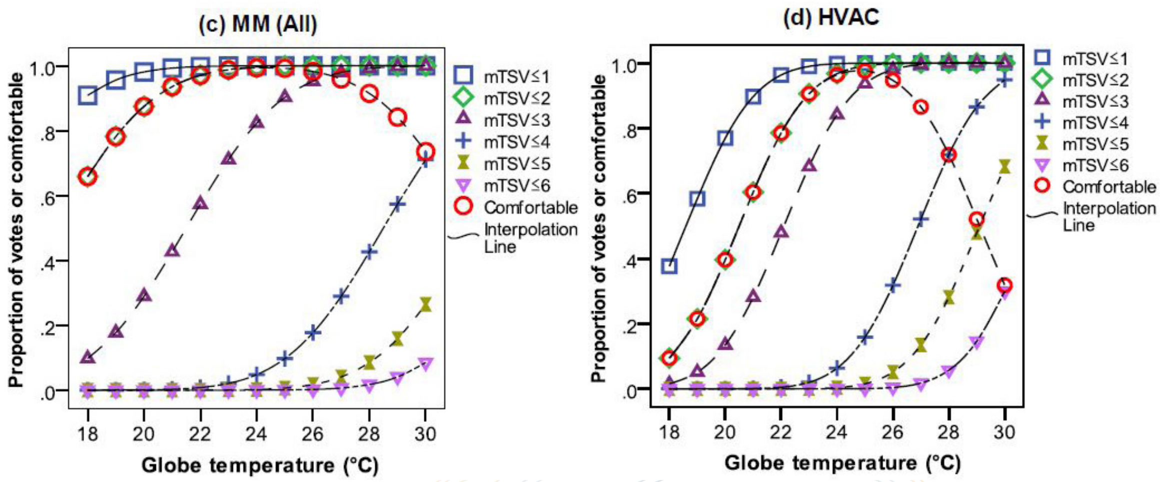


Figure 6: Proportion of votes or comfortable

4. Conclusions

By analysing the data from the field survey at Aichi prefecture, Japan in five MM and one HVAC office building the following conclusions are obtained.

1. The mean globe temperature of MM office buildings for HT and CL were 24.4 °C and 25.5 °C whereas in terms of HVAC buildings, they were 24.6 °C and 24.5 °C respectively. These mean indoor temperatures for HT and CL modes were 3~4 °C different from the recommended values by the Japanese government.

2. The occupants are satisfied with the thermal environment of both MM and HVAC office buildings as most of the thermal sensation votes were in the comfort zone (i.e. "3. Slightly cold" "4. Neutral" and "5. Slightly hot"). From all the data 98% of the occupants in MM and 95% in HVAC were in the comfort zone.

3. MM office buildings had a wider range of thermal comfort zones even under HT and CL mode (20~29 °C) as compared to HVAC buildings (22~28 °C) which suggests that the MM type of buildings are better than HVAC.

5. Acknowledgements

We would like to sincerely thank to the Itsuwa Denki Kogyo Co., Ltd., Kimura Kohki Co., Ltd., SEEDS Co., Ltd., Shinwa Electric Co., Ltd., Yasui Architects & Engineers, Inc. and the local government for their kind cooperation. This research is supported by the Grant-in-Aid for Scientific Research (B) (21H01496). This work was also supported by JST SPRING, Grant Number JPMJSP2118.

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Study on comfort temperature in Autumn season of naturally ventilated office building in Kathmandu

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Abstract

Considering the strong connection between thermal comfort and productivity, it is crucial to establish guidelines for creating a comfortable indoor environment in office buildings. As one of the rapidly growing metropolitan areas in Southeast Asia, Kathmandu valley has witnessed notable changes in land use and cover, particularly in the commercial sector. In this context, we conducted a thermal comfort study in the summer season to determine the comfort temperature in free-running office buildings. In total 148 votes have been collected from a questionnaire survey from four free-running office buildings. Simultaneously, we measured the thermal environment, including air temperature, globe temperature, and relative humidity. We have calculated the comfort temperature from Griffiths' method and found the comfort temperature as 26.9°C. When the fan is on, the comfort temperature is 27.5°C which is 1.3°C higher than when the fan is off. These findings provide valuable insights for creating a comfortable indoor environment in office buildings in Kathmandu valley during the summer season

Keywords - Office building, Free running, Griffiths' method, Comfort temperature

1. Introduction

The number of studies on indoor thermal comfort has significantly increased as a result of the fact that people spend the majority of their time indoors. Because of the shared use of space and organizational culture, office workers have fewer adaptation opportunities than those in other building types [1, 2]. As a result, in terms of giving adaptive options to users, the mode of building can have a considerable contextual impact on occupants' thermal experiences. Thermal comfort studies in office buildings have been conducted in various countries worldwide. A literature review [3] conducted in adaptive thermal comfort studies in office buildings highlighted that existing comfort standards may not be universally applicable to all climates as comfort temperatures in tropical areas tend to be higher than in colder climates and also within the same location, the comfort temperature in winter is typically lower than in summer. Although there are various modes of office, in this study we focused mainly on the freerunning mode: runs freely without Heating ventilation and air conditioning (HVAC) system.

Nepal's urban population has experienced a significant annual growth rate of 4.7%[4]. Kathmandu valley has undergone major transformations in its land use and land cover, especially in the commercial sector. In fact, Kathmandu is recognized as one of the rapidly developing urban agglomerations in South East Asia [5]. The builtup area of the Kathmandu valley has expanded from 38 square kilometers in 1990 to 119 square kilometers in 2012, representing a staggering 211% increase while the proportion of mixed-use buildings has skyrocketed by 524% [6]. And almost all modern office buildings are equipped with HVAC systems. However, Kathmandu being in a temperate climate, various researches [7, 8] have found that there is need of active heating only in a few months. As a result, thermal comfort requirements are essential to optimize the HVAC load. Few relevant studies have been conducted in Nepal, but only in the residential sector [9, 10]. Building regulations in Nepal are primarily concerned with safety, which is the first priority, and not with energy use. In the lack of norms, designers adhere to the strict ASHRAE standard to provide a fully air-conditioned (AC) environment, which leads to over-design and enormous energy consumption. As a result, conducting a thermal comfort survey of office occupants and examining the thermal environment is vital in order to develop a thermal comfort standard for office buildings. The primary objective of this research is to determine the comfort temperature for office buildings in Kathmandu valley during the summer season.

2. Methods

This study lies within the post-positivist paradigm and hence uses quantitative methods for the investigation. After literature review, four free running buildings have been selected from Kathmandu valley as shown in Figure 1. The questionnaire survey method has been employed. At the same time, the thermal environment (air temperature, globe temperature, air velocity and relative humidity) of office buildings has been measured with the help of different equipment. Then, by analyzing the data, comfort temperature has been identified for the summer season in Kathmandu.

2.1 Investigated buildings

Studies were conducted within four free-running office buildings located in Kathmandu valley as shown in Figures 1 and 2. The monthly survey was conducted during the summer season from May to August 2023. Table 1 summarizes general information about the buildings. Office 1 and 3 are located in Lalitpur district whereas office 2 and 4 are located in Kathmandu district. All buildings are reinforced cement concrete (RCC) frame structure. We studied only those floors where we got permission for survey. Out of total votes of 148, 104 votes were from males and the rest were from females.

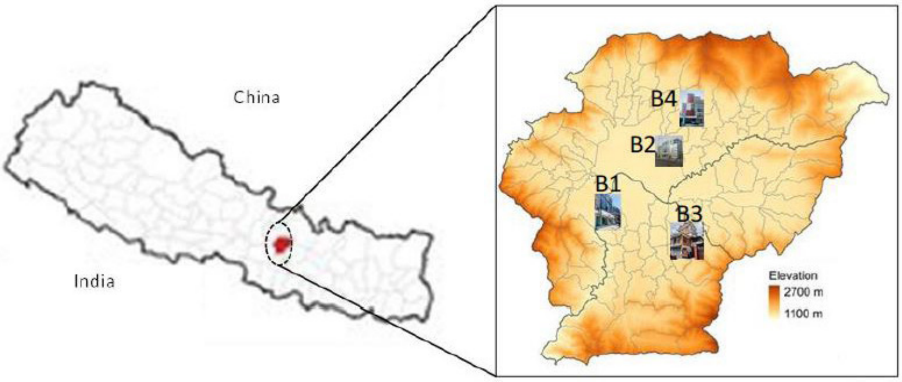

Figure 1: Map of Nepal showing study area

2.1 Investigated buildings

Studies were conducted within four free-running office buildings located in Kathmandu valley as shown in Figures 1 and 2. The monthly survey was conducted during the summer season from May to August 2023. Table 1 summarizes general information about the buildings. Office 1 and 3 are located in Lalitpur district whereas office 2 and 4 are located in Kathmandu district. All buildings are reinforced cement concrete (RCC) frame structure. We studied only those floors where we got permission for survey. Out of total votes of 148, 104 votes were from males and the rest were from females.

Table 1: General information about the building

Building	Investigated floor	Structure typology	Main orientation	Number of female votes	Number of male votes	Total no. of votes	Studied period
Office 1 (B1)	First & Second	RCC	South	8	22	30	June and July
Office 2 (B2)	Third and fourth	RCC	South	6	53	59	May, June, and July
Office 3 (B3)	Ground and first	RCC	Southwest	17	13	30	June and July
Office 4 (B4)	First, Fourth, Sixth & Seventh	RCC	East	13	16	29	August
Total				44	104	148	

RCC: Reinforced cement concrete

Figure 2 Picture of investigated office buildings

2.2 Thermal comfort survey

The thermal comfort survey used here was adopted from previous thermal comfort studies conducted through field studies by many researchers [11-14]. Monthly thermal comfort survey has been done in various offices in summer. During the day of field measurements, the thermal comfort survey forms were distributed to the occupants and they were asked to fill out and return the survey forms at the end time of the measurements. Hence, the occupant perceptions of their thermal environment on a 'right here-right-now' basis were recorded. The seven-point scale of the modified ASHRAE standard was used for the thermal sensation and the five-point scale was used for thermal preference in the questionnaire survey as shown in Table 3. For the thermal environment measurement, HOBO data logger was used to measure outdoor air temperature and relative humidity whereas for the indoor environment, globe thermometer for globe temperature, CO2 recorder for air temperature and humidity, and anemometer for the air velocity was used (Table 2). The equipment was positioned 1.1 meters above the floor level (Figure 3).

Table 2: Detail of instrument

Instrument	Operating range	Accuracy
Hobo data logger	-40 to 70°C , 0 to 100%	± 0.25°C
CO_2 Recorder TR-76Ui	0 to 55°C , 10 to 95%RH, 0 to 9999 ppm	± 0.5°C , 5%, ± (50 ppm + 5% of reading)
Thermo Recorder TR-52i	-60 to 155°C	± 0.3°C , (-20 to 80°C)
TSI 9535-Anemometer	0 to 30 m/s / -10 to 60°C	3% of reading or ±3 ft/min whichever is greater/ ± 0.3°C

Figure 3: Instruments and thermal comfort survey

Table 3: Scale used in survey

Scale	Thermal sensation	Thermal preference
1	Very cold	Much warmer
2	Cold	A bit warmer
3	Slightly cold	No change
4	Neutral	A bit cooler
5	Slightly hot	Much cooler
6	Hot	-
7	Very hot	-

3. Results and discussion

3.1 Indoor and outdoor thermal environment

In summer , the range of mean outdoor air temperature of Kathmandu is 15.7-28.4°C [15]. But in the voting time, the range of outdoor air temperature was 23.9-29.8°C and relative humidity was 38-83%. Whereas, the range of indoor temperature was 24.9-30.9°C and relative humidity was 35-74%. The mean outdoor temperature was 25.9°C, mean indoor temperature was 28°C and mean relative humidity was 56%.

3.2 Indoor thermal environment

Indoor thermal environment (air temperature and globe temperature) has been measured while doing a thermal comfort survey of the occupants. Because of the strong correlation between the indoor globe temperature and the indoor air temperature (Figure 4), the findings may be discussed just using the globe temperature.

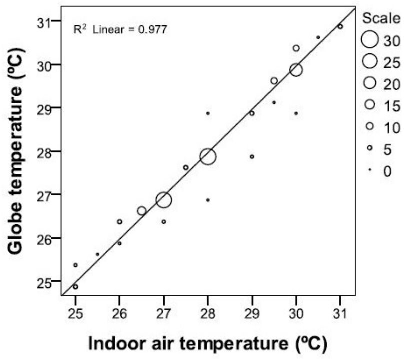

Figure 4: Relation between globe temperature and indoor air temperature

3.3 Thermal sensation and preference vote

Thermal sensation and preference vote has been gathered from the office occupants during office hours. Then, we have analyzed the thermal sensation vote (TSV) and thermal preference vote (TP) using the information gathered during the survey. Out of all the thermal sensations, 45.3% of the votes were for neutral temperature, while 35.1% were for slightly hot, 9.5% were for hot, 8.1% were for slightly cold and 2% of votes were for very hot. In the same thermal environment, the percentage of no change in thermal preferences has changed to 35%, and the percentage of warmer has reached 55% of total vote as shown in Table 4 and Figure 5. The relationship between thermal preference and thermal sensation vote is illustrated in Figure 6. The center three categories (votes 3, 4 and 5) on the thermal sensation can be regarded as comfortable (the thermal comfort zone) [16-18]. In this study, around 90% of the votes fall into three center categories, indicating that the office occupants are comfortable in their thermal environment.

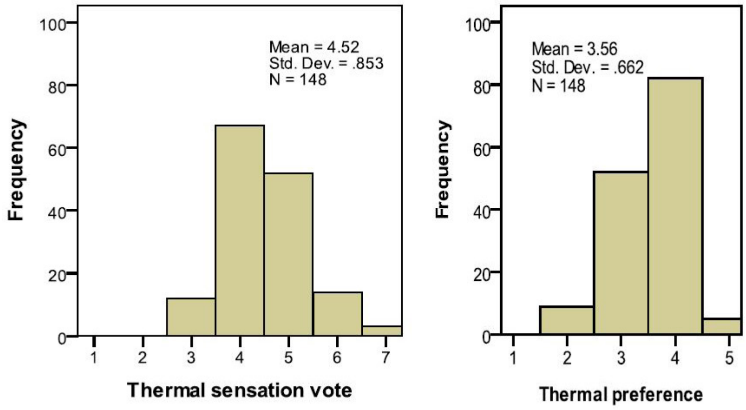

Figure 5: Distribution of number of votes for TSV and TP

We have derived equation (1) to describe the relationship between thermal preference and thermal sensation vote. Interestingly, we found that some individuals preferred to shift from a neutral sensation to a much warmer one. This suggests that a neutral thermal sensation doesn't guarantee thermal comfort, as people may desire different sensations even when feeling neutral. Several researchers [19, 20] have also highlighted that thermal preference is a more reliable indicator of thermal comfort than thermal sensation.

$$TP = 0.35TSV + 1.96 \text{ (N= 148, } R^2 = 0.21\text{, S.E. = 0.057, P<0.001)} \qquad (1)$$

Where, TP: Thermal preference, TSV: Thermal sensation vote, N: Number of vote, R^2: Coefficient of determination, S.E: Standard error of regression coefficient, p: Significant level of regression coefficient

Table 4: Percentage of thermal sensation and preference

Scale	Thermal sensation		Thermal preference	
	Number of vote	Percentage (%)	Number of vote	Percentage (%)
1	-	-	-	-
2	-	-	9	6.1
3	12	8.1	52	35.1
4	67	45.3	82	55.4
5	52	35.1	5	3.4
6	14	9.5	-	-
7	3	2	-	-
Total	152	100	152	100

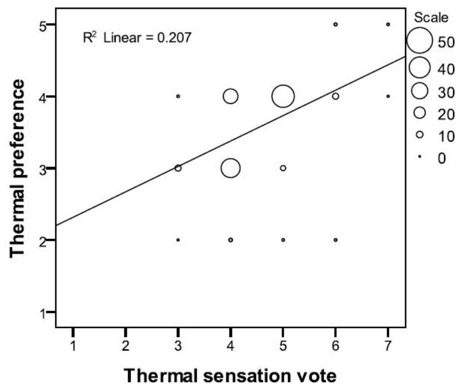

Figure 6: Relation between thermal preference and thermal sensation vote

3.4 *Prediction of comfort temperature*

The comfort temperature is the indoor temperature at which the average subject votes neutral on the thermal sensation scale. One of the key outputs of thermal comfort field survey data analysis is comfort temperature. The linear relationship between thermal sensation and indoor globe temperature determines the comfort temperature (Figure 7). The regression coefficient derived from the regression analysis is used to assess the participants' sensitivity. We derived the linear regression equation (2) shown below.

$TSV = 0.19T_g - 0.99$ (N= 148, $R^2 = 0.134$, S.E. = 0.041, P<0.001) (2) Where, T_g: Indoor globe temperature (°C)

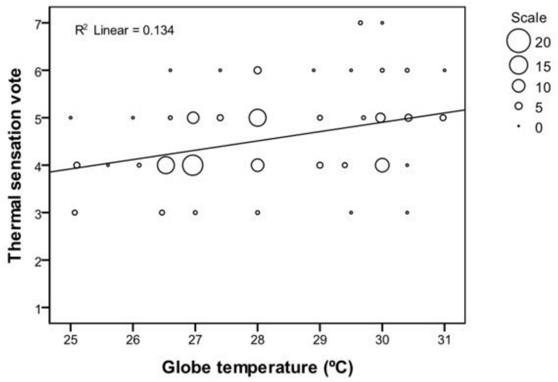

Figure 7: Relation between thermal sensation and globe temperature

In equation 2, the regression coefficient is 0.19, i.e. 5.3°C (=1/0.19) is needed to shift one thermal sensation vote. 5.3°C to change one thermal sensation vote seems outrageous. Sometimes when the TSV is situated away from the neutral point, the linear regression method often leads to an extraneous value as identified by Thapa et al. [21] and Indraganti [22], this was also reviewed by Lamsal et al. [3]. So, in this study, we used Griffiths' approach to calculate the comfort temperature. Griffiths' method is especially useful when the temperature variance during the field survey is not much and a small amount of data is insufficient to provide a valid regression to estimate the comfort temperature. The following equation is used to calculate Griffiths' comfort temperature (Tc);

$$T_c = T_g + (4 - TSV)/a \quad (3)$$

Where,
T_c: Comfort temperature (°C)
T_g : Indoor globe temperature (°C)
a : Griffiths' constant (0.5)

The regression coefficient 0.5 was adopted here, which was adopted by many researchers [11, 13, 23]. For each comfort vote, we calculated the Griffiths' comfort temperature. We found a mean comfort temperature of 26.9°C. The result of this study has been compared with different studies for the summer season in free-running or naturally ventilated office buildings as shown in Table 5. Indraganti et al. [24] and Dhaka et al. [25] found slightly higher values of comfort temperature in India. Rijal et al. [9] found 25.6 °C as summer comfort temperature in temperate climates while doing the study in dwellings, which is more similar as found in this study.

Due to the summer season, 60% of occupants in office buildings are using ceiling or table fans for better thermal comfort. Air movement is key in determining the optimal indoor temperature for comfort in tropical climate [30]. According to a theoretical analysis [31], if the air movement is consistently above 0.1 m/s, it can be like increasing the comfort temperature. Humphreys and Nicol [32] found that increasing the air movement to 1 m/s is equivalent to lowering the globe temperature by some 3°C while doing the studies in UK office building.

Table 5: Comfort temperature found in various studies for summer season in FR or NV office building

Country/City	References	Mode	Variable for T_c	T_o (°C)	T_g, T_a (°C)	T_c (°C)
This study	-	FR	T_g	25.9	28	26.9
India/Chennai, Hyderabad	Indraganti et al. [24]	NV	T_g	25.6	28.8	28
India/ Jaipur	Dhaka et al. [25]	NV	T_g	34	31.9	29.4
India/Darjeeling	Thapa et al. [21]	NV	T_a	19.8	21.7	21.8
Japan/ Tokyo	Indraganti et al. [27]	NV	T_g	27.5	29.4	25.8
Japan/ Fukuoka	Mustapa et al. [28]	FR	T_{op}	28	28.1	26.6
Japan/ Tokyo, Yokohama	Rijal et al. [13]	FR	T_g	24.6	25.8	25.7
Indonesia/ Bandung	Damiati et al. [26]	FR	T_{op}	22.5	26.7	24.7
Australia/ Sydney	Hindmarsh [29]	FR	T_{op}	21.6	-	24.2

FR: Free Running, NV: Naturally ventilated, T_g: Globe temperature, T_{op}: Operative temperature, T_a: Indoor air temperature

Figure 8 shows the comfort temperature under the use of a fan. Occupants were feeling comfortable even in a higher temperature due to the effect of fan. The comfort temperature is 27.5 °C when the fan is on and it is just 26.2 °C when the fan is off. The comfort temperature is significantly higher when the fan is on. Rohles et al. [33] found that a ceiling fan with a velocity of 0.5 to 1.0 m/s compensates for a temperature shift of 2.8-3.3 °C. Rijal [34] found 2.2 °C higher comfort temperature when the fan is on in the study done in Pakistan. Nicol [30] also found that if there are fans available for the building occupants, it's possible to increase the predicted comfort temperature by 2°C.

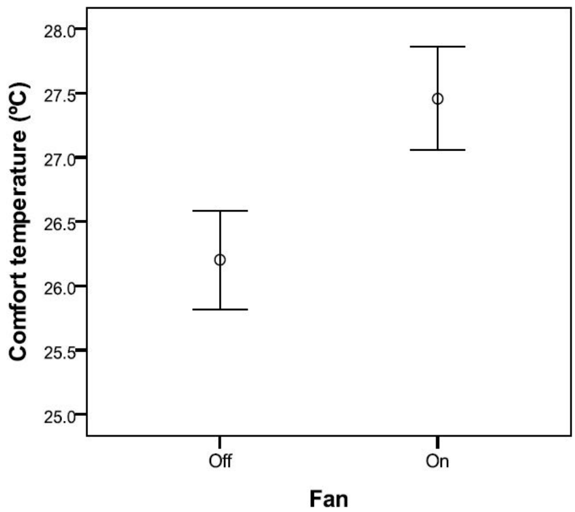

Figure 8: Comfort temperatures under the use of fan with 95% confidence intervals (Mean ± 2 S.E.)

4. Conclusions

This study found the following conclusions while doing the thermal comfort survey in free running office buildings of Kathmandu valley in summer season.

- Out of total votes, only 45.3% office occupants voted on neutral scale, 35.1% voted on slightly hot of the thermal sensation. Almost 90% votes lie within three central categories, so we can say that occupants are satisfied with the thermal environment of their offices. But still, out of the total votes for thermal preference, 55% of votes want to change the thermal environment into much cooler, and 35% of the total votes don't want any change from thermal sensation. So, even if someone feels neutral, it doesn't necessarily mean they're experiencing thermally comfortable. People can have different preferences for thermal sensations even when they feel neutral.

- We have calculated the comfort temperature from Griffiths' method and found the mean comfort temperature as 26.9oC. Which is slightly higher than the comfort temperature found in dwellings of the same region.

- We have also analysed the comfort temperature under the use of the fan. We have found the comfort temperature is 27.5 °C when the fan is on and 26.2 °C when the fan is off. This indicates that air movement is effective in raising the indoor comfort temperature.

5. Acknowledgements

We would like to acknowledge owners of office buildings and occupants for their kind cooperation during the field survey.

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Field studies of thermal comfort in heritage hotel buildings in warm humid climate of India

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Abstract

Heritage Buildings in India roughly constitute 20% of the existing built stock. Significant energy and carbon savings is possible if these heritage buildings are put to new use. However 'Adaptive Reuse' of heritage buildings is a challenging task where energy use is strongly influenced by occupant behaviour and conservation techniques keeping in mind the historic value and traditional construction techniques of the building. This paper showcases field study findings of occupant thermal comfort for a mixed mode heritage building put to new use as a hotel - located in the warm humid climate of West Bengal, India. A total of 205 subjects were surveyed spread over four seasons. The field data was collected through yearlong monitoring of environmental parameters along with occupant surveys through spot measurements and questionnaires. This transverse survey showcases thermal preferences & thermal comfort behaviour of respondents spread over the year indicating roughly 80% of occupants are comfortable with a calculated comfort temperature of 26.7°C. The indoor climatic data was collected by instruments which complied with the accuracy standards of ASHRAE Standard-55 and ISO 7726:2001. The questionnaire was based on standard ASHRAE format for thermal environment. The study showcases the extent of thermal comfort achieved in an adapted heritage hotel along with environmental adaptive design features for suitable thermal adaptation indicating that the environmental adaptive design features alter the outdoor temperatures by an average of 1.2 °C closer to comfort temperature across the summer and winter seasons.

Keywords - Thermal Comfort, Heritage Buildings, Adaptive Reuse, Energy Efficiency, Heritage Hotels

1. Introduction

There is very little research in the field of thermal comfort for heritage buildings in India. Hence, this presents scope for investigation. This research is a pilot study for heritage hotel typology globally. Thermal comfort studies have been attempted for most building typologies like residential, commercial, museums, offices, schools, universities, but none for hotel typology. This research aims to create a starting point for scholarly discourse and further research on related topics. The study also is unique as along with thermal comfort perception, heritage perception of users is also assessed both qualitatively and quantitatively. This helps us in understanding the correlation between thermal comfort, energy efficiency and conservation of heritage buildings, which could lead to sustainable, low energy adaptive-reuse solutions.

Thermal Comfort is a basic human need. Human body has a physiological need to maintain a constant core body temperature. During thermal discomfort the body tries to regulate the heat or cold by sweating or shivering and many other such response mechanisms. One of the basic and important functions of any building is to provide shelter from external adversities. Traditional Architecture is always known to respond and adapt to its surrounding climatic conditions. The passive design features for cooling, heating or ventilation in a heritage building creates comfortable interiors as a response to its climate. India has varied climate zones which range from plains to plateaus to Himalayas to desert. The Koppen Climate classification for India is primarily Tropical Humid climate with more than 70% India falling under this classification (Am).

The varied climatic zones have led to context specific responses from traditional buildings along with numerous passive design features as response to the climate. Until a few decades ago most buildings responding to climate were naturally ventilated. With the penetration of air conditioning systems in our society and its easy availability, the number of conditioned buildings has grown multifold (Yash Shukla, Rajan Rawal, 2014). Most new buildings are designed to be air-conditioned. Even Heritage Buildings being put to new use are incorporating air-conditioning systems for its spaces which were historically designed to be naturally ventilated. The consequence is often high levels of energy use to over-cool buildings in summer and overheat them in winter, all too often resulting in uncomfortable if not unhealthy buildings (Mendell & Mirer, 2009).The increasing reliance on air conditioning has led to an appreciable decline in the standard of passive, environmental design skills among architects. The widespread use of air-conditioning world-wide has discouraged design of buildings that use 'passive' – non mechanical cooling strategies. The need for air-conditioning can often be significantly reduced by improving the thermal performance of the building through strategies such as reduced glazing areas, more shading, use of thermal mass, naturally ventilating the building etc. The key challenge is to design efficient buildings and use adaptive approaches to achieving comfort in them. (F. Nicol et al., n.d.).

1.1 Adaptive Thermal Comfort Model

Globally researchers have been exploring the subject of thermal comfort for more than 6-7 decades which has led to two main prevalent comfort models. The first, Fangers static heat balance model was a lab based model. This model became the basis for providing an index for thermal comfort by some international standards like ASHRAE 55, ISO 7730 initially. Since this model was developed only through controlled environment experiments and no real field data was included, many researchers were unhappy with the approach. Also it lacked research on naturally ventilated buildings. This led to a new adaptive model of thermal comfort introduced by Nicol and Humphreys in 1970's. The adaptive model was based on field survey findings and also included responses of the occupants of the buildings, keeping the researchers' perception at the minimum. The data collected was statistically analysed to arrive at results. Further extensive work in this approach was done by Brager and De dear based on which ASHRAE 55 adopted it in 2004.

Adaptive Thermal Comfort standards liberate the designer to create buildings that use natural energy from wind and sun when appropriate, to run buildings for much of the year on renewable energy and to open the windows again and restore the thermal delight that is too often absent in modern tight skinned buildings. The adaptive approach to comfort is based on the Adaptive Principle: If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort. (F. Nicol et al., n.d.)

The natural tendency of people to adapt to its changing environment is expressed in the adaptive approach to thermal comfort. The adaptive approach works with the field surveys which also take into account the thermal response of the subjects in the form of comfort vote. The aim is to find the temperature or combination of thermal variables (temperature, humidity, air velocity) which subjects consider neutral or comfortable. The comfort temperature is a result of the interaction between the subjects and the building or other environment they are occupying. (J. F. Nicol & Humphreys, 2002). The environmental variables are measured at the same time as the subjective reactions are recorded. Because the aim is to obtain a reaction to typical conditions, there is no attempt to interfere with the environmental conditions, the activity or the modes of dress, and thus the full complexity of the context is included in the responses of the participants.(F. Nicol & Roaf, n.d.)

1.2 Mixed mode buildings

A mixed mode building is one where heating or cooling is achieved through both mechanical means as well as natural ventilation. A naturally ventilated building in most cases functions as a mixed mode building. For eg. in India mechanical cooling may be used in peak summer to arrive at comfort conditions but heating may not be required during winter hence allowing the thermal properties of the building to regulate the comfort conditions along with occupant responses. The mixed mode building has become less prevalent within the modern building design typologies however traditional buildings with their passive design features and natural ventilation utilise the mixed mode of operations to their benefit.

The thermal comfort conditions of most heritage buildings change spatially as well as through time. Different spaces are used at different times of the day as per the external climate and its effect on the indoor environment. The approach to comfort in modern buildings is centred on the use of air conditioning hence assuming that constant conditions are more comfortable than variable conditions. There is a danger that building regulations will require traditional buildings to conform to this modern paradigm, ignoring the intentions of the original designer or builder. The adaptive approach has eroded the notion that unchanging conditions are superior by showing that indoor comfort can change in time according to outdoor conditions. On the basis of adaptive principle there is no reason why this cannot be extended to environments that change in space as well as in time. (F. Nicol et al., n.d.) Conservation of heritage buildings through retrofitting or restoring not only helps to preserve heritage but also provide low carbon, energy efficient solutions for reuse keeping indoor thermal comfort of occupants as their primary concern.

West Bengal state in India is known for its stunningly beautiful palaces and mansions especially Kolkata nicknamed as the 'City of Palaces'. Kolkata, the capital city of the state of West Bengal was the seat of imperial power during the 18th & 19th century. The region then known as the Bengal Presidency has been witness to great social, political, and historical turmoil during the period referred to as the 'Bengal Renaissance'. The building stock of Kolkata and its surroundings is dotted with beautiful Grand Pre and post British era palaces or zamindar baris. The intent to save these heritage buildings was projected by the government of West Bengal as a result of which the phenomenon of rehabilitating old buildings by putting them to new use became rampant. 'The state government has decided to use a cluster of 100 palatial properties across the state to convert them into heritage hotels, a trend accepted by the property owners.' (Tamaghna Banerjee & udit prasanna mukherji, 2022)

With this context, a field study was undertaken to evaluate the indoor thermal comfort achieved within Bawali Rajbari, a heritage building put to new use as a heritage hotel in West Bengal. Occupant thermal comfort analysis was also conducted in order to assess the adequacy / comfort of indoor conditions for the new occupancy pattern.

This paper intends to showcase the thermal comfort solutions by analysing the data gathered in the field study of the heritage hotel in West Bengal. The study showcases the extent of thermal comfort achieved in an adapted heritage hotel along with environmental adaptive design features for suitable thermal adaptation.

2. Methods

2.1 The Rajbari Adaptive Reuse as a Heritage Hotel

The 'Rajbari' is a traditional building typology in West Bengal. These large palatial houses of the British era are representative of traditional residential architecture of West Bengal and contribute to the large spectrum of heritage buildings in the state. There is a prevailing trend of conversions of these heritage houses into 'Heritage Hotels' within the state. This traditional building typology demonstrates many passive design strategies highlighting historic comfort parameters worthy of evaluation. Originally designed as a naturally ventilated building, it is today a mixed mode building (naturally & mechanically ventilated) post its adaptive reuse and presents a case to demonstrate adaptive thermal comfort concept. Bawali Rajbari is located in the town of Budge-Budge, South 24 Parganas district of West Bengal. The Rajbari was owned by the Mondal dynasty in the late 18th century. The Rajbari, an architectural masterpiece, was built 250 years ago. It saw approximately 150 years of continuous occupation till the family lost most of its wealth, and the palatial house fell into disrepair. It was only in 2017 that the Rajbari, was rediscovered, restored and adapted as a heritage hotel to reflect the opulence of the Zamindars of Bengal. The Rajbari today sits on a 3 acre land with ponds and gardens adding to the surrounding.

2.2 The adaptive mechanisms for thermal comfort

The concept of adaptive reuse was executed in a manner to restore maximum authentic existing historic parts of the building. As far as possible original building materials were retained, and new additions were made with compatible materials sourced locally. This traditional naturally ventilated typology displays the following prominent architectural characteristics showcasing its passive design features and climate responsiveness.

- Central courtyard to avoid heat gains and allows the courtyard to act as an air sink to ventilate the surroundings.
- Strategic positioning of large doors & windows, to help achieve comfort ventilation.
- Thermally massive construction to moderate temperature swings.
- Deep verandahs / arcaded corridors on ground and first floor around the central courtyard act as a buffer space to provide filtered daylight, solar shading and ventilation.
- Use of wooden slats between the corridor columns act as a screen to prevent heat gain.
- Proximity to the water body and surrounding greens adds to the micro climatic effect and cools the surroundings.


Figure 1 and 2: East wing – Before & after Restoration 2.3

Field Survey

Transverse field surveys were conducted for the heritage hotel from April 2021 to May 2022. The surveys were spread over a year and gathered environmental variables as well as occupant comfort response data. The environmental variables of air temperature (ta) and relative humidity (RH) was collected with the help of loggers/ sensors through a continuous yearlong data logging. This was supplemented by the spot measurements of the environmental variables (Ta, Tg, RH, Va) taken every quarter (April, October, January, May) during the four seasons, along with the data for comfort vote which was collected through the process of Right Now Right Here (RNRH) survey.



Figure 3,4 and 5: Pictures during thermal comfort survey

2.4 Sampling Stratification & Questionnaires

The survey involved a total of 205 subjects divided over the four seasons of summer, rainy, winter and autumn. Each quarter the survey was conducted over 7/10 days within the chosen month. Nearly 96% of the subjects surveyed belonged to West Bengal and had been living in the state for more than 15 years. It can thus be assumed that they are naturally acclimatised to the climatic conditions of West Bengal. Equal gender and age distribution of the subjects was kept in mind while surveying (Table 1).

Table 1: Distribution of samples by gender and by spatial disposition

	Male	Female	Total		Guestrooms	Public Areas	Total
Mar – Apr 21	24	26	50	Mar – Apr 21	27	23	50
Sep – Oct 21	32	28	60	Sep – Oct 21	36	24	60
Dec – Jan 22	25	30	55	Dec – Jan 22	36	19	55
Apr – May 22	22	18	40	Apr – May 22	22	18	40
Total	103	102	205	Total	121	84	205

The questionnaire was designed borrowing from the ASHRAE format but tweaking it to include heritage perception questions to understand the relationship between heritage perception and thermal perception within the heritage hotel. Besides the basic information the respondents were asked to inform about their educational background, duration of stay, how often they stayed in a heritage hotel, place of belonging, most comfortable part of the hotel and most comfortable time of the day.

2.5 Instrumentation

The following instruments were selected and used for the survey. Table 2 showcases the comparison between range and accuracy of each instrument against the ISO 7726:2001 standard. The data loggers were set to record the measurements at every 30-minute interval.

Table 2: Equipment details against ISO 7726:2001 standards

	Parameter	Range		Accuracy	
		Instrument	Standard	Instrument	Standard
Extech HT30	Globe temperature	0 - 80° C	10 - 40° C	± 2° C	± 2° C
TSI 9545-A	Air Velocity Air temperature RH	0 – 30 m/s -10° - 60° 0 - 90%	0.05 -1m/s 10 - 40° C -	± 0.015 m/s ± 0.3°C ± 3%	± 0.05 m/s ± 0.5° C -
HOBO	Air temperature RH	20° to 70° C 5% to 95% RH	10 - 40° C -	± 0.35°C ± 2.5%	± 0.5° C -
HTC EasyLog	Air temperature RH	40° to 70° C 0% to 100% RH	10 - 40° C -	± 1.0°C ± 3.0 %	± 0.5° C -

2.6 Spaces and Logger Placement

The Rajbari comprises several public and private spaces. For the monitoring and continuous data logging of environmental parameters, private spaces (Guest Rooms) and public spaces (Restaurants, Restaurant Lobby, Bar, Library Lounge & Corridors) were selected. 13 data loggers were placed within various spaces of the hotel (Fig 6&7) guest rooms (5 nos.), corridors (4 nos.) and public spaces (4 nos.). Three types of Guest Room classification were found within the hotel and the rooms were air conditioned and had ceiling fans. The hotel guests had access and control of AC thermostat, ceiling fan regulators, window blinds and door-window operations for modulating thermal comfort within the rooms. The Public spaces were found to be of three types. The restaurant and restaurant lobby were air-conditioned with no ceiling fans and openable windows. The guests did not have access to the AC controls. The Library Lounge and the Bar were air conditioned with provisions to use ceiling fans and operable windows. The corridors were naturally ventilated on both ground and first floor

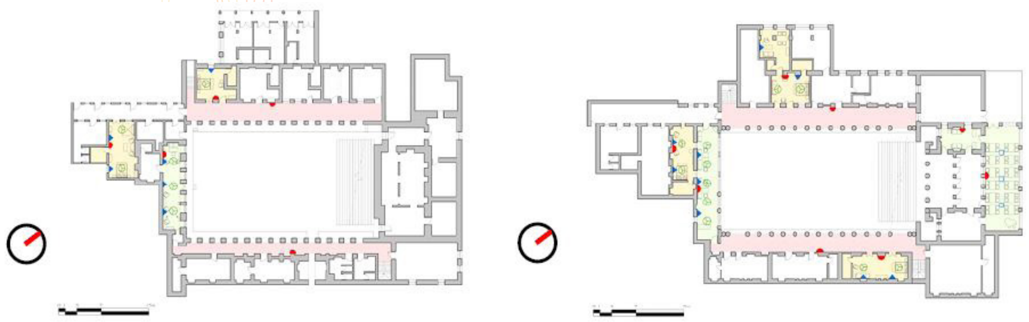


Figure 6 and 7: Ground and First floor Plan

3. Results

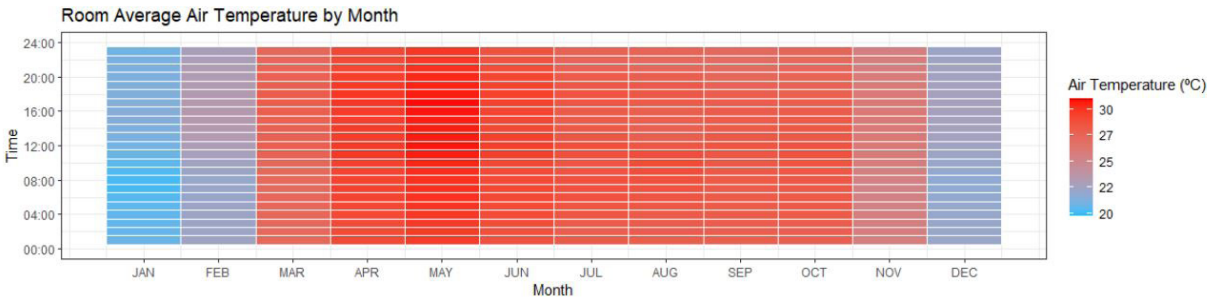
3.1 Building thermal data

The summary of the data gathered during a field investigation carried out at a historical hotel in West Bengal are presented in Table 3, which provides an overview of the mean maximum, standard deviation, and minimum values for air temperature and relative humidity in all sections of the hotel premises.

Table 3: Summary of indoor environment from logging sensor measurements

Spaces	n		T_a (°C)	RH (%)
Public	77586	Max	39.3	94.1
		Mean	25.5	75.9
		Std Dev	2.8	9.4
		Min	18.6	34.4
Private	96985	Max	32.1	97.1
		Mean	24.8	78.4
		Std Dev	2.5	10.8
		Min	19.0	38.4
Corridor	65510	Max	37.1	95.9
		Mean	27.2	76.9
		Std Dev	3.3	10.9
		Min	17.6	25.2

Upon analysing the average air temperature of the building on a monthly basis, it becomes evident that the coldest months are January, February, and December. Conversely, the hottest months are March, April, May, and June, with June being the warmest among them. The transitional months, which align with the rainy season, are March, July, August, September, and October. When examining the diurnal variation throughout the day, it is observed that there is no significant fluctuation in temperature for the entire building on average (Figure 8). However, the warmest period occurs between approximately midday and approximately 16:00 in the afternoon. The diurnal variation is more pronounced when the average temperature is assessed on a room-by-room basis, rather than considering the temperature of the entire structure as a whole (Figure 8).



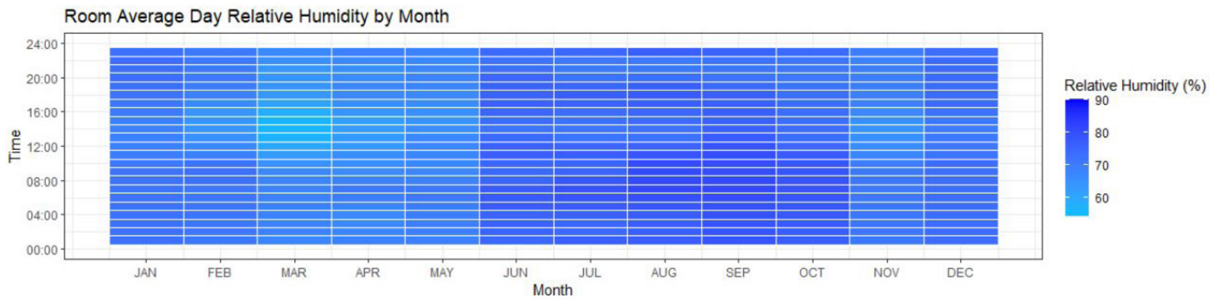


Figure 8: The presented plot illustrates the average daily air temperature (Ta) and relative humidity (RH) each month across the entire building. The data was acquired through placed sensors, with warmer air temperatures represented by the colour red and colder air temperatures represented by the colour blue.

Analysing the monthly average relative humidity within the building, it becomes evident that there is a notable increase in humidity levels during the summer season. The time period characterized by the lowest average relative humidity, typically hovering around 50%, occurs primarily throughout the months of March and April, specifically between noon and approximately 16:00. During the period from June to October, particularly in the morning hours. During the hours spanning from approximately 07:00 to 11:00, there is a notable increase in relative humidity, reaching an average of almost 90%, which coincides with the occurrence of the rainy season (Figure 8).

This study determines the building's warmest and coolest average day by measuring air temperature and relative humidity. A thorough analysis is needed to show how an adapted heritage hotel can achieve thermal comfort. Daily air temperature data shows a 20-24 °C variation in the average temperature during January, February, and December.
January 29th has the lowest average temperature. From April to early July, the average temperature fluctuates between 25 °C to 30 °C, with the highest recorded temperature on May 24th (Figure 9). However, relative humidity remains high year-round, with a lower average during warmer months and a higher average during rainier months.

Figure 9: The Illustration depicts the average daily air temperature (Ta) (top) and relative humidity (RH) (bottom) for the entire building over the course of a year.

The highest summer temperature in the building is between 14:00 and 16:00. During this instance, the peak temperature reached around 28 °C. Note that relative humidity peaks at 15:00 on the hottest summer day, around 78% (Figure). On the typical rainy season day, the building's air temperature rises in the morning and falls in the evening. However, daytime temperature variation is usually one or two degrees, indicating a stable pattern. The average daily variation in relative humidity is 10%. In particular, relative humidity is higher in the morning and decreases in the evening. On the coldest winter day, air temperature and relative humidity are parallel and different from other seasons. The air temperature gradually rises after sunrise, peaking at around 14:00 at 21 ºC. The temperature gradually decreases until night-time, averaging around 20 ºC. On a typical cold winter day, relative humidity drops by 7% as the temperature rises. This decrease in relative humidity occurs from night and early morning to noon and afternoon.

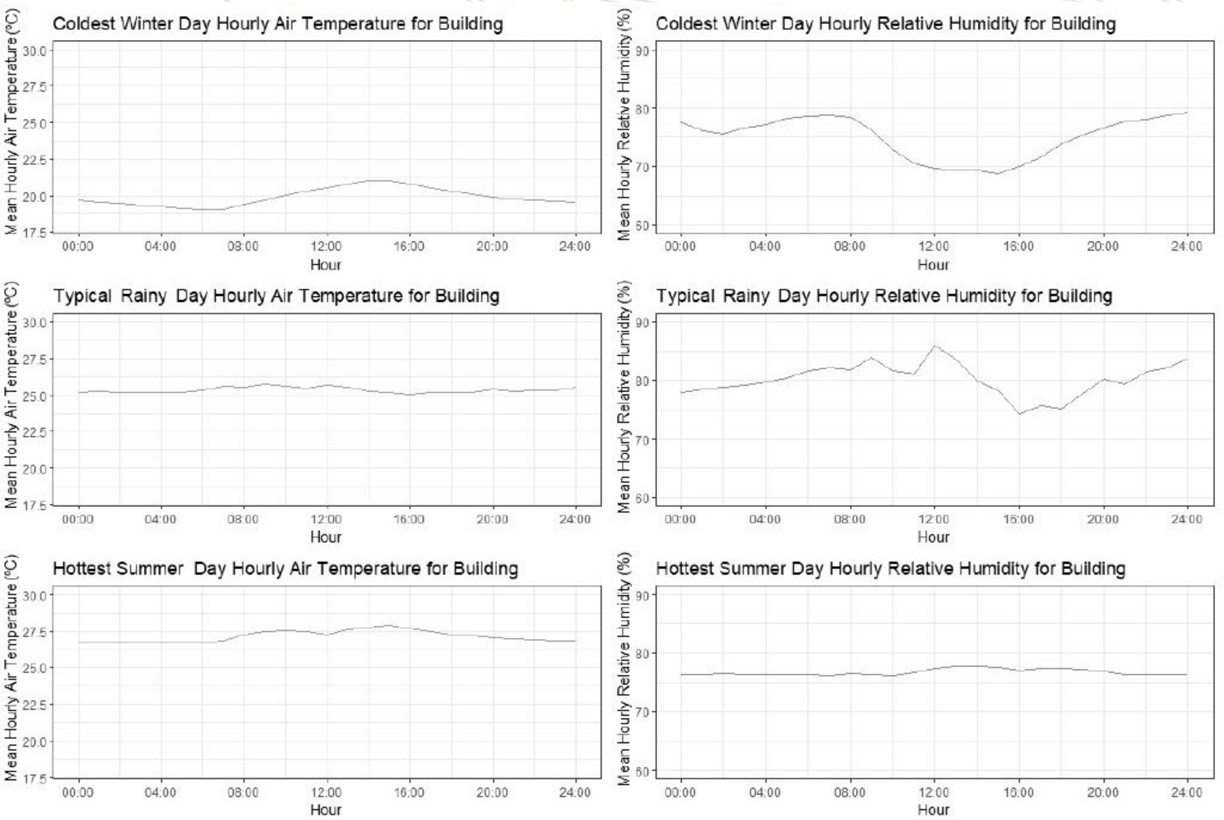


Figure 10: The illustration describes the average hourly air temperature (Ta) represented on the left, and the relative humidity (RH) represented on the right, across the entire building. This data corresponds to the average coldest temperature seen throughout the winter season, on January 29, the average typical temperature seen throughout the rainy season, on October 18, and the average hottest temperature seen throughout the summer season, on May 24, as gathered during the designated data period.

3.2 Building occupant data.

In all four seasons, 205 participants were interviewed for spot measurements (Table 4). In public spaces, females had an average air temperature of 25.5ºC, with a standard deviation of 3.3º. In contrast, males had an average air temperature of 25.7ºC and a standard deviation of 1.6º. The average RH for females was 75.8% and for males 76.1%. These values had a 9.8% standard deviation. Mean radiant temperature (Tr) depends on globe temperature (Tg). The operational temperature (To) was calculated by adding the ambient temperature (Ta) and the (Tr). The study found operational temperature differences by gender and space. Females experienced temperatures ranging from 25.6 ºC in public spaces to 26.0 ºC in private spaces. The temperature ranged from 25.3ºC in public spaces to 25.6ºC in private spaces for males. The mean radiant temperature (Tr) varied slightly by gender and space. Public spaces had an average Tr of 25.6 ºC, while female private spaces had a slightly higher average Tr of 26.7 ºC. In contrast, males had an average Tr of 24.9 ºC in public and 25.6 ºC in private spaces.

Table 4: Summary of indoor environment from spot measurements and occupant thermal perception classified under public & private spaces with gender-based responses.

Spaces		n		T_a (°C)	T_r (°C)	To (°C)	RH (%)	V_a (m/s)	clo	met	TSV	TPV
Public Spaces	Female	45	Mean	25.5	25.6	25.6	76	0.2	0.9	1.6	-0.78	1.78
			Std Dev	3.3	2.6	3.0	10	0.2	0.3	0.5	0.79	0.67
	Male	45	Mean	25.7	24.9	25.3	76	0.2	1.0	1.4	-0.71	1.51
			Std Dev	1.6	2.4	2.0	10	0.1	0.3	0.6	0.63	0.82
Private Spaces	Female	57	Mean	25.2	26.7	26.0	77	0.2	1.1	1.5	-0.68	1.72
			Std Dev	3.0	3.7	3.4	8	0.2	0.1	0.5	0.91	0.92
	Male	58	Mean	25.5	25.6	25.6	76	0.2	0.9	1.6	-0.71	1.64
			Std Dev	3.3	2.6	3.0	10	0.2	0.3	0.5	0.99	0.81

The average thermal insulation value of clothing (clo) exhibited a range of 0.9 clo to 1.1 clo for females in public settings, while for females in private settings it remained at 1.0 clo. In the case of males, the thermal insulation value was 1.0 clo in public settings and decreased to 0.9 clo in private settings. The metabolic rates exhibited a range of 1.6 to 1.5 metabolic equivalents (met) for females in both public and private settings, whereas for males, the range was 1.4 met in public settings to 1.6 met in private settings. In both public and private spaces, the air velocity (Va) remains below 0.2 m/s for both male and female individuals.

3.2.1 Annual occupant thermal comfort.

The present study examines the thermal sensation vote (TSV) and thermal preference vote (TPV) data collected from a sample of 205 occupants in order to gain insights into the level of thermal comfort achieved in an adapted heritage hotel. The thermal sensation vote (TSV) and the thermal preference vote (TPV) are commonly used metrics in thermal comfort research. The Thermal Sensation Vote (TSV) is a quantitative measure that assesses the thermal perception of individuals by collecting their subjective responses on a seven-point thermal scale. This scale ranges from a rating of “cold” (-3) to “neutral” (0) and finally to “hot” (+3). The Thermal Preference Vote (TPV) is a measure used to determine an occupant’s preference for either a warmer or colder thermal environment. It is assessed using a preference scale consisting of 5 points. Each point on the scale represents a vote for a warmer temperature, no change in temperature, or a cooler temperature. Additionally, this analysis sheds light on the environmental adaptive design features that facilitate appropriate thermal adaptation in the hotel. Regarding the TSV (thermal sensation vote), it is apparent that a significant proportion of the individuals surveyed report a rating of -1, signifying a subtle perception of coolness. In relation to TPV, it is evident that the majority of votes primarily lie within the interval of -1 to +1. This finding indicates that a notable proportion of the individuals occupying the building exhibit a preference for maintaining the existing thermal conditions without making any modifications (Figure 11).

The TPV is utilized to assess an occupant’s inclination towards a warmer or cooler thermal environment, as quantified on a preference scale. This scale employs terms such as “cooler,” and “warmer” to, while “no change” acts as the neutral position. The range of votes, span from -1 to +1, suggests a significant level of applicability for the current temperature conditions observed across this study. This observation aligns with several studies that utilize thermal preference voting (TPV)

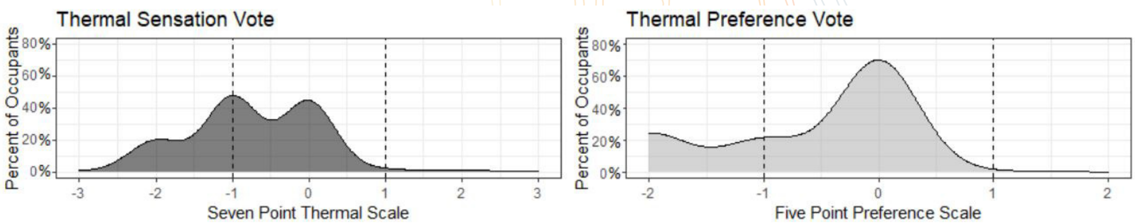


Figure 11: A density plot illustrating the comparison between the thermal sensation vote and the thermal preference vote throughout the entirety of the study period for all 205 occupants surveyed as a total.

as a means to assess occupant preferences. (Indraganti & Boussaa, 2017) (Damiati et al., n.d.) (Aghniaey et al., n.d.) In addition, the thermal acceptance among the sampled population exhibited an average value of 96%.

3.2.2 Seasonal occupant thermal comfort.

The study of thermal comfort on a seasonal basis involved the examination of 205 data points collected from occupants, specifically during the winter, rainy, and summer seasons. The present analysis primarily examined three thermal comfort metrics, specifically the Thermal Sensation Vote (TSV) and the Thermal Preference Vote (TPV) (see Figure 12).

In the context of TSV, it has been noted that there is a moderate decline in voting frequency during both winter and summer seasons, showing a peak in voting activity during slightly cooler periods (-1). However, in the period of increased precipitation, TSV also indicates that individuals may experience a slight sensation of coolness, with a decrease of approximately one degree. Furthermore, it has been observed that there is a rise in the number of individuals who choose to remain neutral (0) during the rainy season (see Figure).

A similar pattern can be observed in the case of TPV, where the most significant level of voting activity occurs during periods of rainfall, with the peak falling between the ranges of -1 to +1. Following this, the distribution gradually ranges from -2 to 0 in both winter and summer seasons with individuals generally preferring to maintain the existing thermal conditions, as evidenced by a majority voting for no alteration (0) (Figure 12).

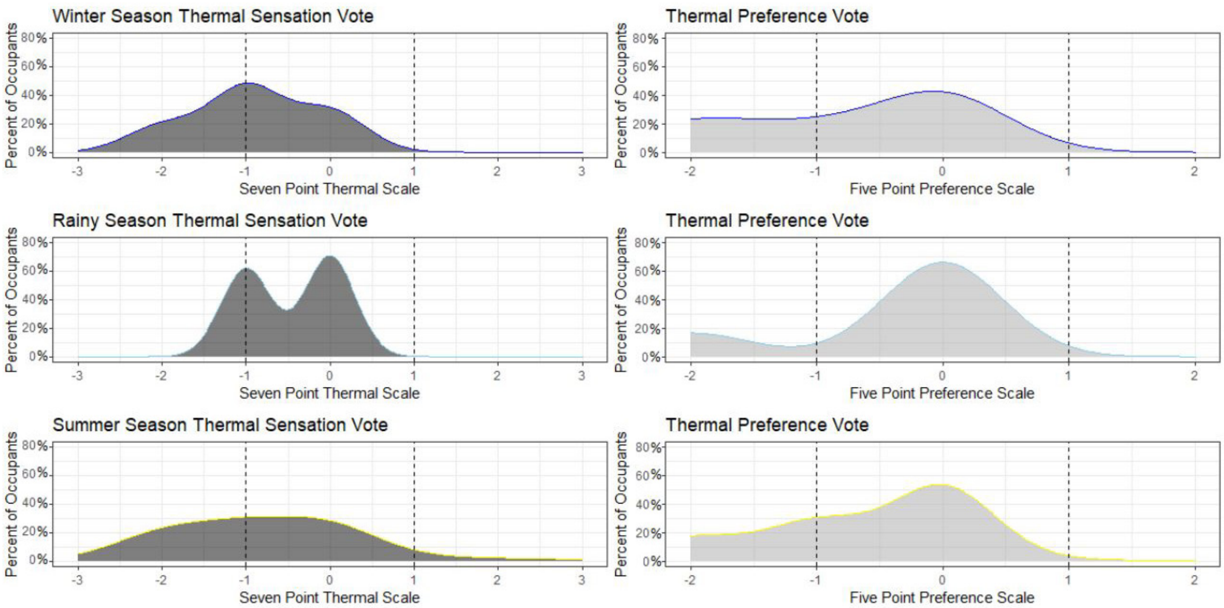


Figure 12: A density plot illustrating the thermal sensation vote (TSV) and the thermal preference vote (TPV) throughout the entirety of the study period for all 205 occupants surveyed across the winter, rainy, and summer seasons.

3.3 Assessment of thermal comfort and the comfort temperature.

To assess the optimal temperature for maximising occupant comfort within a building, the thermal sensation votes (TSV) are analysed in relation to the operative temperature. A regression analysis is conducted to examine the relationship between the thermal sensation vote and the operative temperature, utilising the dataset consisting of a total of 205 votes. The TSV voting results indicate a prevailing trend towards neutrality, as around 40% of the votes are assigned a value of 0 and approximately 80% of the votes fall within the range of -1 to +1. Furthermore, the TSV is recorded on discrete values spanning from -3 to +3. This limitation has a detrimental effect on the precision of the regression analysis conducted for the neutral temperature. This is evident from the R-squared value, which is less than 1% (Figure 13).

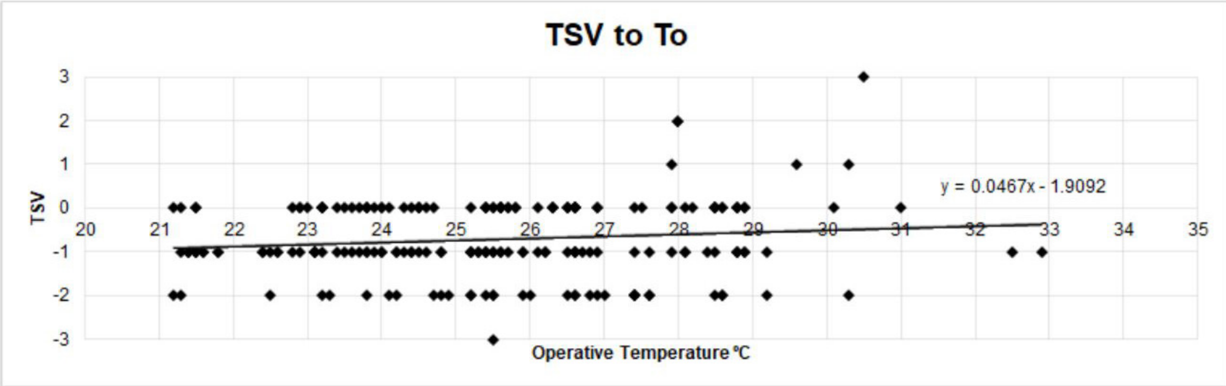


Figure 13: The figure depicts a regression analysis conducted on the relationship between the collected TSV (thermal sensation vote) and the operative temperature for the entire study population consisting of 205 occupants.

In the context of regression analysis, the term "neutral temperature" pertains to the values of the slope and intercept when the seven-point thermal scale is set to zero. These values are indicative of a neutral occupant sensation. The regression analysis conducted for the TSV revealed an observed Tn value of 40.9 °C, which is considered implausible. As the observed Tn surpasses 40 °C, it suggests a diminished level of confidence in the TSV regression model. Nevertheless, the TSV regression model possesses inherent limitations. A low slope with the regression indicates that the occupants have a reduced thermal sensitivity in relation to a specific temperature.

This finding demonstrates that the accuracy of estimating the comfort temperature may be questionable when the regression coefficient is low as evident in similar thermal comfort research. (Aqilah et al., n.d.) (Lamsal et al., n.d.) Hence, the Griffiths method emerges as the most appropriate approach for determining the comfort temperature as frequently deployed in thermal comfort studies in similar regions. (Humphreys & Nicol, n.d.) (Griffiths, 1991) (Humphreys et al., 2013) (Indraganti, 2010b) (Indraganti, 2010a) (F. Nicol & Roaf, n.d.-a) (Alnuaimi et al., 2022).

The Griffiths method is utilized using equation: $Tc=Tr+ (0-TSV)/G$

The determination of the comfort temperature (Tc) was conducted utilising the Griffiths method, encompassing the entire sample size of 205 individuals who participated in the study. The Griffiths method, in a broad sense, correlates the indoor temperature with the individual inclinations of occupants regarding the TSV in order to determine a specific comfort temperature for each individual. Subsequently, the mean comfort temperature of the population is determined by calculating the average comfort temperature for all individuals included in the study. In thermal comfort studies, it is conventional for the Griffiths method to employ a G constant of 0.50, 0.33, and 0.25 which corresponds to a variation of either 2°C, 3°C, or 4°C in indoor temperature, resulting in a shift of thermal sensation by one unit on the 7-point scale, respectfully. Table 5 presents the Tc corresponding to the respective values, and it illustrates an average temperature variation of 1 °C across the range of G values considered. This finding indicates that the average Tc, as determined by the Griffiths method, is approximately 26.7 °C. The estimation of the comfort temperature presented in this study is considered the most plausible due to its alignment with the voting pattern of the occupants surveyed, as indicated by the TSV and TPV.

Table 5: Summary of comfort temperature calculated through Griffiths method.

G Constant	0.5/°C	0.33/°C	0.25/°C
Comfort Temperature	26.2 °C	26.7 °C	27.2 °C

3.4 The effect of the environmental adaptive design features in achieving thermal comfort.

In order to ascertain the extent to which passive systems in the building contribute to thermal comfort, it is necessary to compare the temperatures observed during a given month in the absence of the building (IMD (India Meteorological Department) Temperature) with the temperatures recorded in the unconditioned spaces within the building (Site Temperature) (Table 6). The spaces which depict the site temperature are the four corridors, which are situated on the first floor and ground floor in the eastern and western directions. These corridors are unconditioned, meaning they lack active climate control systems. When conducting a comparison between the two, it becomes evident that during the summer season, the unconditioned spaces of the building tend to exhibit lower temperatures, while in the winter season, they tend to be warmer (Figure 14). The mean site temperature throughout the year is observed to be more closely aligned with the calculated comfort temperature, in comparison to the offsite temperature.

Table 6: Summary of mean daily max. and min. temperature on site.

Temperature						
	Mean Daily Max. [°C]			Mean Daily Min. [°C]		
Months	Site Apr 2021-Mar 2022	IMD* Apr 2021-Mar 2022	Δta max Site/IMD*	Site Apr 2021-Mar 2022	IMD* Apr 2021-Mar 2022	Δta min Site/IMD*
Apr	35.9	34.7	-1.2	26.3	25.6	-0.7
May	34.2	33.5	-0.7	25.9	26.1	0.2
Jun	31.6	32.0	0.4	24.0	26.5	2.5
Jul	31.5	31.7	0.2	23.6	26.5	2.9
Aug	31.2	31.8	0.6	24.2	26.2	2.0
Sep	29.4	31.0	1.6	24.4	25.3	0.9
Oct	27.6	31.8	4.2	23.7	24.6	0.9
Nov	26.0	29.3	3.3	23.6	19.4	-4.2
Dec	23.9	25.3	1.4	21.7	15.3	-6.4
Jan	23.7	24.5	0.8	20.3	14.0	-6.3
Feb	27.4	27.6	0.2	18.6	16.0	-2.6
Mar	33.5	33.5	0.0	24.2	22.5	-1.7

- *IMD (India Meteorological Department)*

The seasons examined correspond to the distinct seasons of summer, winter, and rainy seasons as observed in Figure 9. The observed temperature difference between the Indian Meteorological Department (IMD) and the local site temperature exhibits a mean deviation of approximately 0.2 °C cooler during the summer season, 1.1 °C during the rainy season, and 2.1 °C warmer in winter (Fig. 14). This implies that the implementation of thermal comfort solutions at the heritage hotel in West Bengal contributes to the attainment of thermal comfort in a greater capacity as opposed to site conditions alone.

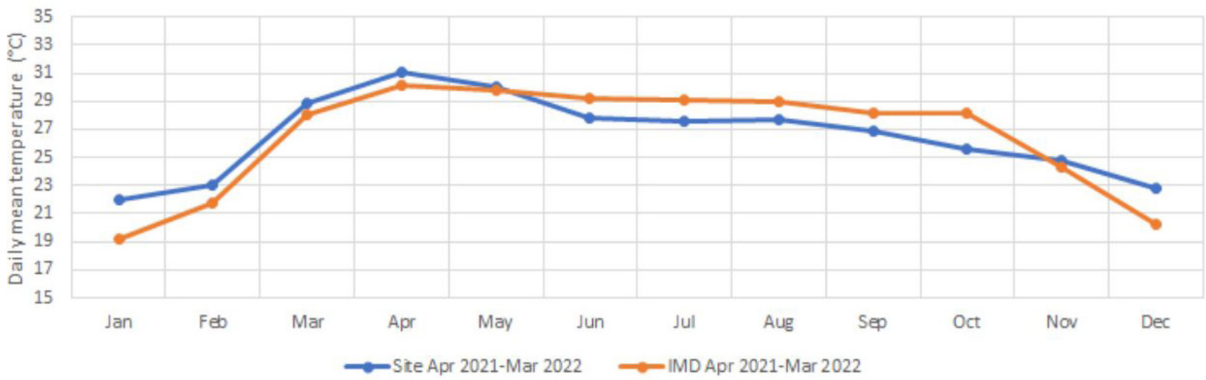


Figure 14: The provided figure represents a plot illustrating the IMD temperature data for the daily mean temperature of each month, in comparison to the daily mean temperature by month recorded from the building site using data loggers that are located in the unconditioned spaces throughout the corridors of the building,

4. Discussion

The data shows three distinct seasons. The winter season runs from December to February. The second season, summer, runs from March to June. Finally, the third season, from July to November, is the typical rainy season due to its similar Ta and RH patterns. 205 occupants were examined, occupant thermal acceptability averaged 96%, suggesting a slight preference for cooler thermal sensations. Winter was slightly cooler and occupants wanted more warmth than summer. This implies that summer passive strategies work better than winter ones. Rainy season had a moderate impact on indoor climate. The building's calculated comfort temperature was 26.7°C using the Griffiths method. Comparing this with other studies conducted in India (Indraganti, 2010a), (Indraganti et al., 2013) the comfort band based on the regression analysis was found to be 26–32.45 °C with the neutral temperature at 29.23 °C. We had 26.7°C which is similar to what researchers have found in similar climates in India.

. The building's passive strategies reduce summertime external conditions, bringing indoor spaces closer to the desired temperature. This shows that the building's passive strategies maintain thermal comfort.

The preliminary results lead to the need for proposing appropriate design solutions towards environmental & thermal adaptations within heritage buildings being put to new use. The study reveals there are comfort standards for new buildings but none for heritage buildings. Mixed mode buildings is increasingly becoming a norm in India especially of 12 with heritage buildings where passive design features exist and can be suitable and adapted to new use. The indoor environment for such buildings can be designed to encourage the use of existing passive design features and reduce dependency on conventional air conditioning techniques. The PMV and TSV analysis shows that people are willing to compromise on thermal comfort for heritage experience.

Evidenced with other energy efficiency and thermal comfort studies done on historic buildings (Sakkaf-Al et al., 2021), (Molina Martinez et al., 2016), the increase in the importance of energy efficiency and thermal comfort as in most parts of the world can also be felt in India demonstrated through the research conducted. It is seen that the user's tolerance level is high while experiencing heritage buildings.

5. Conclusion

The following main points emerge in the paper:

- This paper presents the findings of a field study conducted to assess the thermal comfort of a Heritage Hotel building in a warm and humid climate in India. From the 205 occupant votes, the TSV voting data illustrate an indication of thermal sensation over the year toward neutrality, with 40% of votes being 0 and 80% being -1 to +1 and with TPV majority voting for no change.
- This study aims to demonstrate the efficacy of thermal comfort solutions through the analysis of data collected during a field study conducted at a heritage hotel in West Bengal. Additionally, this study highlights the degree of thermal comfort attained in a modified heritage hotel, as well as the environmental adaptive design elements implemented to facilitate appropriate thermal adaptation.
- Using the Griffiths method, a comfort temperature of roughly 26.7°C is observed. In addition, a comparison between the hotel external temperatures and the local weather station temperature during the span of the study illustrate that the implementation of thermal comfort solutions at the heritage hotel in West Bengal contributes to the attainment of thermal comfort in a greater capacity as opposed to site conditions alone.
- The average winter external temperatures of the hotel are 1.6°C warmer than the local weather station temperature of 22.7°C and in the summer, they are 0.9°C cooler compared to the local weather station average of 29.4°C, which is an average of 1.2°C across summer and winter. This

study examines the mixed mode operations of a heritage hotel building, with a particular focus on minimising the use of mechanical systems throughout the year.

- The study emphasises the importance of enhancing and reusing prevalent passive design features to achieve optimal thermal comfort within the heritage building. This observation suggests that the adaptive approach is a viable strategy for attaining comfort.

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Historic windows with passive heat loss reduction strategies and their effect on indoor thermal comfort

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Abstract

Ireland's ambitious goal of achieving net-zero emissions by 2050 necessitates significant reductions in operational emissions from its building sector, prompting the government to target the energy retrofitting of a quarter of its building stock by 2030. However, retrofitting historic buildings poses substantial challenges stemming from concerns related to architectural conservation, cost, and technical complexities. In this context, focusing specifically on addressing heat loss through single-glazed historic windows, this study revisits traditional heat loss mitigation techniques that were once prevalent in historic buildings but have since fallen out of common use. With in-situ tests, we investigate the thermal performance of curtains, blinds and shutters on single-glazed wooden sash and case historic windows. We present variations in heat loss through the window and its associated thermal comfort in response to each strategy. Test results show significant heat loss reduction from a combination of traditional strategies which is on par with secondary glazing. These strategies offer viable solutions for energy efficiency and thermal comfort in historic buildings without major interventions on the protected historic fabric.

Keywords - Historic windows, Experimental U-value calculation, Thermal comfort, Historic buildings, Passive retrofit strategies.

1. Introduction

It is estimated that 37% of all the Greenhouse Gas emissions in Ireland are attributed to the operation and construction of the built environment with operational emissions accounting for 2/3rd of these emissions [1]. Ireland's Climate Action Plan 2021 sets out to reduce emissions in the building sector by 44-56% by 2030. Among the proposed key actions in the building sector, the National Retrofit Plan targets to retrofit 500,000 homes (one quarter of the building stock) to higher energy efficiency and to reduce 50% of emissions from public sector buildings. Traditional buildings in Ireland constitute 16% of the total housing stock in Ireland [2]. Historic buildings are rarely considered in retrofit policy dialogues due to the architecture conservation agenda and the lack of technically feasible solutions [3,4]. Such impediments often render historic buildings less energy efficient and impact the occupants' thermal comfort. A study based in England estimated 3.2 million tons of avoidable carbon per year due to the preservation of the unique characteristics of neighbourhoods with conservation area status [5]. On the other hand, architecture conservation contributes to maintaining the unique identity of a place and acting as a tangible representation of cultural heritage.

Windows are often considered the weakest part of a building envelope in terms of thermal performance. A previous study reported that a double-pane window could allow as much as 10 times the amount of heat to escape the house compared to the same area of a typical wall [6]. The single-glazed period windows in historic buildings are less energy efficient with low U-values by a factor of 3 compared to Ireland's national building guidelines [7]. In cold climates, they lead to indoor thermal asymmetry and create draughts that reduce local thermal comfort. The colder inside surface of windows creates stronger radiant asymmetry and causes thermal discomfort to the occupants. Retrofit of periodic buildings and windows is often challenging due to the lack of technically feasible solutions aligned with conservation characteristics, expertise, and associated costs. In this context, we revisit a range of traditional passive heat loss reduction strategies to investigate their performance related to heat loss reduction and associated thermal comfort.

Previous studies on the thermal performance of windows with a range of heat loss reduction strategies were carried out in lab-based [8,9] and simulation-based [10] tests. Both the lab-based study report reduced heat loss through the window and an associated thermal comfort improvement for single-paned timber sash and casement windows with shutters, curtains, blinds, and secondary glazing. Secondary glazing provides better insulation overall. However, closed wooden shutters are found to be the most effective traditional strategy to reduce heat loss [8,9]. Another study, with hot box tests, used corrected empirical equations for the effects of window frames and outdoor wind velocity to estimate the U-value of a practical window with a cloth curtain [11].

In this study, we present in-situ tests conducted in the winter months of 2022 and 2023 on single-glazed period windows from 5 different historic buildings of varying typologies and scales across Greater Dublin, Ireland. Tested traditional strategies include the use of blinds, curtains, and shutters. We also compare their performance with modern passive strategies used in historic buildings like secondary glazing and slimline glazing fixed to the existing timber frame. In this study, we primarily test for the change in U-values and conductive heat loss through the centre of the glazing with/without other heat loss reduction options. We also report the interior room facing surface temperature variations associated with it. The implications of such variations on thermal comfort, convective heat loss, and radiative heat loss are also discussed.

2. Methods

2.1 Windows and strategies assessed

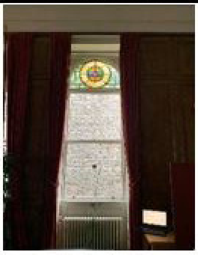
Table 1 reports the summary of the in-situ tests conducted on five different case studies. The windows were tested as found and are not draught proofed. Previous studies have reported that draught-proofing has no significant effect on conductive heat loss [9]. Case studies 1, 2, and 3 explore the performance of the single-glazed period window with/without closed blinds, curtains, and shutters. In case study 4, the impacts of these strategies, if the period window is retrofitted with a secondary glazing system (that was mounted within the staff beads of the period window), were analysed. Finally, case study 5 investigates the thermal performance of a commonly used slimline double-glazed pane that can be retrofitted into the existing timber window frame.

2.2 Experimental test method

The effect of passive heat loss reduction strategies in varying combinations is investigated with the experimental test methods previously outlined by these authors [12]. In-situ thermal transmittance values (U-value) are obtained using the quasi-steady average Heat Flow Meter (HFM) method. All the test scenarios have a Hukseflux Type HFP01 heat flux sensor and type-T thermocouples affixed to the centre of the glass measuring the heat flux through the glass and the indoor room-facing surface temperature. The ambient air temperatures in both the interior and exterior space were also measured using type-T thermocouples. For all the tests, the room heating radiators, except the one below the tested windows, were kept on for the entire duration of the tests. To monitor the exterior air, the thermocouple sensor was carefully probed out through the ventilation duct. The sensors collect data at 1-minute intervals and are stored as 10-minute averages in the datalogger.

Except for the fifth case study, all the tests comprised continuous observation of the thermal performance of the windows in response to various heat loss reduction strategies. For example, after all the sensors are in place, case study 1 starts with blinds and curtains closed. After 72 hours of monitoring, the readings were collected from the datalogger, and the curtains were opened to continue the test. Similarly, the test continued with the blinds closed for another 72 hours. In the third test, blinds were opened and the performance of the single glazing without any strategies was monitored. Now, this third test is used as the baseline for the previous tests. The tests are reported in reverse order (starting from single glazing alone, blinds down and then both blinds and curtains down) to make it easier to understand the heat loss reduction upon adding various options. This procedure is repeated for other windows. In the fifth case study, we investigate the performance of slimline glazing (double-glazed pane that can be retrofitted into the existing timber window frame). Here, we do not have a baseline single glazing as it was retrofitted a few years ago. Therefore, we compare its performance with a U-value averaged from previous single-glazing tests.

Table 1: Summary of the case study windows, and the tested heat loss reduction strategies.

No.	Test site	Case study windows and the test strategies	Notes
1	Dun Laoghaire-Rathdown (DLR) County Hall building	  	Tests conducted- single glazed; closed Roman blinds; closed Roman blinds and curtains. Room function- Assembly Hall, public events.
2	DLR Harbour Master building. (office space)	  	Tests conducted- single glazed; closed wooden shutters; closed curtains; closed shutters and curtains. Sensors placed on both glazing and shutters. Room function- Board room.
3	Leeson Street Upper (residential building)	 	Tests conducted- single-glazed; closed wooden shutters. Sensors placed on both glazing and shutters. Room function- Home office space.
4	Grove Park, Rathmines (residential building)	  	Tests conducted- single glazed; double glazed secondary window; secondary window with closed curtains; secondary window with closed blinds and curtains. Room function- Living room.
5	Richmond Place, Rathmines (residential building)		Tests conducted- slimline glazing on existing window frame Room function- kitchen.

3. Results

3.1 Heat loss reduction

Table 2: Test data for the in-situ experiments conducted on 5 case studies.

Case study	Case Code	Interventions	Indoor air temperature (°C)	Outdoor air temperature (°C)	Heat flux (W/m²)	Effective U-value (W/m²K)
DLR County Hall building	1a	N/A- Single glazed	19.5	11.3	34.5	4.16
	1b	Closed Roman blinds	20.1	10.6	28.9	3.04
	1c	Closed Roman blinds and curtains	20.8	12.8	22.1	2.78
DLR Harbour Master building	2a	N/A- Single glazed	18.3 19.2	8.6	53.0 39.4	5.44 5.02
	2b	Closed curtains	17.0	11.3	23.6	2.40
	2c	Closed wooden shutters	19.7	7.2	26.0	2.69
	2d	Closed wooden shutters and curtains		10.1		
Leeson Street Upper	3a	N/A- Single glazed	15.2	7.6	39.7	5.25
	3b	Closed wooden shutters.	15.5	7.2	26.7	3.22
	3c	Closed wooden shutters, sensors on shutters	15.2	7.6	11.4	1.51
Grove Park, Rathmines	4a	N/A- Single glazed	20.5	11.7	40.6	4.62
	4b	Secondary glazing	20.5	11.7	11.8	1.34
	4c	Secondary glazing with closed blinds and curtains	15.5	8.3	7.0	0.97
	4d	Secondary glazing with closed curtains	16.3	10.5	5.1	0.88
Richmond Place, Rathmines	5a	Slimline glazing on existing frame	16.2	6.7	17.5	1.84

Figure 1: Change in heat loss through the surface and effective U-value for each intervention broken down by case study. All changes are relative to the respective single-glazing baselines.

Table 2 reports the test data for the different interventions considered in this study. Indoor and outdoor ambient air temperatures are tabulated alongside. Figure 1 illustrates the variation in heat loss and the effective U-value for the considered interventions relative to the baseline. The performance analysis baseline for each strategy is set by the performance of single glazing without any heat loss reduction strategies in their respective case studies. For example, code 1a is the baseline for 1b and 1c. In-situ tests report U-values of the single-glazed period windows ranging from 4.16W/m2K to 5.44W/m2K. Conductive heat loss through a surface area of 1m2 at the centre of the period window glazing is impacted by all the tested strategies. A reduction ranging from 87% to 33% is observed when a combination of strategies is tested (tests 1c, 2d, 3b, 3c, 4c, and 4d). Secondary glazing alone reduced heat loss to 71% followed by closing wooden shutters (55% to 33%), curtains (26%) and Roman blinds (16%). A baseline value of 4.85W/m2K U-value and heat flux of 42W/m2 averaged from the previous single glazing are assumed for case study 5. Based on this assumption, the heat loss reduction by the slimline glazing is 58% compared to the single glazing.

3.2 Thermal comfort

In this section, we compare the surface temperature of the single glazing with the surface temperature of the shutters (case studies 3b and 3c) and secondary glazing (case studies 4a and 4b) to understand the thermal comfort improvement achieved upon using them.

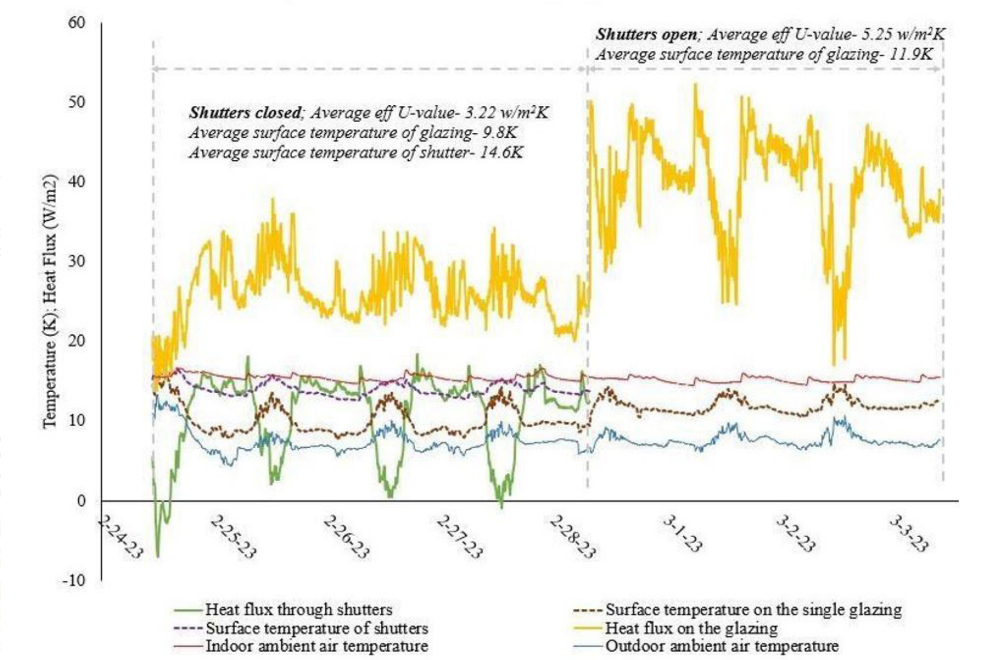


Figure 2: The impact of opening and closing wooden shutters on the surface temperature and heat flux through a single glazed period window.

Figure 2 illustrates the test data from 3c and 3b in a 7-day continuous test. The test started with heat flux and thermocouple sensors fixed on both the single-glazing and closed shutters. The figure summarises the increased heat loss through the glazing when the shutters are opened on the fourth day. On opening the shutters on the fourth day, the heat flux through the glazing increased and the average surface temperature of the glazing increased to 11.9°C when the shutters were open. When the shutters are closed, the average surface temperature of the shutters is 14.6°C, which is 2.7°C lower than the single glazing.

Figure 3 reports the test data from case studies 4a and 4b, a 3-day test conducted side by side on two-period windows but one affixed with a secondary glazing. The results show a reduction of heat loss through the secondary glazing as 71% less than that of the single glazing. While the average interior room-facing surface temperature of the single glazing is 16.6°C, the secondary glazing achieved an average interior room-facing surface temperature of 19.4°C. A 2.8°C temperature difference between single glazing and secondary glazing.

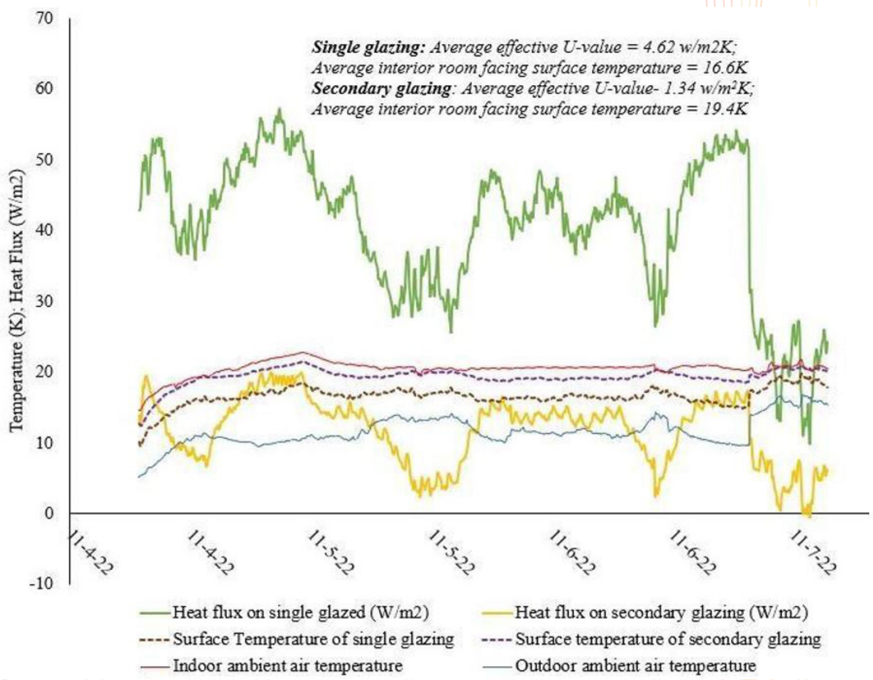


Figure 3: Test data on the performance of single glazing and secondary glazing analysed side by side.

4. Discussion

4.1 Heat loss reduction

This study presented results from in-situ tests conducted on period windows with a range of heat loss reduction strategies. The results imply that simple techniques like curtains, blinds, and shutters can substantially reduce heat loss through single-glazed period windows. Shutters are the most effective traditional solution with conductive heat loss reduction ranging from 55%- 33%. A similar trend in U-value reduction ranging from 56-39% is observed. Previous studies have reported a heat loss reduction of 61-64% [9] and 51% [8] associated with closed shutters. Closing the shutters alongside curtains and blinds can further improve the performance and achieve an effective U-value of as low as if it were retrofitted with secondary glazing. Similarly, employing secondary glazing on periodic windows can significantly reduce the U-value lower than 1.4 W/m2K, required by the Irish regulation for new builds [7]. The results also show that the secondary glazing's performance can be further improved if curtains, and more if shutters are used alongside.

Although the study illustrated a heat loss reduction trend with a range of traditional strategies, there are some exceptions when we compare them. This is primarily due to variations in the sensor placement. Unlike secondary glazing, the rest are not representative of the actual heat flow through the curtains, blinds, and shutters, but the heat loss through the single glazing after the insulation provided by those strategies. While sensors are placed on the surface of the secondary glazing and shutter facing the warm interior air, sensors placed on the single glazing face the colder buffer created behind the curtains, blinds and shutters measure the performance of the rest. The variation in the results is clear from tests 3B and 3C. Tests 3B and 3C are conducted together with two heat flux sensors placed on the centre of the single glazing and closed shutters respectively of the same window (Figure 2). With the performance of the same single glazing tested without shutters closed (3A) as baseline, 3B (on glazing) records a 33% less heat flux and 3C (on shutter) records a 71% less heat flux. Therefore, we cannot numerically compare the results of curtains, blinds, and shutters with secondary glazing and slimline glazing.

4.2 Thermal comfort

All the tested strategies create an insulating buffer zone between the heat transfer from the warmer interior to the colder exterior. The room-facing surface temperature of the wooden shutters was recorded as 18% higher than that of the centre of the single-glazed period window. A similar figure of 17% improvement is recorded with secondary glazing. The improved surface temperature impacts thermal comfort in two ways. A colder single window pane cools the interior air in contact with it, creates downdraughts and enhances the convective heat loss from the human body. A warmer surface, shutters, for example, reduces the downdraught in comparison with a colder single window and reduces thermal asymmetry. Similarly, increased surface temperature will also reduce the radiation heat losses. The lower the difference between the two surfaces, the lower the radiative heat transfer between them [13]. So the thermal asymmetry is reduced by the reduction of radiative heat transfer towards shutters, for example. Radiative heat transfer is also significantly reduced if a grey body, regardless of the surface temperature differences between the heat source, is placed parallel to the transfer as shown in a numerical study by these authors [13(p. 125)]. Therefore, all the tested options reduce conductive, convective and radiative heat losses and are expected to improve the thermal comfort.

4.3 Implications and limitations

For historic buildings where energy retrofit has technical, economic, and policy-related challenges, these simple traditional strategies could reduce a significant amount of operational energy, cost, and carbon by maintaining thermal comfort. Recent research on Net Zero Energy Buildings (NZEB) reveals that, despite achieving an annual net-zero or surplus energy balance through on-site renewable sources, these buildings depend on carbon-intensive energy imported from the grid to meet the elevated energy demands during the winter months [14]. Making use of simple strategies that are often forgotten like curtains, blinds, and shutters can further reduce their grid dependency. Similarly, in older town centres with heating-dominated climates, especially in Europe where the urban fabric has a significant number of inefficient historic buildings, these simple strategies can create a huge impact. Most of the historic buildings in Europe are equipped with these traditional strategies. Utilising them effectively is a leap towards climate action without any additional embodied carbon. The authors acknowledge that these strategies are not always ideal especially, as they can block daylight. Considering the shorter daylight and higher energy consumption during the winter months in Ireland poses a huge potential for these strategies to be used as a nighttime strategy. Lisa Heschong in her book, argues that when thermal comfort is a constant condition, it becomes so abstract that it loses its potential to focus affection [15(p. 36)]. Similarly, the curtains, blinds, and shutters not only provide thermal comfort at night but also a 'sense' of thermal function during the day as well. This is because we appreciate the variability in its thermal function [15(p. 37)] like we open or close the curtains, blinds and shutters. The authors also acknowledge that further research on infiltration and other parameters is essential for a truly conclusive study.

5. Conclusion

This paper presented a comprehensive analysis of a range of heat loss reduction strategies for single-glazed historic windows. In-situ tests on period windows with and without traditional options like curtains, blinds and shutters were tested. Their performance was compared with conventional retrofit strategies used in historic buildings such as secondary glazing and slimline glazing. The results indicate that seemingly simple strategies such as curtains, blinds, and shutters can significantly improve the thermal performance of single glazing. Using all the strategies in combination results is the most effective way to reduce the conductive heat loss through the centre of the glazing. For example, employing shutters, blinds and curtains together on a period glazing improves its thermal performance and can achieve an effective U-value of as low as if it were retrofitted with secondary glazing. Further, the introduction of these strategies to already retrofitted windows, for example, secondary glazing, can enhance its performance. Wooden shutters were identified as the most effective traditional strategy in this study. However, the study also argued that the comparison between those tests cannot be numerically compared due to the variations in the sensor placement. By creating an insulating buffer, all the strategies positively impact thermal comfort by reducing conductive, convective, and radiative heat losses. For historic buildings facing challenges related to energy retrofitting, these traditional strategies offer a cost-effective means of improving energy efficiency by maintaining thermal comfort without any additional embodied carbon. Considering the impact they have on the daylight and solar heat gain, it is advisable a nighttime strategy. These simple strategies with their benefits if advocated properly to the public can have a butterfly effect across the occupants, buildings, neighbourhoods, districts, national and global scale. This research is part of a wider project which aims to further address such impacts of these strategies across different spatial scales.

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Optimising energy efficiency and thermal comfort measures for a low-income residential building in Ahmedabad, India

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Abstract

This study evaluates indoor thermal comfort conditions in a low-income residential building in Ahmedabad, India, with an aim to identify passive strategies for reducing summer discomfort. Despite being designed with environmental and passive strategies in mind, the building's indoor temperatures during the summer reached an uncomfortable average of 37.10C during a 3-day measurement period. The study employs optimisation algorithms and parametric modelling to fine-tune simulation settings and parameters, aligning simulated results with measured data. It utilises energy simulations conducted using Climate-Studio in the Rhino-Grasshopper platform to assess various building parameters like window size, orientation, shading, and ventilation shaft. The results reveal that keeping windows open for natural ventilation significantly reduces indoor air temperatures with a 0.560C reduction on average over a 3-months period. Moreover, various design scenarios, including changes in window size, shading, and the inclusion of a chimney, demonstrate their potential to enhance thermal comfort. However, it is noted that passive strategies alone may not achieve optimal comfort levels and should be complemented by broader landscape and urban planning strategies on an urban scale to create comfortable indoor conditions. Overall, the study provides valuable insights into improving indoor thermal comfort in low-income housing in hot climates, with implications for sustainable architectural design.

Keywords - Indoor air temperature, indoor thermal comfort, hot climate, design optimisation, passive strategies.

1. Introduction

Comfortable indoor environment is essential for meeting the basic health and wellbeing requirements of residents in low-income houses, particularly in tropical climates. A well-designed and thermally comfortable house can offer better resilience to the increasing frequency of extreme heat events and urban heat island effects. Chronic heat stress in tropical urban informal settlements suggests: high temperatures are approaching limits of human survivability (Ramsay et al. 2021). Therefore, the study aims to identify opportunities for reducing summer discomfort through passive design strategies in low-income residential buildings. Using actual measurements and through a simulation-based energy-comfort-optimisation model the study evaluates the indoor thermal conditions in a low-income residential building in Ahmedabad, India. The case-study building is situated within a marginalised, former leprosy-affected low-income housing community that experiences annual flooding. The building itself is the result of an inclusive and collaborative participatory design process, where residents actively participated in the planning, design, and implementation alongside professional experts. Even though the architect adopted suitable environmental and passive design strategies, the house was found uncomfortably hot during the summer with an average temperature of 37.1°C during a 3-day measurement period. Since this house is part of a larger construction scheme, a proper analysis of traditional and passive design strategies will aid in identifying the potential parameters for achieving an optimal design solution that is energy-efficient, thermally comfortable and addresses the sociocultural need of the community.

2. Methods

Optimisation algorithms and parametric modelling play a crucial role in the development of sustainable building designs, offering valuable tools for enhancing efficiency and effectiveness in the design process. This study introduces a calibration methodology that involves multiple stages of fine-tuning simulation settings and parameters until a satisfactory correlation is achieved between the simulated results and the measured data. The energy simulation is carried out using Climate Studio in the Rhino-Grasshopper platform which facilitated the testing of relevant building parameters (window material, size, location, orientation, shading, and use of ventilation shafts) through a number of iterations. The idea is to identify optimal solutions that align with sustainable principles to improve the indoor environmental conditions through optimisation algorithms.

2.1 Study area

The paper is based on a field study in a former leprosy-affected low-income housing located on the outskirts of Ahmedabad, India at 22°59′58.6″N and 72°38′40.0″E which is 8.41 km south-east of Sardar Vallabhbhai Patel International Airport. Named by the Gandhi Leprosy Seva Sangh as the Loving Community, it was formed in 1968 after the land was provided by the Government of Gujarat to accommodate leprosy-affected people from all over India who were socially excluded due to the contagious nature of the disease. The community has 125 houses with a population of approximately 500 people. In this study, we have examined a new architecturally built house which was built under a UK-India Charity Programme.

Case Study House: The primary living spaces within the house consisted of four distinct rooms, namely the main living area, kitchen, bathroom, and toilet facilities comprising a floor area of 24.60m2 (Figure 1). Adjacent dwellings were situated to the east and west of the aforementioned house, while to the south and north lay one private courtyard and one public courtyard, respectively.

Figure 1: Study House, view of the public courtyard in the front of the house

2.2 Measurements

A measurement campaign was carried out in the Loving community during the hot summer months of May. Measurements included air temperature (Ta), relative humidity (RH), wind speed and mean radiant temperatures (MRT) using Testo 480 with humidity/temperature probe (accuracy of up to ± 1% RH), comfort probe for turbulence measurement and globe thermometer (TC type K) for the measurement of radiant heat.

2.3 Energy simulation and validation

Modelling: We created a digital model of the house using the Rhinoceros (Rhino) 3d modeling software and Grasshopper with ClimateStudio for optimisation and environmental simulations. ClimateStudio is an advanced environmental performance analysis software for simulations, predictions, and optimisations of buildings to enhance energy efficiency, daylight use, electric lighting performance, visual and thermal comfort, and various factors contributing to occupant well-being. ClimateStudio enables multi zone thermal simulations using the US Department of Energy's EnergyPlus comprehensive building simulation program.

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Thermal Zoning: The case study house was divided into four areas for thermal modelling. Zone 1 is the main living area, with zone 2 being the kitchen connected to an open wall in the north, and zone 3 is a bathroom in the south. Zone 4 is a toilet located next to the bathroom, which can be accessed from outside (Figure 1). We focused on three main factors to make the house comfortable in terms of temperature and humidity: 1. the size of the windows, 2. the depth of shading, and 3. the stack or chimney.

Material and Construction Details: The materials for construction and the plans for scheduling (including people, equipment, lighting, and ventilation) were made based on the on-site survey. The various components used in building construction are outlined below:

- *External Walls (Load Bearing):* 210 mm thick brick walls with 6 mm plaster and paint on the exterior and the interior.
- *Internal Walls:* 100 mm thick brick walls with 6 mm plaster and paint on the exterior and the interior. - Plinth: Constructed using brick Bats and Morrum soil filling, with a 20-25 mm thick IPS (Indian Patent Stone) flooring over a concrete base at a height of 900 mm.
- *Roof (Single-Storied Building):* 125 mm thick concrete roof with 20-25 mm waterproofing layers.
- *Doors and Windows:* Windows and doors are made of 6 mm steel shutters; some were reused from old houses.

Ventilation: The study has considered natural ventilation. Window opening schedule was determined from the survey data based on the occupancy schedule (Figure 2). The ventilation settings includes: Operable area of 0.9, Discharge coefficient of 0.65, AFN (airflow network) Temperature setpoint of 200C and AFN window availability "AllOn".

Validation: Thermal analysis is validated against the in-situ measurements. The measurements included data collected over three days, from May 19 to 20 with a five minute resolution. The model predicted the Zone Mean Air Temperature to be 34.270C, while the survey recorded it as 37.140C (Figure 2). The Mean Absolute Percentage Error (MAPE) was 8.38%, and the correlation was 87.7%, which is considered acceptable.

Figure 2: Occupancy Schedule and Data Validation

2.4 Optimisation

At this stage, indoor thermal conditions were examined by applying a multi-objective optimisation algorithm for identifying the most effective set of design parameters for the optimal thermal comfort situation. The multi-objective optimisation algorithm involved the following objective functions shown in the Equations (1) and (2).

$$\text{Minimise relative humidity} = f\{(a_1x_1) + (a_2x_2) + \ldots + (a_nx_n)\} + b \quad ..(1)$$

$$\text{Minimise indoor air temperature (due to outdoor solar radiation)} = f\{(a_1x_1) + (a_2x_2) + \ldots + (a_nx_n)\} + b \quad ..(2)$$

where $x_i(i = 1\ldots n)$ depicts the indoor design variables, $a_i(i = 1\ldots n)$ are the derived coefficients.

The objective functions were based on the following design constraints as seen in Table 1.

https://doi.org/10.62744/CATE.45273.1166-523-531

Table 1: Design Parameters for multi-objective optimisation

Design Parameters for multi-objective optimisation		
Design variables	Upper range	Lower range
Window size (horizontal extension from existing size)	1.4 m	0.4 m
Presence and height of stack or chimney	3.0 m	1.0 m
Depth of window shade	1.0 m	0.5 m

Modeling Scenarios (Figure 3):
We examined seven different situations to see how specific factors affect optimisation.

- *Scenario 1:* We checked how changing the size of windows (from 0.4m to 1.4m) affected the microclimate. We had two existing 0.4m wide windows, one facing north and one facing south. These windows could expand to 1.4m towards the east. The height of the window remained the same in all cases. We ran 121 simulations for this.

- *Scenario 2:* We kept the shading depth fixed at 0.5m (actual depth) and explored how extending the window width affected things. We ran the same number of simulations as in Scenario 1.

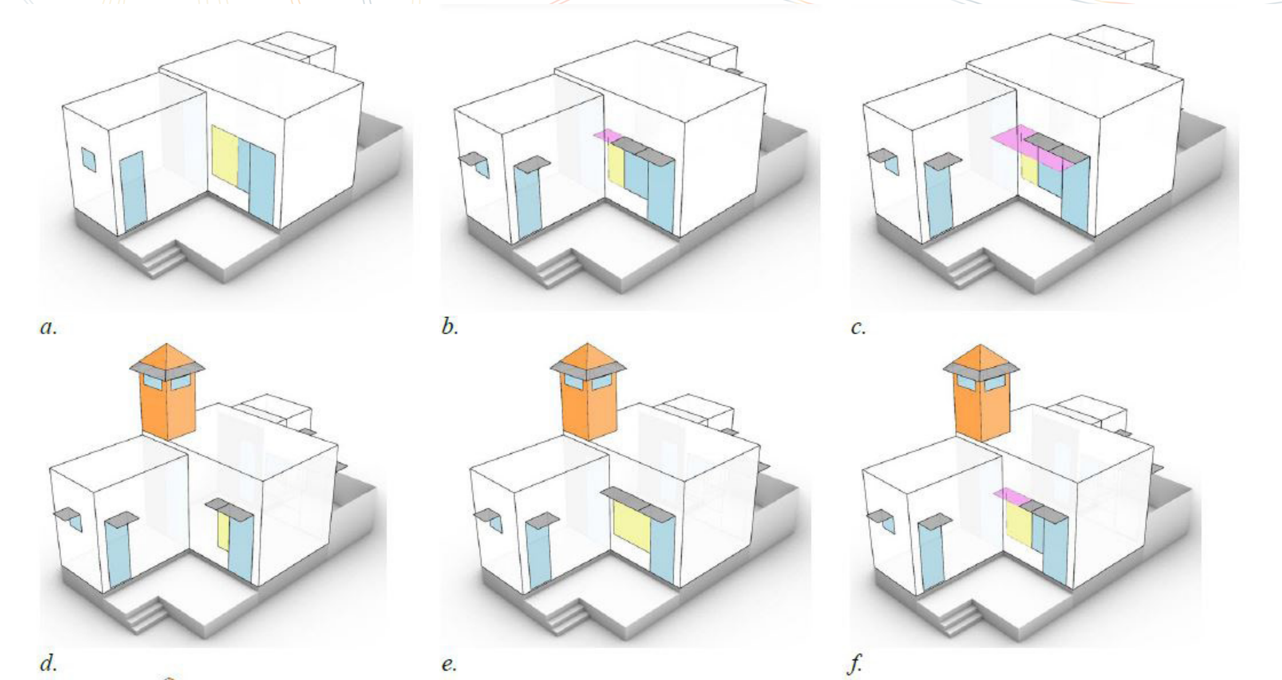
- *Scenario 3:* In this scenario, we played with both window and shading sizes, ranging from 0.4m to 1.4m and 0.5m to 1.0m, respectively. Since both windows were exposed directly to the outside, increasing the shading depth could create a semi-outdoor space, potentially affecting the microclimate during optimisation. We ran a total of 1296 simulations for this scenario.

- *Scenario 4:* We added a chimney to the living space. The chimney's height varied from 1.0m to 3.0m for optimisation. Other features remained the same as in the existing setup. Since there was only one change (the chimney), we ran a total of 6 simulations.

- *Scenario 5:* Similar to Scenario 4, but this time we considered a larger window with a fixed width of 1.4m on both the north and south walls. The number of simulations remained the same as Scenario 4.

- *Scenario 6:* We combined variations in both the chimney (1.0m-3.0m) and window size (width 0.4m-1.4m). This resulted in 80 simulations.

- *Scenario 7:* While scenarios 1 to 6 looked at changing individual parameters, Scenario 7 is a combination of all of them. We altered the window and shading sizes, and chimney height to find the best overall design solution and understand their relationships. We ran a total of 1280 simulations for this comprehensive scenario.



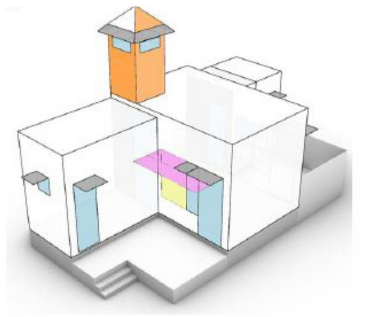


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Figure 3: Optimisation Scenarios: a) Scenario 1 _ variable window size (0.41.4m) without a shading, b) Scenario 2 _ variable window size with a fixed shading depth (0.5m), c) Scenario 3 _ variable window size (0.4-1.4m) and shading depth (0.5-1.0m), d) Scenario 4 _ variable chimney height (1.0-3.0 m) and a fixed small window width (0.4m), e) Scenario 5 _ variable chimney height (1.0-3.0 m) and a fixed large window width (1.4m), f) Scenario 6 _ variable chimney height (1.0-3.0 m) and window width (0.4-1.4m), g) Scenario 7 _ variable chimney height (1.0-3.0 m), window width (04-1.4m) and shading depth (0.5-1.0m)

3. Results

The average air temperature in the Model Zone from April to June was 33.250C, and the average humidity was 67.48% by following the occupancy schedule and ventilation schedule from the survey (Figure 2). Next, by keeping the same occupancy schedule, we let the windows open for 24 hours rather than responding to the actual window opening schedule. This resulted in air temperature reduction to 32.690C, which is 0.560C less or 1.7% lower from the existing model. This means only by keeping the windows open throughout the day and night, it is possible to achieve a significant reduction in air temperature. We used this ventilation schedule in all our simulations.

Figure 4 presents the optimisation results and Table 02 presents the summary of findings from each scenario. In scenario 1, we tested a larger window on the south side. It lowered the average air temperature to 32.620C, which is 0.070C or 1.96% cooler compared to the existing window. When there's shading, the window's size affects the temperature, and the existing window increased the temperature to 32.730C.

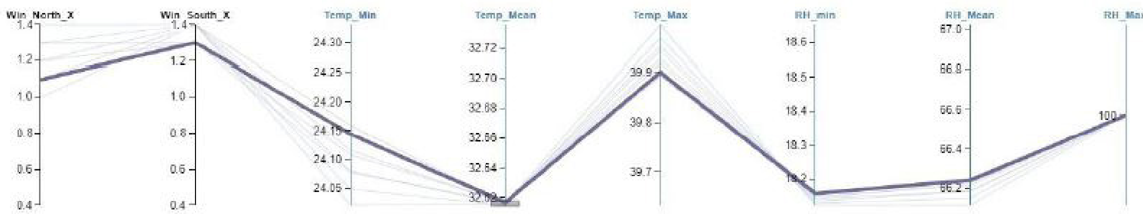
In scenario 2, we introduced shading, which improved conditions. The average temperature dropped to 32.580C, a 2.07% reduction from the initial condition.

In scenario 3, we optimised the size of both the north window and north shading to 0.8 meters and 0.6 meters, respectively, making them smaller compared to the south wall.

In scenario 4, we found that even with a smaller window, adding a chimney significantly reduced the temperature by 2.04%. However, it is possible to lower the chimney height by using a larger window, especially on the south side, as seen in scenario 5.

Scenario 6 Shows by increasing the chimney height from 2.0 meters to 2.5 meters, window sizes both in the south and north wall have decreased to 1.0 meters, and the resulting temperature is 2.32% lower .

Scenario 7 combines all the previous ones and offers various design solutions, achieving highest reductions in air temperature, by 2.38% in some cases. It presents options to adjust parameters like chimney height, shading size, or window size within a reasonable range to find a suitable design solution.



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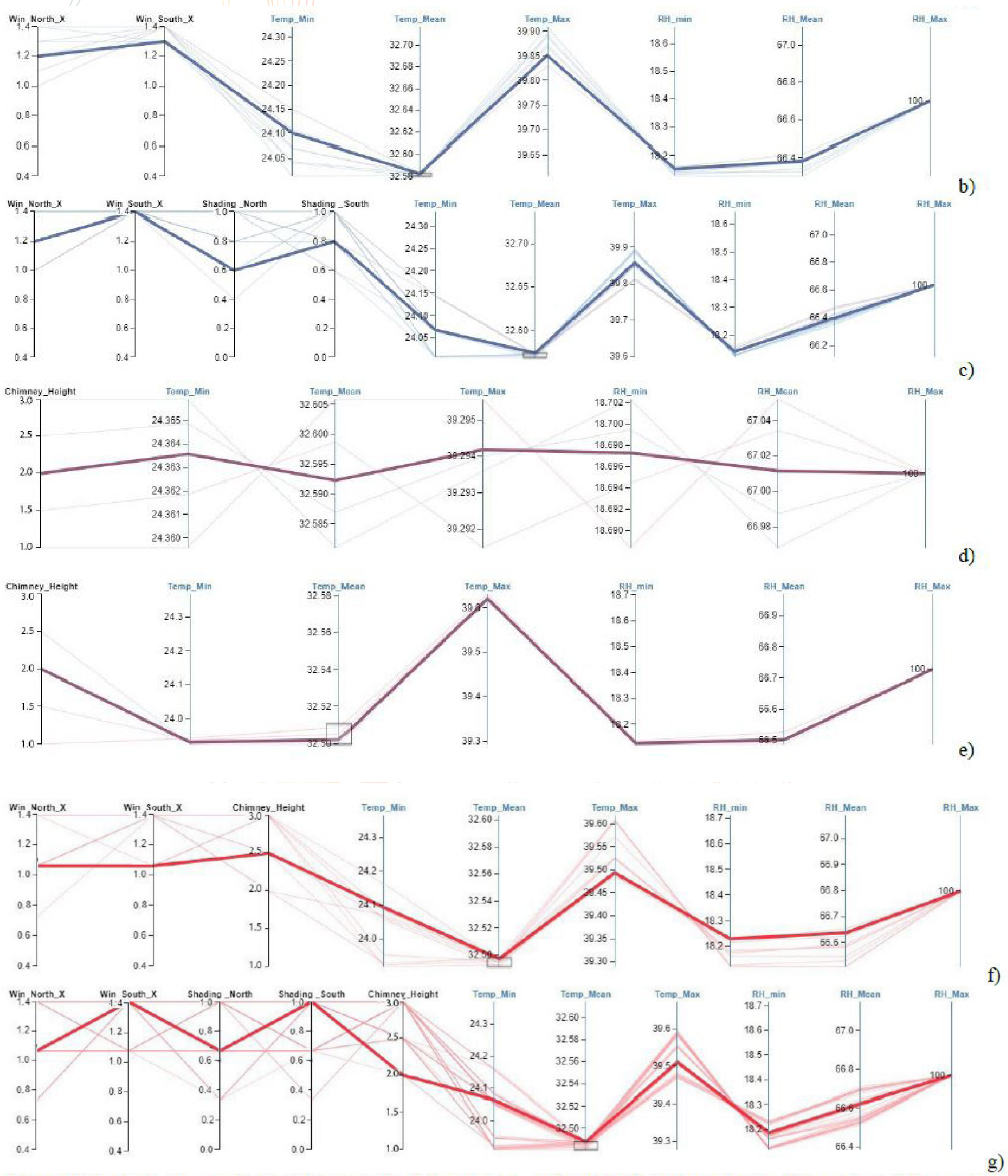
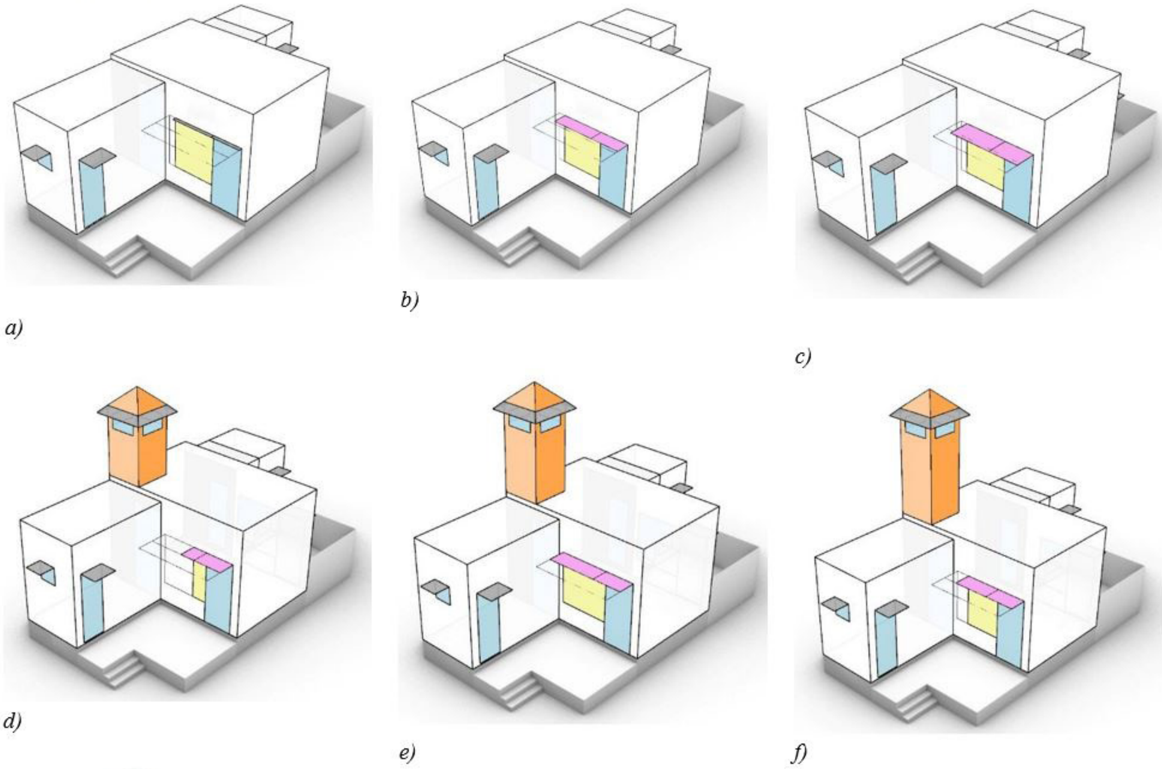


Figure 4: Optimisation result of: a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, e) Scenario 5, f) Scenario 6, g) Scenario 7

Table 2: Finding of scenarios

Scenario	Temp Mean, ^{0}C	Temp Drop from 33.25^{0}C (Existing)	RH Mean	Window South	Window North	Shading South	Shading North	Chimney
Scenario_1 Window Size Only	32.62	1.96%	66.21	1.3m	1.1m	-	-	-
Scenario_2 Window Size + Fixed Shading	32.58	2.07%	66.38	1.3m	1.2m	0.5m	0.5m	-
Scenario_3 Window Size + Shading	32.58	2.07%	66.40	1.4m	1.2m	0.8m	0.6m	-
Scenario_4 Chimney + Existing Window	32.59	2.04%	67.01	0.4m	0.4m	0.5m	0.5m	2.0m
Scenario_5 Chimney + Large Window	32.51	2.29%	66.51	1.4m	1.4m	0.5m	0.5m	2.0m
Scenario_6 Chimney + Window	32.50	2.32%	66.62	1.0m	1.0m	0.5m	0.5m	3m
Scenario_7 Chimney + Window + Shading	32.48	2.38%	66.61	1.4m	1.1m	1m	0.7m	2.0m



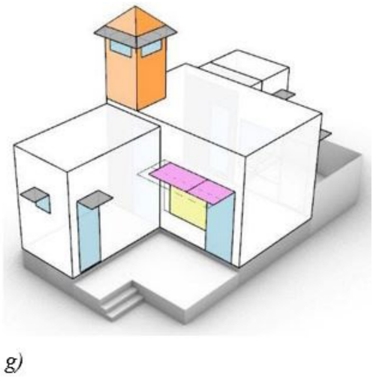
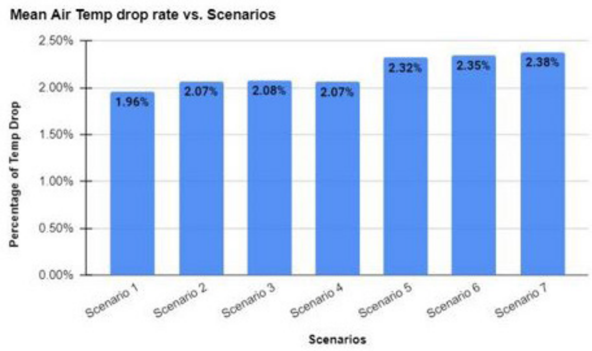


Figure 5: Optimized model of: a) Scenario 1, b) Scenario 2, c) Scenario 3, d) Scenario 4, e) Scenario 5, f) Scenario 6, g) Scenario 7



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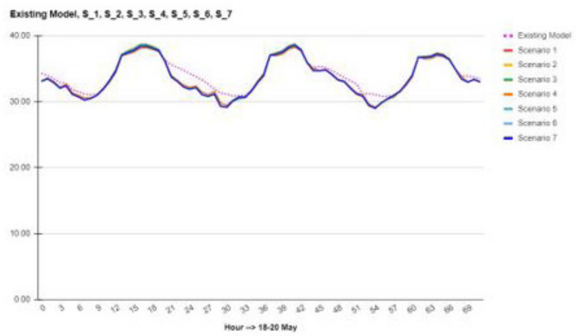

b)

Figure 6: a) Zone Mean Air Temperature drop rate in different scenarios with the existing model, b) Comparison of Zone Mean Air Temperature from May 18-20 in different scenarios with the existing model

4. Discussion

The National Building Code of India establishes a maximum thermal comfort limit of 32.0°C and 60% relative humidity (RH) for naturally ventilated buildings, assuming an air velocity (AV) of 1.6 m/s. Research conducted by (Sharma and Ali 1986) sets the upper limit of thermal comfort at 30.0°C, based on the Tropical Summer Index (TSI). According to the adaptive model for free-running buildings in the hot-dry climate of Ahmedabad, neutral temperature ranges between 25.0°C–31.0°C in summer and 21.5°C –27°C for winter (Udaykumar and Rajasekar 2015). Oropeza-perez and Alberg (2014) has identified 26.85°C as a realistic measure of comfort for indoor conditions in the tropical climate for the whole year. In a more recent study, Rawal et al. (2022) have developed an adaptive thermal comfort model called the India Model for Adaptive Comfort - Residential (IMAC-R) based on yearlong field surveys in eight cities located across five climate zones of India. The IMACR suggests an indoor operative range of 16.3–35 °C. From the on-site measurements, the case study house was found far above the optimum comfort operative temperature with the maximum air temperature reaching up to 40.6°C which is detrimental to the health, wellbeing, and productivity of the occupants. Final simulation results have shown acceptable accuracy in correlation to the measurements from the site for the house, where the air temperature during summer ranged between 23.97°C and 39.54°C. This allows for optimising the thermal performance of the spaces and reaching for acceptable predictions for its simulations in the next steps. The optimisation algorithm will lead to an improvement in usable space and reduced thermal load in the house. The process and results of the study will help architects and designers to find a more sustainable design for the local context.

5. Conclusion

The study has presented passive design strategies to reduce indoor air temperature in the tropical climate of Ahmedabad during summer. Most significant finding was that only by keeping the windows open for natural ventilation during the day and night, it is possible to achieve significant reductions in air temperature. Particularly, during the hot-dry summer seasons, it is possible to cool down the building indoors through the principle of night cooling when outdoor temperature drops down after the sunset. In addition, we have tested 7 scenarios which have a combination of different design parameters related to window size, orientation, shading depth and inclusion of a chimney or stack. Increase of window sizes, especially on the south side of the building showed a positive impact in air temperature reduction. Similarly, inclusion of window-shed and their increasing depth alongside use of chimney or stack shows positive outcomes. Although, increasing the height of the chimney from 2m to 3m did not have much impact. The optimal size of south window and north window were found to be 1.4m and 1.1m with an ideal depth of 1.0m and 0.6m for the window-shed in north and south side respectively and a chimney height of 2.0m. However, it is possible to have numerous combinations of the above parameters to achieve similar thermal conditions which needs to be further analysed with a parallel cost-benefit analysis to select the optimal conditions. Most importantly, it is obvious that the proposed passive strategies were unable to bring down the mean air temperatures in summer within the recommended comfort ranges of 25.0°C–31.0°C or below the upper threshold of 32.0°C as recommended by the National Building Code of India, although all strategies were found have significant impacts. This suggests that passive strategies applied to individual buildings are not sufficient to create comfortable indoor conditions. This must be supported by appropriate landscape and urban planning through climate-responsive strategies on an urban scale.

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Enhancing net-zero energy buildings: a comprehensive critical review of Passivhaus design in the UK

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Abstract

In the effort to reach the UK's goal of having zero carbon emissions by 2050, this study offers a detailed review of Passivhaus designs in the UK's housing area. This research tries to fill in the gaps in existing studies by closely looking at how much energy and carbon Passivhaus homes use compared to other homes in the UK. Focusing on energy efficiency and carbon emissions, this research plans to set a strong basis for further study stages, including creating a user-friendly online tool for easy access and understanding of the results. Using a step-by-step approach, the study gathers information from a wide range of scholarly articles, showing the Passivhaus design as a new way to create energy-saving homes. Initial findings highlight the great potential of Passivhaus designs in significantly lowering the need for space heating compared to the average UK home. However, the review also points out the lack of research on indoor air quality and the comfort of residents, marking an important area for further study. Additionally, the study emphasizes the urgent need to update current databases and approach to include a broader view of the energy embodied in materials and its related carbon emissions. As this PhD research moves forward, it plans to deepen the understanding of the sustainability of Passivhaus homes in the UK, with the goal to suggest changes in current Passivhaus standards to fully address the carbon emissions from embodied energy, leading the way towards a cleaner, more sustainable future in the UK's building industry.

Keywords - Passive Houses, Net Zero Energy Homes, Whole-Life Carbon Footprint, Embodied Carbon Footprint, Operational Carbon Footprint

1. Introduction

In a rapidly urbanizing world, the pressing demand for energy-efficient housing cannot be understated. As the effects of climate change intensify, the onus falls on the global community to undertake significant measures to curb the escalating levels of greenhouse gas emissions, a significant portion of which is attributed to the building sector [1]. The United Kingdom has embraced this challenge head-on, aligning its policy framework to achieve net-zero carbon emissions by the year 2050, a visionary step that underscores the nation's commitment to ushering in a sustainable future [2][3]–[5]. Integral to this ambitious endeavour is the emergence and growth of the Passivhaus or 'Passive House' standard in the UK, a groundbreaking approach that seeks to radically diminish the energy footprint of homes [6]. This study embarks on a meticulous journey to scrutinise the various dimensions of the Passivhaus design within the UK's context, laying bare its strengths and pinpointing areas where it can potentially evolve to become an even more potent tool in the fight against climate change.

Originating from a German prototype developed in the early 1990s, the Passivhaus standard has metamorphosed into a globally acknowledged blueprint for energy efficiency in building design [7][4]. The foundational philosophy of this approach rests on principles such as superior insulation, stringent air tightness requirements, and mechanical ventilation heat recovery (MVHR), elements that are engineered to significantly lower the energy demands of a dwelling [8]. In the UK, this design standard has gradually cemented its place as a preferred choice for eco-conscious property developers and homeowners alike [6], [9], [10]. However, as the reach of Passivhaus expands, it becomes increasingly pertinent to dissect its performance critically, paying special attention to its implications for embodied carbon emissions – domains that have previously remained somewhat underexplored in the broader academic and policy discourse [11].

As we stand at the cusp of a potentially transformative era in the realms of building science and environmental sustainability, it is incumbent upon researchers to delve deeper, analysing the efficacy of Passivhaus designs from multiple angles [12], [13]. It is no longer sufficient to merely highlight the remarkable reductions in space heating energy demands that these structures facilitate [14]–[16]. The discourse must evolve to encompass a more nuanced understanding of the life cycle impacts of Passivhaus homes, dissecting the embodied energy associated with construction materials and scrutinising the actual indoor air quality experienced by the occupants [17]–[19]. It is within this context that the present study situates itself, seeking to bridge the existing gaps in literature and thereby facilitating a comprehensive appraisal of the Passivhaus standard in the UK [10].

Moreover, the critical review presented herein ventures beyond a theoretical analysis of existing literature, aspiring to contribute tangibly to the ongoing efforts to enhance the sustainability of buildings in the UK. One of the cornerstone innovations of this research is the envisaged development of a cloud-based visualization tool, a platform designed to democratise access to research findings and foster a culture of informed decision-making amongst various stakeholders, including policy makers, builders, and the general populace. Through this tool, the study aims to propel the discourse on sustainable building design into a new frontier, where data-driven insights guide the evolution of building standards and practices.

Simultaneously, this research acknowledges the complex web of considerations that influence the transition towards net-zero energy buildings. While the Passivhaus standard offers a promising pathway, it is essential to scrutinise it critically, identifying potential areas of improvement and adaptation to the unique climatic and socioeconomic context of the UK houses [11]. The question of occupant comfort and the potential issues of overheating, particularly in the face of changing climate patterns, are pertinent aspects that demand deeper exploration [20]. Similarly, a focussed investigation into the embodied carbon emissions of Passivhaus homes can unearth insights that can further refine the approach, making it more aligned with the overarching goals of environmental sustainability [21], [22].

1.1. Core Principles and Technical Aspects of Passivhaus Design

1.1.1. Foundational Principles

In the vanguard of sustainable building designs, the Passivhaus standard stands distinguished, underscored by its meticulous alignment with principles that prioritize both energy efficiency and inhabitant comfort [23]. This section embarks on a profound exploration of the foundational principles that underlie the Passivhaus standard, scrutinizing how these principles harmonize to radically decrease the energy demands of a residence.

A linchpin of the Passivhaus standard is the deployment of superior insulation, often perceived as the foremost strategy in energy conservation [19] [24] [25] [26]. This insulation extends beyond merely outfitting buildings with thicker layers of insulating material. It necessitates the incorporation

Table 1: Overview of the main Passivhaus certification criteria [4], [6], [24]

Criteria	Details
Space Heating Demand	Not more than 15 kWh/(m²yr)
Cooling Demand	Matched to the heating demand plus an additional allowance for dehumidification.
Primary Energy Demand	Not exceeding 120 kWh/(m²yr) for all energy used in the building
Airtightness	Maximum of 0.6 air changes per hour at 50 Pascals pressure (n50 ≤ 0.6 /hr)
Thermal Comfort	Should not exceed 25°C for more than 10% of hours in a year
Window Performance	U-value not exceeding 0.80 W/(m²K)
Ventilation System Efficiency	Minimum 75% efficiency

of high-performance insulation materials that bear a remarkable ability to restrict heat transfer, thereby enabling a stable interior climate irrespective of external weather conditions [19] [24] [25] [26]. The goal is not merely to minimize energy loss but to create a buffer that separates the conditioned indoor environment from the fluctuating outdoor climate, enhancing the comfort and health of the occupants [19] [24] [25] [26].

Complementing the insulative strategy is a stringent air tightness requirement that seeks to mitigate uncontrolled air leakage, a potential conduit for energy loss [19] [27]. Buildings designed as per Passivhaus standards are equipped with airtight layers that prevent the infiltration of cold drafts in winter and the intrusion of hot air in summer, thereby sustaining a comfortable indoor environment year-round [19] [27]. This strategy extends beyond energy conservation; by preventing damp and cold spots, it mitigates the risk of mould growth, thus fostering healthier living spaces [19] [27].

The next piece in this synergistic puzzle is the Mechanical Ventilation Heat Recovery (MVHR) systems [28], [29]. These are designed to enhance indoor air quality without compromising on energy efficiency. In essence, the MVHR systems operate by extracting stale air from the building and replacing it with fresh, filtered air from the outside, a process which, incidentally, recovers a substantial portion of the heat energy from the expelled air to warm the incoming fresh air [28], [29]. This cyclical process ensures a continuous flow of fresh air, facilitating a healthier indoor environment while maintaining a high level of energy efficiency [28], [29].

Together, these foundational principles create a delicate ballet of technical elements that work synergistically to establish residences with markedly reduced energy demands, fostering a harmonious balance between human comfort and environmental sustainability.

2. Methods: Unveiling the Research Process

Choosing a systematic literature review over a wider literature review for this scholarly discussion is grounded in the need to provide a thorough and unbiased analysis that aligns with scientific rigor and truth [30]. A systematic literature review demands the use of scientific strategies to carefully identify, evaluate, and synthesize relevant studies that address a specific research question [30]. It strives to present a complete and unbiased collection of evidence, strictly following methodological guidelines. In comparison, wider literature reviews offer a broad overview of existing narratives but miss the structured approach and accuracy that systematic reviews encompass [30].

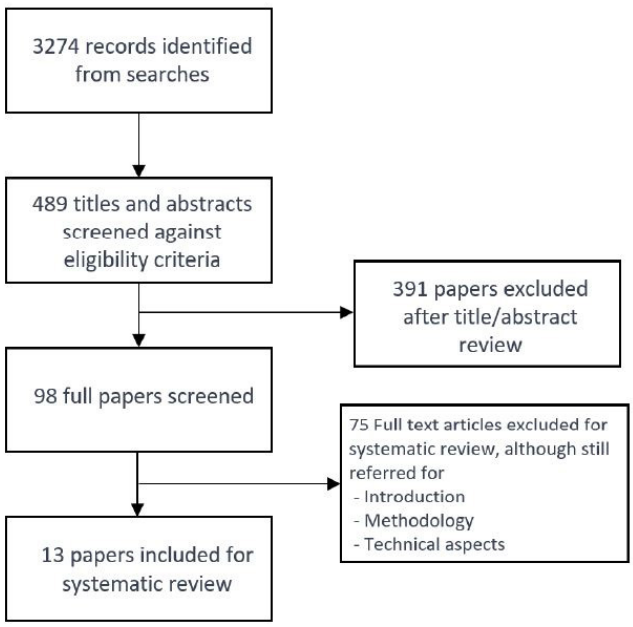

Figure 1: Chart explaining systematic review process for literature review.

2.1. Literature Search and Selection

To sift through the vast amount of existing literature, a combination of modern tools and platforms were used. The process began with the use of applications like "Connected Papers", a novel tool that visually groups research papers based on their similarities and thematic connections, helping to discover hidden links and fostering a deeper understanding. In addition, platforms such as "Google Scholar", "ResearchGate", and "Elsevier" were fertile sources from which numerous papers were gathered, exploring a variety of terms including "passive houses in the UK", "whole-life energy consumption", "embodied carbon passive houses", and "net zero UK".

To ensure a deep and comprehensive analysis, the research initially embraced over 150 peer-reviewed articles. This large body of work was carefully analysed, using both qualitative and quantitative approaches to select the most central works to the research objectives.

2.2. Rationale for Selection

Central to this research is a refined selection of thirteen notable papers, chosen with a steadfast commitment to depth, relevance, and a range of perspectives. This chosen corpus seeks to furnish a well-rounded view of the Passivhaus design scene in the UK, with each paper adding a unique yet harmonized voice to the scholarly conversation. The process of selecting these papers was anything but arbitrary; it was the outcome of a relentless pursuit for quality and pertinence. The existing literature specifically addressing the topic of "whole-life energy consumption and carbon footprints in UK Passivhaus residences" is notably sparse. A meticulous investigation revealed a gap in the literature; studies extensively covering the whole-life energy consumption in passive houses, particularly in any specific geographic locale, are conspicuously absent. Most extant studies veer towards discussions on embodied or operational carbon, without encompassing the entire spectrum of whole-life energy consumption.

Moreover, focusing specifically on the UK market introduces additional layers of complexity, as literature addressing the carbon footprint specific to passive house studies in this region is even more limited. Therefore, the research adapted by integrating various studies that cast light on diverse, yet interconnected facets: comparisons between passive and conventional houses, insights into the UK market's stance on low carbon houses, and investigations into embodied carbon studies in passive houses, among others.

Each paper was therefore scrutinized through a series of stringent criteria evaluating the depth of content, methodological robustness, and the extent to which it contributes to the existing knowledge base. These thirteen papers, which form the foundation of this research, offer a rich array of insights that resonate well with the delineated research objectives, facilitating a comprehensive analysis.

By honing in on these thirteen studies, this research seeks to weave a narrative that is both in-depth and sharply focused, illuminating understudied facets of the Passivhaus sector in the UK. It aspires to construct a discourse that is not only illuminating but also inspires further explorations and discussions in this emerging field.

3. Critical Examination of existing literature and research for Passivhaus Design in the UK's Context

At the start of this intensive research journey, this section carefully explores a collection of thirteen vital research papers that are crucial to understanding the current scenario of Passivhaus design in the UK. Through detailed observation, it will cover a variety of analyses and findings, while also pointing out the shortcomings present in each study. This thorough examination hopes to build a strong route towards a deeper understanding of Passivhaus implementation in the UK, encouraging an academic discussion that is as thoughtful as it is progressive, and making a significant contribution to the growing story of sustainable residential designs in the UK.

Table 2: Overview of 13 papers selected for literature review.

	Source	Location	Study's Focus	Reason of analysing this source
2020	R. Mitchell and S. Natarajan [6]	UK	Investigating the Passivhaus standard's effectiveness in reducing the UK's housing energy performance gap through post-occupancy analysis.	Aids in understanding energy performance gaps in passive houses, fostering a sustainable transformation in UK's residential sector.
2017	X. Liang et al. [31]	UK	Comparative analysis of energy efficiency between conventional and passive houses in Northeast England.	Offers empirical data crucial for analysing energy consumption trends in UK passive houses for my PhD thesis.
2013	A. Stephan et al. [5]	Belgium	Evaluates life cycle energy demands of passive houses, comparing a Belgian passive house with other housing models.	Offers insights into neglected aspects of passive house energy demands, aiding in developing more comprehensive UK policies.
2012	Rosa M. Cuéllar-Franca et al. [32]	UK	Analysing environmental impacts of UK's prominent housing types through life cycle assessment to propose net-zero energy transition strategies.	Guides in-depth study on environmental impacts and energy consumption patterns in UK housing types for my PhD research.
2018	N.G. Fernando et al. [33]	UK	Analyses embodied carbon emissions in various structural elements of a newly constructed apartment building in Sunderland, UK.	Guides efforts to minimize energy consumption in UK passive houses, fostering alignment with contemporary sustainability goals
2023	M. Keyhani et al. [34]	UK	Examines disparities in embodied carbon databases affecting UK's Passivhaus designs; highlights potential emissions reductions through sustainable practices.	Essential for understanding and improving carbon emissions calculations in UK passive houses, aiding in focused, sustainable research development.
2022	L. Jankovic et al. [21]	UK	Analysing Birmingham Zero Carbon House's retrofit process, highlighting material choices and paths to net-zero emissions by 2050.	Guides my PhD thesis on energy consumption in UK passive houses, facilitating net-zero strategies and renewable technology integration.
2017	Zr. Larasati et al. [35]	Indonesia	UK's adoption of refined Embodied Energy calculations in Passivhaus design, using insights from Indonesia's low-cost housing strategy.	Enhances understanding of material production's environmental impact in UK passive houses, aiding in effective strategy development.
2022	N. Anderson et al. [36]	UK	Evaluating and strategizing to reduce embodied energy in the UK's affordable social housing sector.	Informing strategies to reduce whole life energy consumption in UK passive houses for my PhD thesis.
2023	D. Arslan et al. [37]	UK	Exploring prefabrication techniques' role in reducing carbon emissions in UK high-rise residences, using Portland's Place case study.	Guides strategies for minimizing energy consumption in UK passive houses, highlighting gaps in current LCA tools and guidelines.
2020	B. Derbi et al. [38]	UK	Analysing MgO SIPs' environmental impact in UK's nearly Zero Energy Buildings through a North England single-family house case study.	Informing material sourcing strategies for lower energy consumption in passive houses aligning with UK's nZEB goals.

2014	Rosa M. Cuéllar-Franca et al. [40]	UK	Analyses life cycle costs of UK housing stocks, advocating for Passivhaus strategies to enhance economic and environmental sustainability.	Guides in forming energy-efficient strategies and policies for sustainable and affordable passive houses in the UK.

4. Conclusions

Upon conducting a comprehensive analysis of the above 13 studies, I have identified several significant discoveries that should be taken into consideration during the subsequent stage of the PhD project:

5. The literature review emphasizes the need for a larger and more diverse sample to enhance the generalizability of the findings and the importance of incorporating diversified data sources to obtain a more holistic understanding of energy performance.

6. Future research must delve deeper into comprehensive strategies, encompassing economic evaluations and environmental impacts, thereby aligning with broader sustainability goals.

7. The literature review clearly signals the necessity for a paradigm shift in evaluating the energy efficacy of passive houses in the UK, emphasizing an integrated approach that also considers embodied and transport energy demands. This approach advocates for more precise per capita assessments, promising a pathway to genuinely net-zero energy buildings in the UK.

8. The literature review underscores the urgent need to focus on the usage stage of UK residential structures to mitigate environmental impacts, spotlighting potential benefits through optimizing construction materials and promoting recycling initiatives. An expansion to encompass behavioural analyses and sustainable materials exploration could facilitate actionable strategies towards realizing net-zero energy buildings in the UK.

9. To further advance towards a sustainable construction landscape, future research should foster multidisciplinary collaborations and delve into broader contextual factors influencing embodied carbon, thereby guiding actionable, holistic strategies for carbon-optimal designs in passive houses.

10. The literature review underscores the necessity of developing unified, reliable embodied carbon databases to enhance the accuracy of carbon footprint analyses in the UK's residential buildings, urging future research to foster globally adaptable and sustainable practices in the construction industry.

11. To foster a swift transition to carbon neutrality in the UK's residential sector, further studies should evaluate the economic viability and societal impacts of adopting Passivhaus principles on a large scale, focusing on community engagement and comprehensive life cycle assessments of sustainable building materials, thereby guiding informed policy and fostering international collaboration.

12. To attain the 2050 carbon reduction goals in the UK's affordable housing sector, a synergized effort focusing on stringent regulations, knowledge-sharing, and consumer awareness is critical. Addressing financial hurdles and revamping current methodologies for improved accuracy in embodied energy calculations are vital steps towards fostering a sustainable, energy-efficient housing landscape.

13. To facilitate a transition to sustainable construction in the UK, urgent developments in post-construction data sharing, nuanced government guidelines, and comprehensive benchmarking systems are crucial. The industry should embrace collaboration and innovation, alongside fostering transparency and skill development, steering towards global sustainability goals effectively and efficiently.

14. To expedite the UK's transition to nZEB standards, future research should prioritize exploring sustainable material alternatives and socio-economic factors impacting local productions, focusing on enhancing the economic and logistical feasibility of domestic manufacturing.

15. To further the UK's transition to net-zero energy buildings, future studies should focus on a localized approach, exploring diverse UK-centric case studies and expanding analysis to encompass the entire building life cycle, thus providing a more holistic view and actionable insights tailored to the UK's unique climatic and regulatory context.

16. Emphasis should be on examining the rapidly evolving renewable energy landscape and exploring innovative financial strategies, including green financing and governmental incentives, to mitigate the impending housing affordability crisis while promoting responsible energy consumption and sustainability.

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Development of a Comfort Rating Method for Australia's Nationwide House Energy Rating Scheme (NatHERS) – Darwin Houses Case Study

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Abstract

In the face of escalating global temperatures and extreme climate challenges, this study addresses the pressing concern of overheating within homes by introducing a new Comfort Rating Method. Our approach presents a departure from conventional norms in the domain of thermal comfort modelling by incorporating the Effective Temperature index (ET*), which considers not only air and mean radiant temperature but also humidity, essential for holistic comfort assessment. Moreover, we extend our model to account for indoor air movement, a significant contributor to comfort in tropical environments. This method has been embedded in AccuRate, the benchmark software for Australia's Nationwide House Energy Rating Scheme (NatHERS) and validated against real-world data from an extensive Darwin thermal comfort field study.

The new comfort calculation method was applied to examine 1,043 dwellings from Commonwealth Scientific Industrial Research Organisation (CSIRO)'s Australian House Data (AHD) sets. We proposed 10 comfort bands, providing a framework for evaluating comfort in residential settings. This research not only advances thermal comfort knowledge but also offers architects, designers, and stakeholders a tool to create climate-sensitive, resilient residential buildings. While this study focuses on Darwin only, future research can adapt this method to various extreme climates, refining its model based on regional nuances.

Keywords - Thermal Comfort, Effective Temperature, Extreme Climates, Climate-Sensitive Design, Residential Buildings.

1. Introduction

In the realm of human comfort, few challenges are as pertinent and pressing as ensuring comfort amidst extreme climatic conditions. The Northern Territory of Australia, specifically the tropical climate of Darwin, is characterised by its unique climatic challenges, where high temperatures and humidity levels intersect to create a distinctive atmosphere of persistent discomfort. At the heart of these challenges lies the pressing concern of overheating within residential homes [1]. As the mercury rises, homes become potential hotspots for discomfort, posing serious risks to the inhabitants' well-being (e.g., Refs. [2-4]). Overheating not only disrupts sleep patterns but also heightens the susceptibility to heat-related illnesses, thereby warranting a comprehensive exploration of this critical topic (e.g., Refs. [5-6]).

In the pursuit of human health and well-being, the implications of overheating extend beyond mere comfort [7]. Prolonged exposure to elevated indoor temperatures has been linked to a range of health issues, encompassing heat stress, dehydration, and compromised cognitive functioning [8]. Vulnerable segments of the population, such as the elderly and children, are particularly susceptible to the adverse effects of overheating. Furthermore, the compounding influence of climate change and global warming elevates the urgency of addressing this concern [9]. As these phenomena escalate, the potential for frequent and intense heat waves amplifies, casting a shadow of concern over the safety and comfort of inhabitants in extreme climates like tropical climate context [10].

The prevailing thermal comfort standards, exemplified by international standards such as the ASHRAE Standard 55 (2020) adaptive model, EN 15251 (2007), CIBCE Gide A (2015), and CIBSE TM52 [11-14], have predominantly centred around the utilization of operative temperature, a metric that regrettably disregards influential factors such as humidity and indoor air movement [15], though these models allow the correction using air movement. This notable deficiency becomes especially evident when grappling with extreme climates, such as tropical environments, where these unaccounted parameters play pivotal roles. Recognising this oversight, our research endeavours to bridge this gap by using the Effective Temperature (ET*) as the index for our thermal comfort calculation [16]. Unlike the conventional approach, ET* encompasses not only air temperature and mean radiant temperature but also crucially integrates humidity, rendering it an encompassing metric for a holistic comfort evaluation within tropical climates [17].

Additionally, the conventional comfort models have heretofore bypassed the intricate interplay between indoor air movement and comfort, an omission that becomes glaringly significant in tropical climates [18]. As a response to this oversight, we have extended the equation for ET*, encapsulating the tangible impact of indoor air movement. By doing so, we strive to deliver a more realistic representation of the comfort experience in such environments, where air movement can distinctly influence thermal perceptions.

The culmination of our efforts finds expression through integration into Commonwealth Scientific Industrial Research Organisation (CSIRO)'s AccuRate software [19], the benchmark software for the Nationwide House Energy Rating Scheme (NatHERS) [20]. The proposed method was examined against field-measurement data gleaned from an extensive field study conducted on residential buildings in Darwin. Through AccuRate's simulation platform, we examined 1,043 dwellings (from CSIRO's Australian House Data (AHD) sets) and 96 dwelling simulations (for 8 typical houses in 12 variations) and proposed a Comfort Rating scale ranging from 0 to 10 for assumed occupied hours for living room and bedroom zones [21].

This paper sets out with a dual purpose; first and foremost, it aims to extend the horizons of comfort modelling by developing a new rating methodology that accounts for the unique dynamics of extreme climates, specifically tailored for tropical contexts. Secondly, it seeks to integrate the role of ventilation, a vital component in the pursuit of human comfort, into the thermal comfort equation. By delving into the unexplored realm of how ventilation impacts the thermal comfort model, this study aims to address a pivotal gap in existing research. Such a method could be used to, (a) educate architects, designers, and other stakeholders to learn about an applied climate sensitive design for hot humid tropics, including methods to optimise comfort when air conditioning is not used; (b) improve passive comfort outcomes in residential building design; and (c) increase stakeholder awareness of the need to design and build climate change resilient residential buildings, to the extent possible, to reduce health risks when air conditioning is not available.

2. Methods

This section describes the steps that have been applied to develop a new comfort rating method for Darwin Dwellings.

2.1. Proposed thermal comfort calculation method

In order to develop the thermal comfort rating method, we propose using the same index, ET*, which has been used to define comfort neutrality at 29 oC at 50% relative humidity (RH) by Delsante [19]. ET* is an index that includes air temperature (°C), relative humidity (%), mean radiant temperature (°C), clothing value (clo), and metabolic rate (met). The proposed method is presented as followings (Figure 1):

a) To calculate ET* for the given air temperature and humidity (example A in illustrated in Figure 1).
b) Trace along the calculated ET* iso-line until it intersects with 50% RH, which was the relative humidity level for neutral temperature of 29 °C.

c) Degree of Discomfort (DD) will be estimated with a ΔET* (the difference between the nominated point's ET* and the nearest comfort zone boundary ET*, called Comfort ET* (CET).
d) To take account the enhanced Cooling Effect of Ventilation (CEV). CEV was subtracted from the ΔET*, as described in Equation 1. The equivalent temperature benefit of enhanced ventilation has been estimated in Williamson et al. [22] and described in equation 2.

$$DD = ET^{*} - CET - CEV \qquad (1)$$

Where,

DD = Degree of Discomfort (°C)

$ET*$ = Effective temperature for the given air temperature and humidity (°C)

CET = Comfort ET* (°C), the base acceptable adaptive comfort effective temperature at still air conditions

CEV = Cooling Effect of Ventilation (°C)

The equivalent temperature benefit of ventilation was calculated via equation 2 using Williamson et al. equation [22].

$$CEV = 1.67\ ln\ (v) + 3.97 - 0.02RH\% \qquad (2)$$

Where,

CEV = Temperature equivalent benefit of ventilation (°C)

v = Indoor air movement (m/s), limited to max of 4m/s

RH = Relative humidity (%)

The proposed comfort model is illustrated on a psychrometric chart in Figure 1.

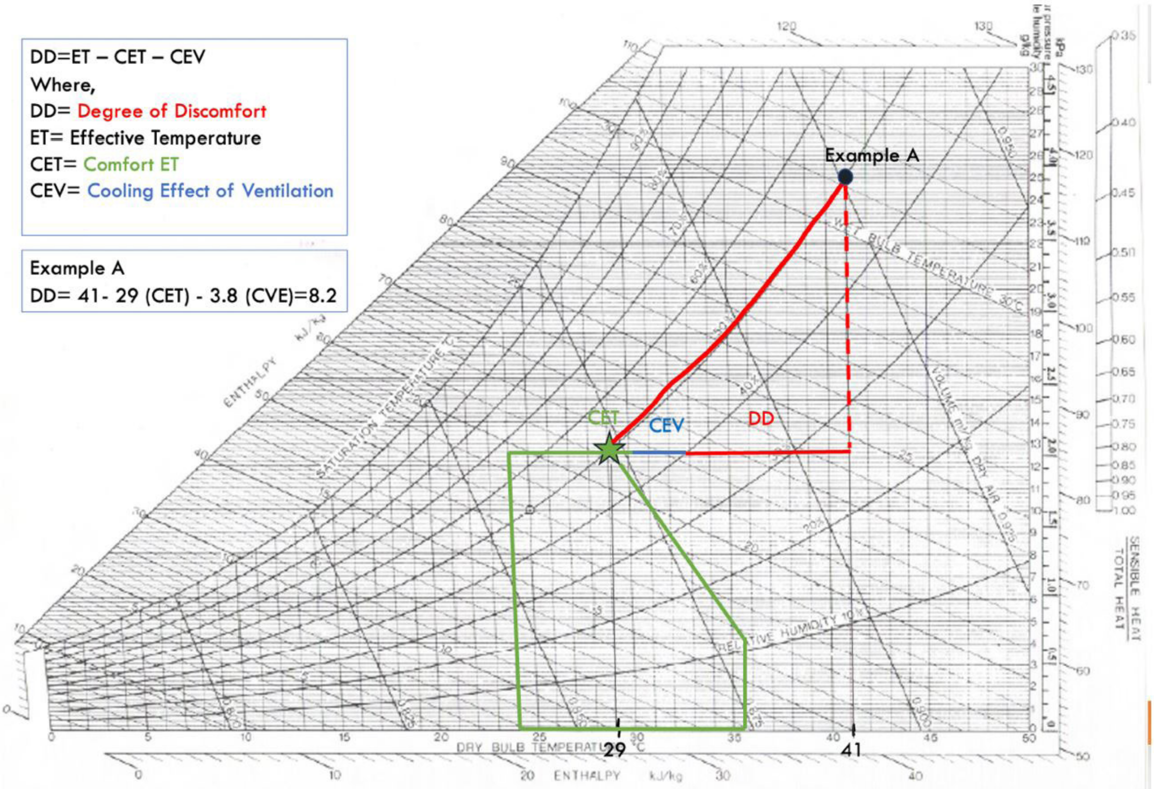

Figure 1: Proposed thermal comfort calculation model.

The maximum acceptable conditions at this study was CET+ 80% acceptability + CEV. The metric that we used in this study was Degree hours of Discomfort (DhD). To calculate DhD, firstly, DD was calculated at each hour for each room/zone. Secondly, all hours of DD readings were accumulated to represent the overall comfort performance of each zone in the house in Degree hours of Discomfort (DhD).

2.2 Field study measurements

Thermal comfort votes and percentage of acceptability were driven from field study, where 58 dwellings in Darwin were monitored [23-24]. Households were invited to participate in 20 houses which were naturally ventilated (NV), and 38 houses were operated under mixed mode. 2415 comfort vote assessments were collected. Environmental parameters including air temperature, humidity and air movement were recorded hourly in the living room and bedrooms. During 12 months period of the study the residents 18 years old and above were invited to complete daily a thermal comfort survey that consisted of three widely used subjective measures of thermal comfort that included; sensation 1=Cold to 7=Hot [11]; preference 1=Cooler, 2=No change, 3=Warmer and; comfort 1=Very uncomfortable to 6=Very comfortable [25]. The survey also asked the respondents to report their clothing level, activity, and window, fan and artificial heating/cooling operation.

During the field study, weather data were obtained from Australia's Brue of Meteorology (BOM) from the station closest to the house to describe the weather conditions during the monitoring periods. The mean monthly outdoor temperature was calculated from this data.

2.3 Comfort rating method

The comfort calculation method was incorporated into a new version of AcuRate (AccuRate Homes V1.0.3.22) , that was modified for this project, and was applied to two sets of dwellings, (a) 1,043 dwellings from CSIRO's Australian Housing Data (AHD), Darwin dwellings that had a Universal Certificate issued for the years 2020 and 2021 (named AHD dwelling sets); and (b) 8 typical dwellings in Darwin (4 detached houses , 2 duplexes and 2 apartments) named typical dwelling sets. All 8 types of dwellings were simulated for the four cardinal orientations and 3 design variations (12 variations for each type of dwelling). Each variant was modelled using 2016 and 2050 Reference Meteorological Year (RMY) weather files [26]. To calculate ET* metabolic rate and clothing value were considered as follows: Living room activity rate (Met) = 1.53; living room clothing level (clo) = 0.38; bedroom activity rate (Met) = 1.25; bedroom clothing level (clo) = 0.33.

We calculate DhD for two sets of dwellings, in two zones, kit/living zone and bedroom during the occupied hours. The maximum DD for all dwellings and zones were also calculated. Based on the results of DhD for each zone, Comfort Rating scale ranging from 0 to 10 has been determined for assumed occupied hours in the kit/living area and the worst bedroom.

3. Results

This section reports the detailed results of one of the 8 typical dwelling sets and comfort rating analysis for the AHD dwelling sets and Typical dwelling sets.

3.1 Typical dwelling sets – DhD analysis

The typical dwelling selected to be reported in this study was a flat roof home (Figure 2), with a large proportion of the understorey. The upper storey consists of a kitchen/living zone and 3 bedrooms. The simulation has been conducted for three different designs of the house (with different energy efficiency features to compare the comfort performance of the house under each design). The simulations for each design have been conducted in four orientations, north, east, west, and south, in total 12 series of simulations were generated.

Annual Degree hours of Discomfort for occupied hours and maximum Degree of Discomfort (DD) for two variations (north facing and east facing) of the most energy efficient design for the house is demonstrated in Figure 3. The figure shows the results for the living/kitchen zone and the worst bedroom during the occupied hours.

The DhD performance (Figure 3a) shows that the eastern orientation provides for a better kitchen/living zone, but only a slightly better worst bedroom. The max DD (Figure 3b) however, shows that the kitchen/living zone in the eastern orientation has a higher 'worst hour', compared to the northern orientation. These charts demonstrate the impact of orientation on comfort, and the challenge of deciding on comfort parameters. Both total DhD and max DD will impact occupants.

Figure 2. A typical dwelling in Darwin, Australia.

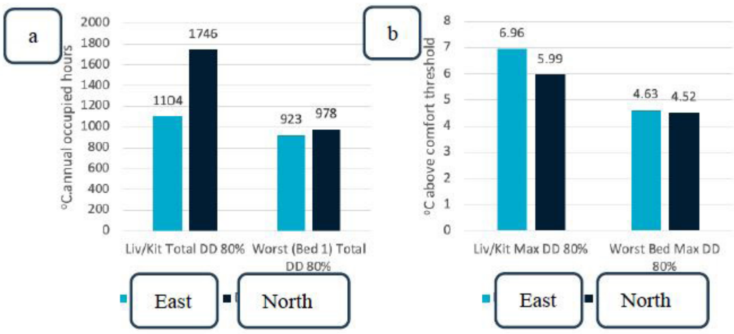

Figure 3: a) Annual Degree hours of Discomfort (DhD) during the occupied hours in living/kitchen and bedroom zones; b) Max Degree of Discomfort (DD) in Living/kitchen and bedroom zones for east and north facing dwellings.

3.2. Comfort rating analysis

Applying the methodology for DhD and maximum DD calculation, we examined 1043 dwellings from AHD data set (AHD dwelling sets) and all the 8 typical dwelling sets (each dwelling under 12 variants) to identify the minimum and maximum annual DhD and DD. A summary of the highest and lowest DD values is provided in Table 1, differentiating AHD dwelling sets and typical dwelling sets (all simulations). The highlighted figures are the highest/lowest figures from the complete set of data and could be used to provide the outer boundaries of the comfort rating.

Table 1: Summary of Maximum (Max) and minimum (Min) annual Degree hour of Discomfort (DhD), and maximum Degree of Discomfort (DD) for kitchen/living room (kit/liv) and bedroom (bed) for AHD dwelling sets and typical dwelling sets.

Criteria	AHD Dwelling Sets	Typical Dwelling Sets
Min DhD kit/liv	233	699
Max DhD kit/liv	17,611	4,230
Min DhD bed	5	66
Max DhD bed	3,185	3,678
Max DD kit/liv –lowest rate	2.58	4.07
Max DD kit/liv –highest rate	13.73	8.79
Max DD bed – lowest rate	0.60	1.61
Max DD bed Max DD bed Highest rate	5.44	7.33

Based on the highest and lowest values of all data sets (AHD and typical dwelling sets), the boundaries for the comfort ratings for the two zones (Living room and bedroom) were proposed (Table 2). The values for comfort ratings 1 and 10 are loosely based on a rounding down of the highest and lowest values from the combined data set. A constant multiplier of 0.6 for comfort bandwidths was found to provide the best fit for DD in both the living zone and bedroom. The proposed comfort bands are illustrated in Figure 4.

Table 2: Proposed comfort rating bands in kitchen/living room (kit/liv) and bedrooms (bed).

Comfort rating	Kit/liv DhD (°Ch)	Bed DhD (°Ch)
1	15000	3600
2	9000	2160
3	5400	1296
4	3240	778
5	1944	467
6	1166	280
7	700	168
8	420	101
9	252	60
10	151	36

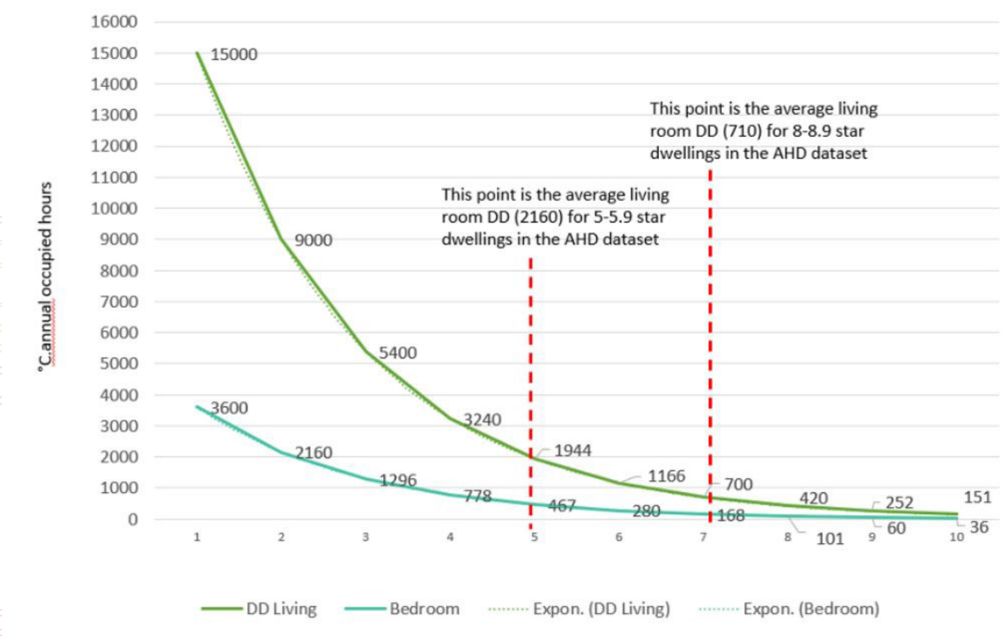

Figure 4: Proposed comfort bands with annual Degree hours of Discomfort (DhD).

3.3. Sensitivity analysis

For further sensitivity analysis, the kitchen/living zone data from AHD data set was used to investigate whether the ranking of total DhD changed with the different climate files (2016 and 2050 RMY files).

Figure 5 shows the rank order comparison of DhD results between the 2016 and 2050 RMY climate files. While DhD was always worse in 2050, the relative ranking between designs doesn't change enough to significantly change the comfort ranking. This was indicated by a high Spearman rank correlation coefficient ρ=0.958.

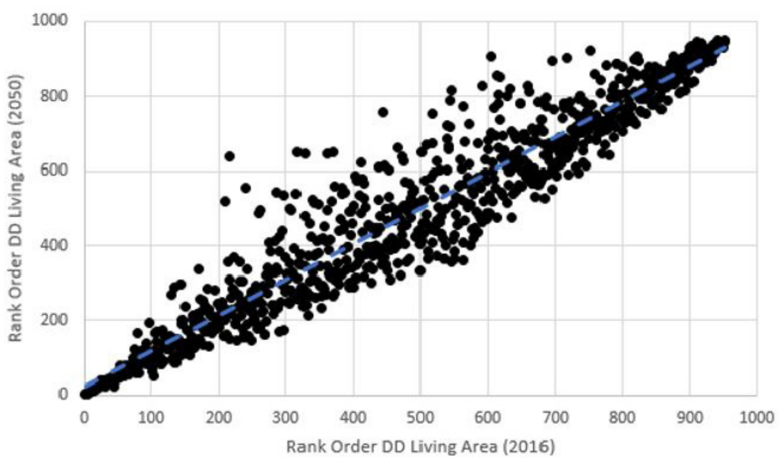

Figure 5: Rank order of houses (kitchen/living zone) for 2016 and 2050 RMT climate data files for ADH dwelling sets.

The comfort rating bands were then applied to the kitchen/living zone of all houses, for both the 2016 and 2050 data results. The 2016 results, shown in light blue in Figure6, have a fairly standard Bell curve distribution. The 2050 results, shown in dark blue, reveal that no dwellings will rate above the comfort rating of 4, with the majority achieving a rating of 2 or 3. Note that there are some dwellings that fail to achieve a comfort rating (shown as band 0). The sensitivity analysis confirms that the proposed comfort rating bands (Table 2 and Figure 4) can be applied to Darwin dwellings to provide more insight into the performance of the dwellings.

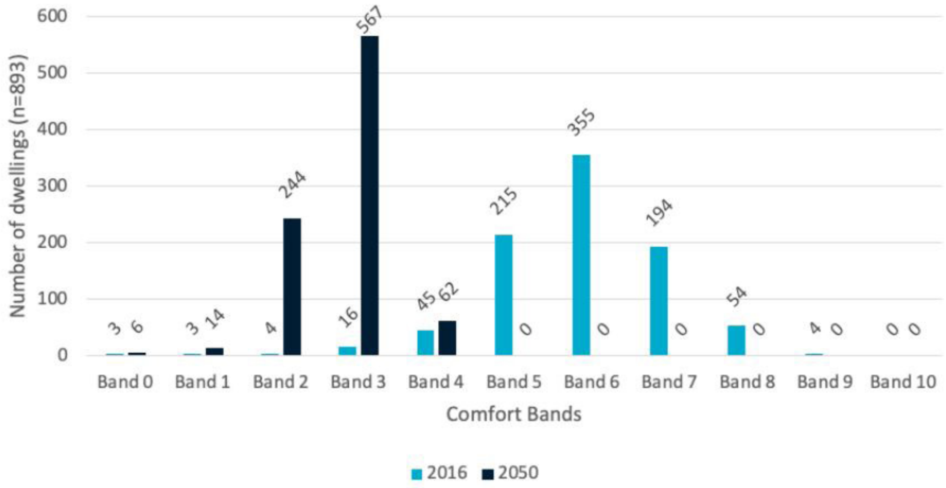

Figure 6: Comparison of comfort rating under 2016 and 2050 RMY data files for AHD dwelling sets for kitchen/living zone.

4. Discussion

In interpreting our findings, it becomes evident that our proposed thermal comfort rating method, incorporating the Effective Temperature (ET*) and indoor air movement, contributes significantly to the understanding of thermal comfort in extreme climates. By addressing the limitations of previous models, our methodology allows for a more realistic assessment of comfort in tropical and sub-tropical climate contexts. The implementation of ET* acknowledges the influence of humidity, which can substantially impact thermal perceptions. Furthermore, our inclusion of indoor air movement recognises its vital role, especially in tropical environments where natural ventilation plays a significant role in maintaining comfort.

Considering the broader perspective, our research offers a departure from conventional norms in thermal comfort modelling. It bridges the gap between theoretical understanding and practical application, enabling architects, designers, and stakeholders to create climate-sensitive and resilient residential buildings. This approach is of utmost importance in light of climate change and global warming, which are projected to intensify extreme climatic conditions, including heatwaves. By addressing these challenges proactively, we contribute to the promotion of human health and well-being in extreme climates, even in the absence of air conditioning.

However, it's important to acknowledge the limitations of our study. Our methodology, while comprehensive, was specific to the context of Darwin and may require adaptation for different extreme climates. Additionally, while our field study provided empirical data, in some cases it was limited to 11 months (in 20 houses) and mixed-mode homes – not only naturally ventilated homes (in 38 cases). Future research should focus on expanding the applicability of our Comfort Rating Method to various extreme climates and further refining the model based on regional nuances.

In addition, neither the 2016 nor the 2050 weather files utilised in this project took into account heat wave conditions (i.e., both files are based on a Reference Meteorological Year (RMY) that uses average weather conditions). As such, the building performances simulated do not reflect the full extent of 'discomfort' that might be experienced during sequential or extreme hot days that exceed the average maximum temperature and humidity for each month.

5. Conclusion

In the face of extreme climatic challenges, as exemplified by the tropical climate of Darwin, Australia, this study aimed to develop a new Comfort Rating Method tailored to Australia's Nationwide Energy Rating Scheme (NatHERS). The pressing concern of overheating within residential homes in such climates necessitated a comprehensive exploration of thermal comfort factors, particularly relevant for vulnerable populations like the elderly and children. Our research has unveiled the limitations of conventional thermal comfort models, i.e., the ASHRAE Standard 55 (2020) adaptive model, EN 15251 (2007), CIBCE Gide A (2015), and CIBSE TM52 [1114], in addressing the specific dynamics of extreme climates. These models often rely on operative temperature, a metric that overlooks crucial factors like humidity and indoor air movement, which are significant contributors to comfort in tropical environments.

In response to these limitations, our study implemented the Effective Temperature (ET*) index in our thermal comfort calculation. ET* not only considers air temperature and mean radiant temperature but also incorporates humidity, providing a more holistic assessment of comfort within extreme climates. Furthermore, we have extended our model to account for the impact of indoor air movement, a factor often neglected in existing models. By doing so, we aim to provide a more realistic representation of the comfort experience in tropical climates. Our efforts culminate in AccuRate, a specialised software integrated into the NatHERS [19] framework and was examined for Darwin climate context. The results were validated against real-world data from an extensive field study conducted on residential buildings in Darwin.

We calculated Degree hours of Discomfort (DhD) and maximum Degree of Discomforts for two zones, living and bedroom zones during the occupied hours. By applying this method into CSIRO'S AHD dataset, we introduced 10 comfort bands from 0-10 corresponding to the comfort threshold of DhD for each band. Through the validation of AccuRate, both theoretically and practically, our approach paves the way for a paradigm shift in the assessment and design of comfortable living spaces in extreme climates. This research not only contributes to the knowledge base in the field of thermal comfort but also holds significant implications for architects, designers, and stakeholders aiming to create climate-sensitive, resilient residential buildings, thus promoting human health and well-being when air conditioning may not be available.

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Furniture layout in residences- the role of thermal comfort

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1. Abstract

People spend most of their active time at home in living rooms. The furniture in living areas is designed based on the multiple activities generally performed in a living space. The objective of the study was to assess the factors influencing the arrangement of furniture layout in the perspective of occupant behaviour research. The behaviour of arrangement of furniture was evaluated in terms of Physical Environmental Triggers (PET), Physical Environmental Factors (PEF), Psychological Factors (PF), Social Factors (SF), Physiological Factors (PHF) and Non-Adaptive Triggers (NAT). The study developed an instrument measuring these factors along with the respondents' satisfaction with the current layout. The collected data was analyzed with Confirmatory Factor Analysis (CFA) and Structural Equation Modelling (SEM). Construct validity of the model has been established by estimating the convergent validity and discriminant validity. The absolute fit indices satisfy the recommended values and indicates that the proposed model has an acceptable fit. Contextual factors which comprises Physical Environmental Factors, Psychological Factors, Social Factors, and Physiological Factors, is identified as a major factor affecting the behaviour. This study will give an insight for architects regarding the perceptions of an occupant which results in greater satisfaction with space with energy implications of the layouts.

Keywords - Furniture Layout, Residences, Satisfaction, Thermal Comfort, Energy Efficiency

2. Introduction

Residences in India primarily consist of a living room, bedroom, kitchen, dining and restrooms. However, a family spends most of the productive time in the house in living space, excluding sleep time [1]. A family spends time in the living area by chatting, watching television, reading books or newspapers, playing and welcoming the occasional guests. The furniture in the space is arranged in such a way to cater to all the mentioned activities. However, the decision of furniture layout may be limited by physical characteristics like the position of doors and windows, location of the ceiling fan, building orientation, extent of the space and layout etc. A layout of the furniture may demand a compromise on certain needs. For example, the furniture arrangement of a type may enhance the spaciousness of the area when the furniture is aligned along the wall, while compromising on air movement from the windows or ceiling fans. The prioritization of different needs results in a specific layout inside each residence. Thermal comfort and need for air movement to achieve thermal comfort is an essential criterion in the decision of a layout in warm and humid climates [2]. The choice of furniture type and material is based on the flexibility for spatial adaptations. In summer, the layout tends to be fan-centric since the primary need is the availability of air movement for thermal comfort. Whereas, in winter, other preferences and needs play a dominant role and results in a variety of furniture layouts in the same space.

While it is generally understood that occupants may change their posture or relocate within a room to improve comfort, no experimental or in-situ results were found in the literature [3]. However, there are many studies which evaluate the airflow characteristics and thermal comfort in a space with the presence of furniture [2,4–11]. Furniture layout is identified as an essential factor determining the indoor air quality, airflow and temperature fields and ventilation efficiency [6,7]. The presence of furniture in a room creates a complicated airflow recirculation and higher air velocities near the furniture edges along with a non-uniform distribution of air currents [4,5]. It was identified that a partition wall plays a significant role in maintaining indoor temperature distribution and airflow characteristics. A unit with lower partition wall height, a higher distance of the partition wall from the window and lesser distance between bed and window is found to provide maximum airflow within the breathing zone [8]. The parameters considered by the subjects in their respective arrangements were visual comfort, view, sunshine, control, privacy, concentration, centralization, relaxation, lighting, circulation, diversity, overheat and warmth.

This study intends to assess the factors influencing the arrangement of furniture layout in a residential living room in the perspective of occupant behaviour research. Occupant behaviour can be defined as proposed by [12] as "a human being's unconscious and conscious actions to control the physical parameters of the surrounding built environment based on the comparison of the perceived environment to the sum of past experiences". The factors influencing occupant behaviour was initially classified as internal factors and external factors by Schweiker and Shukuya [13] where internal factors include preferences, attitude, cultural background etc. and external factors include building and environment-related features. Later Fabi et al.[14] presented a refined classification of drivers of occupant behaviour into five categories: physical, environmental, contextual, psychological, physiological and social factors. A better explanation of the terms 'internal factors' and 'external factors' were proposed by Polinder et al. [15]. Internal driving forces evolved from interactions between biological and psychological aspects, and these are investigated in the domains of social science, biology and economics. External driving forces comprise of building, physical environment and time, which stimulates a reaction in an individual.

Recent research by Wagner et al. [3] categorized the drivers of occupant behaviour as adaptive triggers, nonadaptive triggers and contextual factors as given in Table 1. Contextual factors are considered as the moderators of triggers and behaviour. Adaptive triggers include physical environment triggers and physiological triggers. Physical environmental triggers correspond to the physical properties of the environment, which, when varied, creates stimulation in the occupant. Non-adaptive triggers are the factors that are independent of physical environmental triggers. Contextual factors are grouped into four categories- physical environmental factors, psychological factors, social factors and physiological factors, based on earlier research [14]. Contextual factors remain unchanged for a period, unlike the physical environmental and physiological triggers.
The objectives of the study are: (a) To study the factors influencing occupant behaviour in the context of arranging the furniture layout in a living room, and (b) To evaluate whether all the measures fit the recommended value to indicate a good fit of the structural model for the collected data.

Table 1: Potential influencing factors driving occupants' behaviour in a building [3]

Trigger		Factors
Adaptive Triggers	Physical Environmental Triggers	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, Sound level
	Physiological Triggers	Body temperature, Skin temperature, Skin wetness
Contextual Factors	Physical Environmental Factors	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, View to outside
	Psychological Factors	Knowledge, expectations, Preference, acceptability, Perception, Needs about comfort, health, safety, Awareness, Mood, Habit, lifestyle, View/interaction with outdoors, Previous activities
	Social Factors	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
	Physiological Factors	Age, sex, weight, Body dimensions, Health state, Ethnic group
Non-Adaptive Triggers		Time of the day, Scheduled activity

3. Methods

The recent classification by [3] gives a better understanding of the factors on occupant behaviour. The seven factors proposed by (Wagner et al., 2018) were adopted to develop the questionnaire measuring the perceptions of occupants while arranging the furniture in the living space of a residence. The behaviour of arranging furniture was measured in terms of satisfaction with the current layout. Satisfaction can be seen to serve either as a criterion for evaluating the quality of the residential environment (by measuring the effect of perceptions and assessments of the objective environment upon satisfaction) or as a predictor of behaviour [16] which is relevant in the current study. A five-point scale was used to indicate the agreement or disagreement (Strongly disagree, Disagree, Neither agree nor disagree, Agree, Strongly agree) towards the prepared statements under each factor. The respondents were also asked to rate their level of satisfaction with the current layout on a five-point scale (Very satisfied, Satisfied, Neither satisfied nor dissatisfied, Dissatisfied, Very Dissatisfied). The questionnaires were circulated through a web-based platform to ensure a wider reach into the housing and demographic categories. Data was collected from 305 occupants conforming to the recommendation by Hair et al.[17], which is a sample size which is ten times the number of statements. Collected data were analyzed with the software SPSS 23 and AMOS 23. No missing data was observed as it was mandatory to answer all questions before submitting in the online platform.

4. Results

Descriptive statistics of the profile of the respondents is given in Table 2. Respondents living in apartments (56.4%), as well as individual houses (43.6%), participated in the study. 66.2% of the respondents belonged to a family having four or more members, while only 1.6% of respondents stayed alone. The type of furniture used in their living rooms are lightweight which is easily moveable (24.3%), heavy furniture like a sofa which is difficult to move (33.4%) and a combination of light and heavy furniture (42.4%). The details on the usage of ceiling fans, desk fans/wall fans and air-conditioners are also given in Table 2.

Table 2. Descriptive statistics of the profile of the respondents

Item	Type	Number of respondents	Percentage (%)
House type	Apartment	133	43.6
	Individual house	172	56.4
Family size (Number)	1	5	1.6
	2-3	98	32.1
	Four or more	202	66.2
Furniture	Lightweight	74	24.3
	Heavy	102	33.4
	Both	129	42.4
Presence of ceiling fans (Number)	0	34	11.1
	1	185	60.7
	2	86	28.2
Presence of desk fan/ wall fan (Number)	0	234	76.7
	1	55	18.0
	2	16	5.2
Presence of Air conditioner (Number)	0	261	85.6
	1	35	11.5
	2	9	3.0

Cronbach's alpha coefficient, which is the most widely accepted measure [17] to evaluate the reliability and consistency of the survey instrument, is estimated as given Table 3. Cronbach's alpha value above 0.7 is considered to be ideal[17]. In this case, Cronbach's alpha value above 0.7 is observed for all factors, and an overall Cronbach's alpha value of 0.758 attained, indicating a high level of internal consistency for the scale. Further tests on validity were assessed in terms of convergent validity and discriminant validity at a later stage.

Table 3: Reliability analysis for the survey instrument

Factor	Number of statements	Cronbach's alpha
Physical Environmental Triggers (PET)	5	0.715
Physical Environmental Factor (PEF)	6	0.719
Psychological Factors (PF)	9	0.702
Social Factors (SF)	3	0.826
Physiological Factors (PHF)	3	0.823
Non-Adaptive Triggers (NAT)	3	0.760
Overall reliability analysis	30	0.758

Structural equation modelling is performed to assess the suitability of the model based on the data collected. Confirmatory factor analysis or measurement model was evaluated first to test the reliability and validity of the survey questionnaire as recommended by [18]. Confirmatory factor analysis was conducted using AMOS 23 to evaluate the significance of the statements. 16 out of 30 statements were found to be significant at 1% level (p-value <0.001) and having factor loading greater than 0.5[19]. Further analysis is limited to these 16 statements as these statements measure the construct.

4.1 Structural equation modelling: Model fit assessment

Structural equation modelling assesses whether the data fit into the proposed theoretical model. Model fit is evaluated in Table 4 and the acceptability of the structural model is supported by the recommended values of the common goodness of fit indices. Null hypothesis and alternative hypothesis are framed to test the fit of this structural model.

Table 4. Model fit Indices

Fit indices	Results	Recommended values
Chi-square	78.457 (0.000) DF- 84	
p-value	0.650	>0.05 [18]
Chi-square/ Degrees of freedom	0.934	≤5.00 [17]
Goodness of Fit Index (GFI)	0.970	>0.90 [20]
Adjusted Goodness of Fit Index (AGFI)	0.951	>0.90 [20]
Comparative Fit Index (CFI)	1.000	>0.90 [21]
Normated Fit Index (NFI)	0.952	≥0.90 [21]
Incremental Fit Index (IFI)	1.004	Approaches 1
Tucker Lewis Index (TLI) or Non-Normed Fit Index (NNFI).	1.00	≥0.90 [21]
Root Mean square Residuals (RMR)	0.048	<0.08 [18]
Root Mean Square Error of Approximation (RMSEA)	0.000	<0.08 [18]

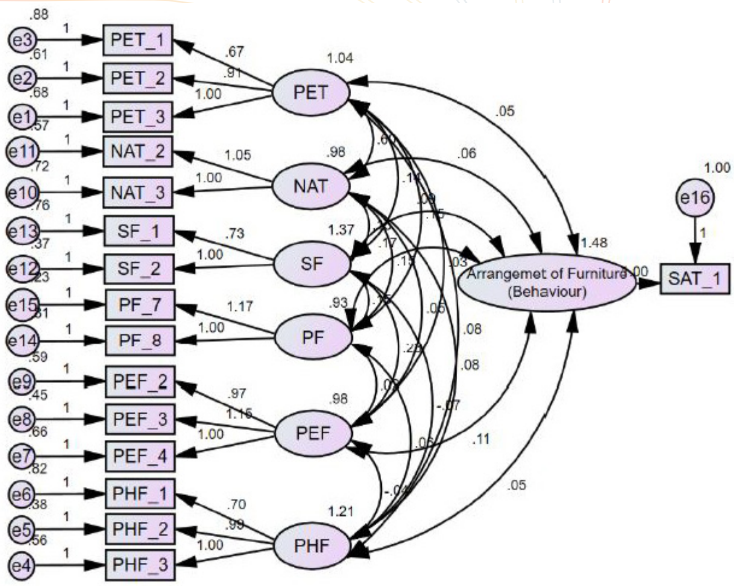

Figure 1: Structural model

Hypothesis

Null Hypothesis (H0): The hypothesized model has a good fit.
Alternate Hypothesis (H1): The hypothesized model does not have a good fit.
The test for our null hypothesis (H0) as shown in the figure resulted in a chi-square value of 78.457 with 84 degrees of freedom with a probability of 0.650 (p-value >0.05). These results suggest a good fit of the model. Table 5 shows the unstandardized coefficients and associated test statistics. Unstandardized regression coefficient indicates the amount of change in the dependent variable created by a one-unit change in the predicting variable. CR stands for Critical Ratio, which is obtained by dividing the estimate with the Standard Error (SE). For every single unit change in PET2, PET would increase by 1.366 units.

Table 5: Regression Weights: (Group number 1 - Default model)

Statement		Factor	Estimate	S.E.	C.R.	P
PET_1 (Fresh air and daylight)	<---	PET	1.000			
PET_2 (Air from ceiling fan)	<---	PET	1.366	.154	8.865	<0.001
PET_3 (Air from the window)	<---	PET	1.497	.169	8.881	<0.001
PHF_1 (Heavy furniture)	<---	PHF	1.000			
PHF_2 (Comfortable for old aged)	<---	PHF	1.403	.126	11.098	<0.001
PHF_3 (Safe for toddlers)	<---	PHF	1.419	.127	11.204	<0.001
NAT_3 (Space for multiple activities)	<---	NAT	1.000			
NAT_2 (Daylight for reading)	<---	NAT	1.049	.126	8.352	<0.001
SF_2 (Aesthetically pleasing)	<---	SF	1.368	.360	3.802	<0.001
SF_1 (Spaciousness to welcome guests)	<---	SF	1.000			
PF_8 (Safety concerns near a window)	<---	PF	.858	.228	3.758	<0.001
PF_7 (Spaciousness)	<---	PF	1.000			
PEF_3 (Fan and light controls)	<---	PEF	1.189	.087	13.707	<0.001
PEF_2 (Building features)	<---	PEF	1.000			
PEF_4 (Not blocking circulation space)	<---	PEF	1.033	.078	13.181	<0.001
SAT_1 (Satisfaction with the current layout)	<---	Furniture	1.217	.083	14.717	<0.001

Table 6 presents the standardized weights for the model. Standardized estimates evaluate the relative contributions of each predictor variable on each outcome variable. Figure 1 shows the structural model with seven factors. From Figure 1, it is evident that occupants attach more value with the satisfaction on the layout while all the factors influence the satisfaction with the layout.

Table 6: Standardized Regression Weights: (Group number 1 - Default model)

			Estimate
PET_1	<---	PET	0.588
PET_2	<---	PET	0.766
PET_3	<---	PET	0.778
PHF_1	<---	PHF	0.650
PHF_2	<---	PHF	0.869
PHF_3	<---	PHF	0.827
NAT_3	<---	NAT	0.758
NAT_2	<---	NAT	0.809
SF_2	<---	SF	0.886
SF_1	<---	SF	0.699
PF_8	<---	PF	0.731
PF_7	<---	PF	0.919
PEF_3	<---	PEF	0.862
PEF_2	<---	PEF	0.782
PEF_4	<---	PEF	0.774
SAT_1	<---	Furniture	0.773

4.2 Construct validity of the measurement model

The validity of the construct is assessed to ensure that the measurement scale accurately represents the concept of interest. The most accepted measures of validity are convergent validity, discriminant validity and nomological validity [21]. Convergent validity establishes that the scale is correlated with other known measures of the concept. Discriminant validity confirms that the scale is adequately different from other similar concepts to be distinct, and nomological validity verifies whether the scale demonstrates the relationships shown to exist based on theory or prior research.

Convergent validity is established by evaluating the factor loadings, Average Variance Extracted (AVE) values and Construct Reliability (CR) values. AVE for each construct is computed as the sum of all squared standardized factor loading divided by the number of items. AVE is recommended above 0.5 [19] to suggest adequate convergent validity. An AVE value of less than 0.5 points out that on average, there is more error remaining in the items than the variance explained by the latent factor structure imposed on the measure. AVE measure should be computed for each latent construct in a measurement model as given in Table 7. It is found that the least AVE value obtained is 0.513 and all the constructs (PET, PHF, NAT, SF, PF, PEF and Furniture arrangement) have attained an AVE above 0.5. Construct Reliability (CR) value of 0.7 or higher suggests good reliability [19]. Reliability between 0.6 and 0.7 may be acceptable, provided that other indicators of a model's construct validity are good. High construct reliability indicates that all measures consistently represent the same latent construct. The calculated CR values for each construct is presented in Table 7.

			FL	Item reliability (IR)	Delta	AVE	Sum of FL	Sum of delta	CR
PET_1	<---	PET	0.588	0.346	0.654				
PET_2	<---	PET	0.766	0.587	0.413				
PET_3	<---	PET	0.778	0.605	0.395	0.513	2.132	1.462	0.76
PHF_1	<---	PHF	0.650	0.423	0.578				
PHF_2	<---	PHF	0.869	0.755	0.245				
PHF_3	<---	PHF	0.827	0.684	0.316	0.621	2.346	1.138	0.83
NAT_3	<---	NAT	0.758	0.575	0.425				
NAT_2	<---	NAT	0.809	0.654	0.346	0.615	1.567	0.771	0.76
SF_2	<---	SF	0.886	0.785	0.215				
SF_1	<---	SF	0.699	0.489	0.511	0.637	1.585	0.726	0.78
PF_8	<---	PF	0.731	0.534	0.466				
PF_7	<---	PF	0.919	0.845	0.155	0.689	1.650	0.621	0.81
PEF_3	<---	PEF	0.862	0.743	0.257				
PEF_2	<---	PEF	0.782	0.612	0.388				
PEF_4	<---	PEF	0.774	0.599	0.401	0.651	2.418	1.046	0.85
SAT_1	<---	Furniture	0.773	0.598	0.402	0.598	0.773	0.402	0.60

Table 7: Average Variance Extracted and Composite Reliability

The initial results support the convergent validity of the measurement model. Although two loading estimates are below 0.7, one of these is just below the 0.7 and do not appear to be significantly harming model fit or internal consistency. The average variance extracted (AVE) estimates all exceed 0.5 and the construct reliability estimates all exceed 0.7 except one case where it is 0.6 but acceptable, provided that other indicators of a model's construct validity are good [19]. Besides, the model fits relatively well based on the model fit indices. Therefore, all the indicator items are retained, and adequate evidence of convergent validity is provided. Discriminant validity measures the extent to which a construct is truly distinct from others. Discriminant validity is proved when the AVE estimates are higher than the square of the correlation between the two factors. All AVE estimates are greater than the corresponding inter-construct squared correlation estimates in Table 8. This indicates the measured variables have more in common with the construct they are associated with than they do with the other constructs.

Factors	AVE	Squared Inter-construct Correlation						
		PET	NAT	PEF	PF	SF	PHF	SATI
PET	0.513	-	0.356	0.000	0.021	0.014	0.004	0.002
NAT	0.615	0.356	-	0.001	0.028	0.016	0.005	0.003
PEF	0.651	0.000	0.001	-	0.000	0.039	0.001	0.012
PF	0.689	0.021	0.028	0.000	-	0.016	0.003	0.019
SF	0.637	0.014	0.016	0.039	0.016	-	0.003	0.004
PHF	0.621	0.004	0.005	0.001	0.003	0.003	-	0.002
SATI	0.598	0.002	0.003	0.012	0.019	0.004	0.002	-

Table 8: Discriminant Validity

5. Discussion

Previous research on the occupant behaviour and triggers focused on the influence of occupant behaviour on energy consumption in a building [3,22,23]. This study follows a different approach, where the triggers and factors concerning the behaviour of arranging furniture layout of a living room is explored with respect to the satisfaction with the current layout. Contextual factors which comprises of Physical Environmental Factors (CR-0.85, AVE-0.651), Psychological Factors (CR-0.81, AVE-0.689), Social Factors (CR-0.78, AVE-0.637), and Physiological Factors (CR-0.83, AVE-0.621), is identified as a major factor affecting the behaviour of occupants as pointed out by [24,25]. These results are agreeable with studies by [3] which also states contextual factors as the moderator of triggers and behaviour. Within contextual factors, Physical Environmental Factors (CR-0.85, AVE-0.651) is identified to be having a significant influence on the arrangement of furniture. Even though the thermal comfort and need for air movement is an essential criterion in the decision of a layout in warm and humid climates [2], the current study proves that several other factors categorized under Contextual factors influence the arrangement of furniture in a living room to a greater extent than Physical Environmental Triggers (Indoor air & mean radiant temperature, Indoor air humidity, Indoor air velocity etc.). Inferences about the relationship between a building and its occupants can inform improvements to future building designs with regards to energy and comfort performance [3]. People prefer adopting mechanical ventilation strategies like AC to alleviate the thermal discomfort irrespective of their ideologies or situational factors [26]. In the current scenario of Covid-19 pandemic, people spend more time indoors owing to the work from home situation and the layout of the rooms is modified to include a working space/ study space for each of the family members [10]. Occupants prefer to have ACs for the 'positive human energy' by being in good physical condition and not struggling while working from home [26].

6. Conclusion

The study aimed to conduct an empirical analysis of the factors or perceptions influencing the arrangement of furniture layout inside the living room of a residence. The behaviour of arrangement of furniture was assessed in terms of Physical Environmental Triggers (PET), Physical Environmental Factor (PEF), Psychological Factors (PF), Social Factors (SF), Physiological Factors (PHF) and Non-Adaptive Triggers (NAT) using structural equation modelling. The study developed an instrument measuring these factors along with the respondents' satisfaction with the current layout. The findings show that Cronbach's alpha for all the factors is above 0.7, which indicates a high level of internal consistency for the scale. Based on the confirmatory factor analysis, it can be concluded that the presented scale in this study shows adequate fit into the collected data. Model validity is established and it can be concluded that the seven-factor model shown in Figure 1 represents the behaviour of arranging furniture layout, thereby supporting the model fit and accepting the structural model. Contextual factors which comprise Physical Environmental Factors, Psychological Factors, Social Factors, and Physiological Factors, is identified as a major factor affecting the behaviour of occupants. This study will give an insight for architects and interior designers regarding the perceptions, or the factors considered by an occupant which results in greater satisfaction with space. This can be applicable while proposing the layout of a new project or a renovation project. This study focuses on the living rooms of a residence. Hence, it may not be generalized for any residential space as the activities and purpose of space may vary, which is not included in the current study. Another limitation of the study points to unavailability of more details for a closer analysis of the situations as it was a web-based survey. Further research is being carried out by incorporating on-site observations and measurements in different settings.

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An assessment of the thermal conditions and users' thermal adaptability in air-conditioned offices in a hot climate region

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Abstract

Indoor thermal condition is a global concern that plays a major role in the wellness, comfort, and satisfaction of office workers. The thermal environment was evaluated in an office building in a hot region using subjective and objective measurements. Considering the former, a questionnaire was distributed to the employees to assess their thermal perceptions. Specialized instruments were used for the objective measurements to monitor thermal parameters following the guidelines of ASHRAE-55 and ISO-7730. A total of 220 employees took part in the survey, and 207 valid questionnaires were included in the analysis. According to the subjective assessment, the thermal votes of the employees were between (cold) to (slightly warm), and the majority were thermally comfortable and accepted the environment. This implies that a temperature of 22.8 ± 1.2°C appears to be a comfortable range. Using the Griffiths method, the comfort temperature (Tc) was calculated as 23.5 ± 1.9 °C. Additionally, the employees ranked 11 indoor factors that influence their work productivity. Noise conditions were ranked as the most important factor. The results of the reported study provide a base for further research and useful information on the comfort temperature of office buildings in hot regions.

Keywords - Thermal adaptive model, hot climate, comfort temperature, office buildings

1. Introduction

Considering the increasingly overheating climates, indoor thermal conditions become a global concern due to their role in the wellness, comfort, satisfaction, and productivity of buildings' users [1]. Thus, maintaining comfortable work environments is essential considering the long daily and continuous use of offices. However, achieving indoor comfort requirements is directly related to energy consumption [2]. On the other hand, it is difficult to identify a satisfactory environment for all users because of the regional and subjective nature of thermal comfort, as it depends on individual, cultural, and climatic differences [3], [4]. However, acceptable environmental conditions can be predicted for the majority of occupants using the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) [5]. If the thermal condition of any space is satisfactory for more than 80% of the occupants, then the space is considered an acceptable thermal environment [6]. Inefficient thermal conditions can affect the occupants and lead to discomfort. To avoid such issues, thermal conditions can be controlled through heating, ventilation, and air conditioning HVAC systems and building design (i.e. building façade and insulation) [7].

Maintaining thermally comfortable environments in hot regions such as the Arabian Gulf region is highly dependent on energy-intensive air-conditioning systems. With the absence of regional thermal guidelines and standards, it is difficult to achieve optimal thermal conditions with sustaining energy. The researchers from the Arabian Gulf region tend to follow the international standards designed for other climatic regions such as [5], [6], [8]; thus, the influences of cultural background, climate, and users' preferences and expectations are not precisely addressed. Added to this, there is a lack of research in the thermal comfort field in the Arabian Gulf region, especially in office environments. Indeed, searching published literature from the Gulf Cooperation Council (GCC) region using the Scopus database and the keywords (thermal AND comfort AND offices AND building AND GCC) returned three studies only [9]–[11]. This highlights the need to evaluate and understand thermal comfort conditions in work environments in the region more thoroughly. Up to the authors' level of knowledge, there is no published research evaluating thermal conditions in office buildings in Oman. The study at hand attempts to fill this gap of knowledge by evaluating the thermal environment of university offices considering the users' thermal sensations, preferences, comfort, acceptance, and adaptability. The importance of the study evolves from its findings that can be used as a base to minimize the energy demand by adjusting the set point temperature of the air conditioning system based on the comfort range of the users, as mentioned in [12].

2. Methods

The offices of Sultan Qaboos University, Oman, were selected as the case for the evaluation reported in this paper. The university is in Muscat city, which is characterised by its hot arid climate based on the Koppen-Geiger climate classification. However, the city's proximity to the Indian Ocean resulted in hot humid conditions [13]. The offices' thermal conditions were evaluated using subjective assessment and objective measurements. For the former, a paper-based questionnaire was distributed to the employees. Table 1 displays the main themes of the questionnaire. For the objective measurements, specialised instruments were used to monitor indoor air temperature (T_a), relative humidity (RH), air velocity (AV), and globe temperature (T_g) following the guidelines of [5], [6], [8] as summarised in Table 2. The instrument was placed at the centre of each office at a height level of 1.1 m from the seated employees. The data was logged at a 1-minute interval. Simultaneously, the employees evaluated their perceptions of the indoor thermal environment using the questionnaire. The survey was conducted during a relatively warm period from 5th March 2023 to 18th April 2023. Moreover, the mean radiant (T_r) and operative (T_o) temperatures were calculated using equations (1) and (2) [14] and the comfort temperature (T_c) was calculated using Griffiths method using equation (3).

$$T_r = [(T_g + 273)^4 + (1.2 \times 10^8\, d^{-0.4})\, v^{0.6}\, (T_g - T_a)]^{0.25} - 273 \quad (1)$$
$$T_o = 0.5\, T_a + 0.5\, T_r \quad (2)$$
$$T_c = T + (0 - TSV) / G \quad (3)$$

Where d is the diameter of the globe, which is 15 cm for the used sensor.

Table 1: The questionnaire themes

Theme	Questions
Demographic data	Employee gender, age and college or department
Thermal perceptions	Evaluation of thermal comfort, acceptance, sensation, and preference
Thermal history	Participants' activity levels, clothing levels, and adaptive actions
Ranking	Ranking 11 items that affect work productivity

Table 2: The accuracy of the sensor used in the physical measurements

Physical parameter	Air temperature	Globe temperature	Air velocity	Relative humidity
Accuracy	± 0.3 °C	± 0.3 °C	± 10 cm/s	1.8%

3. Results

The returned questionnaires were checked to ensure that only complete and consistent questionnaires were included in the analysis. Out of the 222 distributed questionnaires, only 15 were incomplete. Based on the participants' sensations and preferences, none of the questionnaires was inconsistent. Female participants were 111 forming 53.6% and male participants were 96 forming the remaining 46.4%. The participants covered a wide age range starting from 21 to above 65 years old as plotted in Figure 1. Most female participants clustered between 30 and 40 years old, whereas male participants were almost equally distributed over a wider range extending from 30 years old to 55 years old.

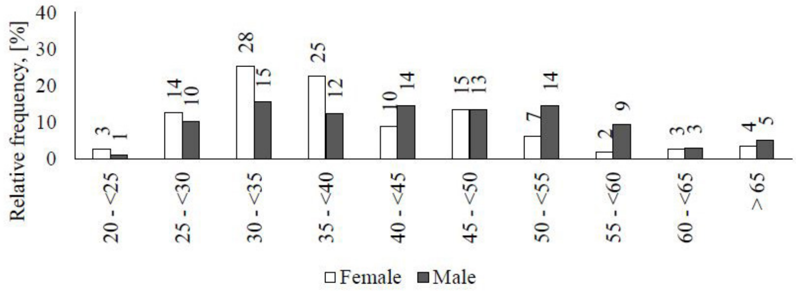

Figure 1: Participants' distribution based on their age and gender (labels are participants' numbers)

The participants were asked about their activities during the last 15 minutes before answering the questionnaire as indicated in Figure 2. More than 140 participants were sitting performing active work and more than 80 were passively sitting. Insulation levels were estimated based on participants' clothing and seat insulation [5], [6], [8] as displayed in Figure 3. Mean insulation level was 1 clo with the mean being 1.14 clo and 0.83 clo for female and male participants, respectively. Maximum and minimum levels were 0.44 clo and 1.96, respectively. It is noted that 58,47, and 40 participants clustered in insulation levels of 0.63-0.82 clo, 0.82-1.01 clo, and 1.01-1.20 clo, respectively.

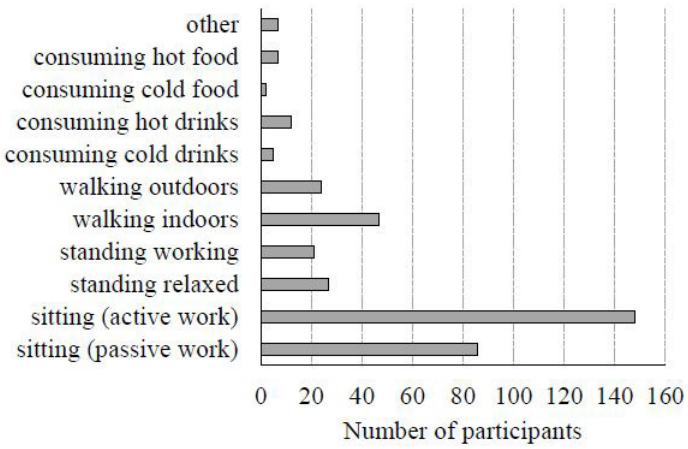

Figure 2: Participants' distribution based on their activity level 15 minutes before answering the questionnaire

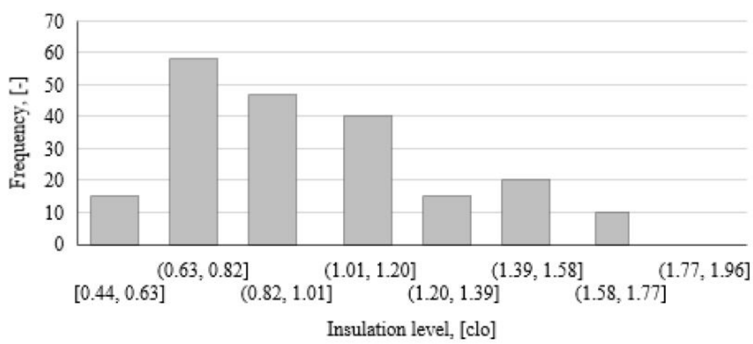

Figure 3: Participants' distribution based on their clothing level during the questionnaire

Table 3 displays some descriptive statistics of the measured physical parameters. Air temperature (Ta) ranged from 19.7 °C to 25.9 °C with a mean of 22.8 °C. Globe temperature (T_g) was recorded between 20.0 °C and 25.5 °C with a mean of 22.7 °C. The correlation between Ta and Tg is 0.95, which indicates an absence of radiant sources in the offices. Relative humidity (RH) fluctuated between 43.6% and 78.4% with a mean of 56.4% and air velocity (AV) extended from 0.0 m/s to 0.3 with a mean of 0.0 m/s. Both mean radiant temperature (T_r) and operative temperature (T_o) were calculated using the measured parameters. (T_r) ranged from 19.7 °C to 26.1 °C, and the mean was 22.8°C. The variation recorded for (T_o) was between 19.9 °C to 25.8 °C.

	T_a	T_g	RH	AV	T_r	T_o
Mean	22.8	22.7	56.4	0.0	22.8	22.8
Standard error (SE)	0.084	0.074	0.441	0.003	0.084	0.078
Median	22.8	22.6	55.8	0.0	22.8	22.7
Mode	22.4	23.1	57.7	0.0	22.4	21.8
Standard deviation (SD)	1.204	1.069	6.348	0.037	1.213	1.127
Range	6.2	5.5	34.8	0.3	6.4	5.9
Maximum	19.7	20.0	43.6	0.0	19.7	19.9
Minimum	25.9	25.5	78.4	0.3	26.1	25.8

Table 3: Descriptive statistics of the physical parameters

For the subjective evaluation, the participants were asked about their thermal comfort, environment acceptance, thermal sensation vote (TSV), and thermal preference vote (TPV). The relative frequency of TSV and TPV are plotted in Figure 4. The participant's sensations clustered in the (cool) category and the comfort range (i.e., slightly cool, neutral, and slightly warm), with 45.9% of votes in the (neutral) category. Moreover, 41.1% felt coldness sensations (i.e., cold, cool, and slightly cool), while 13.0% felt warmth sensations (i.e., hot, warm, and slightly warm). Considering thermal preferences, the participants clustered between (a bit cooler) to (a bit warmer), with 53.1% in the (no change) category.

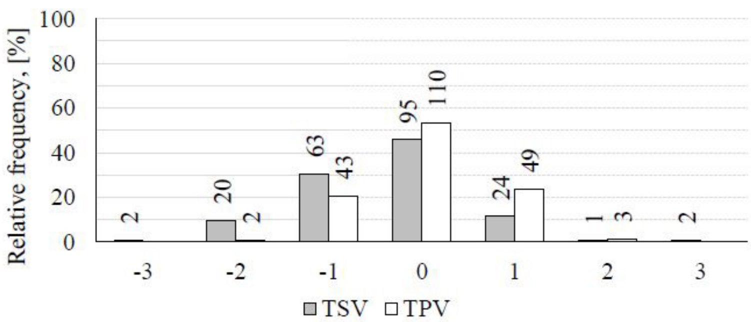

Figure 4: Relative frequency of TSV and TPV (labels are participants' numbers)

Figure 5 presents the thermal sensation distribution based on thermal comfort and acceptance. As noted, the votes clustered between (slightly warm) and (cool), despite comfort level or environmental acceptance. Forming around 91.8%, 190 of the participants evaluated their environments as acceptable. Yet, 180 reported being thermally comfortable. Considering the correlation between comfort and sensations, most participants were thermally comfortable accounting for 87.0%, while 13.0% were thermally uncomfortable. With reference to the distribution of sensations based on comfort, 50.6% of the participants who felt (neutral) were thermally comfortable. On the other hand, 40.0% of those who felt coldness sensations were thermally comfortable, while 9.4% felt warmth sensations. The number of thermally uncomfortable participants was relatively small and around 48.1% of them felt coldness sensations, whereas 37.0% felt warmth sensations and 14.8% felt (neutral).

The environment acceptance is presented in Figure 5 (b). The acceptance rate was high, of approximately 91.8%. Around 47.9% of them were (neutral), whereas 41.6% felt a coldness sensation and 10.5% felt warmth conditions. In addition, around 41.2% of the 8.2% who reported unacceptable environment were (neutral), whereas 41.2% and 35.3% and 23.5% felt warmth and coldness conditions, respectively. It is noteworthy that the percentage of the users felt (neutral) for comfort level and acceptance level was identical for both questions. On the other hand, the results indicated differences in the percentage of the participants who reported environment acceptance and comfort level.

The participants were asked about the behaviours they took to modify the offices' thermal conditions as displayed in Figure 6. Most participants did nothing in spite that around 12.1% were thermally uncomfortable and 7.1% evaluated the ambient environment as thermally unacceptable. Most of the participants opened doors and switched off/on AC. Among the 16 participants who opened the door, 87.5% were thermally comfortable and evaluated the environment as acceptable, whereas 12.5% found it uncomfortable and unacceptable. Considering those who switched on/off AC, 37.5% and 12.5% switched off AC reported uncomfortable and unacceptable conditions, respectively. In contrast, 10% who switched on AC were uncomfortable and did not accept their thermal environment. It is noteworthy that only 20 participants took more than one adaptive action.

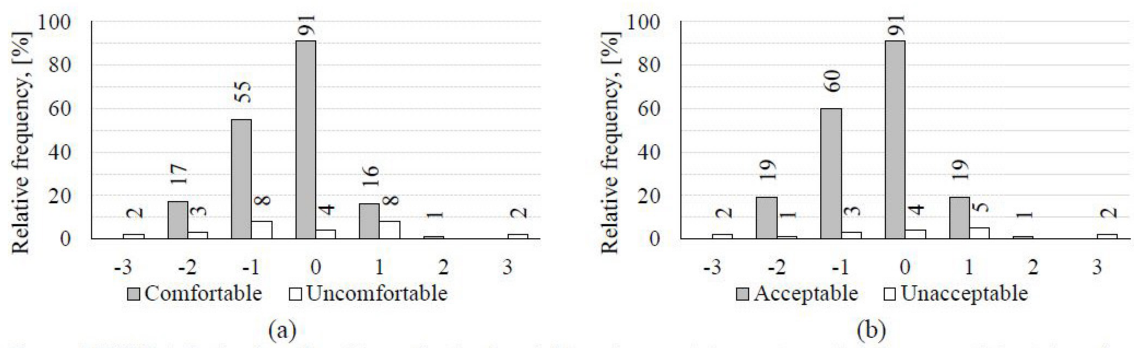

Figure 5: TSV distribution based on (a) comfort level and (b) environmental acceptance (labels are participants' numbers)

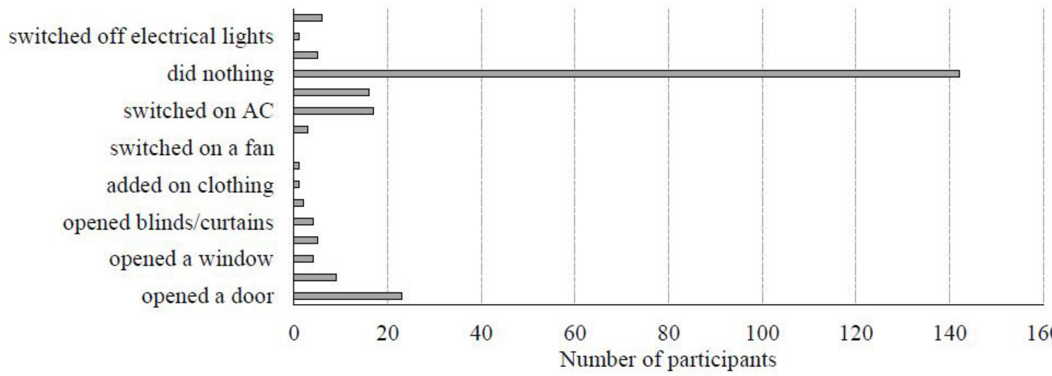

Figure 6: Adaptive actions taken by the participants

The last section of the questionnaire asked the participants to rank 11 factors that affect their work productivity from 1 to 11, where 1 represents the most important factor and 11 represents the least important factor. The results are presented in Figure 7. Considering (noise), it was selected by 67 employees as the first important factor, whereas 19 employees considered it as the second important factor. Considering all factors, (noise) was the most important factor followed by (privacy), (temperature), (cleanness), (lighting), (personal control), (air quality), and (workspace size). The least important factors were (external views), (furniture), and (indoor air movement) that were selected by an equal number of employees, i.e. 5 for each factor.

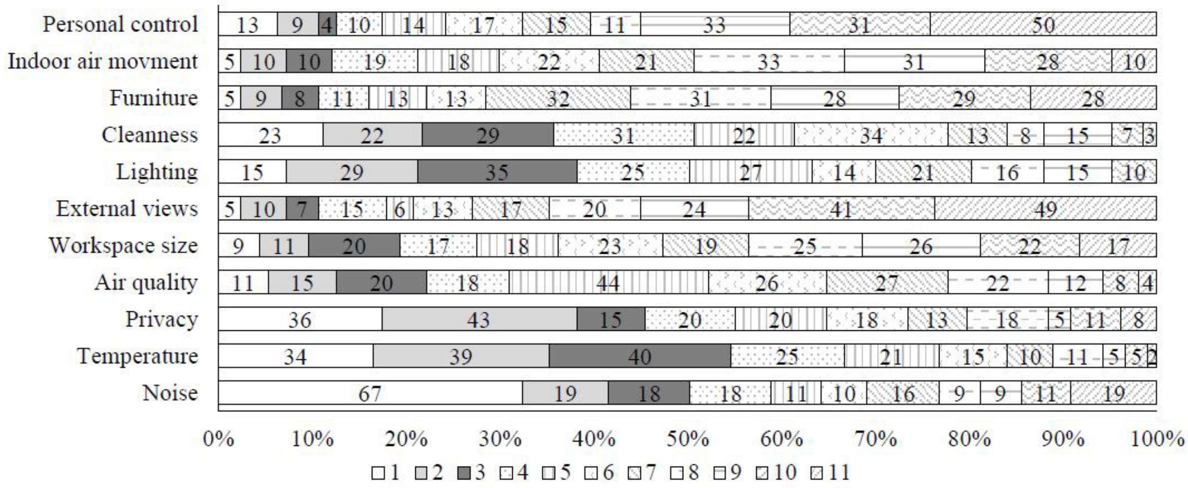

Figure 7: Importance of factors affecting work productivity, 1 = the highest, 11 = the lowest (labels are participants' numbers)

4. Discussion

The thermal sensations clustered between (cool) and (slightly warm), and most of the participants were thermally comfortable and accepted the environment, which implies that an air temperature of 22.8 ± 1.2°C is a comfortable range. The sensation clustered in a different range from the comfort range specified by ASHRAE. This is in line with the findings of [15], where people from hot regions define (neutral) to (cool) conditions as the comfort range. This is expected based on the subjective and regional nature of thermal comfort, which depends on different factors, including individual preferences and climatic and cultural background. The results indicated that the coldness condition is preferable among the investigated employees. Moreover, air temperature (Ta), operative temperature (To), and globe temperature (Tg) were moderately correlated to the participants' sensations. The correlations between each of these temperatures and thermal sensations were moderate as the correlation coefficient was 0.3 in each case. ASHRAE definition of thermal comfort does not distinguish between thermal comfort and thermal acceptance.

However, there was an apparent difference of around 4.8% between comfort and acceptance for the participants. Therefore, the one-way analysis of variance (ANOVA) was applied as presented in Table 4. It is obvious that there was not enough evidence to reject the null hypothesis and, thus, the 4.8% difference can be attributed to natural randomness.

Table 4: ANOVA results of the variations between thermal comfort and thermal acceptance

	SS	df	MS	F	P-value	$F_{criticl}$
Between groups	0.242	1	0.242	2.546	0.111	3.864
Within group	39.082	412	0.095			
Total	39.324	413				

Thermal comfort is directly influenced by insulation and activity levels, which affect heat exchange between people and the environment [12]. During the survey, the participants did not change their clothing; instead, their adaptation depended mainly on modifying their indoor environment, especially opening the door or switching on/off AC. It should be mentioned that windows are operable in a few offices in the university. It is observed that the clothing level for female participants is slightly high with an average of 1.14 clo, which is expected considering the cultural aspects of the society. The clothing level was weakly related to the operative temperature with a correlation of -0.035. Moreover, the noticeable number of participants who did nothing to change their thermal conditions despite being uncomfortable highlights the importance of increasing the awareness of the employees regarding the role of adaptive behaviour in achieving, or at least reducing the gap towards, thermal comfort.

Comfort temperature (Tc) was calculated using Griffiths' method as presented in Table 5. Different researchers apply this method as an alternative to regression analysis, using different slopes [16]–[19]. The method is recommended in the case of small data sets [20]. As noted, applying different slopes resulted in minor changes in the calculated comfort temperatures; a similar observation was reported by [17]. According to [16], [19], [21] a 0.5 slope resulted in a more accurate prediction. To ensure consistency with these studies, a slope of 0.5 was considered when calculating comfort temperature, which was found to be 23.5 ±1.9 °C in terms of operative temperature. However, due to the physiological and psychological differences between individuals, it is difficult to find an optimal comfort temperature, which emphasises the need for personal comfort models.

Table 5: Comfort temperature calculated by Griffiths' method

Griffiths' slope	T_a, [°C]	T_g, [°C]	T_r, [°C]	T_o, [°C]
0.5	23.4 ± 1.9	23.6 ± 1.9	23.6 ± 1.9	23.5 ± 1.9
0.49	23.4 ± 1.9	23.6 ± 1.9	23.6 ± 1.9	23.5 ± 1.9
0.48	23.4 ± 2	23.6 ± 2	23.6 ± 2	23.5 ± 2
0.47	23.5 ± 2	23.6 ± 2	23.6 ± 2	23.5 ± 2
0.39	23.6 ± 2.4	23.8 ± 2.3	23.8 ± 2.3	23.7 ± 2.3
0.33	23.8 ± 2.8	24 ± 2.7	24 ± 2.7	23.9 ± 2.7
0.3	23.9 ± 3	24.1 ± 3	24.1 ± 3	24 ± 3
0.25	24.2 ± 3.6	24.3 ± 3.6	24.3 ± 3.6	24.2 ± 3.6

5. Conclusion

The thermal environment of office buildings in a hot region was systematically evaluated using subjective and objective measurements. A total of 220 employees participated and 207 questionnaires were included in the analysis. The employees' thermal votes clustered between (cool) to (slightly warm), and most of them accepted the environment and were thermally comfortable. Accordingly, the temperature of 22.8 ± 1.2°C can be considered to be a comfortable range. Moreover, the employees cluster in a range that is slightly different from the comfort range specified by the ASHRAE can be explained by the fact that people from hot regions define (neutral) to (cool) as the comfort range. Considering the adaptive behaviour, the participants did not change their clothing; rather, they adapted to the thermal conditions by changing their indoor environment, such as opening doors and switching on/off the AC. Moreover, the noticeable number of employees who did nothing to change their thermal conditions despite being uncomfortable emphasises the need to educate employees about the role of adaptive behaviour in achieving thermal comfort. The comfort temperature (Tc) was calculated as 23.5 ± 1.9 °C using Griffiths' method. In addition, the employees ranked 11 indoor factors that affect their work productivity. Among the factors, noise conditions were ranked as the most important factor followed by privacy and thermal conditions.

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