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Sustainability and Health: the nexus of carbon neutral architecture and well-being

56th International Conference of the Architectural Science Association (ANZAScA)
29th November–2nd December 2023, Launceston, Australia

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Foreword

The Architectural Science Association is committed to the development, documentation and, diffusion of the principles of architectural science, including but not limited to the application of natural and innovative techniques for sustainable architecture. The Architectural Science Association serves as an open, international, interdisciplinary forum to promote high quality research, practice, and education in environmentally sustainable design. The association is an autonomous, non-profit organisation sharing the art, science, and design of the built environment. The Architectural Science Association pursues its objectives through international conferences, exhibitions and workshops, scientific and technical publications and, architectural competitions and exhibitions.

The theme of the 56th international conference of the Architectural Science Association (ANZAScA) was **Sustainability and health: the nexus of carbon-neutral architecture and well-being**. Architecture is now seeing rapid change and innovation in a push to reduce our contribution to greenhouse gases and climate change; but has there been an equal focus on well-being in the built environment? The world over, concern has been raised regarding the Indoor and Outdoor Environmental Quality that the built environment is, or is failing, to provide. Many publications have explored the challenges facing sustainable, low embodied energy, energy efficient and net-zero built environments and the challenges they face in providing healthy spaces for occupants. A key aim of the 2023 conference is putting people back on the agenda. How do we use architectural science to inform the design of sustainable buildings which also provide healthy spaces for humans? And if not, what are we doing about it? The themes explored in the ASA 2023 conference at the University of Tasmania include:

- Indoor/Outdoor Environment Quality / Environmental performance
- Architectural construction, and technology
- Building Physics Energy, sound, light, hygrothermal
- Data driven design, Big data, Parametric design
- Regenerative/reuse (Permanence, transformation, contemporaneity)
- Practice/Practitioner, Community and Industry Engagement, applied science in practice
- The social side of sustainability; communicating architectural science to a wider audience

Researchers, academics, doctoral students, and practitioners were invited to submit research papers and practitioner abstracts, and to attend the Conference to widen our discussion about engaging architectural science and its future trajectories. The conference happened in hybrid modes—face-to-face and online. This publication presents 7 Keynote Speaker abstracts, 57 papers and 2 Practitioner abstracts that were presented at the Conference hosted by the School of Architecture & Design, The University of Tasmania, Launceston, Tasmania, 29 November to 1 December 2023.

The conference website is accessible at: https://www.utas.edu.au/about/events/architectural-science-association-conference-2023
Papers in this proceedings are archived at the ASA website: https://archscience.org/

Each of the submitted papers was reviewed by at least two members of our International Scientific Committee.
While the editors of these proceedings have done their best to ensure that the material presented is accurate and free of errors, the authors are solely responsible for the contents and opinions expressed in their papers. The role of the editors was to arrange the proceedings in a logical and informative order.
On behalf of the Scientific Committee, we would like to sincerely thank all the people who have made this Conference possible. Thank you to all the authors for their valuable contribution to ASA Conference 2023 through quality discussions during the Conference and high-quality submissions, which greatly enriched the overall experience for all the attendees. We are deeply appreciative of the members of the International Scientific Committee for their thorough and meticulous reviews. Their contributions were instrumental in ensuring the high quality of the papers presented at the Conference and enabling us to continue to improve and maintain such a standard.

Dr. Mark Dewsbury
Mr. David Tanton
Ms. Freya Su
Mrs Zahraa Al-shamma
Mr Soo Kang Jack Tan
Launceston, 2023

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WELCOME TO COUNTRY

Fiona Hughes

Yah pullingina meerah.
Ya pullingina mythina noiheera.

Hello everyone and thank you for inviting us.

Welcome to the lands of the good spirit, the homelands of the Leekermariner Clan – Launceston, here family groups gathered, strengthening bonds of kinship through marriages, celebrated births that continued those bonds of kinship.

For generations, the Leekermariner mob gathered along the river plains, here they shared an abundance of resources that had been gathered along the river margins and surrounding wetlands, here they hunted on the vast grassy plains. It is also where they gathered materials to make humpies, spears, waddies, fibre to weave baskets and whatever else they needed for daily life.

I acknowledge our ancestors and pay respects to the descendants of the first peoples of Trowunna – Tasmania who are here today. On this land our people lived, celebrated culture, conducted ceremony beneath the stars, here many family groups met as we are today, traded goods and continued to strengthen the kinship ties with our shared living traditions.

Our ancestors travelled great distances on this land Trowunna, the sun, the moon and the stars guiding their journey, giving us stories of coming into being as a people and our place on this land and the importance of our responsibility to care for our native animals and plants, not only for our continued existence but also for our children and the generations to follow us.

As you are gathered here now, please close your eyes and in your mind see this place in my ancestor's time, hear the songs, listen to the music, watch the dancers, hear the laughter of the children as they play and listen to the language deep in culture that continues to this day.

Welcomes also acknowledge that our culture is alive and strong as it has been for over 50000 years.

Welcomes also honor our ancestors who lived in harmony with the seasons as the first peoples of Trowunna.

The first peoples of Trowunna have welcomed visitors to our shores, the Dutch, the French, who traded goods with us, and we shared our culture, food and water and they left us to our own devices and then we welcomed the English.

Today we continue to carry on those traditions of welcoming strangers to our shores in the same way as our old people did, to trust with honesty, and we hope that you will continue to walk this journey with us as one peoples with diverse cultures and lets also walk beside each other as partners, friends and equals. I welcome all of you here today, friends near and far, strangers who we hope will become friends and our honoured guests.

In these turbulent times, it is great to be able to welcome you and see your smiling faces.

Please stay safe.
Nan Nina To
Wuliku Thank you!

Keynote Speaker synopsis – Lindsay Clare

Principal - Clare Design

Architecture provides a framework for living: not simply sheltering but also sustaining people. 'Sustain' includes the meaning 'to maintain or nourish physical, emotional or spiritual wellbeing'. The Clare's work rises from the desire to make buildings that connect people to place through an architecture that sustains them in the broadest sense. To this end they work to a set of values and principles that prioritise and merge nature, performance, fabric, aesthetics, climate, and context.

An important input for the design process is scientific knowledge: knowledge about the behaviour of components and materials. Architecture uses this knowledge to construct the metaphysical qualitative experience of occupation.

Lindsay will explore through some recent projects how working with these values engenders an architecture that is experiential and particular to place, and architecture that enhances comfort while increasing energy efficiency.

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Keynote Speaker abstract – Hartwig Künzel
Hygrothermal performance of bio-based insulation materials

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Abstract: Bio-based building materials have often a lower carbon footprint than conventional building materials because they are made from plants that sequester CO_2 during growth. Many people associate bio-based materials with being healthier which is arguable when pesticides are involved to prevent moisture-related decay. However, there is no need to use chemicals if adequate constructional measures are employed that protect the materials from insect or microbial attacks. Their main purpose is to keep the construction dry enough during the construction process and under normal service conditions. This can be checked by field testing or hygrothermal simulation. Since the moisture tolerance of envelope assemblies depends not only on the climatic boundary conditions but also on the material characteristics, it is important to understand the performance differences of bio-based and conventional materials. Bio-based materials are moisture susceptible, but at the same time they are quite resistant to temperature or UV-radiation, especially compared to polymers. They are generally hygroscopic and can buffer humidity peaks and often have a higher heat capacity than their conventional peers. Their benefits justify a deeper focus on moisture control design, and more research and development efforts to overcome some of their weaknesses.

Keywords: Bio-based materials, hygrothermal performance, moisture susceptibility, humidity buffering

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Keynote Speaker synopsis – Peter Walker

Principal – Cumulus Studio

Peter Walker is a principal and founding director of Cumulus Studio. Insatiably curious, he uses design to better understand the world around him, seeing each project as a chance to dive into something new - be it place, culture, material or experience. He believes architecture is as much art and poetics as it is engineering or construction and is inspired to create spaces that are connected to their place and evoke deep emotional responses. Peter believes not only in the importance of environmental responsibility but also in the need for long term social and cultural sustainability of projects. In line with a “less is more approach” to sustainability Peter has deliberately sought projects that continue the memories and traditions of a place and include the sensitive transformation of buildings such as a dilapidated Georgian warehouse for UTAS, the heritage hydro buildings at Pumphouse Point, and a timber Apple Shed for Willie Smiths. Awarded nationally and internationally for his high profile tourism project portfolio, Peter’s tourism work projects such as the Cradle Mountain Visitor Centre, Devil’s Corner and Pumphouse Point. His work always has a clear, central idea which informs each design and construction decision. Amongst other awards Peter is a past winner of the Timber Design Association’s Timber Awards and the Tasmanian Emerging Architect Prize.

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Keynote speaker synopsis – Tina Tam

Associate Principal, Lovell Chen

Our practice is founded on our ability to imagine the potential of existing buildings, preserve the spirit of the place and unlock them for continued use into the future. Building physics are embedded in our design process, providing the evidence to support innovation and creativity with measurable sustainable outcomes.

In the face of the changing climate, the ability to creatively reuse existing buildings and extend their longevity is a priority for reducing greenhouse emissions. In a series of case studies, we discuss how building physics have been applied to create Architecture that celebrates the spirit of the place, minimises harm to the environment and provides a comfortable, healthy environment for occupants.

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Keynote Speaker synopsis – Robert Morris Nunn[1] and Jim Gandy[2]

[1]*Principal - Circa Morris-Nunn Chua architects,* [2]*Gandy & Roberts*

Robert Morris-Nunn is regarded as one of the most significant architects currently practising in Tasmania. In 2010 he was awarded the President's Prize (Tas) by the Australian Institute of Architects, a Lifetime Achievement Award by the profession. In 2013 he was appointed as Adjunct Professor at the School of Architecture, University of Tasmania. Recently he became a Member of the Order of Australia. Some recent projects include Moss 39, MAC 01, Brooke St Pier and Saffire.

Jim Gandy is an engineer who has worked on projects with Architects over the years. Of note is his collaboration with Robert Morris-Nunn.

Their keynote address takes the form of a discussion focusing on their collaboration that has spanned many decades, and will examine many of the award-winning designs and solutions it has brought forth.

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Keynote Speaker synopsis – Dayne Davis

Associate – Timber, BG&E Engineering

In the keynote presentation, presented by Dayne Davis, on the St. Luke's mass timber building in Launceston, Tasmania, we will explore its architectural vision, design process, and innovative use of LOD400 modelling. This 5,500sqm project is notable for being Tasmania's most sustainable and carbon-positive office development. Its design, by Terroir, emphasizes environmental sustainability, targeting a 40% reduction in carbon footprint. The rapid construction and topping out of Tasmania's first mass timber building highlights the efficiency of this material in sustainable architecture. The $30 million, 28-metre-high structure represents a significant leap in eco-friendly design. Essential to this project is the use of LOD400 modelling. This technique allows for precise design and production, ensuring an efficient and streamlined construction process, while maintaining the high sustainability standards set for the building. This presentation will delve into how these innovative approaches in architecture and engineering design are undertaken as well as how they are setting new standards for sustainable development.

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Keynote Speaker synopsis – David Ritter - From Biomimicry to the Carbon Nexus

Director – Atelier Ten

Through a reflection on the work of Atelier Ten over 30+ years pursuing the integration of sustainability into architecture it's clearer now more than ever that we need to nurture holistic systems-thinking. It is a complicated reality to grapple with, but it is an approach that is vital to ensure our industry can address the most pressing challenges of the 21st Century.

As engineers our approach and priorities have shifted over recent decades starting from a position of optimizing buildings and landscapes to perform from a passive design and biomimicry inspired perspective to an obsession with trimming operational carbon, to an awakening that reducing embodied carbon is now the urgent focus. This keynote highlights this transition and reflects on the more nuanced balancing act we face today as we arrive at the nexus of embodied and operational carbon systems analysis on our projects.

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A new look at smart ventilation for public buildings in the tropics in the post-pandemic era.

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Abstract: This paper presents part of a study exploring a quantitative model for linking mechanised ventilation systems to provide acceptable indoor air quality. The lack of an indoor air quality index causes communication discord for occupants, facility managers, and design engineers. Specifically, three statistically correlated indexes to occupants' health symptoms are the indoor discomfort index, indoor air pollutant index, and indoor environmental index. The model will be validated through empirical data to be collected from occupants of three separate institutional buildings at the James Cook University campus and Cairns City in tropical north Queensland in Australia. The next phase of this project entails the integration of applicable computer-based predictive analytical tools to control mechanised ventilation systems.

Keywords: Indoor environmental index, Indoor discomfort index, Indoor Pollution index, IAQ Index

1. Introduction

1.1. Background

A new look at smart ventilation systems implies formulating a unified and quantitative strategy to control mechanised ventilation and air-conditioning (MVAC) systems. In tropical workplace environments, occupants heavily rely on MVAC systems, but face communication discord in controlling indoor air pollution. Despite improved thermal comfort, ensuring acceptable IAQ in this post-pandemic era remains uncertain. By definition, acceptable IAQ is a subjective assessment, with the majority of occupants perceiving the air as breathable and posing no immediate risk (ASHRAE, 2013; ISO, 2016). Considering this subjective IAQ perspective, the urgency spurred by COVID-19 requires objective assessment for rigorous control of ventilation systems to ensure acceptable IAQ. Strategically, a simple metric or index to represent IAQ decay, thereby initiating a demand-based control of the MVAC systems. Currently, the integrated carbon dioxide (CO_2) sensors in the MVAC systems are limited in their functionality, (Morawska et al., 2021), allowing other air pollutants like volatile organic compounds (VOC) and particulate matter (PM) to recirculate undetected within enclosed spaces (Ismail SH et al., 2010). Carslaw et. al., used a detailed chemical model to quantify the impact of 63 VOCs as Secondary Product Creation Potential (SPCP) related to the ventilation rate for dilution (Carslaw & Shaw, 2019). The general Air Quality Health Index (AQHI) based on ambient outdoor air served as a valuable communication tool but is not useful for IAQ assessment (Szyszkowicz, 2019). There is a need to develop correlated MVAC control strategies and techniques based on the perspective of indoor environment, health and well-being of occupants as well as energy efficiency (Cao et al., 2020). The development of low-cost devices to monitor IAQ are useful tools to understand the behaviour of indoor air pollutants (IAP) and potentially impact on the reduction of related health impacts. With the rapidly increasing number of studies, projects, and grey literature based on low-cost sensors in enclosed indoor spaces, they are unable to control the MVAC systems. Chojer et. al. summarises the recent research pertinent to the development of indoor air quality monitoring devices using low-cost sensors (Chojer et al., 2020). This paper presents two empirical quantitative indices directly linked to occupants' health symptoms: the Indoor Air Pollution Index (IAPI) and the Indoor Environmental Quality Index (IEQI). Finally, a data-driven machine learning ventilation control system that supports a demand-control model for IAQ and occupants' health conditions is presented.

In tropical regions such as Cairns in the far north of Queensland, Australia, IAQ issues are very challenging in building design, construction, and facility management. The high humidity and temperatures experienced in the region increase the risk of thermal discomfort, moisture problems, moulds and exposure to contagious bacteria and airborne virus transmission (Hall et al., 2021). The applicable IAQ Standard provides minimum guidelines for design of window opening sizes for natural ventilation to control odour, carbon dioxide (CO_2), thermal comfort and indoor air quality (AS1668.2, 2012). The remarkable Queenslander architecture serves as a noteworthy benchmark for passive ventilation design for the tropics (Naylor, 2016). Conversely, present design emphasis is on positively pressurised enveloping systems to rely on MVAC systems for regulating indoor comfort conditions but with minimum energy requirements (Afroz et al., 2018). Interestingly, energy-efficient office buildings in the tropics only became effective after retrofitting with improved IAQ sensors (Revel et al., 2014).

Recent studies on occupants in tropical public buildings revealed three drawbacks in MVAC system's operation. Firstly, steady-state airflow measured CO_2, but VOCs and other gases were recirculated unnoticed in fractioned-recirculated air (Ismail SH et al., 2010). Secondly, solar radiation entering glass window facades increases thermal radiant field asymmetry and vertical air drafts, potentially creating discomfort for occupants and facilitating air pollutant routes(Azad et al., 2018). Thirdly, there is a lack of cognitive awareness in noticing signs of indoor air pollution concentration and controlling MVAC systems to dilute the air pollutants (Snow et al., 2022). Therefore, a rational approach is to develop a simple numerical scale and index for each of the IAPs and attributed health symptoms. The IAP Index should be simple for all occupants, statutory bodies, the public, and building service engineers to access and communicate. The unified metric or index is an indicator of acceptable indoor air quality (IAQ). Key terms to differentiate for this paper are summarised in Table 1.

Table 1: Descriptions of IAQ evaluation index and references

Description of key IAQ indicator	Reference
An index is constructed from several indicators weighted together to describe the total impact on a certain aspect of the broader environment.	(Sæbø & Alfsen, 1993)
A model incorporates a range of measurable attributes or characteristics as predictor variables of an environmental phenomenon with methodologies to gather seminal data to test the objective that represent the natural system's behaviours.	(Gifford, 2016) (Bennett et al., 2013)
Indoor environmental index (IEI) comprises single or multiple environmental predictor attributes associated with a known air pollutant to cause discomfort and illnesses. IEI is an aggregate of Indoor air pollution index (IAPI) and Indoor discomfort index (IDI).	(Bittel et al., 2018) (Cao et al., 2012)
Indoor air is a summation or aggregate of three indices: the Indoor air pollution index (IAPI), Indoor pollutant standard index (IPSI), Index of air quality (IAQ). The IAPI and IAQ had no association with health symptoms except IAPI. Thus, IAPI measure eight indoor air pollutant. It provides index value range between 0 as lowest pollution level, 10 as highest pollution level and mean as acceptable.	(Cedeño Laurent et al., 2021; Moschandreas & Sofuoglu, 2004; Willers et al., 1996)
Indoor discomfort index (IDI) comprises temperature and relative humidity. An index is a unitless single number ranging from 0 (lower discomfort) to 10 (higher discomfort), of which the mean value is comfortable.	(Ma et al., 2021; Moschandreas et al., 2006)

IAPI measures eight IAPs: carbon dioxide (CO_2), particulate matter (PN2.5, PM10), total volatile organic compound (TVOC), carbon monoxide (CO), formaldehyde (HCHO), bacteria and fungi (measured in Cfu denoting colony forming unit). Acceptable threshold limits for the IAPs are given in Table 2.

Table 2: Indoor air pollution demarcation

Threshold Levels	AQI ppm	$PM_{2.5}$ µg/m^3	PM_{10} µg/m^3	TVOC µg/m^3	CO_2 µg/m^3	HCHO µg/m^3	CO µg/m^3	Fungi Cfu/m^3	Bacteria Cfu/m^3
Maximum	400	150	40	50	1000	60	10	500	500

(Adopted from WHO 2020 Guide to the Indoor Air Quality Standard)(WHO, 2020)

Australian IAQ experts recommend evaluating performance of the ventilation systems to control indoor aerosol transmission (Hyde et al., 2021; Morawska et al., 2021; Morawska & Milton, 2020). In this post-pandemic era, devising strategies to supply acceptable indoor air quality and hygienic indoor environment is the priority for environmental engineers (Azuma et al., 2020). Considering the regulators, OzSAGE is the safe indoor air working group in Australia to provide MVAC system operational guidelines (Crabb et al., 2021) which is summarised in Table 3.

Table 3: Comparing operations of MVAC systems for pre-and post-pandemic era.

IAQ Parameters	Pre-Pandemic IAQ from NCC-2022	Post-Pandemic IAQ From WHO Guide
Relative Humidity	40% to 60%	40% to 60%
Temperature	20^o C to 26^o C	20^o C to 26^o C
Airflow Rate	5 to 7L^{-s} per person	7 to 10L^{-s} per person
Air Change per Hour (ACH)	4 to 6 times	10 to 12times
Air Duct Flushing	Subject to heavy use.	1 time monthly
Filter type	MERV 4 - 12	MERV 14 with ISO ePM1 with HEPA 99.7%
Ventilation windows	25% of floor area	25% of floor area

The common method of improving IAQ is to increase the ventilation rate with well-mixed steady airflow to dilute the generated air pollutants (Zhang, 2020) and lower airborne disease transmission (Aliabadi et al., 2011). This is an optimum approach however is not energy efficient given the tropical conditions. A balance is achievable using a smart predictive IAQ sensors to control indoor air pollutants concentration. Higher relative humidity levels in the tropics propagate airborne pathogens, bacteria, moulds and infectious communicable diseases (Birrell et al., 2023).

1.2. Research Questions

The generic research question is: what have we learned from COVID-19 that will enable us to improve the quality of our workplaces? The crucial lesson learned is that under-ventilated indoor spaces can lead to the infiltration of aerosolised viruses, surpassing the threshold for acceptable indoor air quality. (WHO, 2021). While implementing crucial public health measures such as building closures, isolation, and social density control were imperative risk management process, effectively controlling indoor air quality remains a pressing concern. Plausibly, most pre-pandemic workplace environments were under-ventilated, enabling COVID-19 to spread easily indoors. Therefore, post-pandemic occupancy evaluation using objective-based research methodology should establish a benchmark for comparison.

2. Proposed quantitative indoor air quality evaluation model.

MVAC systems play a major role in providing acceptable indoor air quality and thermal comfort. Indoor air quality directly influences human health and the ability to live and work productively. (Frontczak et al., 2011). Airtight buildings and reduced ventilation rate in the tropics increase indoor air pollution, resulting in building-related illnesses and other health conditions. This study adopts the indoor environmental quality model with nine independent environmental factors: indoor air quality, thermal comfort, lighting, noise, acoustics, spatial comfort, privacy, building-related symptoms, and neurotoxic symptoms. The structural model was tested using the LISREL statistical program with strong internal correlation and association to the dependent variables of environmental satisfaction and productivity. Notable association for indoor air quality, thermal comfort, ventilation had internal correlation of 1.0 and separately to building-related illness was 0.8 (González et al., 1997; Lantrip, 1986; Leifer, 1998). Hence, these four variables highly relate to occupants' symptoms of building- related illness (BRI) form composite factors for the indoor environmental index (IEI).

2.1. The IEI

The IEI comprises of aggregated mean index for IAPI and the IDI, expressly represented as (Sofuoglu & Moschandreas, 2003):

$$IEI = \frac{(IAPI + IDI)}{2} \tag{1}$$

Calculations of the IEI is performed from a tree structure or hierarchically for different indoor air pollutant concentrations and discomfort variables. Figure 1 illustrates the tree structure for computing mean indices.

2.2. The IAPI

IAPI is calculated using eight (8) pollutants associated occupants' health and well-being indoor, namely: CO, CO^2, HCHO, $PM_{2.5}$, PM_{10}, VOC, bacteria, and fungi. A linear function is used to calculate the subindices to derive a mean that is the index for inclusion in the IAPI.

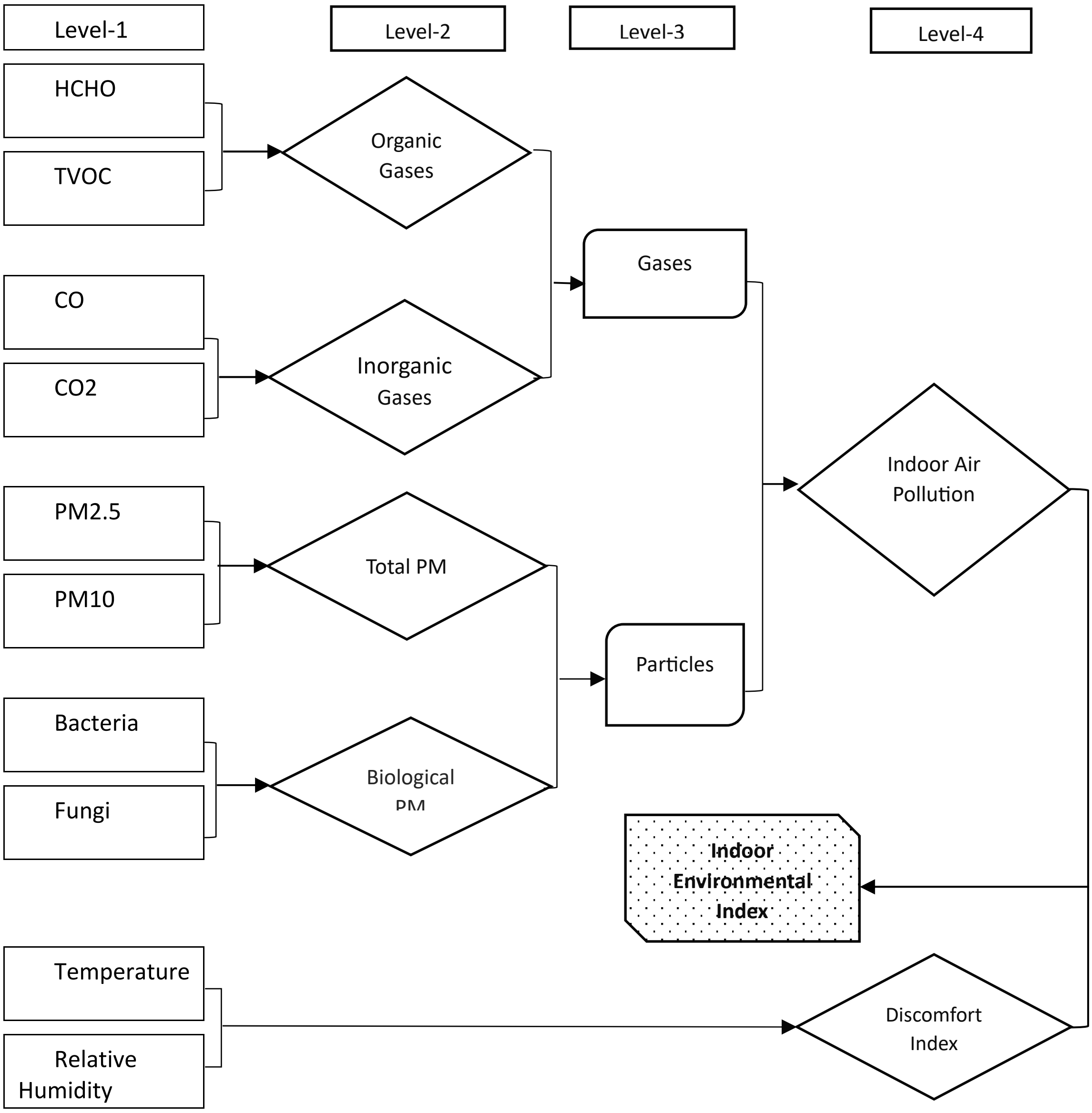

Figure 1: Tree structure for IEI Computation process (Sofuoglu & Moschandreas, 2003)

$$\boldsymbol{IAPI} = \frac{1}{I}\sum_{i=1}^{I} \frac{1}{J} \sum_{J=1}^{J} \frac{1}{K}\sum_{K=1}^{K} \mathbf{10}\left(\mathbf{1} - \frac{C_{ijk}^{max} - C_{ijk}^{obs}}{C_{ijk}^{max} - C_{ijk}^{min}}\left(\frac{C_{ijk}^{dmc} - C_{ijk}^{obs}}{C_{ijk}^{dmc}}\right)\right) \quad (2)$$

for $C^{max} > C^{obs}$ and $C^{dmc} > C^{obs} > C^{min}$

Where *I* is the number of level – 3 groups, I = 2; J is the number of level – 2 groups in each level-3, *J* = 2; *K* is the number of level 1 pollutant variable in each level -2 group, *K* = 2; max is the maximum measured concentration; *min* is the minimum measured concentration; *dme* is the demarcation or threshold concentration; *obs* is the measured concentration in the subject building.

2.3. The IDI

IDI is the aggregated index of two comfort variables: temperature and relative humidity. The standard comfort setting in many MVAC systems is 23°C with 50% relative humidity and considered the mean comfort baseline for average indoor activities (ASHRAE, 2010). A tolerance temperature movement of ± 3°C and 10% RH is the recommended comfortable range. The index is a unitless single number ranging from 0 to 10. A high index value indicates high discomfort, and a low index value indicates low discomfort. Constraints for IDI calculations are: $(i)\ CA_{RH,obs} > 65, (ii)\ CA_{RH,obs} = 25$ when $CA_{RH,obs} < 25, (iii)\ CA_{T,obs} = 28$ when $CA_{T,obs} < 28, (iv)\ CA_{T,obs} = 16$ when $CA_{T,obs} < 16$

$$\boldsymbol{IDI} = \frac{1}{L}\sum_{1=1}^{L} \mathbf{10}\left(\frac{CA_{i,opt} - CA_{i,obs}}{CA_{i,uci} - CA_{i,lcl}}\right) \quad (3)$$

for $25 > 25^{obs} > 65$ for $RH, and\ 28 > CA^{obs}\ 16$ for T

where *CA* is comfort agent, *L* = 2; *opt* is optimum comfort agent value, T_{opt} = 22°C, RH_{opt} = 45; *tcl* is upper comfort level, T_{uct} = 25°C , RH_{ucl} = 55%; *lcl* is lower comfort level, T_{lcl} = 19°C , RH_{lcl} = 35%; and *obs* is measure comfort agent value in the subject building.

3. Method

3.1. The Database

Computation of the IAPI requires a statistics computer database such as LISREL, SPSS or similar regression analysis tool. The formulation of the index model and the development of the tree structure of the index are performed in the database. Thus, the initial step involves acquisition of skills with simple inferential statistics and the relevant computer-based analytical software.

3.2. Buildings for field study

Data for the operations during peak and off-peak periods will be gathered from the building management systems at the Estate and Facility Management Unit of JCU. This information will form critical historical data on occupants' density, indoor air pollutions, temperature, relative humidity, ventilation rate, air change rate, filter replacements and when major repairs or services were carried out on the subject MVAC systems. The other information is the technical specification of the MVAC related to power outputs, filter types, , thermoset temperature, types of air pollutant sensors, ultraviolet germicide sensors, and other in-built controlling systems on wireless sensors. The previous occupants-satisfaction survey will also provide important additional information. All information will be stored in the University computer database.

There are three methods of data collection:

- Questionnaire survey
- Physical measurement of indoor air pollutants
- Observation and diagnostic review of the MVAC systems.

Three modern academic complexes at James Cook University's Nguma-bada Campus in Cairns and an office building in Cairns City will be evaluated. The selected buildings for this study are airtight and high energy-efficient rated green buildings. The MVAC system uses both active and passive water chill beams for inducing cooler air to various breathable zones and spaces through a duct system. Use of a water chilled beam to cool down surrounding warm air through convection is considered an economical option in the tropics. Considering energy efficiency, the MVAC of each subject buildings is interfaced by a computer-based building management system (BMS) program. Generally, BMS activates scheduled and demand-controlled ventilation in the MVAC to ensure thermal comfort and energy efficiency. The BMS analyses factors like working hours, occupant density, weather conditions, specified group events, and designated breathable air zones to efficiently supply the necessary air volume for thermal comfort indoors.

(i) Ideas Lab D004 (ii) Cairns Institute D003 (iii) GRS Building D011

Figure 2: Selected buildings for field study at Cairns JCU Campus

The Ideas Lab building has a fully glazed facade. In contrast, the Cairns Research Institute complex, representing Ayers Rock, and the GRS Centre have partially glazed facades. The D004 building consists of three floors, featuring tropical plants on outdoor walls and within open atrium spaces. The D003 has two-floor levels with an outer shell made of rusty flat steel sheets, an air gap of 600mm, and an inner-skin layer of tinted glass panels. The third building is identified as D011 uses sandwiched expanded polystyrene wall panels and flat ceiling fixed with air-conditioning diffusers on stilt stumps. All have dynamic indoor spaces that accommodate the activities of university staff, research students and other occupants with a diverse array of academic activities. Typically to all buildings, internal spaces promote co-working environment with opened-floor plan having sufficient lightings and thermally comfortable. The location of indoor environmental services such as ventilation ducts and air vents, and lightings are equally distributed and fixed to or suspended from the ceiling. Because buildings are airtight, acoustically sound and noise proof. These subject buildings are less than ten years old and are energy efficient rated buildings.

3.3. Questionnaire Survey

This questionnaire survey is called Building Occupant-Satisfaction Survey (BOSS), which will be administered online. A total of 30 participants is targeted per buildings as a minimum sampled population. This BOSS project will be conducted two times during the beginning of the year between February and January, then repeated in July/August to target the hot and cooler months respectively. Occupants will participate voluntarily to maintain confidentiality and remain anonymous. The BOSS questionnaire comprises of two parts. Part A gathers demographic data and Part B is the environmental evaluation. Both parts adopt simple multiple choices and rating scale for a more objective-based response. Each response will be assessed using simple inferential statistics and lineal regression analysis to determine internal correlation and coefficients to validate the attributes of the Indoor Environmental Index model(IEI)

3.4. Measurement of air pollution.

Digital loggers will be positioned to measure the eight pollutants for this study. A typical room in one of the subject buildings will be randomly selected for measurements. Each test will be identified by date, building type, location, and timing of the measurements. Digital pollutant loggers will be connected via Wi-Fi network to transmit data direct to the master database computer seamlessly. Environmental comfort data including relative humidity, temperature, wind speed and outdoor weather will be gathered.

3.5. MVAC system observation

Walk-through survey and observations of the respective MVAC systems will provide specific technical information and operational data. This part of the survey will require specific approval from the Estate Division of JCU. Most air handling units and exhaust fans are located on rooftops. Three sets of information are required: (1) the technical specification and operation manuals; (2) the building management systems and the types on controls; and (3) and records of major replacements and maintenance data logbook. This information will explain how the proposed IEI will be integrated.

4. Way-forward

Strategically, the simple IEI is a function of two contributing environmental factors of indoor air pollution and air quality factors. The application of this index is the question at hand. Firstly, we need data from the identified buildings in the tropics. Secondly, a computer database must be identified, for ease of formulating the index for each of the eight pollutants following the proposed hierarchical tree structure. By achieving these two interim challenges will place the project in a position to prototype this project.

5. Conclusion

The development of the Indoor Environmental Index (IEI) will provide a key communication metric. With the aim of controlling and optimising the existing performance of the MVACs, the IEI strategically relates to occupants' health needs for acceptable IAQ. Although many other models and indices exist, their predictive and nonlinear associations are low compared to IAPI, and IDI in this IEI model. With challenges in the tropics to consider, the two factors are closely associated with occupants' health symptoms. The aggregated mean from the eight indoor air pollutants and the two discomfort factors of temperature and relative humidity result in a single number between 0 and 10. This simple indicator communicates to MVAC but also to the occupant, the facility and concerned parties about the quality of indoor air. At this stage, more seminal data are needed to test the model for any empirical application and conclusive assertion of its potential for controlling the MVAC system. More must be done, including integration with the two machine learning algorithms of artificial neural networks using sample field data. Therefore, the way forward is to gather field data and test this mathematical model to derive the indices.

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A solar PV-driven heat pump for conditioning a test room

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Abstract: Growing concern over residential carbon emissions has highlighted the necessity to electrify and decarbonize building conditioning by moving away from reliance on natural gas and towards renewable generation. Therefore, this paper experimentally investigates the energy and comfort performance of conditioning a test room using hydronic radiant ceilings connected with an off-grid solar photovoltaic (PV)-driven heat pump. The heat pump is connected to two water tanks that provide heating and cooling energy for radiant ceilings. PV generation, battery state of charge, direct current (DC) loads and heat pump power consumption are measured with a Victron Remote Monitoring application and an AcuDC power meter, respectively. Due to seasonal constraints, only the heating test was performed. The average hot tank temperature and the conditioned performance of the test room are measured at one-minute intervals using a CR10X Campbell Scientific data logger and a comfort cart, respectively. The results demonstrated that the heat pump heated the hot water from 18.8 to 60 °C in less than two hours. During this period, the battery state of charge dropped slightly from 100% to 91% as the PV was simultaneously charging the battery. Additionally, the room yielded substantially stratified temperature results and moved progressively towards comfort, as the predicted percentage dissatisfied (PPD) approached 0.1, and the predicted mean vote (PMV) approached -1 to 0. This paper demonstrates the feasibility of using hydronic radiant ceilings together with off-grid PV-driven heat pumps for space heating. Future research will investigate the energy and comfort performance of this system for space cooling.

Keywords: heat pump; solar PV; test room; conditioning.

1. Introduction

The building sector is one of the largest energy consumers and carbon emitters, representing 30% of global energy consumption and 40% of worldwide carbon emissions (Nordgård-Hansen *et al.*, 2022). Heating and cooling systems are one of the main contributors to this (Sommerfeldt and Pearce, 2023). For instance, they are responsible for at least 40% of energy consumption in residential energy use in Australia (Energy Consult, 2023). In addition, the recent announcement by State government of Victoria (2023) that all newly built homes in Victoria will be gas-free and electricity-based after January 2024, opens up further opportunities to achieve the decarbonization and electrification of residential heating and cooling.

Solar photovoltaic (PV) systems have been increasingly implemented worldwide, for instance, reaching over 30% installation rate in Australian dwellings, resulting in a total installed capacity of 11 Gigawatts (Australian

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Renewable Energy Agency, 2022). On the one hand, solar PV systems have been identified as a great technology for decarbonizing residential loads due to being able to generate renewable electricity and reduce the consumption of grid energy, which is mostly generated from the combustion of fossil fuels (López *et al.*, 2020). Furthermore, the integration of solar panels with the building envelope can result in the formation of a building-integrated PV system, which consequently leads to a reduction in the cooling load of the building (Abdelrazik *et al.*, 2022). On the other hand, there are also some disadvantages to solar PV systems. For instance, the increase in solar irradiation has the potential to yield a substantial amount of electricity; however, the efficiency of PV panels in electricity generation diminishes with elevated temperatures (Hachicha *et al.*, 2019). Additionally, the PV self-consumption rate, calculated by dividing the amount of consumed PV energy by its total generation, is relatively low due to the mismatch between the peak PV generation and house energy load (Wang *et al.*, 2022).

Heat pumps are one of the promising technologies for electrifying building loads due to their outstanding heating and cooling capabilities (Borge-Diez *et al.*, 2022), as well as their ability to employ natural refrigerants with very low global warming and ozone depletion potential (Wang *et al.*, 2023a). Additionally, heat pumps, together with water storage tanks, can be coupled to solar PV systems to produce and store hot and cold water by consuming daily PV energy, contributing to increased PV self-consumption rates (Wang *et al.*, 2021). The stored hot and cold water can be accessed for heating and cooling purposes via hydronic radiant systems, such as capillary mats (Do *et al.*, 2022). Apart from using hydronic radiant systems for heating and cooling space, there are some other types of heating and cooling systems that can be implemented in buildings. For instance, the heating systems include gas-ducted heating systems, traditional boiler and radiator systems, electric resistance heating systems, etc., while the cooling systems are comprised of split-air conditioning systems, evaporator coolers, etc. The main drawbacks of these systems compared to hydronic capillary mats include the consumption of fossil fuels, high electrical power demand (Salvalai *et al.*, 2013), worse thermal comfort levels (Salvalai *et al.*, 2013), etc. Therefore, the performance of using hydronic radiant ceilings made with capillary mats is investigated in this paper.

A number of studies have been conducted to investigate the possibility of using PV-powered heat pumps for heating, cooling and even domestic hot water (DHW) production in residential buildings. For instance, a historical study confirmed the reduction of residential energy consumption by using ground source heat pumps with water storage tanks for heating and cooling compared to conventional electric-based heating systems (Kimiaei *et al.*, 2023). However, the high initial and maintenance cost of using ground source heat pumps has been a major hurdle to their installation in residential buildings (Gaur *et al.*, 2021). Additionally, Li *et al.* (2021) discovered that employing a PV-powered heat pump with water storage tanks for heating, cooling, and DHW could reduce grid energy usage by around 76% per year when compared to using a single heat pump. According to the simulation study, using PV-driven heat pumps and water storage tanks in other cities throughout the world could also have a favorable influence on reducing grid energy use and increasing PV self-consumption (Li *et al.*, 2022). However, these studies lack an illustration of the actual comfort performance of homes after space heating and cooling is accomplished with water-based fan coil units, as they are primarily concerned with the energy performance achievable with the proposed system. Aryal *et al.* (2023) investigated the performance of using a hydronic radiant system for office cooling in Thailand through a simulation study validated using experimental results, and the findings demonstrated that occupants in the office could be comfortably neutralized for 95% of the office hours when the system was effectively controlled. Another study by Koca *et al.* (2022) experimentally supported the effectiveness of using radiant walls for space cooling. Even though these studies did not include heat pumps and PV, they confirmed the viability of using hydraulic radiant systems for space cooling, and future research should investigate the performance of hydraulic systems for space heating.

Our previous work theoretically investigated the energy performance of using PV-powered heat pumps with water storage tanks and batteries for satisfying residential loads, including electricity, heating, cooling and DHW (Wang *et al.*, 2023b). Therefore, this work will experimentally examine both the energy and comfort performance of conditioning a space using a hydronic radiant system connected with a PV-driven heat pump. The novelty of this work compared to the existing literature is that the analysis is based on an actual setup of the off-grid PV and batteries-connected heat pump as well as an existing test room with a hydronic radiant ceiling, making the results more realistic. The remaining sections are organized as follows. Section 2 is a materials and method section that first presents the setup of an off-grid PV-driven heat pump for conditioning a test room, followed by a design of conditioning the test room as well as the explanation of the conditioning parameters. Section 3 discusses the energy and comfort results of conditioning the test room. Section 4 draws a conclusion for this paper.

2. Materials and method

2.1 Off-grid solar PV-driven heat pump for a test room with a hydronic radiant ceiling

Figure 1 shows a schematic of an off-grid solar PV system and batteries connected to a polyvalent heat pump for conditioning a test room using a hydronic radiant ceiling. This combined system has been implemented in a workshop in Geelong, Australia. A 5 kW off-grid solar PV system is installed to provide the electrical energy for charging the 7.2 kWh batteries and operating electrical appliances. The instantaneous PV generation, state of charge of batteries, and the total DC energy loads of batteries are monitored at every minute using the online-accessible Victron Remote Monitoring (VRM) application. The polyvalent heat pump runs on a 48V DC compressor with a natural refrigerant of Propane, and it has three modes, including water heating-only, water cooling-only and simultaneous water heating and cooling mode. The energy consumption of the polyvalent heat pump is measured every minute by an AcuDC power meter. The heat pump is connected to two water storage tanks for storing hot and cold water. The two pumps connected between the heat pump and the two storage tanks also run on DC power drawn from batteries. Therefore, the total DC load measured from the VRM application includes the operating power of the heat pump and the two DC pumps.

In addition, a test room has been built in a workshop with a depth of 4.8m, a width of 3.6m, and a height of 3m. The room was constructed with plaster walls on three sides and a double-glazed window facing solar north on the fourth side. Eighteen capillary mats are installed on the ceiling as a hydronic radiant system to test its performance in conditioning the room. The hydronic radiant ceiling is connected to two 15-meter-long coils within the two 120L water storage tanks, respectively. An alternating current (AC) water pump is used to pump the hot and cold water from the two tanks to the hydronic radiant ceiling for space conditioning, and the energy consumption of the AC water pump is directly drawn from the electricity grid rather than from the PV and batteries mentioned above. The temperatures of the two tanks and the test room are measured at one-minute intervals using Type-T thermocouples and logged into a CR10X Campell Scientific data logger. In particular, thermocouples are placed at three different heights (0.1m, 1.5m and 2.9m from the floor) within the test room to obtain stratified temperature results. Moreover, a comfort cart, constructed according to ASHRAE Standard 55 (ASHRAE, 2017), measures several conditions of the test room, including the globe temperature, air temperature, relative humidity, air velocity, and CO_2 level.

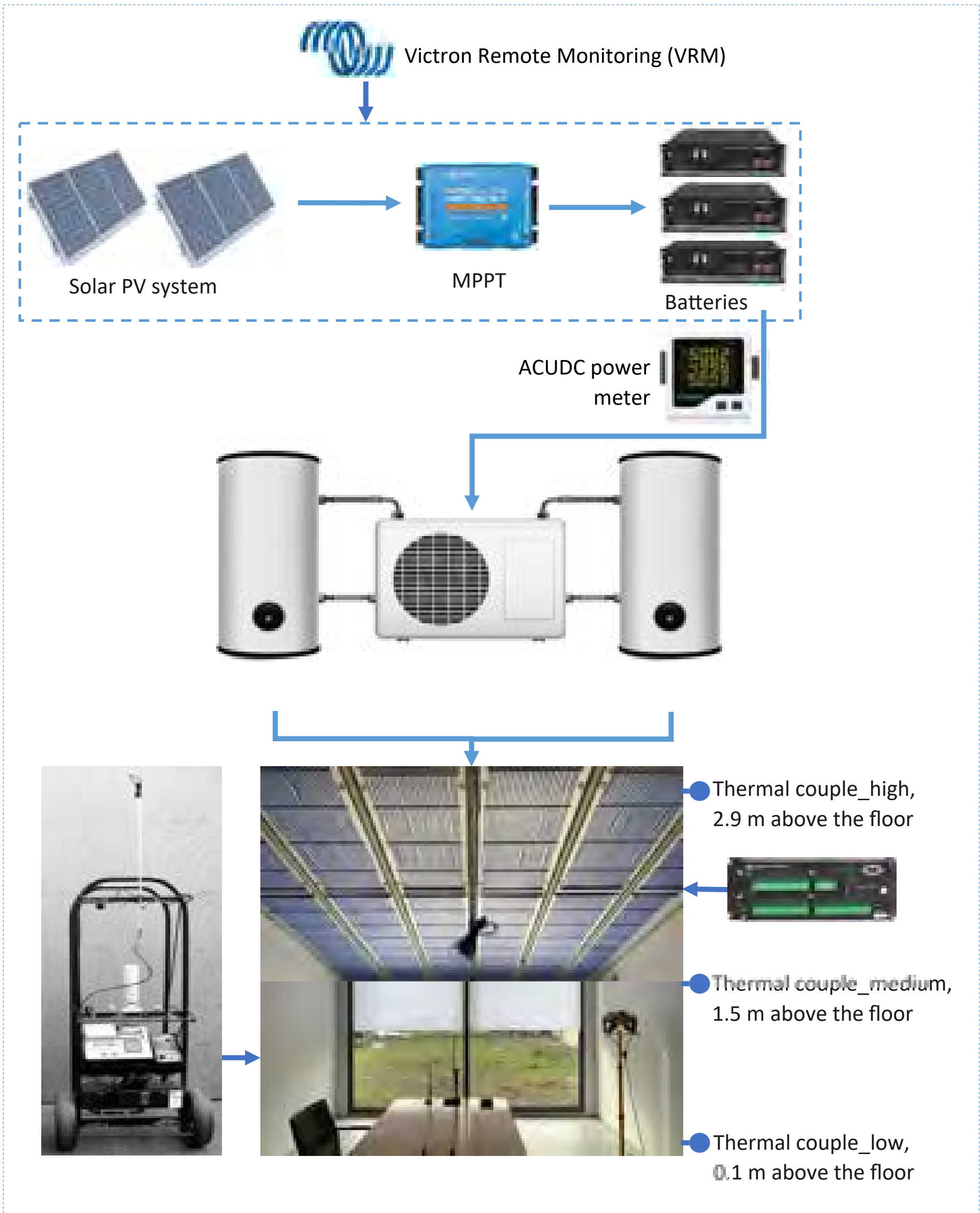

Figure 1. Schematic diagram of off-grid PV batteries connected to a polyvalent heat pump for hydronic conditioning of a test room

The specifications of the equipment used in the combined system are summarized in Table 1.

Table 4: Specifications of equipment used in the combined system

Equipment	Specification
Solar PV system	Brand: Tindo Solar Vertex Model number: TSM-DE09.08 Capacity: 4.86 kW, including 12 panels with 405W for each; Maximum efficiency: 21%
Maximum power point tracker (MPPT)	Brand: Victron energy Maximum PV open circuit voltage: 150 V Rated charge current: 35A
Batteries	Brand: Pylontech US2000 Lithium battery, Nominal voltage: 48 V DC; Charge / discharge current: 50 A; Capacity: 7.2 kWh, including three batteries with 2.4 kWh each
AcuDC power meter	Brand: Accuenergy; Voltage: 0-9999 V DC; Current: 0-50000 A; Power: 0-60000 kW Accuracy: 0.5%
Polyvalent heat pump	Panasonic compressor: (Power supply: 48 V DC; Nominal capacity: 3465W); Plate heat exchangers (Company: Sanhua holding group; Number of plates per heat exchanger: 60; Area: 2.09 m^2); Refrigerant – Propane: Critical temperature: 96.70 °C; Critical pressure: 4.247 Mpa; Latent heat at a dewpoint temperature of 0 °C: 374.7 kJ/kg)
Two water storage tanks	Rated capacity: 120 L each; Built-in coil: length of 15 m for each tank.
Two DC water pumps (Between the heat pump and the two water storage tanks)	Company: Shysky tech; Model number: DC60G-24120A; Voltage: 24V DC; Nominal input power: 100W; Lifting range: 12 m; Maximum flow rate: 20L/min.
AC water pump (Between the two water storage tanks and the hydronic radiant ceiling)	Company: Ouyade Pump; Model number: AUTO15/4-A130; Power: 22W; Voltage: 220-240V; Lifting range: 4m; Maximum flow rate: 38L/min.

Test room	Built inside of a workshop with three sides made with plaster walls and the other side made with a double-glazed window facing solar north; Dimension: 3.6 m (width) * 4.8 m (length) * 3 m (height).
Hydronic radiant ceiling	Company: Beka radiant heating and cooling Number of capillary mats: 18; Total volume of water: 10 Liters
Comfort cart	Standard: Built according to the ASHRAE 55; Measuring parameters: globe temperature, air temperature, relative humidity, air velocity, and CO_2.
CR10X data logger	Readings: one-second readings averaged into 1-min intervals Control strategy: Modbus protocol;
Thermal couples	Name: Type T thermocouple (Copper / Constantan); Temperature range: -270 to 370 °C; Accuracy: +/- 1.0 °C.

2.2. Design of operating the heat pump and conditioning the test room

This work aims to investigate the energy and comfort performance of conditioning the test room using a hydronic radiant ceiling connected to an off-grid PV-driven heat pump. Due to seasonal conditions, only the heating test is performed and reported in this work; future research will report the cooling efficiency of this combined system. The operation of the heat pump and the hydronic radiant ceiling is designed as follows. First, the polyvalent heat pump is operated in the water heating-only mode to produce hot water. To measure the temperature change of the average hot tank without any external influences, the hydronic radiant ceiling is deactivated during this period. As explained in Section 2.1, the average hot tank temperature is measured and recorded using a CR10X Campbell Scientific data logger at one-minute intervals. Using the VRM application, the DC outputs, heat pump power consumption, PV generation, and battery state of charge are measured at one-minute intervals.

After the heat pump stops its operation due to the average hot water temperature reaching its maximum, the next step is to activate the hydronic radiant ceiling to heat the test room. Therefore, the AC water pump is turned on to circulate water from the hydronic radiant ceiling to the coil in the hot tank so that heating energy can be transferred from the hot tank to the radiant ceiling. The temperature stratification of the test room is measured and recorded using the CR10X datalogger, while other parameters, including air velocity, relative humidity, and air temperature, are measured at one-minute intervals using the comfort cart. Additionally, the test room is unoccupied during the experimental period, and the windows and door of the test room are entirely closed. Hence, the CO_2 level in the room is almost constant since no ventilation system is used.

2.3. Performance indicators of conditioning the test room

To evaluate the heating performance of the test room, thermal comfort, defined as the mindset that expresses satisfaction with the thermal environment, is applied here. Thermal comfort is a complex concept, as it is influenced by a number of variables, including air temperature, air velocity, relative humidity, clothing factor, metabolic rate, and mean radiant temperature. The predicted mean vote (PMV) index and the predicted percentage dissatisfied (PPD) index, based on Finger's model, indicate the relative level of discomfort (Fanger, 1973). The PMV Index predicts the average response of a large group of people based on the ASHRAE thermal sensation scale. It produces a rating from +3 (hot) to -3 (cold), with 0 representing thermal neutrality (Anderson and Luther, 2012). The PMV index is a function of the metabolic rate and the thermal load, as shown in Equation 1.

$$PMV = (0.303e^{-0.036M} + 0.028)L \quad (1)$$

Where:

M = metabolic rate; L = the difference between the amount of heat produced by a person's body and the amount of heat dissipated by the actual environment when skin temperature and evaporative heat loss from perspiration are maintained at comfortable levels at the actual activity level, and it is calculated using multiple parameters, such as thermal resistance of clothing, air temperature, radiant temperature, etc., (Khan and Pao, 2015).

The PPD predicts the percentage of a large group of people likely to feel too hot or too cold, and it is based on the PMV values for that group (Olesen and Parsons, 2002). Specifically, PPD is calculated as shown in Equation 2. It has been reported that a PPD of less than 20% and a PMV between -0.8 and +0.8 are considered acceptable levels of thermal comfort (Luther *et al.*, 2020).

$$PPD = 100 - 95e^{-(0.03353PMV^2 + 0.2179PMV^2)} \quad (2)$$

3. Results

3.1. Energy summary during the heat pump operation period

To evaluate the energy and comfort performance of heating the test room using a hydronic radiant ceiling coupled with an off-grid PV-powered heat pump, we conducted an experiment, which included operating the polyvalent heat pump to produce hot water by consuming energy from PV and batteries. The hot water was then delivered into the hydronic system to heat the test room. Figure 2 summarises the instantaneous PV generation, battery state of charge, DC loads, power consumption of the heat pump, and average temperature of the hot water tank. During the hot water heating period, the average temperature of the hot tank increased from 18.8 to 60 °C, as shown in Figure 2-(c).

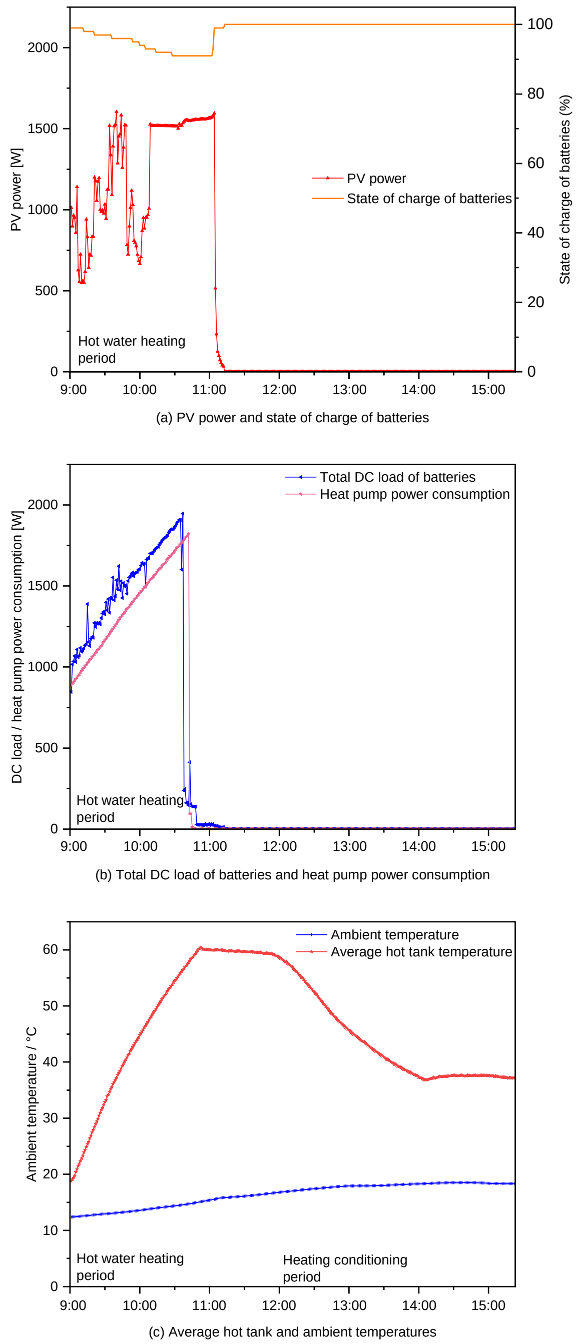

Figure 2. Temperature and power summaries of the combined system during the hot water heating period

In the same period, as shown in Figure 2-(b), the power consumption of the heat pump increased progressively as the compressor required more energy to generate heat so that the average temperature of the hot water tank could continue to rise. In addition, the DC load was greater than the heat pump's power consumption because the water pump connecting the heat pump to the hot water tank was also powered by batteries. Moreover, the solar PV system was generating electricity and charging the batteries, so the state of charge of the batteries decreased marginally from 100% to 91%. It can also be discovered from Figure 2-(a) that during the first hour of operation, the PV generation fluctuated significantly. Various factors, including the self-management of the Victron system and variations in solar radiation, can explain this. Noteworthy, once the batteries were fully charged after operating the heat pump, the solar PV system stopped its generation due to its off-grid connection. This brings us more interest in connecting other appliances to PV and batteries so that renewable PV energy can meet part of the electrical load in the workshop, thus reducing its grid energy consumption.

3.2. Conditioning performance of the test room

Figure 3 depicts the conditioning performance of the test room with hydronic radiant ceilings. As shown in Figure 3-(a), before the heating conditioning period, the temperature in the test room started to increase gradually, which could be attributed to the change in ambient conditions. When the heating conditioning period started, the temperatures at three different heights in the test room increased significantly, and their stratification effect was evident. This is due to the fact that the hydronic ceiling radiates heating energy, resulting in the highest temperatures near the ceiling, followed by lower temperatures at medium and low heights from the floor. Subsequently, the stratification effect of the room temperature was gradually equalized towards the end of the heating testing.

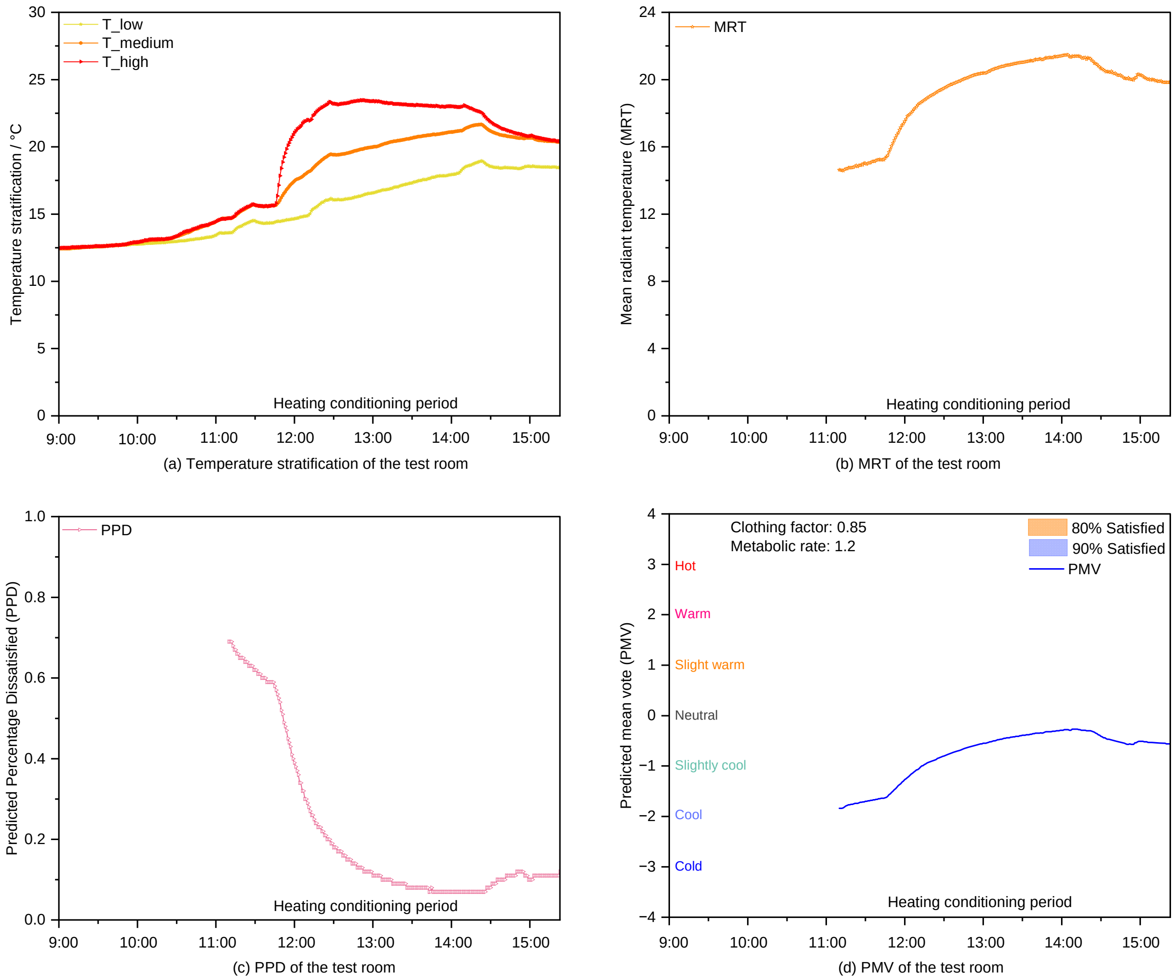

Figure 3. Temperature and comfort summaries of conditioning the test room

In addition, the mean radiant temperature rises substantially after the start of heating. This is consistent with the downward trajectory of the PPD, and its value reaches 0.15 from 0.58 within half an hour after the heating starts, indicating a gradual decrease in the percentage of people who are not satisfied with the thermal comfort level of the room. As mentioned before, a value of PPD less than 0.2 indicates that the comfort level of the room is in the acceptable range. In addition, we can see that the PMV values gradually approach -1 and 0, which indicates that the occupants may feel slightly cold or neutral in the test room. It can also be observed in Figure 2-(c) that the average temperature of the hot water tank dropped by 24 °C during the two hours of heating, and, more importantly, all the energy came from a renewable solar PV system. Therefore, it can be said that this study proves the feasibility of using hydronic radiant ceilings and off-grid PV-driven heat pumps for space heating.

4. Conclusion

This work investigated the energy and comfort performance of conditioning a test room using a hydronic radiant ceiling connected with an off-grid PV-driven heat pump. This comprehensive off-grid system has been implemented in a workshop located in Geelong, Australia. Due to seasonal constraints, only the heating test was conducted, and its results were analysed. The primary procedure of this test was to initially heat the hot water using a heat pump powered by PV and batteries. Then, the heating energy was transferred to the hydronic radiant ceiling from the hot water tank via an internal coil for heating the test room.

The results demonstrated that the heat pump raised the hot water temperature from 18.8 to 60 °C in less than two hours. Due to the concurrent battery charging from PV generation, the battery state of charge decreased slightly from 100% to 91% during the hot water heating period and was then fully charged in approximately 15 minutes. From the perspective of conditioned performance, the room yielded substantially stratified temperature results during the heating conditioning period due to the radiative heating from the radiant ceiling. Then, this effect was gradually balanced out by the end of the test. As the PPD approached 0.1 and the PMV approached -1 to 0 after the heating system was activated, the results further indicated that the room was progressively becoming comfortable. This research confirmed the viability of hydronic radiant ceilings and PV-powered heat pumps for space heating. Future research will investigate the cooling performance of the same system, as well as the prospect of using this off-grid PV batteries to power additional appliances in the workshop.

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A study for implementing and assessing acoustic design in architectural design curriculum

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Abstract: There are few studies on pedagogical approaches to acoustic design in architecture degrees, particularly those addressing how acoustics is taught within design studios and how students apply acoustic design principles. This paper presents a preliminary analysis of the current approaches to acoustic design within architectural design coursework in top-tier universities. It also showcases a unique architecture design studio framework incorporating acoustic performance, developed for, and tested in The University of Melbourne context. Delivering this design studio on acoustic design led to the development of a methodology to categorise and compare student design outcomes.

Keywords: Architectural Design, Acoustic Design, Architectural Design Curriculum, Performance-oriented design,

1. Background

In Australia, the National Standard of Competency for Architects (AACA, 2021) sets out the competencies required of a graduate architect. Acoustic design is considered part of the sustainable environmental systems criteria, alongside water, thermal, and lighting considerations for concept design. Sabine's (1922) Fogg Art Lecture Hall experiments established the fundamental relationship between architectural design and acoustic performance. Nowadays, acoustics are a crucial metric in rating systems like WELL, LEED, BREEAM, and Green Star. Although acoustic design is generally less considered than other well-being factors in architectural practice or education. However, applying basic acoustic principles in the early stages of a design process is better than making costly fixes with acoustic consultants after concluding construction. Therefore, incorporating students in acoustic design principles is critical to the architectural design curriculum.

1.1. State of the art of acoustic design in architectural curricula

Lawrence (1968) offers an example of a course in architectural acoustics to illustrate teaching in the third year of an undergraduate course at the University of New South Wales at the time of her article. The main topics covered start from the physics of sound, including decibel and wave equation calculations, to hearing and perception, noise transmission, and room acoustics. This coursework's order and contents are broadly consistent with how it is presented in engineering courses, as illustrated through the structure

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of Long's *Architectural Acoustics* (2014), a commonly referred to textbook in the field. We will refer to this general coursework framework as *numerical acoustics*.

To understand the contemporary context of acoustic design coursework in architectural schools worldwide, we performed a preliminary survey that identified courses in acoustics or architectural acoustic design offered to students enrolled in undergraduate or postgraduate architectural design programs. We used the Quacquarelli Symonds (QS) World University Rankings to identify the top universities for architecture and the built environment in 2021, updated in 2022. The QS rankings are widely used to compare university performance using indicators such as academic reputation, faculty-student ratio, and citations. The numerical rankings are not essential for this survey as the QS rankings only provide a global selection of popular and highly regarded architectural programs. However, the QS rankings have known limitations, such as biases towards larger institutions. As a result, the list does not necessarily capture all the institutions with acoustics research labs that teach architectural acoustics. In addition, this survey does not include the architectural design studio environment; therefore, we will discuss this issue separately. Table provides an overview of the surveyed courses.

The results from this survey represent a preliminary list of courses and their framework of acoustic design delivery. This information was gathered based on online material found through course catalogues. Where data was unavailable in English, it was translated into English using machine translation. This list does not currently include information about how the coursework integrates into the curriculum, the format and structure of the classes, or the intended learning outcomes (ILOs), as it was not publicly available in all cases.

Table 1. Acoustics, acoustic design, or architectural acoustics courses within architectural design coursework.

Institution	Location	Name of Course	Offered at undergraduate (UG) or postgraduate (PG)	Combined with other environmental criteria	Only available as an elective	Acoustic Framework
Massachusetts Institute of Technology (MIT)	Cambridge, US	Architectural Acoustics	PG		✓	Numerical Acoustics
		Resonance: Sonic Experience, Science, and Art	UG		✓	Soundscape
Delft University of Technology	Delft, NL	Technology Health and Comfort	PG	✓	✓	Numerical Acoustics
University College London (UCL)	London, GB	Building Physics and Environment	UG / PG	✓	✓	Numerical Acoustics
ETH Zurich	Zurich, CH	Building Physics I: Heat and Acoustics	UG	✓	✓	Numerical Acoustics
		Architectural Acoustics I	UG / PG		✓	Numerical Acoustics
Harvard University	Cambridge, US	Environmental Systems 2	PG	✓	✓	Numerical Acoustics
National University of Singapore (NUS)	Singapore, SG	N/A				
Manchester School of Architecture	Manchester, GB	N/A				
University of California, Berkeley (UCB)	Berkeley, USA	Introduction to Acoustics	UG		✓	Numerical Acoustics
Tsinghua University	Beijing, CN	Building Acoustics	UG		✓	Numerical Acoustics
Politecnico di Milano	Milan, IT	Acoustics in Buildings	UG		✓	Numerical Acoustics

	Environmental Acoustics	UG	✓	Numerical Acoustics

Of the ten universities identified, eight offered at least one course that included acoustics, with three of these universities offering two courses. Approximately half of the courses combined acoustics with other environmental performance criteria, such as lighting and thermal considerations. The majority of these courses also used a numerical acoustics framework. Based on the publicly available information, nearly all the courses included practical demonstrations of acoustic effects and mentioned the application of acoustic design principles in specific building typologies. Only five of the eleven courses had acoustic modelling, simulation, and auralisation, meaning less than half integrated with 3D modelling interfaces for architectural design. Only one course approached sound from a soundscape framework, though this was at a university where a numerical acoustics course was also offered.

From this preliminary survey, we understood that numerical acoustics frameworks are viewed as the most effective way to deliver acoustic design education. That can be in design studios and other courses based on a Problem-Based Learning (PBL) approach. As Hillier et al. (1984) argue, design is a two-step process where scientific work provides information, to which the designer can then decompose a problem into its elements, incorporate the information, and propose a solution. As elective courses usually assess learning through exams or theoretical assignments, we concluded that the design studio environment was optimal for experimenting with integrating design and acoustics.

The survey showed that finding information for design studios was challenging as it was rarely published in course handbooks or otherwise released publicly. Where it is available, information is limited to short introductory text or outlines for students. However, it is essential to understand what design studio leaders consider critical acoustic information to deliver in the limited teaching period and expect a student to respond to or incorporate within their design proposals.

1.2 The design studio context

Harvey (2010) identified six categories of design studios incorporating elements of acoustics, which we have summarised as follows:

Sonic-based form generators: A studio that encourages the literal translation of sound, music, or notation into a 2D or 3D representation.

Acoustic design: Studios where sound is understood as numerical data, and the outcome is a distinct program that relies on numerical targets such as a concert hall or lecture theatre.

Acoustic communication: A studio that attempts to achieve a particular spatial design or an auditory experience.

Heightening auditory awareness: A studio conducted that involves the design for people who are deaf or hard of hearing.

Virtual acoustic spaces: Studios that involve sound design for virtual spaces, such as animation, virtual reality, or game design.

Soundscape studies: Studios that focus on the observation, analysis, and documentation of soundscapes.

Harvey did not explicitly identify the corresponding design studios used to develop these categories. We also noted that the categorisation focuses on the student's ILOs rather than the exact delivery framework of acoustic information. Nonetheless, there is presumably an overlap in the framing of acoustic information to the students, so categorisation is helpful to identify approaches to teaching and navigate the literature on acoustic design in the design studio environment. For example, several researchers (Felix and Alsamahy, 2016; Gur and Sen, 2019; Maze, 2002) used sonic-based form generators as a creative tool or for form generation. These approaches drove students to acknowledge music composition to translate elements of music such as rhythm and tempo into architectural motifs. While these publications illustrate creative means of exploring architectural design, they are irrelevant to the science of architectural acoustics and outside the scope of this study.

Several publications also suggest a soundscape approach to introduce students to acoustic design in the design studio. A soundscape is "the acoustic environment as perceived or experienced and understood by a person or people, in context" (ISO12913-1, 2014). Schafer (1994), who popularised the term, used soundscapes to critique how acoustic design usually takes a negative outlook of reducing noise and unwanted sounds. Instead, Schafer presents a positive approach that accommodates sound's scientific and artistic nature as a holistic framework to unify all sound-related studies. Milo (2019) suggests that soundscapes provide a methodology to include the social and cultural dimensions of acoustic design, whereas traditional architectural acoustics give physical and technical dimensions. She offers a range of topics for an acoustic design module, from listening to and documenting aural environments to introducing architectural and environmental acoustics, contributing to the simulation and verification of an outcome. Xiao et al. (2022) attempted to apply Milo's framework. They found that soundscapes provide a theoretical framework with which architectural students can easily engage, allowing them to think holistically about sonic experiences and how sound works in spaces. As soundscape approaches generally concern aural training to build acoustic communication skills, we understood the benefits are predominantly in developing a holistic understanding of acoustics. Additional training in acoustic design is still necessary to translate these communication skills into tangible design outcomes.

Despite the prevalence of numerical acoustics in elective coursework and Harvey's identification of an acoustic design category for design studios, we found only a few examples of literature within the context of the design studio environment. Some researchers (Bernadi, 2017; Sakagami et al., 2013; Satoh et al., 2017) suggested using smartphone applications instead of calibrated measurement equipment as a way for students to access acoustic measurements easily. Sonification, which is the conversion of acoustic data into audio signals, has also been suggested by Cabrera et al. (2006) and Llorca et al. (2019) to make it more accessible and understandable by students. Finally, Sü Gül and Çalışkan (2022) presented a series of exercises that they used to introduce architectural students to specific measures of acoustics in sequence. For example, students are asked to estimate the reverberation time of a room using the Sabine equation and compare them against optimum ranges. Where they fall outside this range, students are tasked with proposing design solutions based on material treatments. While the course described was not a design studio, students were encouraged to use their designs for the acoustic analysis and simulation tasks. Additionally, the students could apply acoustic design considerations to their design studio projects, illustrating a promising implementation of theoretical learning and practical design applications.

This analysis revealed little agreeance on the most critical acoustic aspects to be understood by architectural design students. Comparing the frameworks and outcomes of design studios embedding acoustic design is challenging due to the extent and consistency of documentation available across publications. In the future, we will add targeted interviews with academics on their design studio teaching methods to the online survey.

2. Context at The University of Melbourne

Although there are courses dedicated to environmental technologies that cover environmentally sustainable design (ESD) and internal environmental quality (IEQ), the current coursework did not specifically address architectural acoustic design. In 2020, Professor Donald Bates, coordinator of the Master of Architecture (M.Arch) design studios, invited one of the authors to develop an architectural design studio. It seemed appropriate to propose acoustic design as a topic for the design studio and build coursework to translate acoustic theory into synthesised design outcomes.

In developing the coursework, there were additional factors regarding student backgrounds to consider. In 2008, UoM adopted the Melbourne Model to replace 96 undergraduate courses with seven undergraduate degrees, with several different major, minor, and specialisation pathways that students can select from. The goal was to promote flexibility to solve future challenges, supporting a breadth of understanding across various disciplines and reducing the focus on specialised technical learning. On the contrary, the two-year Master of Architecture at UoM to complete the five years in architectural education promotes a highly specialised skill set.

In particular, the M.Arch Design Studio model operated in a vertically integrated framework until 2023: a student taking their first design studio (Studio C) in the M.Arch could enrol in a design studio with students taking their second (Studio D) and third (Studio E). This was referred to as the CDE Design Studios, which included a range of studios with different agendas. Given the broad differences in technical knowledge for students entering the design studio and for the successful completion of a design project, it was challenging to create incremental educational content for these three stages of learning in a single class.

To facilitate future development and research in the delivery of acoustic design coursework, we have chosen to discuss the framework from the perspectives of our primary goals in approaching the curation of the content and how the design brief complimented these goals.

3. Architecture Design Studio 45: *Resonate*

In 2020 at UoM, the authors of this paper developed a *CDE Design Studio* to test a new framework for a design studio that embedded acoustic principles as a creative component, resulting in the proposal, development, and execution of *CDE Studio 45: Resonate*, which ran three times in 2020, 2021 and 2022. *CDE Studio 45* aimed to address the isolated nature to which acoustic design is usually relegated and design a brief where students were encouraged to associate acoustic quality with various other performance requirements alongside high-level design thinking processes. As a requirement of the *CDE Design Studios*, the marking rubric was developed through the National Standard of Competency for Architects (NSCA) Performance Criteria, adjusted to suit the studio's agenda. The marking rubric was based on constructive alignment (Biggs and Tang, 2011), and the four submissions were marked against eight criteria, which reflected 19 specific performance criteria of the NSCA. Through the definition of the ILOs for *CDE Studio 45 Resonate* – based on (1) Research and Context, (2) Concept Design, (3) Design Development, and (4) Detailed Resolution and Refinement – we defined the overall components of the educational program, including the integration of acoustics into each of the four stages of the design process.

3.1 Development of the design brief

The overarching idea was to build a design and research agenda that could promote independent discovery by each student. To this end, we developed a brief that combined spatial and acoustic qualities of indoor and outdoor spaces with ecological reflections on rehabilitating abandoned quarries in Regional Victoria. Proposing an alternative rehabilitation plan to leave the quarry floor open to people, improve the landscape's health and establish a program that could host a range of creative practices and educational events all year round seemed appropriate to a program that included a versatile, multi-purpose venue for live music performances. We also aimed to let students demonstrate that abandoned mines in Australia don't have to be a liability but can become an asset if properly designed and managed. Across the world, abandoned mines are given new life to support local communities, and this design studio aimed to show that the same approach can be adopted in our country, taking advantage of the national policy for abandoned quarries, which encourages and recommends the reappreciation of these sites, also through the engagement of the local communities. That involves innovative solutions that offer regional Australia employment and training opportunities.

The closest quarry (only partially abandoned) to Melbourne that students could easily visit was a basalt quarry managed by Holcim Australia in Colac. The area is home to the Corangamite Water Skink (CWS) population. Holcim had already set up a rehabilitation plan to leave a high-quality habitat for the CWS that includes waterways with rocky edges throughout the extraction area. The southern extraction area has many canals with rolling grassy knolls throughout. In the northern pit (now water storage), there were six pillars of stone left behind, as they were considered low quality by the previous quarry owners. A wide variety of birds has inhabited these islands.

The brief associated with rehabilitating the Colac quarry was to plan a music and art precinct that included the programming of a music festival. This complex brief encompassed different types of space that had to operate simultaneously and all year round. The brief development included (1) the organisation of the precinct's spaces, circulation, and uses during the festival and non-festival periods; (2) the exploration of design response to the rehabilitation of the quarry; and (3) festival planning and branding. The design responses had to include (1) an acoustic shell for open-air concerts (relative to the types of festivals chosen by students); (2) a music museum, including temporary and permanent exhibition spaces; (3) the revegetation of at least 50% of the quarry; (4) workshop spaces, installations, or temporary pavilions to support the ongoing program.

Curating and developing the Music and Art precinct, which included exhibition areas, workshops and installations, allowed students to tackle different types of space with different performance criteria and design outcomes in mind. For all these architectures, acoustic performances were not addressed, as the goal was to propose new ways to engage with music, artistically and pedagogically. Including the revegetation and the circulation in the entire site forced students to focus on different scales, ranging from landscaping at the scale of 1:1000 to architectural details at 1:10. This encouraged students to constantly engage with the ecological aspects imposed by the brief and review the underpinning decision-making throughout the design process. This task also encouraged students to engage with and reflect on the natural soundscape.

The outdoor performance venue offered the chance to engage with the creative potential of sound as the primary design driver while dealing with a less complex architecture. Students defined the shell's best shape and audience area, followed by a study on tectonics, including material systems and structural behaviour. Being exposed to structural and acoustic principles in a simple, still daring architecture engaged students in an iterative interrogation of the implications of their design decisions.

We developed this set of activities with the ambition to include a holistic understanding of acoustic design within the architectural design context to promote and teach a mode of critical thinking that students could grow to become successful architects able to discuss and collaborate with specialists.

3.2. Delivery of acoustic design

The design studio structure at UoM takes place over 14 weeks, where the teaching period consists of 2x3 hour classes on Monday and Thursday over the first 12 weeks, with students working independently on projects for the last 2 weeks. In addition, given the specialist tasks associated with each assignment, we expanded the teaching team by including the technical support of Gabriele Mirra, Computational Design and AI specialist, and Peter Fearnside, former CEO, and founder of Marshall Day Acoustics Australia. They acted as stakeholders, presenting multi-faceted perspectives on the design brief.

In response to the contextual factors discussed in section 2, the acoustic information presented needed to provide students with a fundamental and holistic understanding of acoustic design considerations while being specific enough to apply directly to a design problem. In the first three weeks, lectures scaffold learning from structural and tectonic requirements through model making. The acoustic information is delivered through (1) traditional numerical acoustic approaches, including the physics of sound and ways to simulate sound through geometry; (2) musician and audience performance requirements, including live demonstrations of acoustic principles such as frequency, ensemble listening, player positioning, and acoustic measurements; (3) measurement and simulation of Sound Pressure Level (SPL) via Aeolus (an acoustic modelling plugin developed to analyse and optimise acoustic shells). While students were taught the tools and skills to acoustically analyse and optimise their designs, the focus was placed on translating acoustic and other performance-based design principles rather than the accuracy of the simulations.

Students are asked to demonstrate their holistic understanding through the first task, Amplify Your Phone (AYP), which involves the development of physical models of small acoustic shells to amplify a smartphone (Colabella and Mack, 2023). This exercise was developed with Problem-Based Learning (PBL) principles in mind, allowing students to reflect-in-action on the learned acoustic principles through the initial low-stakes exercise (Schön, 1985). Entrustment, described by Ghani et al. (2021) as assigning roles to students in PBL, encourages students to act as assessors and both givers and receivers of feedback through the aural observation of acoustic qualities. Linking design manipulation, performance simulation, and acoustic outcomes facilitates an effective translation of theoretical material into design.

After the first three weeks, we introduced the brief for the quarry and the outcomes of this first task were translated (by similarity or difference) into the design of the Music and Art Precinct acoustic shell. Following the PBL pedagogy proposed by Ghani et al. (2021) of posing real-life problem scenarios as a context in which students collaborate and learn, students were not provided with a fully developed brief as they prepared their own master plan and festival plan in teams of four, following the identification of target goals for the local communities, a specific set of goals for the sustainable use of the quarry in the long run, including their interpretation of what an "art precinct" should be.

The lectures shift focus on precedents and design principles relative to performance venues, landscape, and site-specific design strategies. Students were taken on a site visit to The Edge building at Federation Square, a venue for speakers and small-to-medium-sized music and theatre performances in the core of Melbourne's CBD, helping students understand the function of a performance venue within a similar art and music context.

Following the proposal of their precinct master plan and festival program, the lectures move to performance requirements, including basic principles of structures, material systems and detailing alongside technical sessions using multi-objective optimisation with Aeolus. A site visit to the Melbourne Conservatorium of Music facilitates the discussion of weighing architectural and acoustic design intentions while providing students with practical examples of acoustic design strategies. Table provides an overview of the 12 teaching weeks following the 2021 edition of the CDE Studio 45.

Table 2. Outline of the lecture topics and core deliverables for CDE Studio 45.

Week	Lecture / Tutorial Topic	Student Deliverables
1	Physics of sound and fundamentals of acoustics Model making and analogue acoustic testing	
2	Introduction to acoustic simulation with Aeolus Architectural form-finding techniques Music, ensemble, and orchestration Live demonstration of acoustic principles	
3		AYP assignment
4	Landscape design and master planning workshop	
5	Site visit at The Edge, Federation Square	
6	Shell structures and tectonics	Music and art precinct plan proposal
7	Acoustic optimisation with Aeolus (Pt.1) Material systems and structural typologies	
8	Acoustic optimisation with Aeolus (Pt.2)	
10	Site visit at Melbourne Conservatorium of Music	
12		Architectural proposal for acoustic shell and museum, planning of the site, development of the festival program, and optimisation of the acoustic shell

By the end of the semester, students will have (1) developed a new brief for the Music and Art Precinct; (2) designed a live-performance venue at different scales, from 1:1000 to 1:10; (3) defined the acoustic qualities of their architectures and improved them progressively through acoustic simulations; (4) communicated their design concepts and propositions through a variety of media, including verbal presentations an external panel of architects and engineers.

4. Categorising student outcomes

Despite the scaffolded learning predominantly centring around a *numerical acoustic* approach, it became apparent that the holistic nature of the studio's approach encouraged students to find creative ways of incorporating acoustic design within their design process and agenda. In assessing the student projects and documentation of their projects, we identified three categories of outcomes based on when, in the design process, students began to consider acoustic design. We found a strong relationship between this timing and how students integrated acoustic design with the architectural context. These categories became a useful method of comparing students' design processes, analysing the outcomes, and understanding the design decisions made by students. Each of these categories will be described through selected drawings of the student projects and compared against the initial goals of the design studio. The students' works were analysed and categorised considering the marking rubric we refined over the years to align the studio outcomes with the NSCA Competency Profiles.

4.1 Acoustic performance as a design instigator

Students who approached acoustics performance as a design instigator usually looked for ways to involve sound and music within every aspect of the design brief in the early stages of the project initiation and conceptual design. This approach generally unveiled novel approaches to acoustic design, primarily through early precedent or research work. The design strategy for the Music and Art precinct and site regeneration usually focused on using acoustics to generate design solutions, from the circulation map through soundscape and music installations to a school or a museum that could engage the local communities.

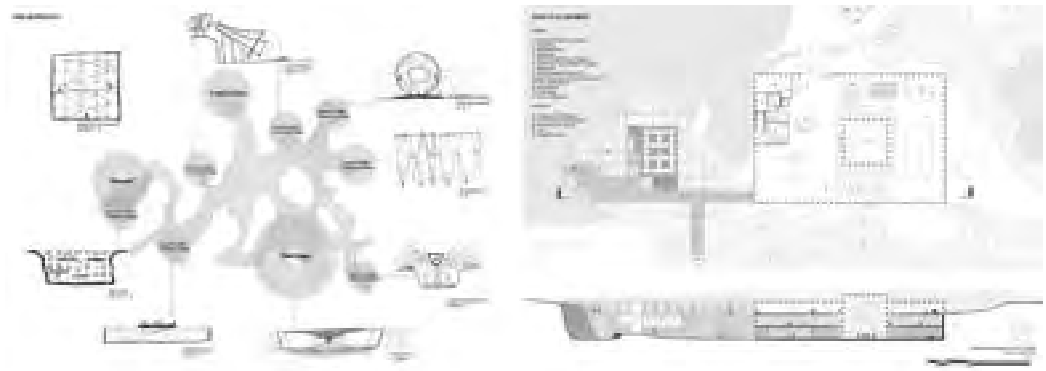

Figure 1. Master plan and architectural drawings of the music museum showing an array of acoustic installations by Student A. Reproduced by permission.

Student A's project focused on wayfinding and exploration as a core design aspect, which is illustrated through the master plan of the precinct (Figure). Festival goers could wander around the quarry to find hidden sound installations that used the dense acoustic qualities of the quarry walls or the height difference to the ground plane as part of installation art. Student A referenced the designs for these installations from precedent research, distilled the acoustic principles, and modified them to reflect the site. This process highlighted Student A's understanding of acoustic principles and how they might be used to produce novel experiences. The museum plan continued this exploration by featuring electroacoustic installations, one of which created ambient soundscapes within a 3-storey sound cube at the centre of the museum.

As a trend, students whose projects fell into this category were generally less successful in delivering the technical components of the earlier AYP exercise as well, as they tended to focus more on creating an innovative festival program and precinct; overall, they opted for a less rigour in evaluating acoustic performance and a more creative approach to acoustics at the early stages of design. However, some projects made well-reasoned arguments based on learned acoustic principles rather than numerical evidence for developing their proposals for the museums, exhibitions, or installations; they often did not perform a numerical analysis or a well-established MOO. These arguments demonstrate that although some students might be less technically inclined, they can still engage with acoustic principles from a holistic perspective and use acoustic knowledge to inform the preliminary design research and when developing the conceptual design.

4.2 Acoustic performance as a design driver

Students who approached acoustics performance as a design driver usually tried to draw on their new knowledge of acoustics and incorporate acoustic goals within the core drivers of their design proposals. Unlike the previous case, this approach did not necessarily occur at the project initiation, as it was often introduced soon after the conceptual stage was deemed satisfactory to optimise the project's performance.

Student B's project proposes a retractable awning structure that could provide rear reflections to the audience area. The section drawing and details illustrate the proposed mechanism for the adjustable shell design (

Figure), which could offer an intimate experience mimicking an indoor acoustic environment. By understanding and embedding these considerations into the design process after the conceptual design, the creative tectonic solution of the mechanised awning could be refined to a high level of detail, leading to a very successful and convincing proposal.

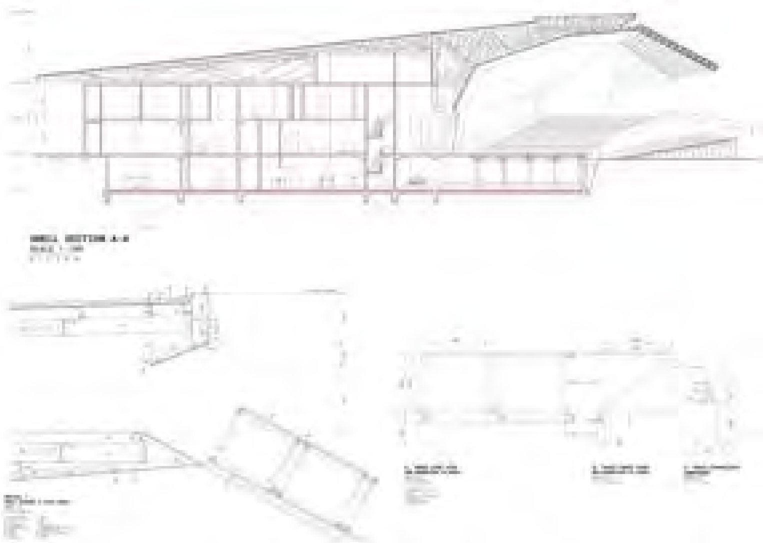

Figure 2. Section drawing and details of the acoustic shell and main stage showing the retractable awning for rear reflections and immersive experiences by Student B. Reproduced by permission.

Student C's project also used acoustics as a design driver. However, instead of combining it with structural and tectonic considerations like Student B, she embedded acoustic considerations within her site response. Student C aimed to utilise the lake on the site as it was adjacent to the site entry points to create a 360-degree viewing experience for visitors to enjoy concerts from canoes or kayaks, as shown through the section and isometric drawings (Figure). However, as water does not provide any acoustic support, Student C included the design of the audience rake and shell structure for the stage in the MOO to compensate and provide better acoustic reflections.

Figure 3. Section and axonometric drawing showing the design for a stage on the water by Student C. Reproduced by permission.

The projects within this category identified, analysed and integrated acoustic information into a coherent project design. However, the extent and complexity of these projects were unexpected and very well regarded by the teaching staff and guest critics. Ambitious projects like those from Student B and Student C typically combined acoustic goals with material selection, structural and construction systems and complex design outcomes. They also resolved and presented coherent, detailed design solutions. Successful projects that dealt with this complexity were highly rigorous throughout the design process, usually leading to well-justified and high-quality architectural proposals. These also demonstrated a holistic understanding of acoustic performance in architectural design.

4.3 Acoustic performance as a design validator

Students who approached acoustics performance as a design validator tended to separate the design and refinement of the acoustic shell from the analysis of the acoustic performance. They generally focused on the detailed design phase to introduce materials, finishes, fittings, components and systems; these were often based on consideration of quality and performance standards and, in some cases, included reflections on the life cycle of the materials involved or the environmental costs of their project.

The project by Student D focused on rehabilitating the site as a conceptual driver, shown in the axonometric drawing of the proposed revitalised park and installations (Figure). As a result, Student D designed the program for the festival around bringing awareness to the sustainability and rehabilitation initiative and raising funds for future projects. The acoustic shell design involved material considerations and a modular fabrication method, allowing easy assembly, adaptability, and dismantling to minimise the impact. The shell could also be adapted for night and amplified performances to facilitate various local artists. After the design was essentially completed, the acoustic performance was analysed and optimised using MOO to adjust the final design.

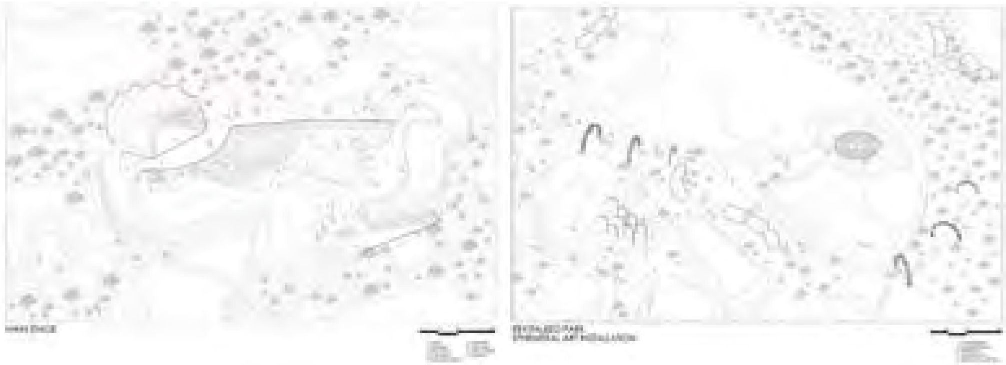

Figure 4. Axonometric drawing of the revitalised park and festival's main stage by Student D. Reproduced by permission

Projects in this category could demonstrate high acoustic performance and architectural resolution. However, from the perspective of *CDE Studio 45's* objectives, these projects were generally the least successful as we anticipated more integrated and holistic design approaches incorporating other performance criteria. This category of projects may be more appropriate in a different design studio context with a greater focus on acoustic quality and performance. Students approaching the task this way may have benefitted from a smaller brief and more technical learning on acoustic analysis and simulation.

5. Conclusions

Running *CDE Studio 45 (Resonate)* for three years in a row allowed us to investigate modes and frameworks for acoustic design integration in the design studio environment. The context at The University of Melbourne meant that no prior applied acoustic knowledge could be expected, and the timeframe of the design studio offered challenges to what acoustic information and skills could be reasonably taught while still permitting reasonable flexibility for creativity within the architectural design studio environment. A series of mapping and brainstorming exercises helped us to evaluate and refine our teaching goals while defining (for our students) a cognitive and computational framework for acoustic integration in design at all levels of the design thinking process.

The design of the studio brief was a valuable tool for communicating our performance design expectations to the students and interpreting the students' approach to integrating acoustics in their design proposal. We found that students tended to associate acoustic integration with different stages of their design process, driven by their previous knowledge and skills, new acquisition of acoustics and stage design, and personal inclinations. This association and variety of projects that ensued led to the analysis and categorisation of the student outcomes. The observations of the first delivery of CDE Studio 45 in 2020 allowed us to interpret the outcomes of our students' learning journey and propose a series of changes to scaffold their use of technical knowledge in subsequent iterations. The categorisation of outcomes has implications for how design studios may structure ILOs regarding the expectations and manner in which students can incorporate performance design criteria. Although we set out to use a predominantly numerical acoustic approach, we framed acoustic design within performance-based design considerations. Therefore, students would be inclined to treat acoustic design considerations similarly to how they would usually approach performance criteria in the past. Students could still incorporate their design approaches and agendas for their architectural proposals, leading to various design approaches.

We found that categorising and discussing student outcomes is a worthwhile exercise for understanding how students tend to translate technical understanding into design outcomes. Our future investigations will address how acoustic information can be scaffolded across architectural curricula and delivered in various pedagogical modes, such as seminar and elective subjects, to assess how this impacts student approaches to acoustic considerations in design thinking processes.

6. Acknowledgements

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A Test-cell for Building Conditioning Experimentation

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Abstract: Over the years, empirical experimentation has been proven to be a favourable method for understanding the performance of various building systems. A literature review provided information on past experimental setups. This paper introduces the design of a test room (the TEST CELL) emulating a realistic high-rise perimeter office for experimentation with instrumental measurement. An example for testing is a new hydronic radiant panel system developed for perimeter zones in office buildings. The Test Cell is contained within a workshop adjacent to a north-facing corrugated steel sliding door. The Test Cell has a double-glazed (6mm, 12.5mm cavity, 6mm) 7.5m2 window facing solar North. At present, the room can be passively heated to temperatures above 40°C, even at medium outdoor ambient. The Test Cell provides for different conditioning systems and various glazing and shading systems to be tested. A weather station accompanies the location, and the Test Cell contains numerous instrumentation for determining interior performance on comfort as well as its required energy inputs. The most recent testing involves hydronic conditioning systems and a polyvalent heat pump that provides for the conditioning of the room. The room is divided into four zones; two on the ceiling and two on the floor. Conditioning is provided through a solar-driven air-to-water heat pump. The instrumentation, data reporting, and graphical templates for this experimental Test Cell are reported in this paper. Several initial testing results and a proposed method of analysis and energy simulation verification are addressed.

Keywords: Empirical experiment, instrumental measurement, radiant conditioning, radiant panel.

1. Introduction

1.1. Test chamber in building science

Test cells have been an ongoing historical part of empirical research in architecture and building conditioning systems, materials, and occupant responses. Environmental technologies in building systems, such as for comfort, air quality, lighting, and acoustics, have all been researched via test cells or rooms. An example of a testing facility specifically directed to the thermal and energy performance of windows was designed and built at the Lawrence Berkely National Laboratory (Klems, 1979). There are also test chambers dedicated to other fields of building science, such as acoustic experiments (Boesch et al., 2000). Konstantzos et al. (2015) also use a dedicated test chamber to study daylight glare. In studying thermal comfort, dedicated climate test chambers are heavily utilized in studies of pioneering researchers such as Povl Ole Fanger or Richard de Dear (Charles, 2003).

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In a review paper, de Dear et al. (2013) pointed out two main methods of studying thermal comfort: climate chamber study and actual building field study. The authors state that the climate chamber provides better control in experiment conditions and validity in experiment design. Hence, this method is widely used among researchers in the field. For example, experiments conducted by Díaz and Cuevas (2010), Gallardo and Berardi (2022), and Tian et al. (2012) are facilitated in dedicated test chambers to study the performance of radiant systems. Also, researchers can set up their test chambers in suitable rooms of a real-life building or construct a test chamber that suits their needs.

In the past few decades, there is also an increase in the usage of simulation software programs like EnergyPlus, or TRNSYS, in studying thermal comfort (de Dear *et al.*, 2013). However, there are still limitations in the application of simulation programs in thermal comfort studies, and data received via simulation is still inferior to the data extracted through test chamber experiments or full-scale real-life measurements (de Dear *et al.*, 2013). Several designs were proposed in radiant conditioning system development but only evaluated via simulations or numerical calculations rather than instrumental experiments. For example, Xing and Li (2022) integrated the water piping directly into the radiant surface but could only test the new proposed design in numerical simulation. Meanwhile, the real-life thermal performance of such designs has yet to be discovered. In such cases, the simulations should be verified by the result of instrumental experiments.

The authors of this paper are developing new designs for lightweight, modular, and dynamic radiant panels and designing empirical experiments on the thermal and energy effectiveness of the system in the condition of perimeter zones in office buildings. Reviewing the previous studies, the method of empirical experiments with instrumental measurement in a test chamber is chosen for its feasibility, recognition, and quality data. Hence, our test cell is built according to Australian standard to emulate the conditions of perimeter zones in office buildings and dedicated to testing radiant conditioning systems, thermal comfort, and building energy performance.

1.2. Empirical experiment and instrumental measurement

In order to study thermal comfort, demonstrate, and evaluate radiant conditioning systems, several methodologies have been utilized. For example, Bojić et al. (2013) used computational simulation (Energyplus) to study and compare the performance of various radiant heating arrangements. On the other hand, Imanari et al. (1999) used a real-life experiment with participants and questionnaires to evaluate the thermal performance of radiant ceilings. However, among the methodologies, empirical experiments with instrumental measurement seemed to be preferred in highly regarded research papers. In the review paper of de Dear, et al (de Dear et al., 2013), empirical data and instrumental measurement play a critical role in the progress of the thermal comfort study.

In such studies, researchers collect the required empirical data via instrumental measurement. Andrés-Chicote et al. (2012) conducted an experiment on the cooling capacity of the radiant ceiling. The author used temperature sensors to measure the temperature of the wall, floor, and radiant ceiling. To measure thermal comfort, the authors use a set of measuring equipment, including air humidity, air temperature, air velocity, and operative temperature sensors for computing thermal comfort. Causone et al. (2009) use a series of temperature sensors and an infrared thermal imaging camera to measure the temperature of the radiant ceiling and its thermal effect on the subject environment. The collected data can then be used to calculate the heat transfer coefficients between the radiant ceiling and the room. Feng et al. (2014) conducted an empirical experiment on the difference between the cooling load of convective and radiant systems. To collect the required data, the authors use several sensors, including temperature sensors, thermocouples, a water flow meter, an air velocity sensor, an anemometer, and an emission meter.

2. Requirements of a Test Chamber

2.1. Test chamber and instrument that suits the experiment

As mentioned, the test chamber allows researchers to control the conditions and validate the design of the experiments. Hence, in all of the research utilizing test chambers, the test chamber must emulate the required conditions in which the experiment is to be conducted. In our case, it is a test chamber for experimenting with the thermal performance of radiant conditioning systems in perimeter zones of office buildings. In context, other experiments with similar test chambers were studied and used as models.

For example, Jia et al. (2018) developed a test chamber in a real-life office building to run experiments on radiant systems in office buildings. The test chamber has the size of an enclosed office working room, with 9.14m in length, 6.1m wide, and 4.5m high. There is a set of 10 clear glass windows on the solar-facing 6.1m wall. The windows and the length allow the test chamber to emulate the condition of both perimeter and core zones in office buildings. The height of the chamber allows the installation of a radiant ceiling at 2.74m high. The radiant ceiling is heavily insulated with 100mm of insulation. The walls are also well insulated. A series of thermal sensors were used to monitor the temperatures of walls, floor, and ceiling. Three stratification strings, one was placed near the windows, one in the middle, and one at the back of the room to monitor the temperature difference at different high.

Another example is the test chamber in the experiment of Rhee et al. (2021). The authors aim to create the conditions of a core zone in office buildings with dynamic cooling requirements. To emulate such conditions, the chamber is built indoors with heavily insulated SIP panels. The dynamic heat gain is provided by electrical dummies simulating occupants and equipment. The chamber is 8m long, 4m wide, and 2.7 m high. Fresh air is supplied via a “dedicated indoor air system”, allowing control over the airflow and air temperature inside the chamber. Sensors are used to measure the air temperature, humidity, and water flow rate.

Overall, the test chamber must meet several requirements.

- Condition emulating and control capability: The test chamber must be designed to emulate and control the conditions required for the experiment.
- Adequate size: The size of the chamber must be appropriate to house the experiment along with the required instrument.
- Well insulated: To fully control the experiment conditions and reduce undesired external effects, the test chamber should be well insulated.

2.2. Our test cell

In the context of our study, the test cell needs to emulate the conditions of a room in the perimeter zones in office buildings. The perimeter zones or near window areas in office buildings are about 3-5m deep, depending on the height of the ceiling and the size of the windows. In modern architecture, the window-to-wall ratio of office buildings is high, driven by the need to introduce natural lighting and external view. However, the unwanted effect of having such a large window is heavily affected by the external environment, such as direct solar radiation or air temperature. In Victoria, North facing perimeter zones appears to be the most disadvantaged due to heavy solar gain. The test chamber should also have an adequate floor area of an office working room and be high enough to house a suspended ceiling system. Figure 1 shows the test cell under construction.

Figure 1: Test cell frame, ceiling, and floor under construction

Our test cell is 4.8m long, 3.6m wide, and 3.6m high, built inside a shed to minimize the effect of undesired external conditions. A Metal stud wall with gypsum cover complying with Australian building standards is used. Figure 2 shows the section of the test cell and how it is set up. The chamber is built right next to a north-facing (solar-facing) sliding gate. On the 3.6m wide north-facing wall of the chamber, there is a 3.2m wide and 2.6m high fixed window (curtain wall). The window is fitted with double glazing with 6mm of air cavity between 2 layers of 6mm glass. The sliding door allows control of the exposure of the window-fitted wall of the chamber to the elements of the external environment such as direct solar radiation and air temperature. The window is also fitted with Basic Indoor roller blinds. The blinds are made of white block-out fabric and can cover up to 80% of the window area. The rest of the walls are heavily insulated with glass-wool insulation. The height of the test chamber allows the installation of a drywall ceiling or suspended ceiling system at a height of 3m from the floor. At the moment, a hydronic radiant conditioning ceiling system with 25mm of foil board insulation is integrated into the suspended ceiling. Also, there is hydronic radiant conditioning floor installed with 25mm of rigid insulation board. Both currently installed ceiling and floor radiant systems are modular, lightweight, and easy to install or remove so that different radiant system configurations can be tested. The radiant floor and ceiling are capable of both heating and cooling. The floor and ceiling are divided into the near window and back wall zones. In total, there are four radiant zones in the test chamber.

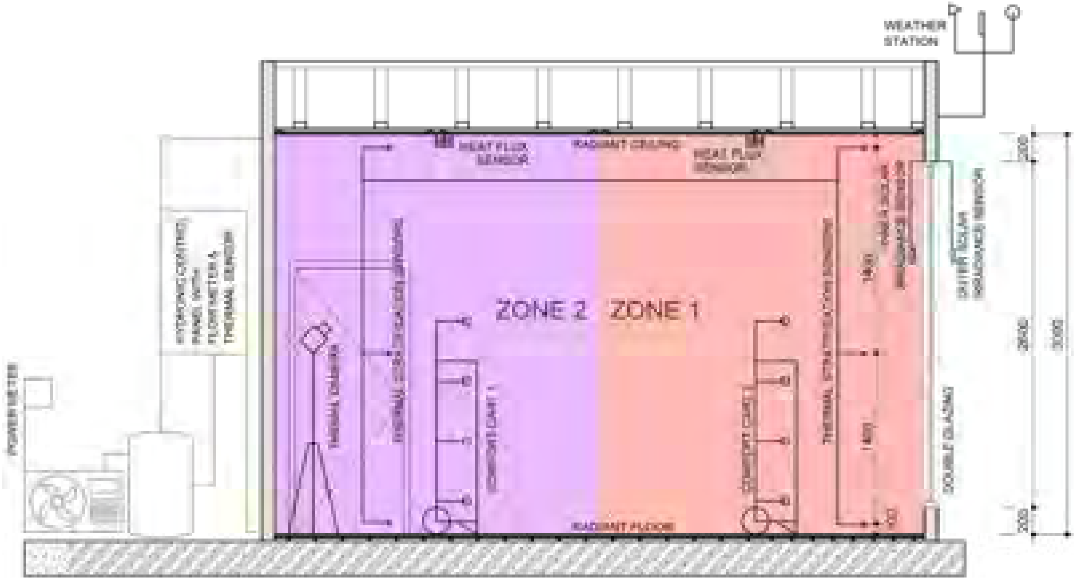

Figure 2: Test cell setup

Figure 3A shows the radiant ceiling that is currently installed in the test chamber. The 25mm foil board insulation on top has an R-value of 1.05 m^2K/W. Under the insulation, there are capillary tube mats used to distribute the water evenly throughout the ceiling area. The ceiling is designed with modularity. In a ceiling model, an insulation board is machined to house capillary tube mats, and the two components are glued together into one panel. The ceiling panels can be installed with relative ease. The finishing layer is the commonly used drywall finish. However, it is not yet installed. The ceiling panels in one zone are arranged in parallel so that the water is distributed equally through all of the capillary tube mats. The ceiling holds about 9L of water. The radiant floor is shown in Figure 3B. This is an embedded dry radiant floor system. The radiant floor is laid onto the concrete floor slab of the shed or 19mm thick chipboard flooring. The radiant floor consists of a 25mm rigid insulation board, a 6mm cement sheet, and a finishing hybrid flooring bond. The insulated boards are 1.2x0.6m and roughed to house the water piping. On top of the insulation boards are 0.4mm thick aluminium pans used to distribute the heat more evenly. The piping used in this floor system is Ø16 PEX radiant pipe. The floor finishing layers include 6mm fibre cement boards and hybrid cement/plastic plank flooring. There is about 10L of water on the heating floor.

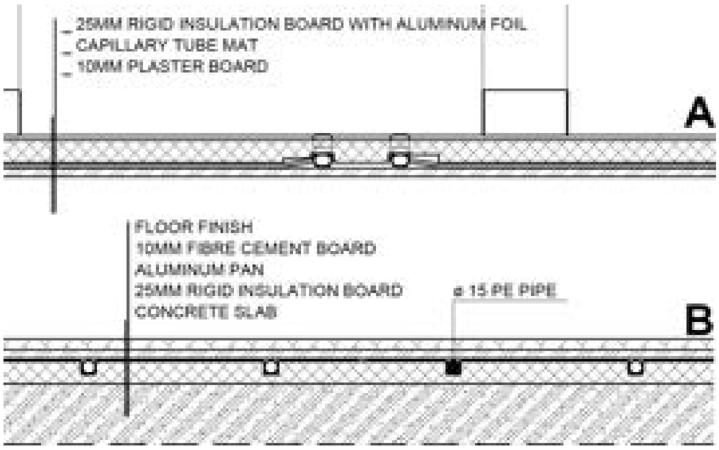

Figure 3: (A) Radiant ceiling section, (B) Radiant floor section

To supply fresh air to the test chambers while maintaining the room conditions, an Energy Recovery Ventilation (ERV) system is installed. The ERV is variable speed applying Ø100 air ducts are used to supply fresh air and exhaust return air. The variable airspeed allows for low, medium, and high supplied velocity yielding between 0.5 to 3 air changes per hour (ACH) for the room. The supply air diffuser is located near the back wall, while the return diffuser is placed next to the window. This allows efficient air circulation in the chamber. The ERV system is controlled via a control panel with built-in air temperature, CO2, and humidity sensors.

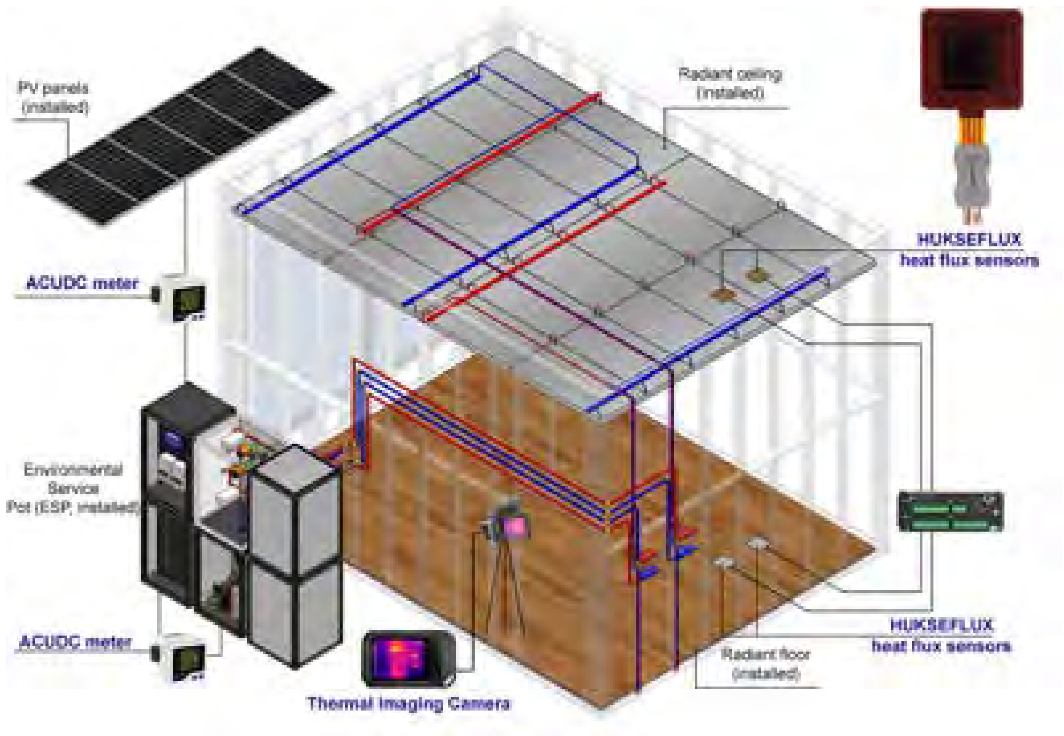

Figure 4: Radiant floor and ceiling monitoring arrangement

Figure 4 shows the setup of the radiant conditioning floor and ceiling. The heating and cooling water is supplied to the radiant ceiling and floor by two thermal storage tanks of a set of Environmental Service Pods (ESP). The ESP in an integrated energy and hydronic system. The ESP consists of an electricity control cabinet, a battery storage cabinet, a heat pump, a hydronic control cabinet, and 2 water storage tanks for hot and cold water. The electricity control cabinet is connected to a solar panel system, monitors, and controls the electricity received by the solar panel. The electricity is stored in the battery storage cabinet or used to run the heat pump. The heat pump is capable of producing hot and cold water that is stored in the two tanks. In other words, the thermal energy is stored in the tanks to be used later for the radiant conditioning system. Inside a water tank is a 15m length of heat exchanger coil linked to the hydronic control cabinet. The hydronic control cabinet controls and monitors the water inside the radiant floor and ceiling. Conditioning mode (heating or cooling), inlet water temperature, and water flow rate for the radiant system can be controlled via the hydronic control cabinet.

2.3. Parameters to be measured and instruments

To emulate the conditions of perimeter zones, the chamber is heavily affected by the elements of the external weather environment. Hence, monitoring weather conditions is required, and weather data such as air temperature, solar radiation, wind speed, and humidity need to be collected. A weather station is installed and consists of all necessary sensors to collect such data. This set of data is received via a CR10X logger board. One of the most significant external elements that affect the perimeter zone is direct solar radiation received via glazing windows. To monitor and collect this vital data, two solar Irradiance sensors are installed inside and outside the chamber to monitor the direct solar radiation received by the window and go through the window into the chamber (Figure 1). The internal temperature of the window is monitored using a thermocouple. The data is also received via a CR10X logger board.

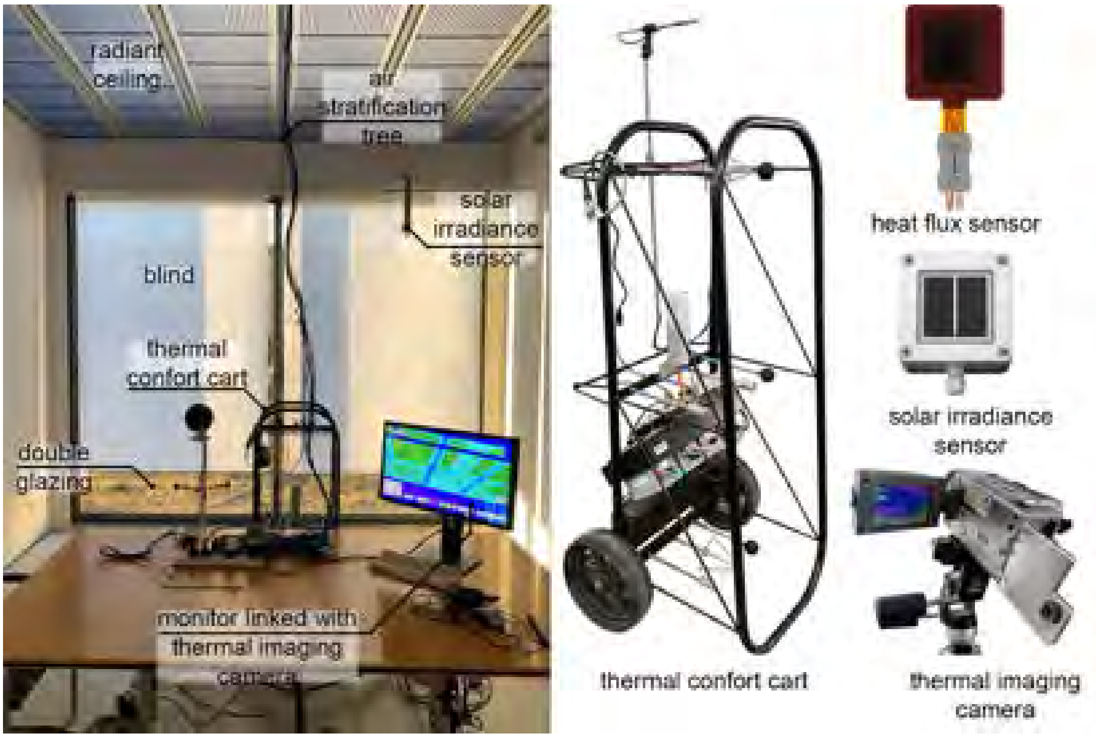

Figure 5: Test cell interior and measuring equipment

Elements of the indoor environment, such as air temperature, air velocity, humidity, mean radiant temperature, CO2 level, and air temperature stratification, need to be measured. Figure 5 shows the interior of the chamber and several key instruments inside the chamber. Two air stratification trees and two thermal comfort carts are used. The two air stratification trees monitor air temperature near the floor, at head high (1.6m from the floor), and near the ceiling. One stratification tree is located near the window, and one is placed near the back wall (Figure 1). A thermal comfort cart comprises several sensors, a CR23X logger board, and batteries. The comfort cart can monitor the thermal conditions at feet high (near the floor), waist high (0.9m), sitting head high (1.5m), and standing head high (1.6m) (Figure 5). The measured parameters are air temperature, air velocity, globe temperature, humidity, and CO2. One thermal comfort cart is placed near the window, and the other one is near the back wall. For the radiant floor and ceiling, surface temperature and energy transfer (heat flux) are the two parameters that determine their thermal performance. Hence, four heat flux sensors with built-in thermocouples are used to monitor their thermal performance (Figure 4). A thermal imaging camera will also assist in the reading of the sensor (Figure 5). Other parameters to be measured in radiant systems are water flow rate and the temperature of the inlet and outlet water. The energy that the system draws from the tank can be calculated using these parameters. To measure such parameters flow meter sensor and two thermal sensors in the hydronic control cabinet will are used. The measuring equipment is shown in the table below.

Table 1: Measuring equipment

Areas	Instrument/ sensor	Measurement/Usage
Weather station	Wind speed anemometer Global solar irradiance sensor Weather Humidity sensor Air temperature sensor	External wind speed External solar radiation External humidity External air temperature
Window	Solar Irradiance sensors	Solar radiation received by the window Solar radiation goes through the window into the chamber
Thermal comfort cart	CO2 sensor Humidity sensor Globe thermometer Anemometer thermocouple	CO2 level Relative Humidity Globe temperature for mean radiant temperature calculation Air velocity Air temperature
Chamber, Radiant floor, and ceiling	thermocouple Heat flux sensor Air temperature stratification tree Thermal imaging camera	Radiant surface temperature Energy emission/ energy transfer Air temperature stratification Chamber surface temperature

As the test cell is designed to run complex experiments involving many sensors and equipment, instrument calibration proved to be an issue. Also, sensors and equipment can be highly sensitive and fragile. The constant and accurate reading of the sensors and equipment is crucial to future experiments. Currently, running official experiments is yet to be feasible due to the differences in instrument readings. Calibration processes are being conducted, and the test runs also allow the function of the instruments to be verified and a few instruments to be calibrated.

For example, the thermocouples and air stratification trees can easily be calibrated using icy and bolted water as well as highly accurate mercury thermometers (0.1°C accurate). The most complex instruments are the comfort carts, with 16 sensors for each. Velocity, humidity, globe temperature, and CO2 sensors are difficult to calibrate. External standardized equipment, such as a sling psychrometer for humidity or a hot wire anemometer for air velocity, are used. The heat flux sensors are also somewhat difficult to calibrate. Fortunately, the Hukseflux FHF01 sensors are certified as calibrated; hence their reading is used as the benchmark.

3. Preliminary testing

Several preliminary test runs were conducted in the test chamber to examine the chamber and the operation of the radiant systems installed. The test runs include passive heating and radiant heating and cooling tests.

3.1. Passive Heating

This preliminary test run examines the effect of external weather conditions on the test chamber and confirms if the chamber is functional as a perimeter room in office buildings. The test run lasted seven days and took place during a winter period. The northern façade and window of the chamber are fully exposed to the external environment, and the external warehouse sliding door is closed at all times. The absence of solar radiation is the proper arrangement for conditioning the test cell under a heating mode. All radiant systems and the ERV are turned off, and the shading blinds are retracted during this test run. As the chamber is heavily insulated, elements that can affect the thermal conditions inside the chamber must be introduced passively via the window. Note, even in the wintertime, direct solar radiation can cause overheating and thermal discomfort in perimeter zones in office buildings.

Two sets of data need to be collected in this test run, the weather data and the thermal conditions inside the chamber. Consequently, the instruments used in this test run are the air temperature stratification string, the thermal comfort carts, the weather station, and the two solar irradiance sensors at the window.

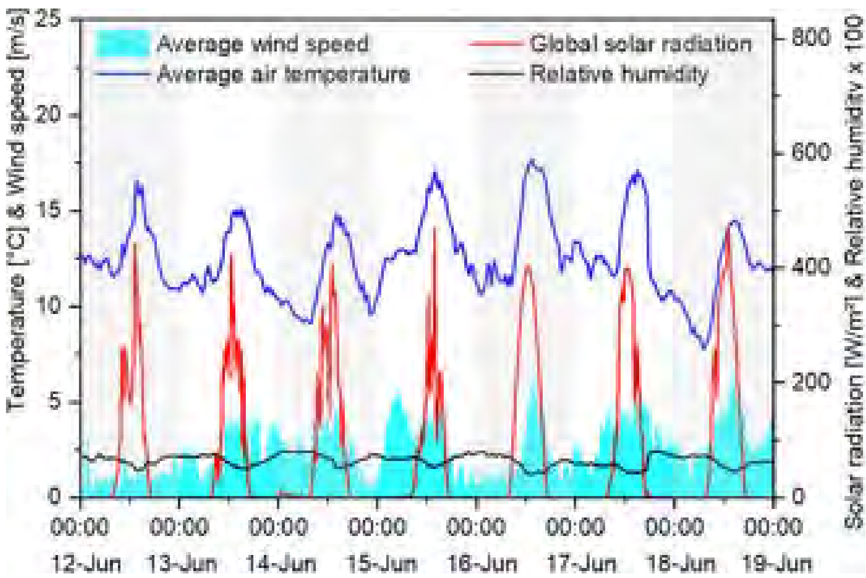

Figure 6: External weather data from the weather station

Figure 6 shows the data from the weather station. In winter, the highest air temperature in a day can barely reach 17°C. The 16th to 18th of June are consistent sunny days, while on other days, the global solar radiation readings have fluctuated due to clouds and rain.

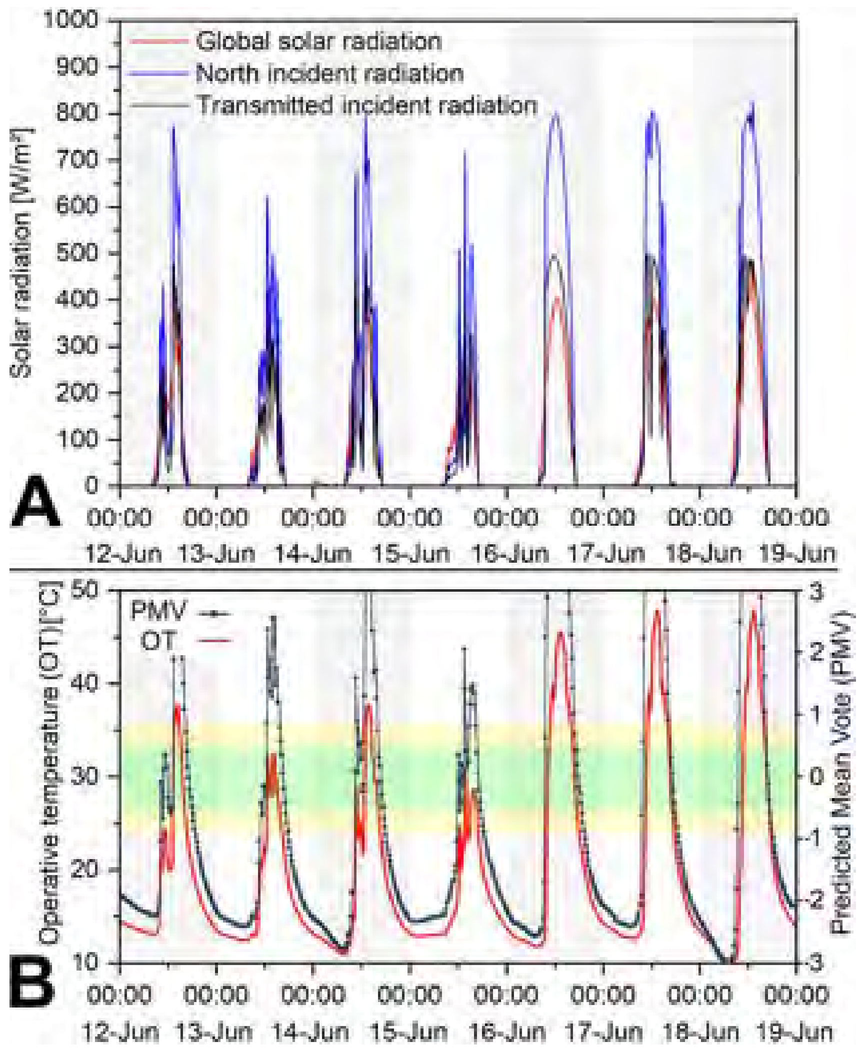

Figure 7: (a): Global solar, north incident, and transmitted incident radiation and (b): Operative temperature in the test chamber from a comfort cart

The weather data is reflected in the readings of the vertical solar irradiance sensors at the window shown in Figure 7. Note, Figure 7A shows that the solar gain of the vertical plane is almost double the global solar radiation. This can be the result of low sun angle in winter. Also, the double-glazing window is capable of blocking about 35% of solar radiation. Figure 7B shows the operative temperature inside the test chamber gathered by a comfort cart. Even in the cold wintertime, a perimeter room in office buildings can easily be heated up only with solar heat gain. The operative temperature can even reach 50°C while the external air temperatures are only about 17°C. On cloudy/rainy days, the operative temperature can easily reach 30°C. The result is high levels of thermal discomfort (Figure 7B).

3.2. Radiant conditioning test runs

Several preliminary heating test runs were conducted in wintertime evenings. In such test runs, the northern façade and window are covered during the day to prevent passive heating and fully exposed to nigh time low external air temperature and even strong wind. Both the radiant ceiling and floor are operational in heating mode. The hydronic control cabinet supplies hot water to the radiant system at the rate of 8.5L per minute, and the ERV is at low speed, providing 0.5 air changes per hour. The inlet water temperature is about 50 °C. The heating test runs were conducted in ceiling heating only and combination heating. Results of the heating ceiling test run are shown below.

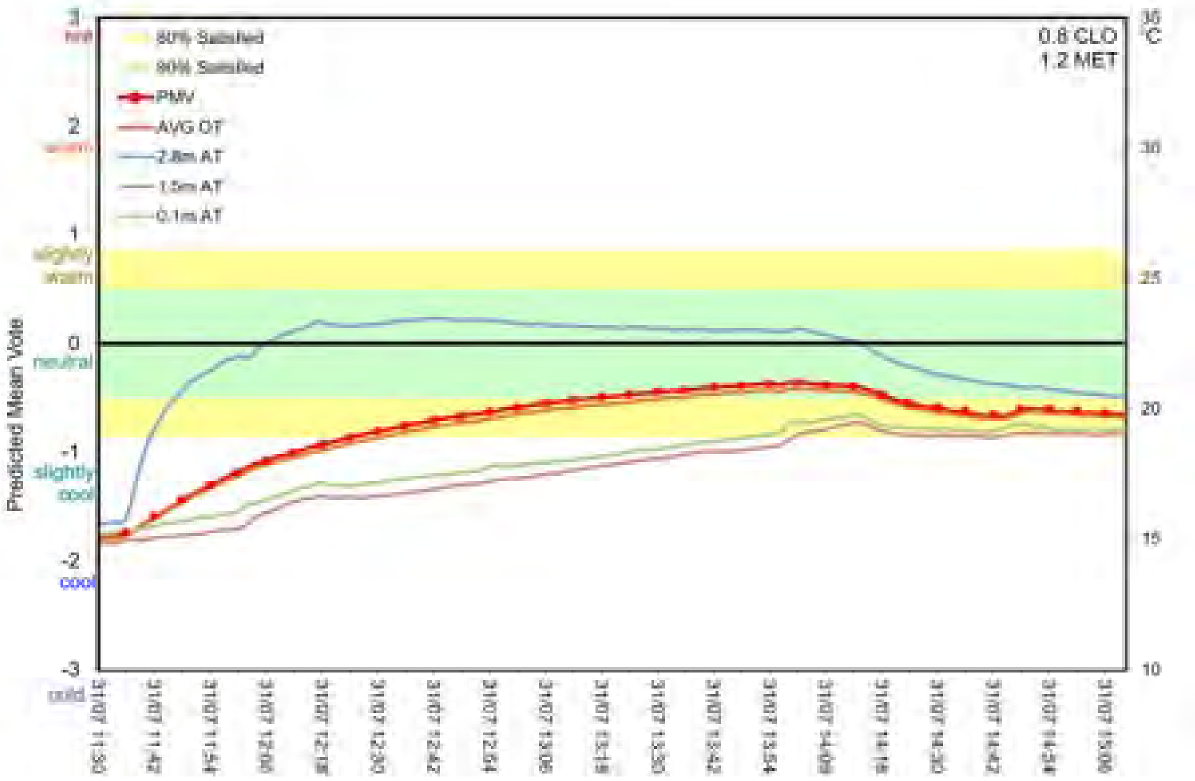

Figure 8: Air stratification, operative temperature, and PMV for Ceiling heating

Figure 8 shows that a radiant heating ceiling is capable of providing thermal comfort. The predicted mean vote (PMV) increases from cool -1.8 to -0.5 indicating a significant improvement in thermal comfort reaching the 90% satisfied thermal comfort zone. The high air temperature at the ceiling (2.9m) indicates the operation of the heating ceiling. The steady increase of air temperature at the floor (0.1m) and in the middle (1.5m) also shows the convective effect of the heating ceiling. Interestingly the trend of average operative temperature is also identical to that of the PMV indicating almost no changes in air velocity or humidity.

A few preliminary cooling test runs were also conducted during the day. The chamber is passively heated to around 30°C. The northern façade and window are fully exposed to direct solar radiation. Both the radiant floor and ceiling are operational in cooling mode and supplied with cool water at the rate of 8.5L per minute. The shading blinds are fully deployed, and the ERV is operational at the highest speed yielding three air changes per hour. However, the result is undesirable and the readings are inconsistent. Nevertheless, there are difficulties in conducting radiant cooling. Further test runs will be conducted.

4. Result and lesson learned

4.1. Effect of the external environment and overheating in cold winter.

As mentioned, the test cell can be heated passively only with solar heat gain. The high window-to-wall ratio is the main factor behind this phenomenon. Interestingly, the vertical solar irradiance readings outside the window are higher than the globe. In winter, the Solar zenith angle is lower than in summer, allowing more solar infiltration to get through the window. Meanwhile, in day times, the external air temperature has a limited effect on the internal conditions of the test cell. Only at night, the internal temperature of the test cell drops fast toward the external air temperature. On several days when the weather change dramatically, there is also fluctuation in test cell internal temperature. Nevertheless, this also indicates that the test chamber can be heavily affected by the external environment, especially solar gain. Hence the test cell can emulate the dynamic conditions of perimeter zones in office buildings.

4.2. Heating ceiling vs heating floor

One of the most significant findings in heating test runs is the effectiveness of the radiant heating ceiling. The radiant ceiling is commonly used for cooling instead of heating to fully utilize the convective effect and maximize its effectiveness. Babiak *et al.* (2007), in the radiant condition guidebook of REHVA (Federation of European Heating, Ventilation, and Air Conditioning Associations), pointed out that the head and upper part of the human body prefer to be cooled. Hence even in a full heating mod, the recommended maximum surface temperature of the ceiling is only 27°C (Babiak *et al.*, 2007), 10°C lower than human body temperature. Meanwhile, the highest surface temperature recommended for the radiant heating floor is 40°C (Babiak *et al.*, 2007), and capable of carrying out most of the heating load.

However, there are difficulties with the radiant heating floor as well. Furniture can cover and block a huge proportion of the radiant effect of the heating floor. Also, retrofitting with radiant floor systems can be difficult as the height of the floor finish can increase notably. In our test cell, as the radiant floor is installed, the door must also be modified and cut down to tackle the increased height of the floor finish. This is not the case for the radiant ceiling system, as they are not blocked and can be retrofitted in existing buildings with relative ease. Also, the ceiling-only heating test run proved to be effective, raising air temperature by 10°C in 25-30 minutes. Due to the capillary tube mat configuration and the parallel arrangement of the ceiling, water can flow through the system with relative ease leading to faster response to control commands. Initial measurement with a thermal imaging camera shows that the surface temperature of the ceiling can increase by 10°C in 10 minutes, while it is about 30 minutes for the floor.

4.3. Difficulties in radiant cooling

Different from heating, passive, or radiant, radiant cooling is significantly different and may even be more difficult to achieve. Cooling from the ceiling may at first sound theoretically correct and feasible; however, there are several principles and conditions to observe when considering cooling. First, the main principle is that radiant energy transfer accounts for approximately 70% of the conditioning. This implies that regardless of its surface position in the room, it is dominantly transferring radiant energy to its surroundings. Second, the remaining 30% of conditioning occurs through convection, which is ideal for cooling since heavier, cooler air is dropping from the ceiling and provides for a balanced mixing within the space.

Cooling periods are also very active conditioning periods, meaning that solar gains can significantly combat the cooling provided. It is important to cut back these potential loads through shading devices at the window, preventing large gains as well as other surfaces and furniture from heating up. The hydronic ceiling usually offers 80-110 W/m2 of cooling potential. It is important to note that this may not be adequate to fight a huge continuous load and that other forms of conditioning and prevention may need to take place. It is expected that HVAC, convective conditioning, would take place in an office building and that a radiant system would contribute to the additional cooling load requirement at the perimeter. It is worth noting that heating periods are quite different from cooling periods and that the loads maybe 6-8 times less than a cooling load in W/m2 heat transfer. Therefore, conditioning studies between heating and cooling solutions to the perimeter zone are quite different problems.

5. Conclusion

Through the design and construction process of the test cell as well as the test runs, several conclusions can be drawn:

- The test cell is well designed and suits the need of providing conditions for the upcoming experiments. The test cell is large enough to house the subject radiant systems. The thermal conditions inside the test cell can be significantly affected by the external environment, especially solar radiation, emulating the conditions of the perimeter zones in office buildings.
- The concept of heating the ceiling shows good potential. Although this arrangement is not recommended in previous studies and guidelines, the initial test runs show that radiant heating ceilings can be feasible. Also, heating ceiling systems are not blocked by furniture and are easier to design and install. Further investigations are needed to verify the thermal performance of radiant heating ceilings.
- Radiant cooling seems difficult to achieve, especially in perimeter zones with high solar heat gain. The radiant cooling capacity of 80-110 W/m2 may not be adequate to combat solar infiltration. This needs to be investigated in further experiments. Also, systems such as heavy shading systems and even convective conditioning systems should be added in the upcoming experiments.

At this point, we have not performed adequate testing on cooling the TESTCELL. However, we have made some preliminary claims from initial experiments, as stated here. We anticipate a more thorough reporting in the near future.

6. Acknowledgments

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Affect theory, digital heritage and circular economy; the fate of Dennys Lascelles Wool store in Geelong

Affect, Digital heritage and circular econonomics; the fate of Dennys Lascalle Wool store in Geelong

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Abstract: This abstract explores the connection between affect, digital heritage, and the circular economy through Dennys Lascelles Wool Store in Geelong. Despite the demolition of its bow truss structure, the site prompts vital preservation questions amid urban change. Affect, encompassing emotional and sensory experiences tied to a place, plays a pivotal role in preserving cultural legacies. In the digital era, virtual platforms enhance the accessibility of heritage, facilitating the collection, preservation, and sharing of intangible aspects. Critics have long noted that the Authoritative Heritage Discourse (AHD) primarily focuses on physical preservation and overlooks intangible elements and emotional connections to a site. This paper addresses these concerns by exploring how digital heritage can enhance preservation, documentation, and public involvement in a circular city context. By integrating affective heritage and digital tools with circular economy principles, sustainable practices in heritage preservation can be enhanced. While the bow truss building can only be digitally preserved, the remaining complex can be recycled and repurposed. The synergy of affective heritage and the circular economy, using digital tools, benefits the local economy and environment. This paper underscores the importance of acknowledging the emotional and historical value of industrial and cultural heritage, advocating for appropriate digital tools for preservation and engagement, and endorsing sustainable practices for the potential adaptive reuse of historic sites in the digital age. It highlights the necessity of reimagining preservation strategies for enduring accessibility to cultural heritage.

Keywords: Affective heritage; digital heritage; circular economy; wool store.

1. Introduction

The future of the currently vacant former Dennys Lascelles Wool store, aged more than a hundred and located at 20 Brougham Street, is under dispute between the state government and a property developer (Figure). This building was once part of the old Dennys Lascelles wool store. The store had different parts: the current National Wool Museum Building, which is now a museum and protected for its heritage, and the legendary bow truss building, also heritage listed. Unfortunately, the bow truss building got demolished in the nineties. Now, there's a new TAC building on that spot. As for the building we are talking about, it has been empty for many years. The state government raised opposition against the proposed design reuse plan with the argument that the developer has neglected the building's contribution to a valuable part of Geelong's history and identity (Tippet 2022).

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The founder of this wool store company, Charles John Dennys, has been described as the father of Geelong's wool industry. During the late 19th and early 20th centuries, his company, Dennys Lascelles Austin & Co, established numbers of wool stores concentrated within a city block, strategically positioned between the commercial hub of Geelong and the harbour vicinity in Corio Bay, which not only housing the wool bales but also displaying them for potential buyers (Allom, 1986). Constructed between 1872 and 1926-30, these wool stores covered a substantial portion of the city block in Moorabool and Brougham Streets. Within this complex of buildings, two of them have evaded demolition; one has been adapted into a Geelong National Wool Museum, but the other, as a legacy of the expansion of Dennys Lascelles in the early 1950s, has sat vacant for decades with its future being under a debate and at risk of unresponsive redevelopment.

Figure 1: The future proposal of the site. (Source: Tippet, 2022 as cited in Masoomikhameneh, 2022)

2. What should we preserve: Authoritative Heritage Discourse

Since the initial stages of acknowledging the imperative for protecting world heritage, historic landscapes generally faced two dominant black-and-white scenarios based on international corporations' defined scope of heritage. In accordance with their approved rules, regulations, principles, and charters, if a historic landscape were of Outstanding Universal Values (OUV), it would be heritage-listed and enter the process of preserving and showcasing; otherwise, it would be subject to potential demolition and subsequent reconstruction. This approach to heritage has limitations and potentially can lead to counterproductive effects.

In the context of Geelong and, specifically, the subject case, criteria for the assessment of significance are based on two documents of the Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance (2013) and its Practice Notes. Having undergone several amendments, this charter has shifted its focus from traditional fabric-centred approaches to adopting evolving concepts of heritage, dynamic economic or political conditions, and a wide array of distinct locales (Avrami *et al.*, 2019). However, its overreliance on the intrinsic values of places and focus on preservation still can potentially hinder the advancement of adaptive reuse or developmental projects, besides the challenges associated with its practical implementation (Zancheti *et al.*, 2009).

As such, the scenario in which historical materials are without assigned heritage significance is susceptible to memory and legacy loss, and the buildings are also subject to destruction, which is inapposite with sustainable frameworks. Following the more recent registered conventions and charters, other heritage dimensions have received recognition, and it is not merely monumental and grand tangible buildings but also intangible as a point of history that matters. In this term, current heritage approaches acknowledge both intangible and tangible, as physical landscapes cannot be separated from intangible immaterial people's experiences (Meskell, 2015). However, buildings like Dennys Lascelles wool store still have not gained the protection layer, and their future fate is trapped amidst debates.

The scenario in which buildings have attained heritage designation and acquired preservation has also prompted specific limitations. This value-based viewpoint of heritage, mostly through the lens of museumification approaches, objectified historical materials and was to recognise them as precious objects that should be preserved and curated carefully. These traditional views of heritagisation provided by earlier conventions and charters have presumed heritage to be aesthetically pleasing static material, non-renewable, fragile, with innate values and concerned with physical preservation (Smith and Akagawa, 2008). Smith (2006) critically called this viewpoint on approaching heritage 'Authorised Heritage Discourse' (AHD), Harrison (2013) called it 'Official Heritage', and Lesh (2022) called it the value-based model of conservation.

During the last two decades, Critical Heritage Studies (CHS) supporters have examined the range of cases and presented that AHD approach and the mere concentration on tangible aspects of heritage can elicit a myriad of shortcomings and ethical issues, such as (i) consumerist practices in which heritage and memory turn into sell point and industry, (ii) commodification and displacement (social and cultural evacuation of space as a result of gentrification and space cleansing) (iii) inequality and historical denialism, and (iv) hegemonic practices over minority groups during religious and ethnic conflicts by oppressing or empowering them (v) gentrification and the exclusion of many narratives and voices, (vi) place branding, just to name a few (Smith, 2002; Herzfeld, 2006; Apaydin, 2020; van Knippenberg and Boonstra, 2022). Another drawback, which stems from this tangible and objectified viewpoint ending up with strict physical preservation, is the condition of ignoring the economic pressure for resource development and urban growth in line with sustainability principles.

Parallel to the ever-changing world, the requirements of built environments and their societies keep inevitably transforming. Accordingly, the heritage definition, with its dynamic nature, is not exempt from this and 'Static government-endorsed definitions' are not well-suited to such fluid circumstances (Fairclough, 2009, p. 34). Heritage advocates in critical heritage studies believe the meaning of the past is constantly redefined in each present setting (Gentry and Smith, 2019). In critical views on AHD, heritage is not a past product to be discovered but rather a contemporary process and action (Tunbridge and

Ashworth, 1996; Harvey, 2001; Smith, 2006; Harrison, 2013). In this term, Faro Convention's main suggestion is to challenge the conventional approach of heritage as a valuable asset to be preserved and to encourage viewing it as a resource to be actively utilised and exploited for various purposes (Fairclough, 2009, p. 41).

However, given the higher preservation status assigned to historic urban areas compared to other parts of the city, it is difficult to implement different strategies except those involving strict preservation (Gravagnuolo *et al.*, 2019), and this results in unsustainability. Therefore, the two conventional scenarios for historical landscapes can potentially result in unsustainability. It must be noted that preserving buildings in their original state encompasses various issues and challenges like inadequate insulation, high embodied carbon, water inefficiency, environmental degradation, and limited adaptability, to name a few. As such, recent studies on curated decay, toxic substances, urban mining, and the circular economy (CE) have brought forth pivotal viewpoints regarding alternative prospects for built heritage. In this manner, waste management and material reuse practices are starting to challenge the conventional notions of heritage that categorise elements of the built environment as either 'value-bearing' or 'of no value' and encourage a more inclusive and holistic approach to heritage management (Ross and Angel, 2020).

In this term, if we shift from the long-lasting traditional paradigm that development undermines conservation and recognise that the transformative potentials of historical spaces can be consistent with heritage preservation, their future fate can be aligned with the sustainable ethics of not generating waste and heritage decay can be mitigated (Arlotta, 2020; McCarthy and Glekas, 2020). Also, there has been a rising interest in exploring methods for design revolving around the reuse of reclaimed materials due to the magnitude of waste produced from demolition activities, resource scarcity and landfill burden (Ross and Angel, 2020). Adaptive heritage reuse not only ensures the preservation of our historical landscapes but also adapts them to meet the requirements of the present by fostering socially inclusive environments, driving economic growth, and promoting environmental sustainability within cities (Lesh, 2022).

In the meantime, this modification process of making useful responses for the current purpose of buildings can also sacrifice aspects of their historical significance. This can be resolved by recognising and representing the plurality of heritage narratives through innovative heritage approaches like digital heritage. So, this paper intends to bring affect theory as an additional complementary attribute for heritage preservation besides digital theory as a tool to augment the range of choices for preserving various aspects of heritage. This can be applied in the situation of being left with no option other than modifying and removing a part of the heritage in conditions with irresolvable issues like safety concerns, heat waste, unsustainability, etc., as the ultimate goal is to make the building functional.

3. Circular city-recycling, reuse and repurpose

A circular city embraces the principles of the circular economy throughout its urban landscape, forming sustainable systems that optimise resources and eliminate waste. These cities foster local economies by extending product life, reusing, refurbishing, remanufacturing, and recycling while transitioning from linear to circular models. Collaboration across diverse aspects, including humans, businesses, systems, and infrastructure, drives this transformation. In the circular economy, materials circulate without waste, creating resilient and inclusive urban spaces that benefit all residents. The circular city is closely connected with the circular economy, a closed-loop system that uses waste as a resource. As Foster (2020) states:

> ‘Circular Economy is a production and consumption process that requires the minimum overall natural resource extraction and environmental impact by extending the use of materials and reducing the consumption and waste of materials and energy. The useful life of materials is extended through transformation into new products, design for longevity, waste minimisation, and recovery/reuse, and redefining consumption to include sharing and services provision instead of individual ownership. A CE emphasises the use of renewable, non-toxic, and biodegradable materials with the lowest possible life-cycle impacts. As a sustainability concept, a CE must be embedded in a social structure that promotes human well-being for all within the biophysical limits of the planet Earth.’

Hence, the existing building stocks, whether historic, partially demolished or heritage, are considered resources for a circular city. Considering the city of Geelong as a case, where the city and its surroundings are changing as large businesses close and are replaced by luxury residences, hotels, and new office buildings, among other things. As a result, due to continuous development, the once-industrial town and its associated architecture are quickly fading from city dwellers' memories. This disappearance of both visible and intangible memories raises concerns about potential gaps or untold histories in the city's industrial past and heritage. While much of Geelong's CBD is being reshaped for the twenty-first century with new buildings, refurbished structures, alleyways, and new activities, certain areas of the CBD continue to be gaps/voids with empty, abandoned buildings, dark alleys, and vacant lots. In this context, a circular economy could be used as a strategy to mitigate this consumption by preserving and reusing historic buildings rather than demolishing and rebuilding them.

Heritage economics examines cultural heritage assets as integral components of a city's cultural capital within the context of urban conservation. In such contexts, a heritage asset is perceived as more than an entity possessing mere economic value; it encapsulates cultural significance. This amalgamation of cultural and economic value imparts enduring worth over time, generating a continuum of services, consumable or utilisable in the production of additional goods and services (Throsby, 2001).

When we aim to match old historical assets with new needs and uses, the adaptive reuse of cultural heritage often requires making significant interventions (Douglas, 2006; Bullen and Love, 2011). Thoughtful use of materials and people to take care of, maintain, and make use of heritage assets creates a lasting flow of valuable things and services. This makes adaptive reuse a meaningful part of the creative economy. As stated by Ost (2021).

> ‘Heritage conservation is the economic process of providing and investing additional resources in cultural capital to keep it generating cultural and economic values in the future.’

In the context of Geelong, the fate of industrial vacancies predominantly ends in abandoned sites waiting to be demolished or transformed if not listed as heritage. However, as architecture, these buildings are the only tangible evidence, the paramount query that reminiscences the historic narrative of the city and the place. Certainly, the importance of preserving historic buildings to maintain their historical, aesthetic, and architectural value is widely recognised.

One approach to preserve these values is by skillfully using the existing structure of the buildings. This means restoring, recycling, and repurposing old buildings while also safeguarding their unique architectural features and traditional methods that make them environmentally sustainable. However, this presents a challenge in two directions.

Firstly, if a building is considered a heritage site and protected by certain regulations (AHD), how can we make changes to it without losing its historical significance? Especially when we need to adapt it to new functions and roles in a fast-changing world. Sometimes, this even requires changing the infrastructure around the building to suit its new purpose.

On the other hand, if the building isn't officially recognised as a heritage site, how can we keep the intangible historical and urban values it holds, whether we decide to tear it down or completely renovate it to match today's needs? This is a challenge we are grappling with right now. In our case, the core of this issue revolves around the Denny Lascelles wool store. The portion with heritage status was completely demolished, while the remaining part isn't officially recognised as heritage and is seemingly viewed as a basic abandoned structure, open to demolition and reconstruction, as we explained at the beginning of this paper.

In a previous study (Rashid *et al.*, 2021), the team tried to uncover and revive the story of the missing section using digital tools. Now, in this paper, we are further investigating the potential of today's digital tools and the concept of 'affective heritage'.We are doing this within the context of a circular city, aiming to safeguard the city's architecture and cultural capital.

4. Affect theory and heritage

'Adaptive reuse' prioritises new purposes over conserving original heritage, especially when defined by the 'authorised heritage discourse' (AHD) (Smith and Campbell, 2017). We explore how a broader heritage definition can overcome AHD limitations while preserving historical value. This paper introduces 'affective heritagisation,' where existing building value mediates between program needs and heritage, fostering a symbiotic relationship between architecture and history.

According to David Lowenthal, heritage is a celebratory aspect of history, not an in-depth investigation. Our Geelong 'Wool Store Precinct' subtly celebrates the wool industry, avoiding 'heritagization' and 'commodification' (Micieli-Voutsinas and Person, 2020; Thouki, 2022). Carman (2003), an archaeologist, explains heritage's emergence from categorisation, influenced by curatorial agendas, which Denny Lascelles does not fit with.

Tolia-Kelly *et al.* (2016) state heritage engagements are primarily emotional responses to triggers like pain, joy, nostalgia, and belonging. Zeisel (2006) underscores understanding human perception for appropriate built environment design, beneficial for heritage maintenance on the Denny Lascelles Wool store and similar projects.

'Heritagisation,' a term from the late 20th Century, transforms history into exhibits for cultural tourists. Fluid definitions challenge this concept and the dominant 'authorised heritage discourse' (Smith and Waterton, 2012). 'Heritagisation' is a dynamic process, evolving based on research, discourse, cultural values, and various group involvement (Kolesnik and Rusanov, 2020)

'Affect Theory' explains how experiences impact us physically and mentally. Tolia-Kelly *et al.* (2016) note heritage engagements are primarily emotional responses. Fielding (2022) expands this beyond emotions, involving mundane interactions, information, and others' reactions, affecting perception. For Fielding, affect theory in heritage is more than emotional manipulation; it's about how understanding and reacting to the past impact present life. Affective heritagization suggests heritage through materiality, space, culture, and history.

Adaptive reuse of historical buildings prioritises new programs over heritage preservation, sparking tension between conflicting priorities, especially within the 'authorised heritage discourse.' This discourse perceives heritage as 'material, non-renewable, and fragile.' To reconcile these concerns, the concept of 'affective heritagization' emerges, recognising the active role of existing structures in balancing programmatic needs and heritage significance. Focusing on the Dennys Lascelles Wool store, this research highlights the importance of 'historic narrative' in crafting a meaningful heritage experience.

Memory encompasses information storage and recall, while nostalgia triggers emotional responses from physical and non-physical cues. Despite negative connotations, nostalgia can deepen engagement with history. For successful adaptive reuse and experience-centred architecture, emotions like nostalgia must be understood.

The Dennys Lascelles Wool store offers a model for heritage projects that emphasise the spatial and textural facets of the original structure, foregoing 'heritagization' and 'commodification.' This approach prioritises an affective architectural experience, redirecting public learning towards emotional heritage understanding.

Heritage discourse has evolved into dynamic understandings, with affect theory exploring how experiences impact us. Affective heritagization proposes heritage through emotional triggers, fostering personal engagements. Ultimately, heritage emerges from interactions with material culture, shaping current social and political narratives.

5. Discussion: digital heritage and affective preservation

This study critically explores the potential of digital technology to address 'affective heritage,' which simultaneously preserves building memories and repurposes them within the context of the circular economy. Grounded in the notion that architecture offers insights into human nature, values, and culture (Prakash and Scriver, 2007), the project employs digital tools to meticulously reconstruct Geelong's wool industry history for widespread dissemination. The concept of 'Virtual heritage' enables non-invasive monument restoration through immersive multimedia experiences (Abdelmonem, 2017), effectively benefiting conservators, historians, archaeologists, and urban designers by ensuring the preservation of historical buildings within the principles of the circular economy. While 3D models considerably aid in the restoration process, capturing intangible values remains a notable challenge for architectural historians.

The study takes a comprehensive approach by effectively integrating digital technologies to capture both tangible and intangible memories (Richards and Duif, 2019). Understanding a building's significance within the present context but devoid of traditional interactions poses a unique challenge (Abdelmonem, 2015). Although architecture inherently encapsulates collective memories, the process of engagement with them can be intricate and nuanced (Connerton, 1989). The study itself revolves around the concept of 'Affective Heritage', which seeks to broaden heritage understanding by meticulously examining historic structures to holistically capture human experiences. The ultimate goal of the endeavour is to bridge temporal gaps, enabling present-day individuals to form a profound connection with the past, thereby shaping collective memory and fostering cultural preservation.

The study takes a critical stance by investigating the challenges surrounding the reconstruction of the lost architectural narrative of the Bow truss building, the primary structure within the Dennys Lascelles Wool Store complex. Despite the building's heritage listing, it faced demolition, thereby disconnecting current citizens of the city of Geelong from its original architecture and historical significance as an initial study proposed a virtual diachronic model of the building, which views architecture as a dynamic process (Rashid and Antlej, 2020) and employs a linked open database to meticulously reconstruct the historical trajectory of the site. This approach effectively bridges the gap between the tangible and intangible aspects of heritage. The project is carried out through five distinct stages: data collection, identification of historical narratives, creation of a digital model, development of a user-friendly storyboard, and dissemination of findings via an interactive website (Figure) (Rashid *et al.*, 2021).

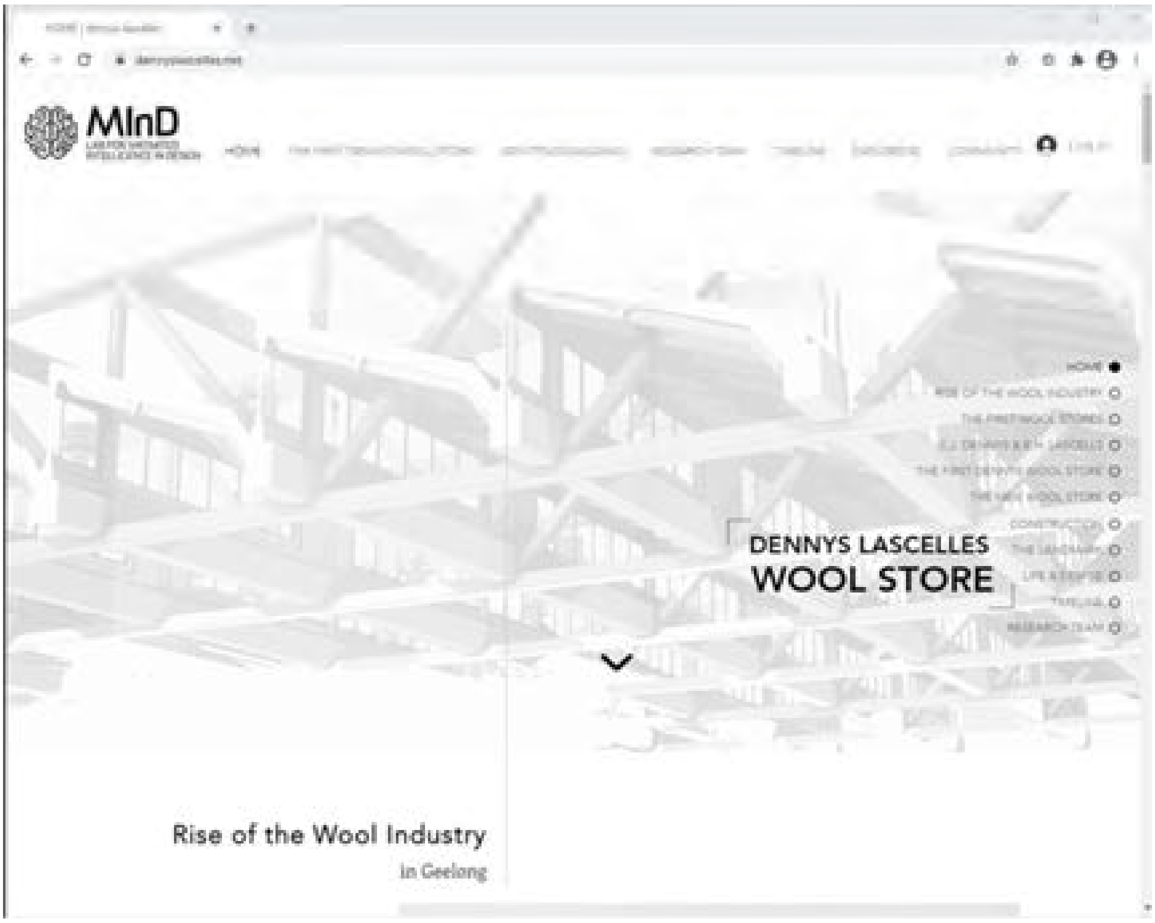

Figure 2: User-based interactive website of the wool store.

The first part of the study conclusively affirms the pivotal role that architecture and digital tools play in effectively preserving heritage while ensuring public engagement. The introduction of an Augmented Reality (AR) experiment utilising QR codes for virtual walking tours is particularly noteworthy (Figure). The study's limited surveys yielded positive responses, which significantly underscore AR's potential for engaging users with historical spaces (Rashid *et al.*, 2021). The project's ongoing innovation revolves around the intricately intertwined narratives, promoting an inclusive heritage experience that actively involves the community. As technology continues to advance rapidly, the study envisions a future where architectural interfaces play an instrumental role in disseminating heritage while promoting engagement with architecture.

Figure 3: An Augmented Reality (AR) experiment of demolished Dennys Lascelles Wool Store that utilising QR codes for virtual walking tours with the augmented historical information and 2D/3D visual content.

The ongoing reactivation project unveils a novel narrative, intricately weaving an inclusive heritage experience accessible through a user-friendly interface. This fusion of narratives offers an immersive journey that rekindles cultural memories via spatial and non-linear storytelling, thus infusing heritage with enduring 'Affect.' Concurrently, the project envisions repurposing buildings to align with circular economy principles. Amidst the rapid evolution of digital technology, the paper posits that the realm of 'affective heritage' holds the key to engaging with vanished structures and bygone eras. This approach stands not in contrast but rather in tandem with physical preservation endeavours, broadening the horizons of heritage conservation and dissemination, ensuring a sustainable circular future. The key argument is unequivocal. On one hand, digital tools offer myriad ways to immerse the audience in heritage buildings without the need for physical preservation. This conveys the building's heritage value in an affective and holistic manner, leaving the physical structure available for contemporary and future uses, promoting recycling and repurposing in accommodation functions. Physical preservation is no longer essential, as it can limit adaptability to rapidly evolving technological requirements. Thus, introducing the concept of 'Affective Digital Heritage' enables us to utilise existing building stock in cities, repurpose them, and preserve their heritage value without destroying it. This illustrates how the concept of affective heritage directly contributes to the idea of a circular economy. In this context, the team is actively exploring better digital tools to document the historic building, such as 'Digital Twin' and 'Human Building Interaction,' among others. Dezen-Kempter *et al.* (2020) has observed that the application of Digital Twins (DT) in Heritage involves creating intelligent 3D models (HBIM) that manage and enhance information accessibility. According to Nagakura and Woong-ki (2014), digital historical models aid building investigations cost-effectively, unlike physical artifacts stored in labs or museums. Technologies like photogrammetry and 3D laser scanning efficiently generate these models (Nagakura *et al.*, 2015). Augmented Reality (AR) further aids interaction with these models, enhancing understanding and social engagement (Nagakura and Woong-ki, 2017). In future study anticipates exploring combining the Digital Twin with the Human-Building Interaction (HBI) through architectural interfaces and augmented digital content (Khoo *et al.*, 2018), drawing parallels to prior instances such as the BIX façade and the tower of winds media façade. Foreseeing forthcoming technological strides and the evolving landscape of human-computer interaction (HCI), the study envisions historic building façades or interior walls as conduits for disseminating the building's historical essence, enriching user engagement sans the reliance on mobile devices and augmented technology. Khoo *et al.* (2018) research demonstrates the potential of integrating mobile spherical robots and projected digital visual contents as architectural interfaces for the existing built environment. The ever-evolving digital landscape potentially ensures a multifaceted understanding of heritage, effectively guaranteeing its continuity within a sustainable and circular future. The project's findings and the anticipated future developments underscore the remarkable potential of affective heritage in reshaping heritage preservation and dissemination.

With the ever-changing digital world, we can better understand and keep heritage alive, ensuring it continues into the future. This project's discoveries and upcoming changes show that affective heritage, using digital tools, can play a big role in preserving and sharing heritage. In the end, this way of thinking suggests that affective heritage, using digital technology, could be a guide for protecting heritage in circular cities. This modern perspective combines technology, history, and how people connect to create a story where heritage not only survives but also thrives, adapting to the present while holding onto its cultural roots.

6. Conclusion

The fate of Geelong's Dennys Lascelles Wool Store exemplifies the delicate balance between heritage preservation and the circular economy's imperatives. Traditional preservation models fall short, unable to reconcile historical significance with adaptive reuse demands. Enter 'affective heritagization': a paradigm that interweaves emotional connections with architectural legacy, fostering a more comprehensive understanding of heritage. This dynamic approach harmonises with the circular city concept, aligning heritage preservation with sustainable resource utilisation.

Digital innovation emerges as a vital conduit, bridging heritage and contemporary experiences. By immersing individuals in virtual and augmented heritage journeys, these platforms restore buildings' stories, rekindling their essence within the community. Architectural interfaces and mobile technologies further amplify the engagement, ensuring heritage's resonance amid modernity.

In sum, the Dennys Lascelles Wool Store's trajectory echoes the broader dialogue on heritage and sustainability. Affective heritage, fueled by digital augmentation, pioneers an inclusive path forward. This paradigm shifts not only safeguards heritage but also propels a circular city vision where the past and present harmoniously coexist, enriching our shared urban tapestry.

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An Investigation of the Effective Reuse of Heritage Buildings to Achieve Resilience in New Zealand Small Towns: A Literature Review

An Investigation of the Effective Reuse of Heritage Buildings to Achieve Resilience in New Zealand Small Towns: A Literature Review

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Abstract: Small to medium-sized towns in Aotearoa New Zealand (NZ) have a substantial number of heritage buildings built before the 1931 Hawkes Bay earthquake, mostly earthquake-prone. The seismic vulnerability, along with the rising industrialization of agriculture that prompted a migration to larger urban centres, has led to the abandonment of numerous historic structures in small towns worldwide. In turn, these affect the town's seismic and social resilience, which can create a negative spiral of town vitality. Strategic and thoughtful adaptive reuse is an important tool. It has the potential to contribute to UNESCO's Sustainable Development Goals (SDG) like SDG 8, Decent Work and Economic Growth, SDG 11, Sustainable Cities and Communities, and SDG 12, Responsible Consumption and Production. The literature review in this paper examines adaptive reuse through the lens of UNESCO's SDGs to understand its challenges and benefits within NZ's small-town context, focusing on Whanganui as a case study. The literature review revealed four themes concerning adaptive reuse in NZ and the SDG: Causes of Obsolescence; Seismic Risk; Environmental Sustainability; and Heritage Conservation. Reusing and retrofitting, rather than demolishing, obsolete buildings can contribute to the solution of the housing problem while lowering NZ's carbon footprint in line with the legislated goal of becoming net zero by 2050.

Keywords: adaptive reuse, heritage conservation, resilient towns, sustainable development goals

1. Introduction

Adaptive reuse or changing the function of a space to fit contemporary needs, often for economic reasons, has been evident since ancient times (Cunnington, 1988). The new function also helped preserve numerous historic buildings that might have otherwise been lost, such as the transformation of churches into mosques in Anatolia, Türkiye (Korumaz and Kilit, 2020) and the repurposing of Roman structures in Britain (Cunnington, 1988).

Published themed literature reviews have focused on different literature resources and perspectives (Plevoets and Van Cleempoel, 2011; Wise et al., 2019; Arfa et al., 2022; Aigwi et al., 2023). In this paper, we will explore aspects of adaptive reuse with particular reference to the structure of the United Nations Educational, Scientific and Cultural Organization (UNESCO) Sustainable Development Goals (SDG).

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association *2023,* M. Dewsbury, D. Tanton (eds.), *pp. 78 - 92.*

Seventeen SDGs were introduced by United Nations General Assembly in 2015 as a part of the 2030 Agenda for Sustainable Development (United Nations, 2015). The SDGs related to the adaptive reuse of heritage buildings are SDG 8 Decent Work and Economic Growth in relation to the economic sustainability of the town; SDG 11 Sustainable Cities and Communities in relation to town vitality and SDG 12 Responsible Consumption and Production in relation to the environmental sustainability of reuse of existing buildings. Seven international cultural organisations have also proposed a new "cultural" SDG related to heritage conservation and adaptive reuse (Arterial Network et al., 2022; 2023).

Economic sustainability of adaptive reuse (SDG 8) has been studied from different angles, such as construction cost (Shipley et al., 2006), circular economy (Dişli and Ankaralıgil, 2023), valorisation (Di Giulio et al., 2006), property values, rate of return and job creation (Mohamed et al., 2017; Murphy, 2020), economic input-output (Chan et al., 2020), the economics of conservation (Nahkies et al., 1998), and financial hardships and obstacles in New Zealand provincial towns (Filippova and Noy, 2018; Filippova and Noy, 2020; Aigwi et al., 2021). This paper does not examine the economic sustainability of adaptive reuse, rather, it explores the relationship between adaptive reuse, obsolescence, environmental sustainability, seismic risk, and heritage conservation.

2. Theoretical Development

Eugène Emmanuel Viollet-le-Duc, in his 1854 book, can be regarded as one of the earliest scholars to address building reuse, asserting that the optimal approach to preservation was discovering a functional purpose for the structure (Viollet-le-Duc, 1990). A hundred years later, 1950s architects such as Carlo Scarpa, Raphaël Moneo, Herzog & Demeuron challenged their design skills with work on historical buildings (Plevoets and Van Cleempoel, 2011). In 1964, the Venice Charter was published by the International Charter for the Conservation and Restoration of Monuments and Sites (ICOMOS). It notes,

"The conservation of monuments is always facilitated by making use of them for some socially useful purpose. Such use is therefore desirable, but it must not change the layout or decoration of the building. It is within these limits only those modifications demanded by a change of function should be envisaged and may be permitted" (ICOMOS, 1964, p. 2).

The topic of adaptive reuse became a crucial subject in architecture and architectural conservation in the 1970s (Plevoets and Van Cleempoel, 2011). Reuse was also mentioned in the 1999 version of the Burra Charter as "Adaptation means modifying a place to suit the existing use or a proposed use" and "Adaptation may involve the introduction of new services, or a new use, or changes to safeguard the place" (ICOMOS Australia, 1999, p. 2, 7). In the 2013 version, the term "adaptive reuse" was added (ICOMOS Australia, 2013). In the ICOMOS New Zealand Charter, adaptation was defined as,

> "The process(es) of modifying a place for a compatible use while retaining its cultural heritage value. Adaptation processes include alteration and addition" (ICOMOS New Zealand, 2010, p. 9).

Throughout the years, different names have been given to this concept, including 'remodelling', 'retrofitting', 'conversion', 'adaptation', 'reworking', 'rehabilitation' and 'refurbishment' (ICOMOS, 1964; Plevoets and Van Cleempoel, 2011; ICOMOS Australia, 2013). The contemporary "adaptive reuse" is defined as the transformation of an obsolete building to give it a new, useful life. For heritage buildings, it also means restoring the building to contemporary standards while conserving heritage and creating functional spaces (Cucco et al., 2023). It is fair to say the definition of reuse has moved from functional change to upgrading the buildings to contemporary standards (Douglas, 2006). Depending on their research focus, scholars redefined the term, such as “an alternative to the end of life and repurposing functionally obsolete buildings” (Chan et al., 2020) or “giving a new life to a building to create sociocultural, economic and environmental benefits” (Aigwi et al., 2023). Since the focus of this paper is the relation between SDGs and adaptive reuse, we will define adaptive reuse as the reuse of an obsolete building to create contemporary spaces that contribute to sustainability while conserving its authenticity.

3. Aspects of Adaptive Reuse

The literature review revealed five critical themes related to adaptive reuse in NZ small towns: economic sustainability; causes of obsolescence; environmental sustainability; seismic risk and heritage conservation.

The economic sustainability of small towns and the effect of adaptive reuse has been discussed extensively (Cunnington, 1988; Di Giulio et al., 2006; Shipley et al., 2006; Rypkema, 2013; Filippova and Noy, 2018; Chan et al., 2020; Duffy et al., 2020; Filippova and Noy, 2020; Aigwi et al., 2021). Of the other four, causes of obsolescence relate to SDG 11, environmental sustainability to SDG 12 and seismic risk to SDG 11. Seismic risk is important for NZ since most unoccupied heritage buildings are likely to be earthquake-prone. Heritage conservation also relates to SDG 11 as well as to the missing “cultural” SDG (Arterial Network et al., 2023).

3.1 Causes of Obsolescence

Obsolescence is an adaptive reuse context is described as “the inability to satisfy increasing requirements or expectations” (Langston, 2011b). Types of obsolescence include: physical; economic; functional; technological; social; and legal. These may cause a building to become obsolete before its physical end of life (Langston *et al.*, 2008). As noted, the obsolescence of buildings in small or provincial towns relates to SDG 11, “Sustainable cities and communities”, which aims to “make cities and human settlements inclusive, safe and resilient and sustainable” (United Nations, 2023).

Population loss is the leading cause of small-town building obsolescence (Yakubu et al., 2017; Nel et al., 2019). It is a worldwide issue created mainly by the industrialisation of farming and industrial globalisation. In turn, this can create a downward spiral for the town centre. Termed "neighbourhood blight", unoccupied buildings result in the neighbourhood becoming unattractive, potentially leading to an escalation in crime, prompting wealthier individuals to leave, resulting in even more vacant properties (Mohamed et al., 2017).

Langston et al. (2008) defined legal obsolescence as being “created because of the seismic and safety regulations,” which is the relevant situation for many NZ small towns. Yakubu et al. (2017) found that one of the main reasons for unoccupied NZ town centre buildings was building code and seismic regulation issues.

Utilizing adaptive reuse has the capacity to create urban housing and combat the issue of vacant buildings in city centres. This approach may be faster and more economical than new construction, all while preserving the sense of place and heritage. This would also link with SDG 11, target 11.1: “By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums” (United Nations, 2023). Worldwide, many projects have converted office buildings into apartments, returning people to city centres (Langston et al., 2008). The excellent condition and occupation of the refurbished buildings have the potential to positively shape residents' and visitors' attitudes (Mohamed et al., 2017). Schilling (2002) introduces the notion of "smart growth," advocating for increased urban population density to reduce reliance on cars and lower carbon emissions. This can include the adaptive reuse of city centre buildings as housing.

Scholars have worked on the challenges of adapting buildings to dwellings. Itard and Klunder (2007) noted the new spaces need to meet the current expectations for house size and quality. Langston et al. (2008) concluded that changing the use may require compliance with different regulations to those in place when the building was constructed, such as building code compliance (including fire safety) and heritage restrictions.

Whanganui, New Zealand, a small city on the west coast of the north island, is an excellent example of such a town. The population between the 1996 and 2013 censuses (Statistics New Zealand, 1996; 2018), created many unoccupied buildings in Whanganui town centre (Yakubu et al., 2017). On the other hand, a steady increase in population has been observed since the 2013 census (Statistics New Zealand, 2018). There may be several reasons for the increase, including an increased population shift from major cities to small towns during the 2020 Covid-19 pandemic (Oteri, 2020; Nelson and Frost, 2023) and the town vitality strategies developed by the Whanganui District Council (Whanganui District Council, 2019) to draw newcomers to the town. The strategies made extensive use of the character created by the heritage buildings.

3.2 Environmental Sustainability

Heritage conservation and adaptive reuse of heritage buildings are, by nature, environmentally sustainable acts since their main aim is to reuse and extend the physical lives of buildings. The SDG related to environmental sustainability within this scope is SDG 12, Ensuring sustainable consumption and production patterns, which is also recognised by ICOMOS (United Nations, 2015; Labadi *et al.*, 2021).

The environmental aspect of adaptive reuse has also been frequently studied. Most literature considers the adaptive reuse of a building, whether contemporary or heritage, to be environmentally desirable as it lowers the carbon footprint by reutilising the building's embodied energy and materials. Reuse also reduces the construction waste that would otherwise arise from demolition. Additionally, if the building undergoes refurbishment, there is the possibility of decreasing its operational energy use (Langston, 2008; Mohamed et al., 2017; Wise et al., 2019; Rypkema, 2021; Paschoalin et al., 2023). Research focused mainly on three aspects: energy; physical life; and construction materials (Bullen, 2007; Itard and Klunder, 2007; Ijla and Broström, 2015; Merlino, 2018; Wise et al., 2019; Duffy et al., 2020; Labadi et al., 2021; Aigwi et al., 2023).

3.2.1. Energy

The building energy footprint may be divided into three topics: embodied; recurring embodied; and operational.

Embodied energy is

> "All the energy used to produce the materials that make up the building. It includes the energy used in mining, manufacturing and transporting the materials, as well as the services in the economy that support these processes" (Crawford and Hall, 2020).

Using an existing construction, adaptive reuse utilizes less material to create the desired spaces, although there will be impacts from the refurbishment.

UK research shows that initial embodied energy represents between 28- 31% of a new-build's life cycle emissions (Duffy *et al.*, 2020). Crawford states that a typical Australian veneer brick house's initial embodied energy takes up 37% of its total energy consumption within its 50-year lifespan (2014). Itard & Klunder's research also shows that the initial embodied energy of a building corresponds to ten to eighteen years of operational energy (2007). Therefore, it is fair to say that about one-third of the energy used during the life span of a building is used during its initial construction.

There are two types of embodied energy: 'initial embodied energy' used during the construction phase and 'recurring embodied energy' used during repair, maintenance and refurbishment (Merlino, 2018).

Recurring embodied energy is "the production of all the materials used in repairs or renovations over the life of the building" (Crawford and Hall, 2020). Preventive maintenance, repair and refurbishments are essential works that are required to prolong a building's life, on the other hand they also increase the lifetime energy footprint of the building.

Crawford (2014) states that a typical veneer brick house's recurring embodied energy takes up 22% of its total energy consumption within its 50-year lifespan. The frequency and choices made during repair and refurbishments will affect the recurring embodied energy. Duffy *et al.* (2020) note that if the materials needed for a refurbishment project are high, the conversion also requires a high embodied energy. According to Chan *et al.'s* (2020) Canadian research, which utilizes input-output analysis, the environmental sustainability of adaptive reuse versus demolition and reconstruction varies based on factors such as material reuse and final demand. Langston *et al.* (2008) state that poorer quality buildings require more resources to maintain and repair, increasing their recurring embodied energy.

Operational energy is the amount of energy consumed by the building (including occupant use) over its lifetime. Crawford's (2014) study shows that it has the most significant proportion among other energy consumptions of the building, although this may not be the case for more energy-efficient buildings.

Langston *et al.* (2008) claim heritage buildings have a heavier external envelope, which may reduce the operational energy of a building, although this will obviously depend on their construction. On the other hand, Duffy *et al.* (2020) conclude that focusing only on the embodied energy of a heritage building is not enough to make it environmentally sustainable. Retrofitting to reduce operational energy consumption is also required.

Adaptive reuse projects have the potential to meet the highest energy efficiency standards. For example, many projects have been awarded the US Green Building Council LEED's top Platinum certification (Langston, 2011a). Itard and Klunder (2007) concluded that the operational energy use of transformation (adaptive reuse) buildings and new buildings was the same when the same level of thermal insulation was used. Paschoalin *et al.*'s (2023) research found in three case studies; a deep energy retrofit of a heritage building in NZ has the potential to lower the operational energy demand between 50-70%.

Typically, the primary environmental sustainability argument for adaptive reuse centres around embodied energy. Conversely, buildings require upkeep and repairs to remain standing until their expected lifespan concludes, using operational energy. When a building's purpose becomes outdated, refurbishment becomes necessary to align with its new function. The research suggests that heritage buildings also need energy-efficient retrofits to be able to compete with new build's operational energy use. All of these interventions have energy footprints. To make a case for the environmental sustainability of adaptive reuse, it is essential to understand the realistic energy consumption.

3.2.2. Physical life

Similar to living entities, buildings also have a lifecycle: they are constructed, utilized, and eventually they are demolished or collapsed. However, buildings also have the unique ability to endure for significantly extended periods. A building's lifespan encompasses two dimensions: the physical life, which denotes its intended duration of standing, and the functional life, indicating the span before the building becomes obsolete.

Different elements of a building have various life expectancies. Kohler and Yang (2007) stated that with a sturdy structural frame, buildings have the potential to last more than a century, given proper repair and maintenance. Duffy (1990) stated that contemporary buildings' shells, foundations, roofs and façade are built with a fifty-year physical life expectancy, which is the modern expectation. The New Zealand Building Code (NZBC) Clause B2 states that the expected life of a building's structural elements is fifty years (New Zealand Ministry of Business, 2021). Duffy (1990) states that services are expected to last fifteen years. The NZBC affirm that building envelope, exposed plumbing in the subfloor space, and in-built chimneys and flues should have a life expectancy of fifteen years (New Zealand Ministry of Business, 2021).

The physical life of heritage buildings is shaped by numerous factors, including maintenance, quality of the construction, and resilience to natural disasters and destructive incidents (Lukito and Rizky, 2017). The heritage buildings of today may have already outlived the physical life expectation of fifty years. The main focus of preventive maintenance and restoration is making the physical life of a building longer than it would have been without intervention. Adaptive reuse may happen before its end of physical life when the building reaches the end of its functional life, giving it an alternative to its end-of-life demolition (Chan et al., 2020).

To assess the environmental sustainability of an adaptive reuse project, researchers must determine the physical life or lifespan of the building. When the building's physical life is longer, the embodied energy is used for a longer period, providing environmental benefits (Langston and Shen, 2007; Langston, 2011b; Conejos et al., 2013). Knowing the potential remaining physical life of a building is essential to justify its adaptive reuse (Langston, 2011a; Langston, 2011b). Langston (2008) created a physical life calculator to support the adaptive reuse potential (ARP) method by considering the environmental context, occupational profile and structural integrity. The ARP was applied to sixty-four buildings and it was found that the physical life of buildings differs from 50 to 300 years (Langston, 2008). On the other hand, Itard and Klunder (2007) decided to use a 50-year life span as the physical life of a building after a renovation so that they were able to directly compare it with a new built.

The functional life of a structure refers to the duration it fulfils its intended purpose. A building might accommodate multiple functional phases within its overall lifespan. The primary objective of adaptive reuse is to provide obsolete buildings, which have a considerable remaining physical lifespan, with a renewed functional purpose. It is vital for a structure to be loose fitting, which means the ability to change its function to be able to facilitate reusability with minimal interventions and financial investments (Conejos et al., 2013). Langston et al. (2008) and Conejos (2013) worked on different aspects to determine if the building has the potential to host a new function within its physical life.

The research shows that it is crucial to understand if a heritage, or for that matter any, building has enough physical life to be reused with a new function. A simple fifty-year lifespan without refurbishment is considered unrealistic. Both Langston's physical life calculator and the recommendations of Itard & Klunder, suggesting fifty years after a renovation, provide a credible basis for the assessment of heritage buildings.

3.2.3. Construction Material

Construction material includes all the materials used for construction, which ultimately become construction and demolition waste (C&DW), and the possible reuse or recycling of these materials.

The construction sector uses 60% of raw materials in the U.S.A. annually, excluding food and fuel. It might not be to the same detail, but construction is the leading consumer of materials in many other countries and this contributes to their greenhouse gas emissions (Mohamed et al., 2017). Research by Itard and Klunder (2007) showed that building reuse could potentially use 60% less material than demolition and rebuilding. Langston *et al.* (2008) and Bullen and Love (2010) agree that reuse or refurbishment requires fewer materials since most of the building elements already exist. On the other hand, Langston *et al.* (2008) point out that building regulations, fire safety and construction quality may be the causes of the increase in material use during adaptive reuse. Mohamed *et al.* (2017) state that the choice of materials is essential. To achieve environmentally sustainable adaptive reuse, energy-intensive products and inefficient systems should not be used unless their lifetime benefits are demonstrated.

C&DW may be defined as waste generated during the construction, renovation, and repair of individual buildings, commercial structures, and various building types (Kabirifar et al., 2020).

Reduction of C&DW is rated the highest priority to achieve an environmentally sustainable future in line with SDG 12 (Kabirifar et al., 2020).
C&DW takes up 26% of the urban waste in the USA, 34% of all industrial waste in the E.U. (Jin et al., 2017) and 15% in the UK (Duffy et al., 2020). Mohamed et al. (2017) state that the demolition of a building creates almost half of the solid waste that was created during the lifetime of the building. On the other hand, research by Itard and Klunder (2007) shows that transformation (architectural refurbishments and insulation) creates 11-19% less waste per square meter than demolish and new build.

To create an environmentally sustainable construction industry, it is necessary to move towards a closed-loop material system to reduce the need for raw materials (Saleh and Chini, 2009). Opting for building reuse stands as a decision that prolongs the materials' lifespan. Deconstruction is the alternative to demolition, which allows the reuse of the components and materials as well as recycling (Saleh and Chini, 2009). This was partially applied to heritage buildings after the 2010-2011 Christchurch earthquake sequence. A heritage waste management policy was implemented, directing the retrieval and preservation of heritage items, including selected building materials (Stevens, 2015).

In New Zealand, low or no construction waste disposal fees contributed to the idea that demolishing and building new was cheaper than reuse. In 2021, the waste disposal levy was expanded to include C&DW. The fees came into force in 2022 and will annually increase till 2024. This levy aims to reduce construction waste and promote reuse and recycling (New Zealand Ministry for the Environment, 2022). During the literature review, no research has been found focusing on the effect of adaptive reuse on waste in New Zealand. It can be asserted with confidence that the recently implemented C&DW fees should shift the economic balance between reusing existing structures and demolishing and rebuilding, favouring the side of reuse.

Buildings consume 40% of primary energy in the USA and European Union (Cao et al., 2016), and C&DW makes up most of the contemporary waste. To accomplish SDG 12, “Ensure sustainable consumption and production”, the construction industry has to do its part. Research (Crawford, 2014; Ijla and Broström, 2015; Duffy et al., 2020) shows that even though adaptive reuse lowers the energy needed to create new spaces, it is not enough without refurbishments, especially energy-efficient refurbishment. Adaptive reuse also reduces material use and demolition waste drastically at first glance, yet the research on the amount of material used and waste created during refurbishment and maintenance is minimal. It can be confidently stated that adaptive reuse stands as a potent strategy for reducing energy and material consumption, along with minimizing construction waste in the construction industry.

3.3 Seismic Risk

Adaptive reuse is only feasible if the constructive elements of the building are strong enough to last at least till the end of the new functional life. In a country like New Zealand, where the seismic risk is high, it is essential for a building to be able to withstand an earthquake. Therefore it is crucial to investigate the seismic risks related to adaptive reuse. Seismic risk is one of the few aspects of the NZBC which apply to current buildings. This means the relevant requirements change, then both new and existing buildings are also required to comply with the new rules.

The topic of seismic risk is related to Sustainable Development Goal 11, “Make cities and human settlements inclusive, safe, resilient and sustainable”. Disaster risk reduction (DRR) is an essential part of SDG 11, and this is recognised in the 2030 Agenda for Sustainable Development (United Nations, 2015; 2023). Adaptive reuse, which includes seismic refurbishment, can contribute to achieving that goal.

In New Zealand, territorial authorities have been required to evaluate all buildings within their district for their seismic strength since the implementation of the Building (Earthquake-prone Buildings) Amendment Act 2016 in July 2017. This process must be completed within fifteen years for low-risk areas (before 2032), five to ten years for medium-risk areas (2019 to 2027) and two and a half to five years for high-risk areas (2019 to 2022) (New Zealand Ministry of Business, 2017a). There are three types of buildings that are considered earthquake-prone: unreinforced masonry; pre-1976 buildings that are either three or more storeys or 12 metres or greater in height; and pre-1935 buildings that are one or two storeys. These exclude all timber-framed buildings (New Zealand Ministry of Business, 2017b). If the building is considered earthquake-prone, a message is sent to the owner of the building. The owner needs to respond with a detailed seismic assessment by a structural engineer (New Zealand Ministry of Business, 2017b). Structural engineers evaluate the constructive elements of the building and give them values, comparing them to the seismic requirements of the New Building Standard (NBS). Buildings are given an NBS percentage related to their weakest constructive element. Buildings with a value of NBS lower than one-third (34%) are considered earthquake-prone. For example, an unreinforced masonry building’s load-bearing walls might be 67% NBS, yet its roof is 25% NBS, giving it an NBS of 25%, making it an earthquake-prone building (EPB). Earthquake-prone buildings need to be refurbished to at least 34% NBS before their lawfully required time frame, which is thirty-five years for low-risk areas, twenty-five years for medium-risk areas and fifteen years for high-risk areas. However, the time period is halved for priority buildings which means these buildings must be strengthened by 2027 or within 4 years at the time of writing (New Zealand Ministry of Business, 2017a).

Although New Zealand’s built heritage consists mainly of timber, small-town shops and offices are often unreinforced masonry or concrete buildings with some reinforced concrete buildings. All unreinforced masonry buildings are considered EPB if they have not yet been seismically reinforced, according to the Building (Earthquake-prone Buildings) Amendment Act 2016 (New Zealand Ministry of Business, 2017a). During any type of adaptive reuse or restoration, they will need some type of seismic refurbishment.

Another aspect of seismic risk is its relation to town resilience. Following any type of natural disaster, a consistent observation globally has been the need for an operational town centre to provide essential services to those affected by the catastrophe. A recent event was the earthquake sequence in Türkiye at the beginning of 2023. The earthquake survivors couldn't find basic amenities for weeks (Suat, 2023). Hence, the town centre structures must be capable of enduring a potential earthquake and provide necessary amenities for post-disaster support. By reusing or restoring town centre buildings while also making them earthquake-safe has the potential to contribute to earthquake resilience.

Seismic reinforcement and seismic resilience of adaptive reuse is a topic that is not usually covered in international literature. In northern Europe, where extensive research has been conducted on adaptive reuse, earthquakes are not a concern. However, in New Zealand, seismic design is an integral part of the adaptive reuse of heritage buildings. As discussed above, the physical life of a building depends on its resilience to natural disasters.

Case Study

Whanganui, NZ, is also a prime example of an earthquake-prone small-town centre. Twenty per cent of all town centre buildings are considered earthquake-prone, as seen in Figure 1. The map was produced by the author through the synthesis of the collected data and information. The base map and listed heritage building information were gathered from the Whanganui District Council "District Plan" (https://eplan.whanganui.govt.nz/eplan). EPB information was gathered from the town regeneration strategy plan (Whanganui District Council, 2016).

Figure 1 shows there is an alarming number of earthquake-prone (EP) heritage buildings on the main evacuation zone, Victoria Avenue. An earthquake could seriously damage the integrity of the town centre and jeopardize its capacity to effectively serve its residents in the aftermath of an earthquake.

In New Zealand, earthquakes may be one of the main causes of the early end of the physical life of many heritage buildings. New Zealand's heritage buildings are racing against time due to impending legislative changes and the constant looming threat of a new earthquake. By using adaptive reuse as a tool to seismically refurbish heritage buildings in small town centres, this can achieve earthquake-resilient town centres as well as prolong the physical lives of heritage buildings.

Figure 1: Whanganui CBD EP Heritage buildings.

3.4 Heritage Conservation

The traditions of past generations are represented through historical monuments (ICOMOS, 1964). Conservation aims to safeguard the places of cultural heritage significance (ICOMOS New Zealand, 2010). Heritage buildings conserve and represent the human history of the settlement, giving occupants a sense of place. Heritage buildings can also create human-scale spaces with walkable streets to make vibrant city centres (Labadi *et al.*, 2021).

The SDG that relates to heritage conservation is SDG 11. Target 11.4, is the specific target focusing on conservation: "Strengthen efforts to protect and safeguard the world's cultural and natural heritage" (United Nations, 2023). Therefore, SDG 11 also relates to the reuse and restoration of existing buildings (Labadi *et al.*, 2021). The additional benefits of a new cultural heritage goal have been discussed earlier in Section 1 introduction.

ICOMOS charters around the globe have stated not only the importance of ongoing use of heritage buildings but also highlight the importance of respecting the integrity of the buildings' fabric, structure and character while creating contemporary adequate living conditions (ICOMOS, 1964; ICOMOS New Zealand, 2010; ICOMOS Australia, 2013). The rationale for this lies in the fact that when a building is in use, it undergoes essential maintenance and repairs, extending its physical lifespan and preserving its heritage for future generations.

In locations with seismic risks, earthquakes are an important threat to heritage buildings. Stevens (2015) reported that the Christchurch earthquake sequence severely damaged 40% of the heritage buildings in the city. Ultimately, nearly 50% of these buildings had to be demolished (Stevens, 2015). The

Christchurch earthquake sequence showed the devasting impact earthquakes have on heritage buildings, as well as the loss of community memory and sense of place. Christchurch is an important example and the consequences of an earthquake may be worse in small towns with less seismically refurbished buildings.

Seismic and fire refurbishments are a crucial part of any restoration or adaptive reuse, which are practical tools to prevent the loss of heritage, sense of place and create social resilience for towns, which contributes to their town vitality.

4. Conclusion

This literature review identified five significant themes concerning the adaptive reuse of heritage buildings in New Zealand small towns: economic sustainability; causes of obsolescence; environmental sustainability; seismic risk; and heritage conservation. The sustainable benefits of adaptive reuse of heritage buildings can be comprehended through UNESCO's sustainable development goals (SDG). The SDGs related to the adaptive reuse of heritage buildings encompass various aspects. SDG 8, addresses the economic sustainability of towns. SDG 11, concerns seismic risk, heritage conservation and town vitality. SDG 12, highlights the environmental advantages of the reuse of existing structures. An additional "Cultural Goal" has been put forth by seven cultural organizations, relating to heritage conservation consequences of adaptive reuse. For this literature review, the economic sustainability dimension of adaptive reuse was omitted due to its pre-existing thorough examination by many experts.

This literature review has shown there is only limited research on the issues and potential of adaptive reuse of heritage buildings in New Zealand, especially in small towns. Since construction types, legislation and risks are different from other countries, it is vital to work on the adaptive reuse of the architectural heritage of New Zealand. Small towns have been losing their population for decades but on the other hand, in some towns, there has been some population increase in the last five years. Whanganui serves as an example with a range of earthquake-prone heritage buildings located within its town centre. The population increase shows the potential for unoccupied buildings to be adaptively reused as mixed-used or housing buildings. For effective adaptive reuse, buildings must comply with the current NZBC, including fire and seismic safety, while also catering to modern requirements, including layout, thermal insulation, and hygrothermal comfort. To establish a compelling argument in favour of the environmental sustainability of adaptive reuse, a comprehensive understanding of the actual energy consumption is imperative. Creating the ideal way to adaptively reuse heritage buildings will help create environmentally sustainable spaces while improving the town centre's resilience to earthquakes. On the other hand, it is essential to remember that the main reason for adaptive reuse is the conservation of heritage, so respecting the building's character should be one of the main priorities.

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Architectural Design Andragogy: Insights from Online Learning

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Abstract: Architecture education traditionally based on a distinctive andragogy, revolving around design studios and hands-on architectural technologies with a strong emphasis on face-to-face discussions. However, the COVID-19 pandemic necessitated a rapid shift to online learning, fundamentally reshaping the conventional studio format, which has now become the prevailing norm. In this paper, we present a rigorous study that scrutinizes the effectiveness of online design learning in terms of learning outcomes, challenges, users' feedback and future adaptations. Our research combines an online survey encompassing more than ninety undergraduate and postgraduate students who experienced both face-to-face and online learning, supplemented by interviews with educators. The findings emphasize the advantages of online learning, particularly in pre-design phases such as site analysis, research, program development and validation. Nonetheless, students expressed notable limitations in developing their design ideas through discussions with tutors and peers, leading to slower progress and dwindling commitment, ultimately fostering dissatisfaction and demoralization. Educators also encountered challenges in gauging students' reactions, emotions, progress, and learning. Notably, junior students exhibited reduced motivation and commitment within the online studio environment. To foster sustainable and authentic learning experiences, the paper concludes with recommendations for post-COVID architectural design education, focusing on infrastructure improvements, integration of hybrid modes, and enhancing students' engagement and well-being, while preserving the quality and effectiveness of learning. Overall, our research underscores the pivotal role of traditional design studios in fostering creativity and collaboration among architectural students. While online learning offers certain advantages, particularly in pre-design phases, the irreplaceable value of face-to-face interactions in the architectural education process remains evident, emphasizing the need for a balanced and hybrid approach in the post-pandemic architectural education landscape.
Keywords: Architecture education; online learning; hybrid modes; well-being; studio culture.

1. Introduction

Architectural education distinguishes itself from other academic programs through its central reliance on the 'design studio' model, characterized by face-to-face small group discussions among students, tutors, and peers (Lee J.H. et al., 2021). Within this context, design questions take on an exploratory and unstructured nature, evolving iteratively through refinement, realization, and validation processes. These processes find expression primarily in the form of design sketches and physical models, supplemented by digital drawings and models. Feedback mechanisms embedded within the design studio framework constitute established andragogical models employed in architecture schools worldwide (Gallagher and Stephen, 1996; Schön, 1992). Despite significant technological advancements in design communication

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and representation, the pedagogical foundation of architectural education remains deeply rooted in human interaction and has traditionally been considered incompatible with online modes of instruction (Kvan, 2001; Radford et al., 2013).

In addition to design studios, architectural education encompasses theory courses delivered through diverse modes, including classroom lectures, laboratory sessions, building visits, guest lectures, seminars, and conferences. However, the onset of lockdowns and social distancing regulations left little room for traditional practices, rendering access to design studios, other essential facilities, and classrooms. Instead, educational institutions were compelled to adapt to online meeting platforms, designed primarily for general communication and lacking the specialized features required for delivering unique architectural curricula (Hrastinski, 2008; Jegede et al., 2001).

In this study, our primary objective is to comprehensively evaluate the effectiveness of delivering architectural design education through online platforms during the unprecedented COVID-19 pandemic. We aim to investigate the quality of online learning, the challenges, and the potential adaptations required to guide future developments in architectural education, including strategies for enhancing the effectiveness of online teaching and the evolution of future learning models.

Design studio culture vs. online studios

In Hong Kong, architecture design courses span an entire academic year, comprising two semesters and a substantial credit load. This necessitates a higher number of contact and non-contact hours compared to many other academic disciplines. Design tutorial discussions, a core component of architectural education, typically extend for 3-4 hours for undergraduate students and 4-5 hours for postgraduate students, conducted twice a week. While scheduled pauses are included, the transition to computer screens as the primary interface for learning posed challenges in maintaining an ideal learning environment.

More than just physical spaces, design studios foster a unique 'studio culture' where students collectively invest a significant portion of their time learning and collaborating with peers. ‘Studio culture’ supports the need for face-to-face interaction for creating a sense of community with peers and tutors (Conole, 2008; Grieve, 2019; Kemp, 2014). Particularly in densely populated urban settings like Hong Kong, where many students reside with their families, the 24-hour accessibility to studio facilities becomes indispensable, supporting long working hours and providing dedicated spaces and resources for model making (Hargreaves, 2005; Healey and Jenkins, 2009). (Kvan and Thilakaratne, 2003) emphasize the significant role played by physical models in design conversation. Role of full-scale model construction has been a proven as an effective andragogical instruments in studio settings (Amato et al., 2005, 2003).

Studios have evolved into multifunctional 'work,' 'live,' and 'play' environments for architecture students (Groat and Wang, 2013). The culmination of semester-long design projects is celebrated at final design critiques, where students showcase their work through printed design panels and physical models, engaging in critical design discourse with invited external critics, studio tutors, and fellow students (John Zeisel, 1984; Schenk, 2017).

In the late nineties and early 2000 years, there have been a variety of successful Virtual Design Studios (VDS) that transformed the design studio into a online only format. They varied from local to internationally distributed studios (M.A. Schnabel & J. J. Ham, 2014; M.A. Schnabel & T. Kvan, 2003).

The outbreak of the COVID-19 pandemic necessitated an abrupt shift from traditional face-to-face educational methods to online learning, with minimal time for preparation or adaptation. Predominantly, platforms such as ZOOM and TEAMS were employed for remote instruction, supplemented by MOODLE or similar content management systems. Both ZOOM and TEAMS, primarily designed for video conferencing, offered limited capabilities for interactive and engaging learning experiences. These observations align with findings from (Cho et al., 2023) who underscored the challenges posed by remote learning environments.

Typically, distance and online learning programs are designed with an inherent emphasis on learner responsibility and self-directed learning (Anderson and Dron, 2011; Garrison and Cleveland-Innes, 2005). However, the unanticipated transition left little room for the comprehensive transformation of curricula or program structures to suit online delivery. Consequently, students often assumed passive roles in the learning process, displaying lower levels of engagement and commitment (Swan et al., 2009; Vonderwell and Zachariah, 2005). Previous studies have consistently emphasized the importance of active engagement and exploration to foster higher-order learning (Garrison and Cleveland-Innes, 2005; George Siemens, 2006; Kolb, 1984), a pedagogical model deeply rooted in the tradition of design studio education spanning centuries.

2. Methodology

2.1 Data Collection Process

In order to gain insights into the effectiveness of online learning during in architectural education, we conducted an online survey to gather perceptions from both undergraduate and postgraduate students who experienced both online and face-to-face learning within a relatively short timeframe.

This study was conducted in accordance with ethical guidelines and institutional review board requirements. We obtained informed consent from all survey participants and interviewees, assuring them of the confidentiality of their responses.

2.1.1 Survey Respondent Selection

To ensure a representative sample, we employed a stratified sampling technique, that categorized students based on their academic level (undergraduate or postgraduate) and selecting a random sample from each category. The sample consisted of fifty-three undergraduate architecture (BSc Architectural Studies) students and thirty-eight postgraduate (MArch) students from the same institution. This diverse sample allowed for a comprehensive examination of perspectives across different levels of architectural education.

2.1.2 Interviews with Educators

In addition to the survey, we conducted interviews with ten experienced studio teachers from undergraduate and postgraduate levels who are involved in teaching studios and theory courses. These teachers represent, history & theory, architectural design and technology domains in the curricula. Questions focused on pros and cons and suggestions for improving online studio experience and adaptability of online learning for theory courses. These interviews provided a qualitative dimension to this study, enriching our understanding of the challenges and opportunities faced by both students and educators.

2.2 Survey Instrument

The survey consisted of 25 questions; 17 Likert scale questions that are ranked from 1-10, 3 multiple choice questions and 5 open-ended questions. Questions were designed to investigate various dimensions of the online learning experience, specifically focusing on learning in design studios and theory courses when delivered online compared to the traditional face-to-face format. Questions focused on quality and effectiveness of online learning in architectural education, prospects and limitations, impact on students' academic performance and direction for future architecture education.

2.3 Data Analysis

Data sets included both quantitative and qualitative responses. Descriptive statistics were used to analyse and summarize quantitative data. Qualitative data were analysed using thematic coding and content analysis, to extract deeper insights from the open-ended responses. Knowledge from literature reviews validated and contextualized our findings.

3. Results and discussion

3.1. Quality and effectiveness of learning

The preferences and experiences of students and teachers shed light on the quality and effectiveness of online learning in architecture education. Students who displayed resilience in adapting to the online learning environment often highlighted their preference for face-to-face studio sessions, the value of studio culture, and access to physical facilities. Impressively, 73% of students emphasized the importance of face-to-face studio interactions, while 70% acknowledged the value of maintaining the studio culture. Additionally, 66% of students, particularly those in their graduating years, stressed the need for access to printing and model fabrication facilities. Figure 1 presents these preferences, that notably remained consistent across both undergraduate and postgraduate levels.

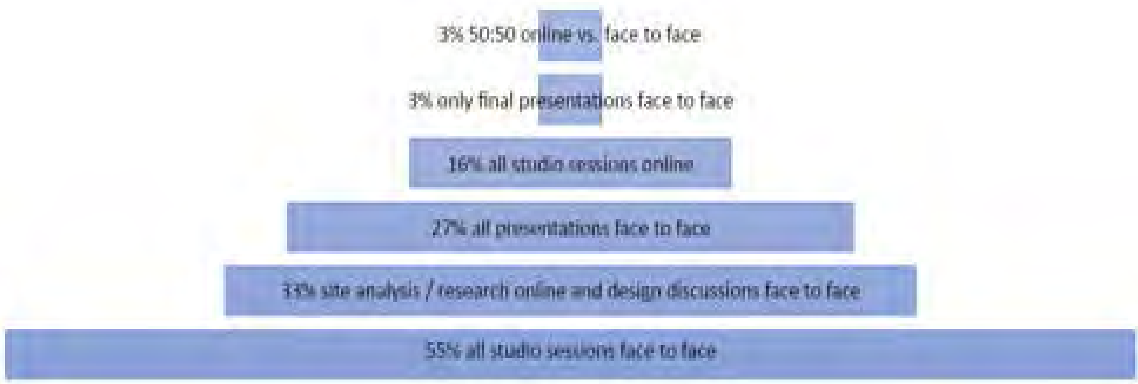

Figure 1: Students' preferences for online vs face-to-face studio during different project stages.

Some stages in the design process, such as research, site analysis, programme development and validation, demonstrated successful adaptation to online studio environments, with 79% of students reporting effectiveness and progress during these stages. However, challenges emerged during teamwork, suggesting that certain collaborative elements were compromised in the online setting. Conversely, design studio courses, which heavily rely on face-to-face discussions, faced difficulties in transitioning to an online mode. Notably 68% of students reported a negative impact on their studio performance during online studio sessions, with 61% expressing limitations in freely expressing design ideas through online platforms. 83% appreciated having access to recordings of online sessions for revision purposes, especially when English is their second language.

Teachers also shared their experiences, highlighting the unprecedented challenges posed by the shift to online instruction. Unlike physical studios, teachers found it difficult to maintain students' momentum remotely, impacting the overall learning experience, group dynamics, and the quality of output. In physical settings, learning is enriched by discussion, interactions, and emotions; all of which were challenging to replicate in the online environment. A design tutor who has been teaching the Master of Architecture studio for over five years shared his opinion about the importance of face-to-face interaction; “it is difficult to observe students’ reactions through an online platform as often they turn off their videos; facial expressions and emotions are important non-verbal forms of communication that helps tutors to read students, for example whether they understand or agree with the discussion”. Another tutor’s response was “we are not certain whether they are attentively present during the whole group discussion as they typically don’t respond to their peers’ projects. Tutors need to initiate this layer of engagement during the online studio, which would organically happen during face-to-face settings”. “Face to face studio interactions and the ‘studio culture’ fosters mutual understanding, and trust that leads to enhancing confidence and hence good academic performance especially in small group settings”. Conole, 2008; Grieve, 2019; Kemp, 2014 share similar views.

Notably, the online platforms struggled to facilitate traditional design discussions that involve tracing paper sketching and rough study models that supported perception of scales, options comparison and constructability. These limitations were especially challenging for junior students. There was a clear consensus among both students and teachers about the necessity of resuming face-to-face teaching, particularly at the beginning of design projects, to foster coherent flow of ideas through sketching, models, and discussions (Amato et al., 2005; Kvan and Thilakaratne, 2003).

3.2 Prospects and constraints in online learning

While challenges were evident, 57% of students indicated improvements in time management, and 60% reported enhanced self-discipline and learner responsibility compared to face-to-face learning. On a positive note, online platforms offered efficient utilization of various media and digital resources, opening up limitless possibilities for collaboration with overseas universities and guest critics, aligning with the findings of (Iranmanesh and Onur, 2021). A tutor shared that she was able to invite guest critics from overseas universities for online studio reviews, which would not have been possible otherwise.

Recognizing the growing importance of online communication in professional settings, this experience could serve as a precursor for future workplace scenarios. Teachers also appreciated the ‘small groups/ breakout rooms’ function in online platforms that improved participation in discussions. These platforms offered valuable features, including the recording of lectures and studio discussions, attendance reports, and user statistics. Moreover, online platforms eliminated certain limitations inherent in physical studios and classrooms, such as background noise and the need for facility bookings. Additionally, students appreciated saved commute time and access to recorded lectures, findings consistent with the study by (Murray et al., 2023).

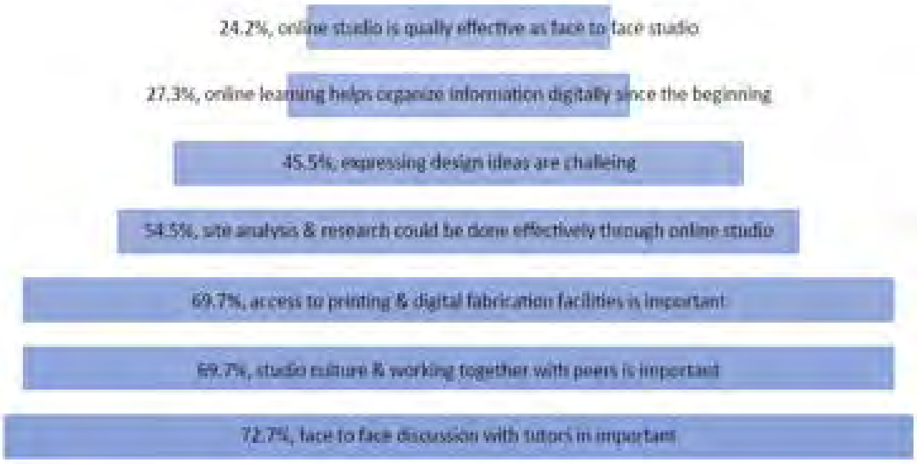

Figure 2: Pros and cons of online learning mode specifically through the ZOOM platform.

Figure 2 summarizes the pros and cons of online learning mode specifically through the ZOOM platform. Students expressed challenges when expressing design ideas and engaging in discussions with tutors and peers through online platforms. Background noise, lack of privacy at home, internet connectivity issues, prolonged screen time, and difficulties understanding lectures, especially for technology-focused courses, which often require hands-on experimentation further justified the limitations. Over 75% of students emphasized the importance of face-to-face studio sessions for effective learning. Certain tools and processes that aid design learning, such as access to printing and fabrication facilities, the nurturing of studio culture, and face-to-face discussions with tutors and peers, remained fundamental to students' learning experiences.

However, there was notable differences between the preferences for online learning for design studios vs. learning theory courses. Educators who teach technology related subjects expressed the challenges in demonstrating certain technologies and equipment and building visits. One educator who teaches history and theory expressed higher class attendance with online learning and the opportunity for him to use several modalities. Figure 3 presents students' preferences for online studios vs learning theory courses online.

Figure 3: Students' preferences for online learning for design studio vs. theory courses

3.3. Impacts on students' performance

The shift to online learning had discernible impacts on students' academic performance and overall learning experiences that were reflected on their project outcomes. Certain compromises made such as replacing physical models with walk-through videos or animations and online final presentations instead of face-to-face open reviews seem to have affected students' motivation and perception of their optimal performance (Amato et al., 2005; Kvan and Thilakaratne, 2003).

The absence of face-to-face interactions and the constraints of online platforms often led to a sense of disconnection and reduced engagement among students. This resulted in some students struggling to meet the expected learning outcomes, particularly in design studio courses where collaborative problem-solving and immediate feedback are integral to the learning process. A significant number of students reported challenges in maintaining their academic performance through online learning environment.

Moreover, junior students reported notable setbacks in their academic progression. The absence of physical studio spaces and working with physical models during the process hindered their design development. It was evident that the online format did not provide an adequate substitute for the tangible experiences typically associated with architectural education. Furthermore, the technical challenges, such as unreliable internet connections and difficulties in accessing required software and resources, further hindered their performance.

The absence of peer-to-peer interaction and the limited opportunities for spontaneous discussions with tutors also had a negative impact on students' academic experiences. Many students reported feelings of isolation and missed the camaraderie that is often fostered through face-to-face interactions in studio culture. These social and collaborative elements, that are essential for comprehensive learning, were challenging to replicate in the online environment.

Figure 4: Students' opinion on whether their learning ability improved with online learning.

3.4. Future learning models

As we map the course for the future of architectural education, it is imperative to not only acknowledge the lessons learned during the pandemic but also to remain attuned to the cutting-edge developments that are reshaping the educational landscape. The architecture profession is undergoing a profound transformation driven by digital innovation, AI, Web3 technologies, and the burgeoning metaverse. Here, we explore the evolving landscape of architectural pedagogy and the potential integration of these advancements.

3.4.1. Design education beyond borders

Twenty-four-hour studios collaborating with overseas architecture schools and design practices is a an advantage of online learning. This approach will add diversity and exposure to education programmes offered in other schools, learn from experts, share resources and innovative technologies, opportunities for research collaborations, greater understanding of future higher education and overseas internship opportunities.

3.4.2. Hybrid learning reimagined.

In a post-pandemic era, the concept of hybrid learning takes on a whole new dimension. Beyond the mere blending of in-person and online education, the hybrid model must adapt to harness the power of emerging technologies. The metaverse, a parallel digital universe, allows for immersive and collaborative design experiences that bridge geographical boundaries (Sheenan, 2021) . Architecture students could explore virtual studio spaces, engage in design critiques with peers from around the world, and create interactive architectural simulations.

3.4.3. Decentralized learning communities

Web3, characterized by decentralized networks and blockchain technology, offers the potential to revolutionize how architectural education is delivered and experienced (Tapscott and Tapscott, 2016). The Web3 era empowers students to take ownership of their education through decentralized learning communities. By leveraging blockchain-based platforms, students can curate their educational journeys, select courses from a global marketplace of offerings, and earn credentials on a blockchain ledger that is recognized worldwide (Government, 2018). These platforms facilitate peer-to-peer learning, enabling students to collaborate directly with experts and fellow learners, transcending the constraints of traditional educational hierarchies (Tapscott and Tapscott, 2016).

According to the (OECD, 2021), AI has made significant strides in personalized learning. AI algorithms can analyse students' learning patterns and tailor educational content to their specific needs by utilizing AI-driven learning management systems.

3.4.4. Metaverse-enabled design studios

The metaverse, with its immersive 3D environments and virtual reality capabilities, opens up new horizons for design studios (Baszucki, 2021). Architectural students can gather in virtual spaces to co-create designs, simulate built environments, and engage in real-time design critiques. Virtual architecture studios equipped with spatial design tools enable students to translate their ideas into digital prototypes, fostering a more fluid and dynamic design process (Ferguson et al., 2020).

3.4.5. Augmented Reality (AR) and Virtual Reality (VR) integration

Augmented and virtual reality technologies continue to evolve, providing architectural students with powerful tools for design exploration (Liarokapis et al., 2020). By integrating AR and VR into the curriculum, students can visualize their designs in three dimensions, walk through virtual buildings, and experiment with spatial configurations in real time. These immersive experiences enhance design comprehension and creativity, bridging the gap between theoretical concepts and tangible architectural solutions (Ochoa, 2017). These technologies allow experience of projects that are not easily accessible, i.e. conservation sites, overseas projects.

4. Conclusions and way forward

In conclusion, our study delved into the effectiveness of online learning in architectural education during the COVID-19 pandemic, addressing several key research questions. We aimed to discern the impact of online instruction on students' learning experiences, identify challenges faced by both students and educators, and explore potential adaptations for the future. Through a combination of surveys and interviews involving students and teachers, we have gained valuable insights into the evolving landscape of architectural education.

4.1. Addressing the Research Questions

Our first research question focused on assessing the quality and effectiveness of online learning in architectural education. The findings reveal that while certain aspects of the design process, such as research, site analysis, and programme development adapted successfully to the online learning environments, the unexpected transition posed significant challenges to design stages that depended on face-to-face interactions. Junior students, in particular, experienced reduced engagement and setbacks in their academic progression.

The second research question probed into the positive aspects and limitations of online learning. While some students reported improvements in time management and self-discipline and saved travel time the study highlighted the continued importance of face-to-face studio sessions, access to physical facilities, and the nurturing of the studio culture. Challenges persisted in freely expressing design ideas and engaging in meaningful discussions online.

The third research question investigated the impact of online learning on students' academic performance. The data showcased that maintaining the same level of performance in online environments proved challenging for many students. The absence of peer-to-peer interaction and technical challenges further hindered their learning experiences.

4.2. Future Directions

Looking forward, findings and insights from this study offer valuable guidance for the future of architectural education. The enduring value of traditional design studio experiences has been reinforced throughout our research, emphasizing the importance of face-to-face interactions and access to studios and fabrication facilities, especially in Hong Kong where living environments are compact. Physical models could be supplemented with walk-through videos and digital model renderings to reduce the demand for model making facilities during lockdowns.

However, as online teaching continues to be a relevant component of education, we advocate the optimization of current teaching platforms and curricular adjustments to bridge the gap between traditional and online learning. To enhance the online learning experience, we propose several critical measures, including access to well-equipped computer rooms at the school, encouraging students to keep their cameras on during online sessions, and curriculum adjustments that incorporate interactive elements.

It was evident that certain stages of the design process such as site analysis, research and validation could be effectively done through online studios. Hence, a balanced fusion of the best attributes of in-person and online education, known as the hybrid approach, is recommended. This approach can offer students a flexible and adaptive learning environment that capitalizes on the strengths of both modalities.

In summary, our research contributes to the ongoing dialogue surrounding the future of architectural education. By addressing the research questions and highlighting potential avenues for improvement, we aim to ensure the resilience and relevance of architectural education in a rapidly changing world.

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Architectural green infrastructure: Native living wall impacts on building façade microclimates

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Abstract: Living walls can improve building envelope performance and contribute to human well-being; however, their value to native biodiversity is often not considered in their design or the study of their performance. Native biodiversity is essential for ecosystem health and the provision of ecosystem services that support human well-being and foster climate adaptation. This research aims to quantify and assess the biodiversity and cooling effects of native living walls on building façades in Wellington, Aotearoa New Zealand. Light and temperature data were collected from two types of felt-pocket living walls over six months. The living walls provided up to 89% more shade than bare walls. Temperature impacts were most notable during the hottest part of the day, with the living walls recording substrate air temperatures that were 0.8 – 1.3°C (5-8%) cooler than bare walls. The living walls with smaller, denser plant pockets supported more native plant biodiversity and had higher leaf coverages and cooling effects than those with larger pockets. This research demonstrates a potential alignment between biodiversity and thermal performance outcomes for living walls, which could help inform the design of living walls that optimise cooling effects while providing diverse plant communities for local, native biodiversity in warming cities.

Keywords: Living walls; urban biodiversity; urban cooling; green infrastructure.

1. Introduction

The habitat loss and degradation that result from rapid and increasing urbanisation are a primary threat to global biodiversity (Ceballos *et al.*, 2015). The disruption to ecosystems and the pollution caused by built environments also drive climate change at local and global levels (Garrard *et al.*, 2018). Built environments are responsible for 38% of global carbon emissions (United Nations Environment Programme, 2020), with building envelopes (walls and roofs) affecting a significant portion of overall building energy consumption (Capeluto, 2019). The interlinked issues of biodiversity loss and climate change destabilise ecosystems, which will make sustaining biodiversity in built environments increasingly difficult as climate change impacts, such as flooding, coastal inundation, and heatwaves, degrade or reduce the already limited habitat provided by urban green spaces (Mahmoud, 2020). However, growing evidence shows that integrating vegetation with building envelopes could contribute to a potential solution to these interlinked issues (Pedersen Zari, 2016; Irga et al., 2023).

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The habitat provision and building thermal performance benefits of green roofs have been well documented in the literature (Partridge and Clarke, 2018). However, wall area can greatly exceed roof area for multi-story buildings. Though less well-studied than green roofs, green walls present an opportunity to increase the amount of vegetation in cities despite the limited availability of horizontal open space (Chen *et al.*, 2020). Living walls, particularly, have demonstrated some biodiversity and thermal performance benefits (Wang *et al.*, 2022). Living walls consist of a modular system of stacked plant pots/pockets containing a growth substrate with an integrated irrigation system, enabling them to support a wider variety of plant species than other green wall types (Bustami *et al.*, 2018). Living walls have been shown to improve the thermal performance of building envelopes by providing shade and cooling the air through evapotranspiration (Perez *et al.*, 2014). A review conducted by Ascione *et al.* (2020) found that living walls can reduce external wall temperature by up to 30°C and provide up to 75% energy savings depending on the climate. Less research has been conducted on the biodiversity of living walls (Filazzola *et al.*, 2019). However, there is evidence that suggests positive relationships between vegetation on walls and bird abundance (Chiquet *et al.*, 2013). A review by Radic *et al.* (2019) demonstrated living walls' ability to provide resting and nesting habitat for important pollinator species, like birds, butterflies, bees, and other insects.

While cities may be in short supply of available ground-level habitat, there is an abundance of underutilised building envelopes that could provide habitat for species in cities while improving building thermal performance. Though there is promising evidence of the thermal performance and biodiversity benefits of living walls, research on these benefits is often conducted separately. This limits our ability to identify potential relationships between biodiversity and thermal performance that could be managed or optimised in living wall designs. This research investigates native living walls in Wellington, Aotearoa New Zealand, to quantify and assess biodiversity and cooling effects. The objectives of this research are to quantify the diversity and growth of native plant communities on living walls and measure their light and temperature impacts on the façade microclimates to identify any potential synergies or trade-offs. Identifying synergies between biodiversity and thermal performance outcomes for living walls could inform how living walls are designed to maximise both benefits to urban biodiversity and building envelope performance. If applied at a large scale, these living walls could help address habitat loss and carbon emissions in urban environments, which contribute to the global interlinked issues of species loss and climate change.

2. Materials and Methods

2.1. Site

Wellington is located on the North Island of Aotearoa New Zealand, in the South Pacific, with a population of 203,000 (Statistics New Zealand, 2018). The region's native plants are adapted to its coastal, temperate climate and high winds and support the many endemic bird species unique to Aotearoa New Zealand (Parlato *et al.*, 2015). The living wall experimental setup was constructed on the Te Herenga Waka Victoria University of Wellington Kelburn campus in Wellington, Aotearoa New Zealand (Figure 1). It was the site of a recently demolished house in a small valley of native vegetation, neighboured by academic and residential buildings. The remaining concrete retaining walls, one facing south and one facing east, were used as a base for the construction of seven 1m x 1m timber-framed wall panels. However, the total treatment area for each wall panel was 1m x 1.5m by using 500mm of the concrete retaining walls.

Two wall panels, one on each retaining wall, were left bare to act as a comparison for the living walls and control for the impact of orientation on measurements (Figure 2). The felt-pocket style of living walls was selected for this experiment due to its commercial availability, affordability, and ease of installation. Four 1 x 1.5 m living walls were attached to the wall panels, two small-pocket (54 pockets 150mm x 160mm in size) (Trade Tested, 2023) and two large-pocket (12 pockets 220mm x 300mm in size) living walls (Hanging Gardens, 2023). One of each living wall type was installed on the south and east orientations. A 1 x 1.5 m polystyrene insulation panel (50.8mm thick) was attached to the last east-facing wall panel to compare the impacts of vegetated and non-vegetated external insulation techniques on shading and cooling.

Figure 1: The site for the experimental living wall setup was situated in a valley of native vegetation, neighboured by residential and academic buildings, resulting in a partially shaded environment. (Source: Author with datasets from Eagle Technology (2022) and Wellington City Council (2018))

Figure 2: The experimental living wall setup in Wellington, Aotearoa New Zealand, in February 2023. The bare walls act as controls for orientation and are used to compare the effects of the living walls. (Source: Author)

2.2. Plant Community

The target plant species selected for the living walls were all Aotearoa New Zealand natives that could tolerate the partial shade conditions of the site and produce nectar, fruit, or seeds for native birds (Table 1) (Wellington City Council, 2023; Leacroft Nurseries, 2023). Native birds are a high conservation priority in Aotearoa New Zealand due to their endemism and cultural significance (Department of Conservation, 2020). Plants were grown and installed on the living walls with a good-quality potting mix as the growth medium. The position of the plants on the walls was determined by plant size and shading from neighbouring plants. Due to the relatively large size of the nursery plants, not all pockets on the small-pocket living walls could be filled without risking overshading neighbouring plants. An automatic irrigation system watered the living walls twice daily for four minutes in the morning and afternoon.

Once the plants were installed on the living walls, Shannon's Diversity Index (H) (Shannon and Weaver, 1963; Tramer, 1969) was used to calculate the plant diversity of the living walls.

$$H = -\sum p_i * \ln(p_i)$$

Where:

p_i = proportion of the plant community comprised of species i.

As the value of H increases from 0 (a community with one species), the higher the diversity of the plant community, with typical values ranging from 1.5 to 3.5 (Ortiz-Burgos, 2016). Because the formula requires at least one species present, Shannon Diversity Index values could not be calculated for the control and insulation panel walls as no plant species were present throughout the entire study period.

ImageJ version 1.54t (Rasband, 2022) is a free image processing program that can be used to analyse plant characteristics and growth in a non-destructive way (Agehara, 2020). Images of the seven wall panels were taken 2-3 times a month from August 2022 to February 2023 using an iPhone 6 (2022 images) and iPhone 13 (2023 images). Photos were then cropped in Photoshop to the wall panels' dimensions (1 x 1.5 m). Images were opened in ImageJ, and the scale was set based on the width of the wall panels (100 cm). The colour threshold was adjusted to isolate green pixels to determine the percentage of leaf coverage. The selection of green pixels was edited using the Binary, Paintbrush, and Noise tools to ensure only green pixels from plants were included. The measurements were set to "Area" and "Limit to threshold" and measured, yielding an area result in cm^2.

Table 1: Living wall plant community species and abundance.

South Small-Pocket	East Small-Pocket	South Large-Pocket	East-Large Pocket
Acaena anserinifolia (2) *Arthropodium cirratum* *Carpodetus prostrata* *Coprosma lucida (2)* *Coprosma repens (2)* *Coprosma robusta* *Dianella nigra (2)* *Griselinia littoralis (4)* *Kunzea ericoides (2)* *Macropiper excelsum (3)* *Metrosideros carminea (3)* *Muehlenbeckia complexa (8)* *Phormium cookianum (3)*	*Acaena anserinifolia (2)* *Arthropodium cirratum (2)* *Coprosma kirkii* *Coprosma lucida (2)* *Coprosma repens (3)* *Coprosma robusta (3)* *Dianella nigra* *Griselinia littoralis (5)* *Kunzea ericoides (2)* *Macropiper excelsum (2)* *Metrosideros carminea (3)* *Muehlenbeckia complexa (6)* *Phormium cookianum (2)*	*Arthropodium cirratum (3)* *Carpodetus prostrata* *Dianella nigra (2)* *Metrosideros carminea* *Muehlenbeckia complexa* *Phormium tenax (2)* *Pittosporum 'golf ball'* *Pittosporum 'silver ball'*	*Arthropodium cirratum (2)* *Carpodetus prostrata (2)* *Dianella nigra (2)* *Metrosideros carminea (2)* *Phormium tenax (2)* *Pittosporum 'golf ball'* *Pittosporum 'silver ball'*

2.3. Light and Temperature

Light levels were measured at the wall substrate and 20 cm from the substrate using a Protech Multifunction Environment Digital Multimeter (QM1594) (Jaycar, 2023). Measurements were taken at midday (11:30 – 14:00) at least four times per month from August 2022 to February 2023 (excluding September 2022 due to changes in experimental methods that were unsuccessful).

Inkbird Smart Thermometer Temperature and Humidity Monitor Hygrometers (IBS-TH2 Plus) (Inkbird, 2023) were installed on the experiment walls from September 2022 to February 2023, with a protective plastic covering (Figure 1). The plastic coverings had holes drilled into them along the bottom so they would have the same ambient temperature as the surrounding air. The hygrometers took measurements every 10 minutes. The stored measurements were downloaded once a week using the Engbird app (Shenzhen Inkbird Technology, 2023) and exported as Excel files for data analysis.

3. Results

3.1. Plant Community

Both living wall types supported at least 7-13 different plant species. The higher density of pockets on the small-pocket walls resulted in 2.3 times more plant diversity than the large-pocket walls (Table 2). The overall plant survival rate for the four living walls was 96%. One *K. ericoides* plant died on the south small-pocket wall due to shading from neighbours and was not replaced, decreasing the diversity of the wall by 2.5%. The *Pittosporum* cultivars were not thriving and were replaced in October 2022 with *C. repens* and *P. cookianum* on the south large-pocket wall (no loss of wall diversity) and *G. littoralis* and *A. cirratum* on the east large-pocket wall (6.5% loss of wall diversity) that were left over from the initial living wall construction. The plant diversity of the small-pocket walls remained 2.3 times more than that of the large-pocket walls.

The average leaf coverage of the four living walls over the study period was 53% (Figure 3). The east and south small-pocket walls had average leaf coverages of 57% and 64%, respectively. Leaf coverage was, on average, 15% lower for the large-pocket walls (44% coverage for the east wall and 46% coverage for the south wall). Leaf coverage on all living walls increased from August 2022 to February 2023, with a 32% and 15% increase for the east and south small-pocket walls, respectively, and a 23% and 14% increase for the east and south large-pocket walls, respectively. More growth occurred on the east walls than on the south. The south small and large-pocket walls started with 21% and 11% more leaf coverage, respectively; however, by the end of the study period, there was only a 1-2% difference in leaf coverage compared to the south walls.

Table 2: Shannon Diversity Index for the living walls.

Living Wall	# of Species	# of Plants	Shannon's Diversity Index
South Small-Pocket	13	34	2.38
East Small-Pocket	13	34	2.44
South Large-Pocket	8	12	1.07
East Large-Pocket	7	12	1.04

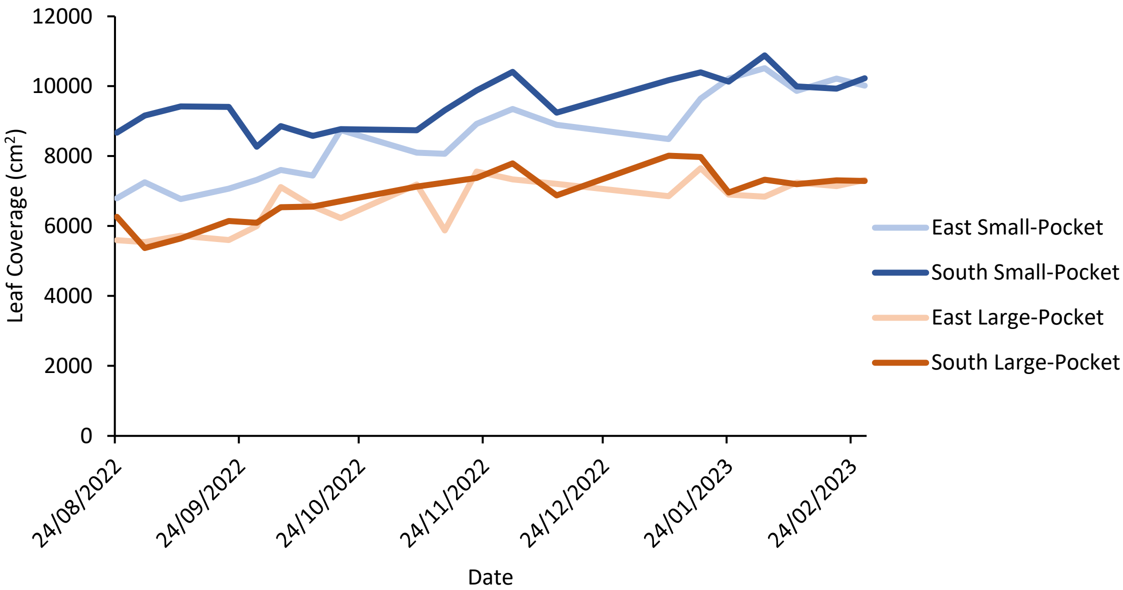

Figure 3: Living wall leaf coverage from August 2022 to February 2023. The control and insulation panel walls had zero leaf coverage throughout the study period and were not included in the graph.

3.2. Light

On average, the living walls provided 72-90% more shade than the bare walls (Figure 4). The small-pocket walls provided the most shade of all the wall types, with an average of 93% and 74% lower light levels at the substrate and 20 cm from the substrate, respectively, compared to the control walls. The large-pocket walls provided slightly less shade, with an average of 86% and 71% lower light levels at the substrate and 20 cm from the substrate. There was no consistent impact of orientation on light levels due to shade from neighbouring buildings and trees. The insulation panel wall was the least shaded by neighbouring vegetation and buildings, resulting in large light level differences (97% at the substrate and 82% 20 cm from the substrate) compared to the bare walls. Therefore, shading from neighbouring objects must be considered, in addition to orientation, when interpreting the plant growth and temperature results for different wall types.

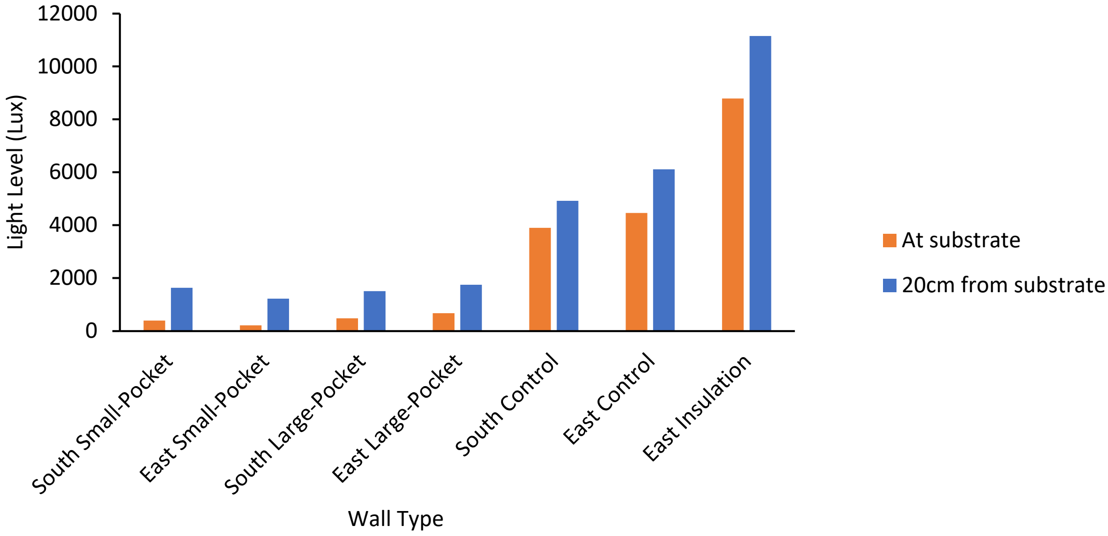

Figure 4: Average midday light level measurements over the study period.

3.3. Temperature

When calculated as monthly or daily averages, the variations in substrate air temperatures of the different wall types were minor. The air temperatures of the living walls were, on average, 0.3 - 0.4°C (2 – 3%) cooler compared to the control walls. Due to its unshaded position, the insulation panel wall recorded, on average, 1°C (6.5%) higher air temperatures than the control walls, which were partially shaded by overhanging tree branches. However, the temperature variations between the different wall types fluctuated over the day, with air temperatures similar at night but diverging during the day, particularly during the hottest part of the day (12 – 14:30) (Figure 5). On average, the small-pocket and large-pocket walls recorded 1.3°C (8%) and 0.9°C (5%) cooler temperatures, respectively, than the controls during the hottest part of the day. There was no noticeable impact of orientation, except for the insulation panel, which recorded 2.9-3.3°C (16.7-19.2%) higher air temperatures than the control walls due to its unshaded position.

(a)

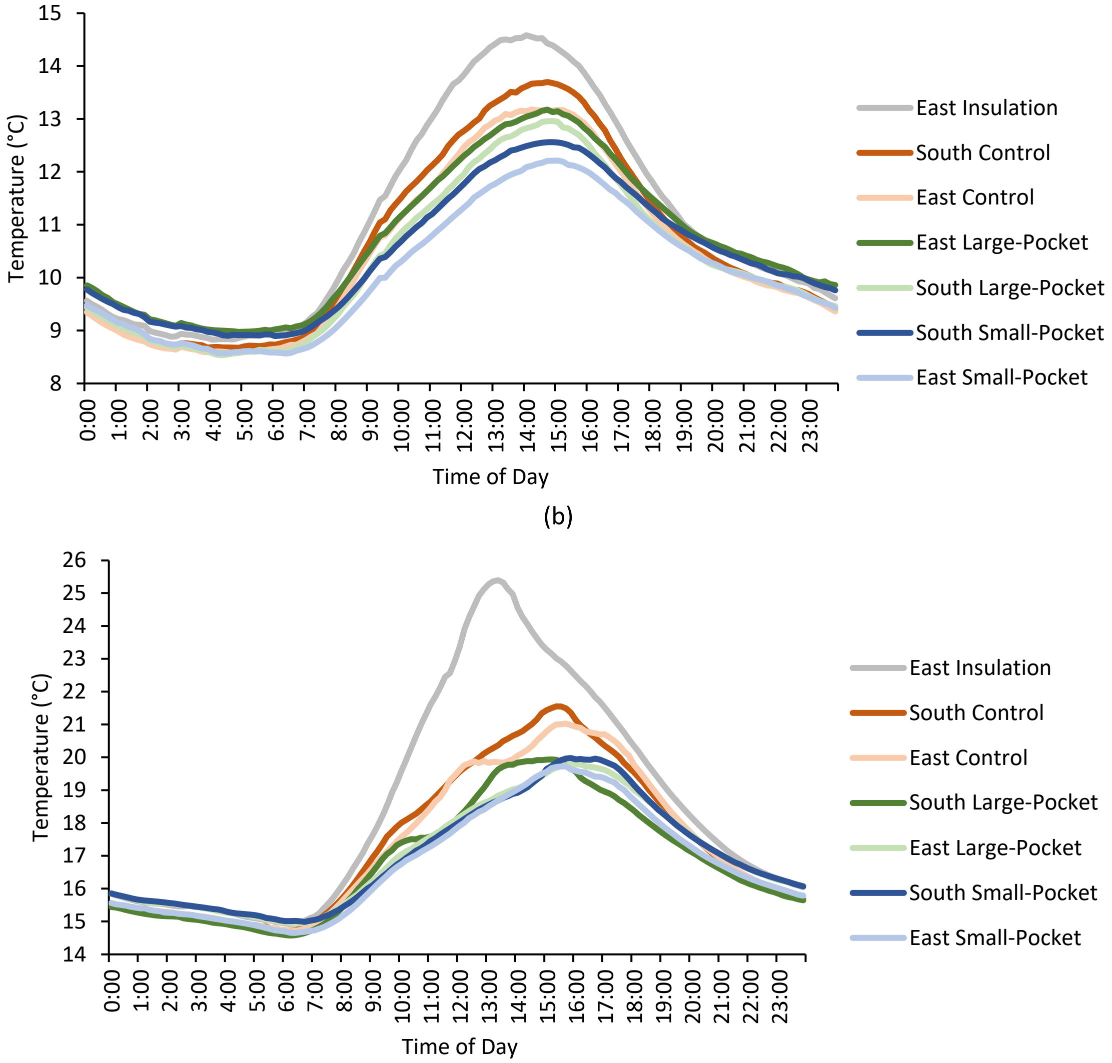

Figure 5: Average daily temperature fluctuations at the substrate for: (a) September (the coldest month during the study period) and (b) January (the warmest month during the study period).

4. Discussion

The results of this study demonstrate that the living walls created a cooler (up to 1.3°C or 8%) and shadier (up to 93%) façade microclimate compared to the bare walls. The small-pocket living walls provided 5% more shade and lowered peak air temperatures by an additional 0.4°C (2.5%) than the large-pocket living walls, likely due to their 15% higher leaf coverage. The small-pocket living walls also supported 2.3 times the biodiversity of the large-pocket living walls, indicating that living wall designs with smaller, denser plant pockets may be better for both plant community diversity and cooling benefits. The most notable impact of orientation was found for plant growth, with the east-facing living walls having up to 17% more plant growth over the study period than the south-facing walls, likely due to their position with fewer overhead branches.

While these results show a potential alignment between biodiversity and building thermal performance outcomes for living walls, there are some limitations to the conclusions that can be drawn from this study. Though the results show that the small-pocket living walls, which had more biodiversity and leaf coverage, had the most cooling benefits, the impacts of the higher diversity of the plant community on air temperature cooling could not be isolated from the impacts of leaf coverage. A future study where monoculture and diverse living walls with similar plant coverages are compared could help isolate the impact of plant community diversity on cooling effects. Despite having less diversity and lower leaf coverage, the large-pocket living walls supported larger individual plants. Future research should consider whether plant size impacts living walls' ability to support other species, such as insects and birds, to more holistically consider biodiversity benefits during design. There were also some limitations to the native plants available from local nurseries, which could be improved in future studies by collecting seeds from the desired local native forest plants (particularly epiphytes) and growing them in a small nursery before transplanting them to living walls. This also could have facilitated the selection of more shade-tolerant species that may have flourished on the more shaded bottom sections of the living walls. Though the experimental design attempted to control for orientation differences, the more significant variability came from shading from neighbouring vegetation and buildings. This could be better controlled for in future studies by selecting a more open location with fewer tall neighbouring objects. In addition to orientation and wall position, some of the variability in the leaf coverage results was due to the impact of different outdoor lighting conditions at the time of imaging on how well ImageJ detected green pixels.

This is the first study to quantify the shading and cooling effects and biodiversity of living walls in Aotearoa New Zealand. However, similar results have been found in international research on building wall vegetation. Dede et al. (2021) found maximum temperature reductions of 3-6° for the different green walls studied compared to the bare building. Zhang et al. (2019) found that a vertical green façade reduced peak outdoor temperature by 2.7°C during hot days in the subtropical city of Guangzhou, China. Freewan et al. (2022) found that, in a hot climate, living walls lowered peak air temperature by 6 - 11°C. Using different leaf coverage scenarios, the authors found that 60% leaf coverage provided 1.5°C more cooling than 50% leaf coverage; however, there appeared to be a plateau in cooling benefits at 80% leaf coverage. Suárez-Cáceres et al. (2023) examined the growth of seven ornamental grass species on living walls in a Mediterranean climate and found leaf coverages of 40-79% over the study period, which is a similar range to the leaf coverage (44-64%) of the living walls in this study. However, leaf coverage could have been improved by using plants with denser foliage and may have resulted in larger temperature differences between wall types. Wellington's more temperate climate and/or the partially shaded experimental site may also have contributed to the smaller temperature differences found in this study compared to Zhang et al. (2019) and Freewan et al. (2022). Tang et al. (2021) found that the average temperature reduction was 7-13% more for green facades with irrigation compared to those without irrigation, indicating that irrigation contributes positively to the evapotranspiration cooling effect of living walls. The 96% plant survivorship on the living walls in this study was on the high end of the plant survivorship ranges found in other studies (Suárez-Cáceres et al., 2023; Dvorak et al., 2021), likely due to the hardiness of the locally-adapted native plant species selected, but it could have been improved by more careful plant positioning to avoid overshading by neighbours.

Several areas of future research would improve and expand upon the results of this study. This research monitored living walls planted with local, native Wellington species that provide resources for native birds; however, many other plant species, growth media, and living wall styles should be investigated to develop living walls that maximise the benefits to local species and ecosystems. Plant selections and irrigation regimes also need further research to increase leaf coverage and optimise the cooling effect of living walls while reducing irrigation demands. Quantifying the biodiversity and thermal performance benefits of living walls, particularly in different seasons and climates, could increase their implementation by building owners and drive their integration into policies and building codes related to biodiversity and climate change.

5. Conclusion

As cities warm and building regulations become more strict on energy usage, native living walls could be an important tool for improving the thermal performance of buildings while providing vegetated habitats for urban species. Increasing the implementation of living walls will require theoretical and practical knowledge from ecologists, horticulturalists, and architects working in collaboration to produce effective living wall designs and supportive policies to incentivise their implementation by developers and building owners. Describing and optimising the synergistic relationship between biodiversity and thermal performance outcomes for living walls could inform urban greening strategies that use buildings to regenerate habitats and the vital ecosystem services they support, leading to healthier and more resilient cities.

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Assessing opportunities for enhancing home thermal efficiency in Australia

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Abstract: Majority of Australia's housing stock lack optimal thermal and energy performance necessary to transition to low energy and net zero carbon future. Improving dwelling thermal efficiency in both existing and new housing is a critical opportunity area for low-energy and net-zero carbon transition. An opportunity assessment was conducted to engage with industry stakeholders to examine and deliberate upon current issues and challenges related to home thermal efficiency improvements. Out of the eight research themes identified to accelerate the adoption of home thermal efficiency, four were ranked by industry as high priority: *building fabric*, *home thermal performance assessment*, *home retrofits and decarbonisation* and *benefits of improved thermal performance*. The study also conducted a scenario modelling using a database of dwelling designs to assess thermal performance and potential for energy efficiency improvements. Results show that improvements to 5 per cent of the entire housing stock would result to energy cost savings of upwards of around AUD185 million-AUD439 million per year and estimated CO_2 emission reductions of 12.58 to 28.78 Mt CO_2. This paper reports on the assessment undertaken in identifying the research opportunities and focuses on the top ranked priorities established by industry.

Keywords: home thermal efficiency; building performance; home retrofit; building decarbonisation.

1. Introduction

Buildings use an estimated 30 per cent of the energy consumed worldwide (UNEP, 2020). Energy consumption in residential buildings is a major contributor to global anthropogenic carbon emissions (IPCC, 2022). In Australia, buildings account for around 19% of the total energy use and 18% of direct carbon emissions (Commonwealth of Australia, 2023). Residential buildings account for approximately 8.4% of total energy use (Commonwealth of Australia, 2022), 24% of overall electricity use and 12% of total carbon emissions (DCCEEW, 2022b). Depending on the climate zone, heating and cooling can account for 20-50% of energy used in residential buildings (DCCEEW, 2022a). Given the effects of climate change experienced and anticipated in Australia, energy used to maintain human thermal comfort in the existing housing stock is expected to increase unless there is significant and widespread retrofit action.

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As early as 1990, the residential sector was highlighted as an integral part of the strategy to reduce greenhouse gas emissions, and a key feature in developing Australian climate change mitigation policy. Specific actions and approaches at state and federal levels have varied over time to include voluntary and mandatory approaches, awareness and disclosure programs, industry education and training programs, demonstration projects, providing financial incentives, and developing technical tools (COAG Energy Council, 2018b).

The Australian Building Codes Board (ABCB) introduced into the Building Code of Australia (BCA) minimum energy performance requirements for houses in January 2003. The BCA now forms part of the National Construction Code (NCC) and has been adopted by all states and territories. New residential buildings in Australia must comply with the NCC's energy efficiency provisions prescribed in the building permit. Majority of new residential buildings demonstrate compliance using a Nationwide House Energy Rating Scheme (NatHERS) accredited software tool (replaced with BASIX in NSW). NatHERS estimates the thermal performance of a building shell based on its structure, design, construction materials, and the climate where it is built (DoEE, 2019b). The Star rating system provides estimates of a home's thermal performance – how much energy is required for heating and cooling. The higher the Star rating, the less energy is needed to heat and cool the home to keep it comfortable. A Star rating of 6 or above is required in most parts of Australia for detached dwellings, with some jurisdictions moving to 7 Stars under provisions of NCC 2022 for adoption from 1 May 2023 (ABCB, 2022a; 2022b). In addition to requirements for a 7-Star rating, changes in NCC include introducing an 'energy budget' for major appliance, equipment, and rooftop solar energy performance. Subsequent Building Code updates in 2025 and 2028 will address the need for net zero carbon ready buildings by 2030, including consideration of embodied energy (COAG Energy Council, 2018b). However, embodied energy is not within the scope of this opportunity assessment. The climate files in NatHERS-accredited software tools were updated in 2022 with more recent and more accurate weather data from 1990 to the end of 2015 (DoEE, 2022). New Star bands have been included in NatHERS-accredited software tools (BERS Pro, HERO, FirstRate5) to minimise potential impacts of climate change on energy star ratings. To comply with NCC 2022 standards, NatHERS software has been updated to include a thermal bridging capability, and the revisions require that steel-framed construction energy rating calculations match the thermal performance of timber-framed construction (NatHERS, 2022b).

Australian housing energy standards have improved at various points in time, but they still fall short of world's best practice, both as a minimum performance target, and in what is required to transition to a more energy efficient and environmentally sustainable built environment (ACIL Allen, 2021). Residential buildings in Australia are typically not built to provide a high quality of thermal comfort, and indoor winter temperatures of homes are often lower than in considerably colder countries that require higher minimum standards for insulation, weatherproofing, and energy efficient appliances. Research has shown that Australian homes are generally significantly less energy-efficient than homes in the USA, Canada, and the UK (Horne and Hayles, 2008). Poor thermal efficiency increases energy costs, escalates respiratory and cardiovascular ailments, and exacerbates some mental health conditions (Dignam and Barrett, 2022). In Adelaide, Australia, cold conditions in homes result in increased mortality rates due to unnecessarily low indoor temperatures (Daniel *et al.*, 2019). Furthermore, with 31% households on rentals (ABS, 2022b), poor housing conditions significantly affect renters as owners are not motivated to address the situation. In contrast, owner-occupied homes would have greater incentive and opportunity to make homes thermally comfortable (Liu *et al.*, 2019).

2. Scoping study

This scoping study aimed to identify priority research areas to accelerate the adoption of home thermal efficiency and was conducted through a mix of desktop research (review of Australian and international literature), consultations with key stakeholders and an Industry Reference Group (IRG), as well as modelling various retrofit scenarios. Insights from consultations with the IRG fed into the in-depth literature review and scenario modelling.

An initial orientation of the literature was conducted as a broad scan of the market to identify existing housing stock conditions and performance. This initial review was also aimed at understanding relevant policies on residential energy efficiency, current rates of construction and housing stock upgrade, as well as identifying Australian and international industry practices. Outcomes of the work from the *Trajectory of Low Energy Buildings* (COAG Energy Council, 2022) were reviewed to set the framework for the scoping study. Available research, knowledge, and data were used to map current literature and identify data gaps. Key Australian and international resources were used, and existing technical know-how was leveraged (including emerging in-house data and expertise from several team members' research projects). Furthermore, resources and data were leveraged from energy efficiency programs of key industry partners – Victoria Department of Environment, Land, Water and Planning (DELWP), Commonwealth Scientific and Industrial Research Organisation (CSIRO), New South Wales Department of Planning and Environment (DPIE), and Housing Industry Association (HIA).

The industry reference group (IRG) comprised of RACE 2030 partners and representatives across the building and construction value chain. The 25 IRG members were chosen for their expertise and knowledge about the subject and included representatives from builders, builder associations, windows and weather resistant membrane manufacturers, glass and window associations, insulation industry associations, consumer associations, a professional body of building designers, and other peak organisations. Four (4) IRG workshop-meetings were held between April to August 2022. After the second IRG workshop, a further literature review was carried out and involved in-depth investigation of each of the themes identified in the initial IRG workshops. Concurrently, a scenario modelling was conducted to understand the performance of existing housing stock in Australia and to assess potential improvements in energy efficiency.

From the detailed literature review, a list of barriers or challenges was developed. Stakeholders were interviewed for further clarification. To address the barriers, research questions were developed, and this was summarised into eight themes. These research questions were presented to the IRG to better understand key industry priorities. The top ranked research priorities formed the essential framing elements of this Opportunity Assessment. This conference paper mainly reports on the exercise undertaken in identifying the research priorities and focuses on the top ranked priorities established by industry which revolved around building fabric and improved thermal performance.

3. Opportunity assessment

The research priorities identified through the survey and review of literature and industry collaboration outlines 8 main themes incorporating 22 research questions (Table 5).

Table 5: Home thermal efficiency research opportunities in Australia.

Technology and envelope performance focuses on the baseline set up of Australian housing thermal performance, including ventilation, indoor air quality, and vapour management.
Assessment and quality assurance will identify and test reliable assessment tools for home thermal performance and select tools for cost-efficient retrofit strategies. This theme also focuses on the assessment of air tightness and condensation in the residential construction industry during design, specification, and construction stages to ensure building fabric performance.
Capacity building and delivery seeks to formulate a guide for developing courses for home thermal performance through investigating building specifications and practices and mapping existing courses for home thermal performance.
Home occupant direct- and co-benefits aims to assess non-financial and co-benefits from improved home thermal performance in ways that more effectively communicate positive outcomes. This includes risk assessment and heat management under extreme weather conditions.
Home occupant engagement and communication will improve public awareness of home retrofit by introducing information and resources such as the 'one-stop shop' and incentives/grants.
Research, development, and innovation aims to provide new research evidence to support home thermal performance. It evaluates new concepts and methods of home retrofit to improve standards, guidelines, and regulations.
Policy support and regulatory framework will support Australia's decarbonisation target by 2030 through home retrofit and product/service innovation.
Market, funding (subsidies) and financing aims to encourage the industry to supply more affordable and more effective products to achieve residential energy efficiency.

These themes stemmed from the initial review of technology and market status and potential, a further review of current research on home thermal efficiency and impacts, alongside a scenario modelling of building envelopes to assess the performance of existing housing stock and the identification of barriers that need to be overcome before large-scale implementation will be possible. Further consultations with the IRG on aligning the opportunities with industry views elicited ranking of the eight priority research theme areas, among which four were ranked as high priority (Table 6). '*Building fabric*' was ranked as the highest priority item, followed by '*Existing home performance assessment*,' '*Home retrofits and decarbonisation*,' and '*Benefits of improved thermal performance*.'

Table 6: Prioritised research areas on home thermal performance.

Building Fabric (Windows/glazing, air tightness, condensation, pre-cooling) *Evaluation of new methods of retrofitting existing glazing (RQ5)* *Quantification/inclusion of air tightness in NatHERS (RQ6)* *Assessment of air tightness and condensation during construction and renovation (RQ7)*	High
Existing Home Thermal Performance Assessment *Tool selection for cost-efficient home retrofit strategies (RQ2)* *'One-stop shop' for home retrofit program (RQ3)*	High
Home Retrofits and Decarbonisation *Support Australia's decarbonisation target through home retrofit (RQ21)* *Identify the role of home thermal performance in the transition to electrification (RQ22)*	High
Benefits Of Improved Thermal Performance *Assessment of non-financial and co-benefits from improved home thermal performance (RQ1)*	High

3.1. Review of existing building (housing) stock

The NatHERS database was reviewed to characterise the building stock. The NatHERS scheme measures thermal comfort aspects of the NCC minimum energy performance requirement for residential building (ABCB, 2019; DoEE, 2019a). In 2020-21, around 90 per cent of building approvals used NatHERS for assessment (NatHERS, 2022a). Majority of the assessments come from NatHERS and BASIX databases and were generated from submissions before a building is constructed. In the NatHERS database, the average Star rating of new detached dwellings in Australia is 6.2 Stars whilst for apartments, the average rating is 6.6 Stars. It is important to note that the Star rating scheme is not linear. This means an improvement from 1 to 2 Stars achieves a much larger energy saving than an improvement from 5 to 6 Stars, to some degree reflecting the relative cost in achieving that additional Star (Pears, 2022). For example, for Melbourne, a shift from 1 to 2 Stars saves five times as much energy as a shift from 5 to 6 Stars: 175 MJ/m^2 compared with a shift from 5 to 6 Stars which saves 35 MJ/m^2. This means research studies using Star ratings as a metric for improvement potentially distort perceptions of energy outcomes. A one-Star improvement in existing 1-2 Star (low performance) homes is far more significant than upgrading the performance of a 5-Star dwelling.

Most Australian homes are only designed to the minimum energy efficiency requirements as required by the NCC, often missing cost-effective opportunities to reduce household energy bills. The decrease in prices of energy efficient technologies has been offset by increasing energy costs; hence consumers are failing to benefit (COAG Energy Council, 2022). There is no systematic process to ensure they are built as designed, and often houses not being built as expected is one of the barriers (Wang *et al.*, 2020). Residential structures in Australia account for 70% of total building floor area (Gaterell and McEvoy, 2005). However, a major portion of residential stock is in poor condition and inefficient from a thermal performance perspective. Approximately two-thirds of extant structures are more than 30 years old, while approximately 40% are more than 50 years old (Poel *et al.*, 2007).

Existing buildings outnumber new constructions, with new builds contributing to 1% or less of the existing stock annually. Refurbishing and/or retrofitting existing residential buildings can be a valuable solution to enhancing the building sector's environmental performance (Poel *et al.*, 2007). With less than 2% of Australia's building stock replaced each year, there is a clear need to reduce carbon emissions in homes that have already been built and occupied (Whitehouse *et al.*, 2019). More than 7 million homes in Australia were built before energy efficiency standards were introduced into the NCC. Many of these homes are draughty and have insufficient insulation (Murray-Leach, 2021). According to the data from CSIRO's Australian housing data portal, the average existing house is rated 2.2 stars for energy efficiency (Cranney, 2022). Revisions to NCC energy efficiency requirements in 2022 include a more holistic approach to residential energy efficiency standards by increasing the thermal performance requirement to 7 Stars (ACIL Allen, 2021) and combining this with rating of appliances for a whole-of-home assessment.

3.2. Review of building fabric and thermal performance

Many technologies are readily available which improve energy efficiency, thermal performance, and decarbonisation in the building sector. However, deployment and integration are identified as the main challenges (ClimateWorks Australia, 2020). In the residential building sector, improved energy efficiency throughout the building system combined with electrification and use of renewable energy for power, heating and water services, is an available, mature and commercially competitive pathway (ClimateWorks Australia, 2020) that has been demonstrated at scale (COAG Energy Council, 2019). New homes have improved and increasingly become more energy efficient with insulation standards and required energy ratings (COAG Energy Council, 2018a). However, many of Australia's ten million homes are characterised by poor thermal and energy efficiency performance (Fox-Reynolds *et al.*, 2021).

The building fabric has the longest life span in comparison with technology-based installations, and typical savings for building fabric technologies fall in the range of 9-27% per doubling of cumulative production and 18% on average (Berry and Davidson, 2015). Studies show that existing NatHERS 5 or 6 Star building designs can be modified to achieve higher energy performance (thermal comfort) with reduced total construction cost of nearly 2% if designs are modified to suit climate and orientation rather than increasing building specifications such as insulation levels (Sustainability House, 2012). Building insulation is mature, well-established technology and a cost-effective solution in reducing energy consumption via building envelope (Johnston, 2022). While insulation is not the only design strategy for building thermal performance, it is considered the cornerstone to all energy efficient building design (Clarke *et al.*, 2020). Technological advances and development of insulating materials continue to improve performance.

Building fabric material choice affects vapour diffusion with some materials able to store moisture, and some materials can stop vapour from migrating through the built fabric. Hence, it was suggested that successful condensation mitigation must be part of the building fabric as a complete system (Ambrose and Syme, 2015). Dewsbury and Law (2017) found that up to 40% of all Australian homes constructed in the last 15 years have a visible internal formation of condensation. Condensation and associated problems (such as mould, damage to materials) are also linked to the production of water vapour in homes due to clothes drying, bathing, and even indoor plants and aquariums. Heat pump clothes dryers, automated management of ventilation, and other measures including occupant education are key elements in addressing the problems.

Vapour diffusion and vapour management are critical issues in building fabric performance in Australia. A report published by Dewsbury et al. (2016a) on condensation risk management for Tasmanian housing, estimated that about 10 litres of water vapour is generated per person per day due to various human activities in a residential building (Dewsbury *et al.*, 2016b). If the moisture is not released, the building fabric elements will continually absorb and accumulate moisture, leading to structural risk and decay (US EPA, 2013). Good understanding of vapour diffusion properties of materials in terms of temperature and relative humidity ensures architectural and engineering designers are informed about the proper construction assembly and material use to create an enclosure that manage water vapour in buildings. In Australia, vapour resistivity values of common building materials are limited or unavailable (Olaoye and Dewsbury, 2019).

A fundamental issue in building envelope performance is the installation of building fabric and its integration with other elements during construction. Windows are key building envelope components with mature technologies generally available but retrofitting with high performing windows tends to be a costly exercise. As substantial sources of heat gains and losses, windows have a significant effect on thermal performance. While advanced framing is commonplace elsewhere, there are relatively few high-performance windows in new and existing Australian housing (CSIRO, 2022b). Buildings are also typically less energy efficient than predicted due to factors such as absence of (or gaps in) insulation; poor installation practices including windows; tradespeople potentially damaging insulation when installing wiring and lighting, and complex thermal bridging issues. Poor installation of insulation and weather sealing reduce energy performance of houses (Ambrose and Syme, 2015) and unintentional building envelope leakages, infiltration and exfiltration, are prevalent in Australian houses. Air-tightness is essential to improve energy efficiency, prevents structural damage, and maintains healthy indoor air (Pro Clima Australia, 2020). The lack of guidance and specification on air leakage rates until NCC 2015 contributed to construction of leaky homes. The NatHERS software does not define a specific level of airtightness to be achieved and the air change rates are roughly estimated with the stack, infiltration factors, and wind speed (Ren and Chen, 2015). An average rate of 15 ACH @ 50 Pa could result from the use of the NatHERS methodology (Ambrose and Syme, 2017). NatHERS methodology underestimates annual heating energy consumption by assuming better airtightness than the industry can typically provide. NatHERS airtightness assumptions should be set to an average level that the industry can achieve, and with options of higher air tightness levels to be included in the software.

3.2.1. Equipment and appliances for thermal efficiency

End-use technologies in the residential building sector associated with thermal efficiency are used for space heating and cooling, cooking, water heating, appliances, and lighting. These energy-efficient technologies continue to become cheaper and more effective. For example, LED lighting costs have declined (Energy Rating, 2021b) while efficiency has continued to improve over time. Space heating and/or cooling accounts for an average of 40% of household energy use in Australia (Energy Rating, 2020), and depending on the climate zone and building performance, this can range 20% to 50% (DCCEEW, 2022a). Technologies installed at any location depend on the type of climate (heating or cooling dominated), humidity conditions, and available energy sources (notably gas). Gas appliances have lower efficiencies, ranging from 60% to 90%. Electric appliances can have varying efficiencies; for example, 100% for an electric fan heater, and 300% to 600% for a reverse-cycle air-conditioner (heat pump) (Ryan and Pears, 2019). Reverse-cycle air-conditioners can be very economical in operation, with coefficients of performance of around three to six (Energy Rating, 2022). Ducted heating is found in newer homes and is expensive to operate due to significant gas consumption and electricity use for running fans, and heat losses through ductwork and pressurisation effects. For hydronic heating, initial cost can be high but running cost could be reduced by using solar or electric heat pumps. Portable gas heaters can cause health, safety, condensation, and mould issues. In New Zealand, almost a third of the households that relied on portable gas appliances for home heating reported problems with mould (BRANZ, 2022). Air-conditioner energy efficiency has improved by 50% over the last ten years (Energy Rating, 2021a). Residential air-conditioners in Australia have been subject to MEPS since 2004 and sizes up to 65kW have been regulated since April 2020. From October 2022, air-conditioners above 65 kW will need to meet MEPS standard (Energy Rating, 2022). Evaporative coolers, though costly to purchase, use only 50% of the energy used by air-conditioners. However, these work better with low humidity. Effectiveness diminishes with high humidity and extreme temperatures. Evaporative cooling systems require air outlets or open windows, which potentially add to air leakage sources.

3.3. Performance of existing housing stock

As part of identifying the research opportunity areas on home thermal performance, a scenario modelling was conducted to assess the performance of the existing housing stock and potential for energy efficiency improvement. A database of energy Star rating for existing old dwellings, or a pseudo-old building stock, covering all states and territories was developed by CSIRO using 208,204 residential building designs collected from the Australian Housing Data portal (CSIRO, 2022a). These buildings were built before 1991 and are assumed to have no insulation as thermal insulation as a contributor to energy efficient homes was introduced after 1991. These sample dwellings represent around 90 per cent of the total 229,142 dwellings approved for construction in 2021 and cover 68 climate zones (CZs) out of the 69 NatHERS CZs in Australia, with no new dwelling designed in 2021 for CZ 51, Forrest, Western Australia, since its population is zero according to the 2016 census (ABS, 2022a). The dwellings include Class 1A buildings – detached houses or one of a group of attached dwellings (for example, a town house, terrace house, or the like) and Class 2 buildings – apartments.

Table 7: Three improvement categories to the pseudo-old building stock.

Improvement Category	Items improved	Improvements
Rehab	Insulation	Ceiling R3.0
	Infiltration	0.5 ACH at natural pressure
	Curtain	Heavy drapes
	Window Shade	Roller shutter
Refurb	Insulation	Ceiling R3.0, Floor R2.0
	Infiltration	0.5 ACH at natural pressure
	Curtain	Heavy drapes
	Window Shade	Roller shutter
	Window system	Addition of a glass insulation layer
Renovate	Insulation	Roof/ceiling R3.0, Floor R2.0, Wall R2.0
	Infiltration	0.2 ACH at natural pressure
	Heat recovery ventilation	0.4 ACH at natural pressure, 85% heat recovery efficiency
	Curtain	Heavy drapes
	Window Shade	Roller shutter
	Window system	Energy efficient double-glazing

Simulations were carried out for the sample dwellings using AccuRate Sustainability V2.4.3.21 SP1 under rating mode (using standard NatHERS assumptions) for the energy efficiency rating. These dwellings were simulated without envelope insulation to represent pre-1990s buildings. Assessment of energy efficiency for different building improvements were investigated under the current climate and projected future 2030 and 2050 climates using RCP 8.5 future climate scenario developed by CSIRO (2022c). As recent dwellings are generally around or above 5 Stars, the following modifications to the original designs were implemented as the base case to back-construct the pseudo-old building stock: (1) **all insulation in walls, floors, rooves are removed and insulation in ceiling to roof spaces is assumed to be R0.25; (2) infiltration at ambient conditions is assumed to be 1.0 ACH (air change rate per hour); and (3) all windows are assumed to be clear 3mm single glazing with timber window frame.** Three levels of building improvements were investigated in this study (Table 7): rehabilitation, refurbishment, and major renovations. Details of the scenario modelling and simulations are not covered in this conference paper and will be reported in another publication.

As overview of results from the scenario modelling, the average Star rating of 2.15 in Victoria closely matches the average 2.1 Stars for the 14,901 existing old dwellings reported in the Australian Housing Data portal (CSIRO, 2022a). The national average Star rating of this pseudo-old building stock is calculated to be around 2.47. The highest average Star rating of existing old dwellings is found in Northern Territory at 4.46. Although dwelling designs and floor plans of the 2021 designs may be somewhat different from existing old dwellings, the average Star ratings from this pseudo-old building stock gives the depth of data on each house upgraded.

To calculate the potential savings across the entire existing housing stock, ABS data was used to determine dwelling numbers for each state and territory. Further, the split between houses and apartments followed the ABS average of 16% of total stock being apartments and was applied to all jurisdictions. Based on the calculated heating and cooling energy costs, the energy cost savings for different building improvement strategies were estimated. As summary, assuming improvements to 5% of the entire building stock as Business-as-Usual Scenario (retrofitted by 2030), energy cost savings are estimated to be around AUD185 million, AUD207 million, and AUD439 million per year for rehabilitation, refurbishment, and major renovation, respectively in comparison with the base case (without any improvement). The CO_2 emission reductions are estimated to be 1.57 Mt, 1.76 Mt, and 3.6 Mt CO_2 per year, respectively. For an Accelerated Scenario (considering improvement 40%), the total energy cost savings are estimated to be around AUD1.48 billion, AUD1.66 billion, and AUD3.51 billion, and the CO_2 emission reductions are estimated to be 12.58 Mt, 14.09Mt and 28.78 Mt CO_2 for rehabilitation, refurbishment, and major renovation respectively. While the difference between rehabilitation and refurbishment is relatively small at 12%, there is massive, 137% cost saving and emission reduction when comparing rehabilitation with major renovation.

These results formed part of the information package presented at the final IRG workshop in August 2022 where the identified research opportunities were ranked to formulate recommendations for priority areas.

4. Conclusion: Home thermal efficiency research opportunities

The buildings sector is a contributor of a large share of emissions due to energy use (electricity and gas) in the residential sector (DISER, 2021), and a high proportion of peak demand at times when variable renewable energy production is low. Electrification of homes would be in step with the Net Zero by 2050 Scenario (Wood *et al.*, 2023). Such transition leads to all-electric buildings powered by solar, wind, and other sources of electricity (Wood and Ha, 2021). Electrifying an average household typically involves installing solar panels on the roof and replacing gas appliances with efficient electric models. As buildings that consume low energy are easier to electrify, energy efficient building design and integrating high-performing envelopes are important steps toward fully electrified buildings. However, full electrification is easier and cheaper in new buildings compared to old buildings. Heat pumps (hot water systems and reverse-cycle air-conditioning units) are the enabling technology for widespread building electrification, and paired with solar, are a popular way to reduce grid reliance. Rooftop solar is a mature technology if storage is not a factor. Almost 390,000 rooftop solar systems were installed in 2021, and there are now more than 3 million solar homes in Australia – one in three Australian households (Clean Energy Council, 2022). Energy efficiency and building performance are key to decarbonisation and reducing household energy bills. But in Australia, the focus is on rooftop solar and storage, not making buildings, reducing its thermal needs and appliances work well.

Why is thermal efficiency important and how can it be achieved? Homes providing occupant thermal comfort (heating and cooling) accounts for a major portion of residential building energy consumption, and thus emissions. However, due to the relatively hidden nature of energy performance, it is found to be of a lower order concern for homeowners and buyers among many other factors such as cost, design, location, and convenience. Given the imperative to achieve net-zero carbon emissions, address climate change and the associated risks of more frequent extreme weather events, the need to increase the thermal efficiency of homes is becoming more important. Improving thermal efficiency has been proposed by researchers and policymakers around the world to reduce carbon emissions from the housing sector.

This scoping study highlighted recommendations on enabling solutions, technologies and policy instruments, centring on low-cost solutions for existing homes. Engaging with industry stakeholders provided clarity on the salient and topical issues and challenges around home thermal efficiency and how focusing on priority research areas can accelerate decarbonisation of the built environment in Australia.

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BIM energy retrofitting frameworks: a critical review

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Abstract: In the light of local carbon targets responding to climate change and global warming, countries need to curtail the energy consumption of their building sectors. Existing building stock represents most projects in that sector and energy retrofitting of existing unsustainable buildings is, hence, essential in achieving the above goal. Yet, energy retrofitting is a multiplex process plagued with inefficiencies, resulting in the low rates of uptake in Australia and globally. Using Building Information Modelling (BIM) can accelerate energy retrofitting and presents numerous advantages if applied properly. Many studies have presented BIM-Energy Retrofitting Frameworks (BIM-ERFs) that successfully adopt BIM for the ER process. However, the BIM-ERFs in these studies appear to be dispersed in nature, with varying BIM implementation level, scope, software(s), interoperability, and analysis methods. This dispersion can be counterproductive for BIM implementation in retrofitting. The authors identified a need for further research that critically examines and evaluates the current BIM-ERF approaches. In response, the paper presented here fills a knowledge-gap by critically reviewing 64 recently published BIM-ERF studies via a systematic literature review. The review reveals that BIM-ERFs are comprised of four main stages including pre-retrofit, design and analysis, construction, and post-retrofit stages. When critically examined, it is found that most of the studies are focused on the design and analysis stage using BIM and energy simulation and fail to sufficiently address the other critical stages. Accordingly, this review presents the future research priorities for studies to adequately address issues in all BIM-ERF stages.

Keywords: Energy retrofitting; BIM; frameworks; critical review.

1. Introduction

The buildings sector, owing to its extensive energy and environmental loads, will play a major role in the fight against climate change and a transformation to a sustainable future. According to the International Energy Agency (IEA), the sector is responsible for 37% & 34% of Carbon Dioxide (CO2) emissions and energy demand globally, respectively (IEA, 2022). It is suggested that a reduction of 32 Gt in overall emissions by 2050 is required in the global buildings sector to limit the earth's temperature rise within 2°C (Wang et al., 2018). In addition to new developments being sustainable, existing buildings will play a crucial role in the transformation to a sustainable future. The inevitable way forward for the existing unsustainable buildings is to energy retrofit them.

Fundamentally, the definition of energy retrofitting is to upgrade a building's components that directly or indirectly contribute towards its energy use by implementing Energy Efficiency Measures (EEMs) (Asif

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et al., 2023). Three of the main objectives in energy retrofitting projects are to reduce the energy consumption, minimize the environmental impact, while maximizing the economic value of the buildings (An et al., 2023). To achieve this, a wide range EEMs can be implemented with varying complexities, investment, and impact. The energy, environmental, and economic objectives of implementing these EEMs are considered as conflicting, and this necessitates quantifying and comparing the trade-offs of the three while making the decision to implement EEMs (Toufeili et al., 2022). This process of analyzing, selecting, and implementing the right EEMs in energy retrofitting is a multiplex task that can be facilitated by using Building Information Modeling (BIM).

Using BIM can accelerate energy retrofitting and presents numerous advantages if applied properly (Okakpu et al., 2022). Many studies have presented BIM-Energy Retrofitting Frameworks (BIM-ERFs) that successfully adopt BIM for the energy retrofitting process. However, the BIM-ERFs in these studies appear to be dispersed in nature, with varying BIM implementation level, scope, software(s), interoperability, and analysis methods. This dispersion of the BIM-ERFs forms a disconnect between theory and application of BIM for energy retrofitting and discourages its implementation in practice. There is a need for a study that examines and critically analysis the current BIM-ERF approaches to guide further research and bridge this disconnect. The aim of this study is to examine and critically analyze BIM-ERFs in existing studies by performing a critical systematic review.

2. Methodology

The systematic review followed guidelines by PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) for review studies. The guidelines layout the steps needed for a systematic review study including the search method, selection criteria, and analysis methods (Cao et al., 2022). The steps of this study are presented and explained in the following subsections.

2.1. Data search and selection criteria

The data collection method for the study was a keyword search-based method. Three main databases were searched including Google Scholar, Scopus, and Web of Science. These three were utilized as they are the most widely recognized and reliable databases in the scientific world. The keyword search included different combinations of the term Building Information Modelling (BIM) and energy retrofitting, energy renovation, BIM Techno-Economic Analysis (TEA), BIM Life-Cycle Analysis (LCA). All the relevant search results were then filtered based to narrow down the articles to be included in the review.

The searched research articles were then filtered through a selection criterion to make sure that only relevant articles are selected. Firstly, articles published since 2018 and above were considered to keep the systematic review up to date with the trends in the BIM-ERF research. Furthermore, articles published in Indexed Journals were considered only to keep the systematic review credible. Additionally, due to the extensive number of articles that the first search resulted in, the authors decided to limit the articles to journal articles only. In terms of the content, articles that have implemented BIM for energy retrofitting were considered only as this is the scope of the study. This was recognized through an initial abstract and title screening and a detailed secondary reading of the articles. In the end, a total of 64 articles were identified for the review.

2.2. Analysis methods

The selected literature studies were analysed using bibliometric and critical content analyses. The following subsections explain these two analyses in detail.

2.2.1 Bibliometric analysis

Bibliometric analysis is a quantitative method that is adopted in systematic reviews to map the patterns in literature (Oraee et al., 2021). The analysis can reveal links and relationships within the literature that content analysis may fail to show. Additionally, the bibliometric analysis results can be visualized using tools such VOSviewer to identify the co-occurrences and relationships among various research themes (van Eck & Waltman, 2014). In this study, three themes are analysed in the bibliometric analysis including, year of publication to reveal the interest in the research area, a keyword-co-occurrence map using VOSviewer to identify the main relationships and missing relationships, and lastly the BIM and energy, Life-Cycle Costing (LCCA) and LCA software/method adopted by studies.

2.2.2 Content analysis

The content analysis in the BIM-ERF studies was based on the energy retrofit process and the stakeholders involved. The process comprises of four main stages typical of any construction project (figure 3) (Thuvander et al., 2012). The first stage is the pre-retrofit stage where the preliminary analysis is done, capital is raised, and the building is audited. The second phase is where the EEMs are designed and selected. The next two phases are construction and commissioning/post-construction phases.

Using this process, the analysis involved identified and presented the involvement and use of BIM at each stage. Additionally, the scope of the presented BIM-ERF studies was mapped across the project cycle to identify where the studies are currently focusing and to present critical gaps in the studies.

3. Results

3.1. Bibliometric analysis

3.1.1. List and year of publications

The 64 studies identified are referenced in Table 1. In addition, Figure 1 presents the year these studies were published from 2018 to April 2023. It can be observed from Figure 1 that BIM-ERF studies are an extremely trending and relevant research area. More than 50% of the studies were published in 2021 and 2022 while in the four months of 2023, ten articles were published in the topic area. Given the trend, research in adopting BIM for energy retrofitting is maturing rapidly and is a high interest research area in the topic area.

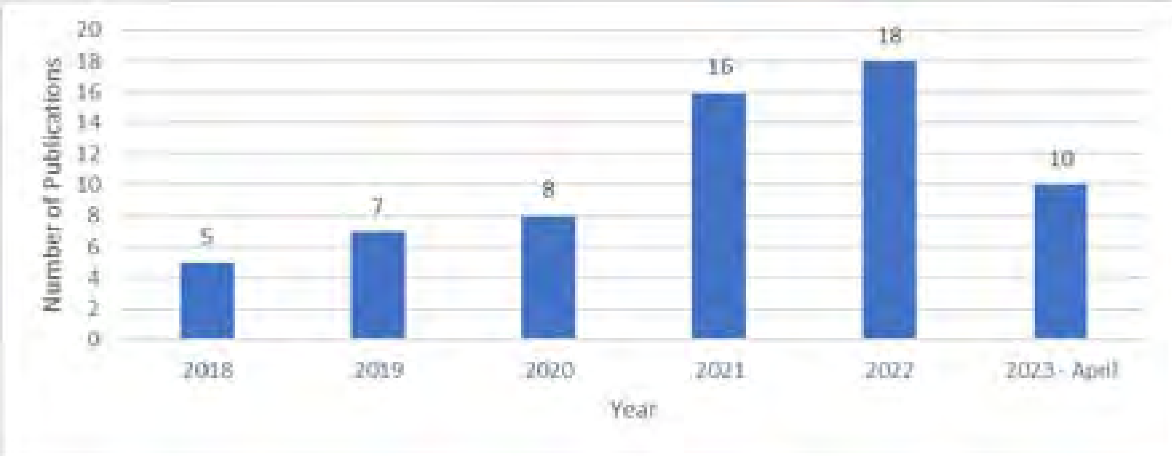

Figure 1: Year of publications.

3.1.2. Software/Method Used

The software and methods used in these studies have been categorised into four main areas including BIM authoring software, energy analysis, LCCA, and LCA (Table 1). With regards to the BIM authoring tool, it is observed that Autodesk Revit is the main software for the studies being utilized in 59 out of the 64 studies. Autodesk Revit has gained popularity over other BIM tools such as ArchiCAD and MicroStation. However, it is important to mention that this may be due to unintended BIAS due to the geographical location of the studies, and it is important to explore other tools/platforms of BIM.

On the other hand, this dominancy of one software is not observed in the energy analysis, LCCA, and LCA software/method used. The analysis can be done using the BIM in three ways, either a fully inherited tool in the BIM authoring software, or a tool integrated with BIM software and capabilities using third-party plug-ins, or a compatible tool with BIM that can make use of the exported information from BIM (Banihashemi et al., 2022). It is observed that the studies have adopted the three ways of analyses with Energyplus/DesignbBuilder being the preferred for energy analysis and calculations from exported data for LCCA and LCA (Table 1).

Table 1: Software/method used in the studies. (X = Not reported)

No.	Reference	BIM Authoring	Energy Analysis	LCCA	LCA
1	(Shibata et al., 2023)	Autodesk Revit	Elmhurst Design SAP 10.2	One-click LCA	One-Click LCA
2	(Razzaq et al., 2023)	Autodesk Revit	Autodesk Revit	SPP Calculation	Calculation
3	(Matana Júnior et al., 2023)	Autodesk Revit	Autodesk Revit	SPP Calculation	X
4	(Marzouk et al., 2023)	Autodesk Revit	IESVE	NPV Calculation	IESVE

5	(Maaouane et al., 2023)	Autodesk Revit	Calculation	NPV Calculation	x
6	(Hosamo et al., 2023)	Autodesk Revit	Simulink	X	X
7	(Forastiere et al., 2023)	Autodesk Revit	Design Builder	One-Click LCA	Calculation
8	(Danial et al., 2023)	Autodesk Revit	Insight/Design Builder	X	X
9	(Altaf et al., 2023)	Autodesk Revit	Ecotect	NPV Calculation	X
10	(Alexandrou et al., 2023)	Autodesk Revit	DesignBuilder	X	X
11	(Tushar et al., 2022)	Autodesk Revit	FirstRate5	X	Tally
12	(Turk et al., 2022)	Autodesk Revit	X	X	X
13	(Shehata et al., 2022)	Autodesk Revit	X	X	X
14	(Seghier et al., 2022)	Autodesk Revit	Matlab	Matlab	X
15	(Ruggiero et al., 2022)	Autodesk Revit	DesignBuilder	X	
16	(Amorocho and Timo, 2022)	Autodesk Revit	COMSOL	One-Click LCA	One-Click LCA
17	(Motalebi et al., 2022)	Autodesk Revit	Green Building Studio	Mathematical Calculation	Tally
18	(Liu & Wang, 2022)	Autodesk Revit	Ecotect,Phoenics	X	X
19	(Jiang et al., 2022)	Autodesk Revit	Energy plus	Mathematical Calculation	Calculation
20	(Dauletbek & Zhou, 2022)	Autodesk Revit	Revit	Simplified Profitability Analysis	WebLCA
21	(Daniotti et al., 2022)	Autodesk Revit	X	X	X
22	(D'Angelo et al., 2022)	Autodesk Revit	IES-VE	CPP Calculation	X
23	(Chen et al., 2022)	Autodesk Revit	X	X	X
24	(Chae & Kim, 2022)	Autodesk Revit	ECO-CE3	X	X
25	(C et al., 2022)	Autodesk Revit	Equest/Insight	X	X
26	(Barone et al., 2022)	Autodesk Revit	Energy plus	SPP and NPV Calculations	MCO2 Index Calculations

27	(Ali et al., 2022)	ArchiCAD	ArchiCAD	Mathematical Calculation	Calculation
28	(Albdour et al., 2022)	Autodesk Revit	Energyplus plugin	X	X
29	(Zhuang et al., 2021)	Autodesk Revit	Rhino.Inside	X	X
30	(Zhao et al., 2021)	Autodesk Revit	DesignBuilder	X	X
31	(Zhang et al., 2021)	Not Mentioned	BECS2018	X	X
32	(Tushar et al., 2021)	Autodesk Revit	FirstRate5	X	Tally
33	(Sharif et al., 2021)	Autodesk Revit	Design Builder	Simulation	X
34	(Mazzoli et al., 2021)	Autodesk Revit	Energy plus	X	X
35	(Li et al., 2021)	Autodesk Revit	DesignBuilder	X	X
36	(Khudhaire & Naji, 2021)	Autodesk Revit	Insight 360	X	X
37	(Hamida et al., 2021)	Autodesk Revit	DesignBuilder	CPP Calculation	X
38	(Desogus et al., 2021)	Autodesk Revit	x	X	X
39	(De Oliveira et al., 2021)	Autodesk Revit	DesignBuilder	X	X
40	(Carriço de Lima Montenegro Duarte et al., 2021)	Autodesk Revit	DesignBuilder, Insight 360	X	X
41	(Bughio et al., 2021)	Autodesk Revit	DesignBuilder	X	X
42	(Angrisano et al., 2021)	Edificius	Termus	X	One-Click LCA
43	(Alhaidary et al., 2019)	Autodesk Revit	IESVE	X	X
44	(A. Ahmed et al., 2021)	Autodesk Revit	IESVE		Calculation
45	(Wei & Chen, 2020)	Autodesk Revit	Ecotect	Cost coefficient	X
46	(Rodrigues et al., 2020)	Autodesk Revit	GBS	X	X
47	(Rocha et al., 2020)	Autodesk Revit	DesignBuilder	Savings to investment Ratio	X
48	(Piselli, Romanelli, et al., 2020)	Autodesk Revit	DesignBuilder	X	X

49	(Piselli, Guastaveglia, et al., 2020)	Autodesk Revit	DesignBuilder	X	X
50	(Hu, 2020)	Autodesk Revit	X	X	Athena
51	(Feng et al., 2020)	Autodesk Revit	HOT2000	X	SimaPro
52	(W. Ahmed & Asif, 2020)	Autodesk Revit	DesignBuilder	CPP Calculation	X
53	(Tzortzopoulos et al., 2019)	Autodesk Revit	SAP	Mathematical Calculation	X
54	(Stegnar and Cerovsak et al., 2019)	Not Mentioned	IDA ICE	X	X
55	(Sharif & Hammad, 2019)	Autodesk Revit	DesignBuilder	Simulation	ATHENA
56	(Kaewunruen et al., 2019)	Autodesk Revit	GBS	Insight	X
57	(He et al., 2019)	Autodesk Revit	DesignBuilder	X	X
58	(Hasik et al., 2019)	Autodesk Revit	X	X	Tally
59	(Ahsan et al., 2019)	Ecotect	Ecotect	SPP Calculation	X
60	(Schlueter & Geyer, 2018)	Autodesk Revit	Energyplus	X	X
61	(Kim, 2018)	Not Mentioned	eQuest	X	X
62	(Kim and Park, 2018)	Autodesk Revit	IES VE	X	X
63	(Kim and Park, 2018)	Autodesk Revit	IES VE	IMPACT	IMPACT
64	(Hu, 2018)	Autodesk Revit	Sefaira	NPV Calculation	Tally

3.1.3. Keyword co-occurrence

A keyword co-occurrence map (Figure 2) was generated using the keywords of the 64 studies. The keywords were simplified and unified to remove duplications and iterations of the same words. After that the map was generated using VOSviewer.

The map indicates the revolving topics around the main word of 'BIM'. The size of the circles representing the words indicates the amount of time the word is repeated. This in turn indicates the main themes of the studies. As seen in the map, the secondary size of the main words includes keywords BEM (Building energy Modelling), retrofit, energy efficiency, sustainability, energy retrofitting, and LCA. Thus, the revolving themes of research of the BIM-ERF are withing these keywords.

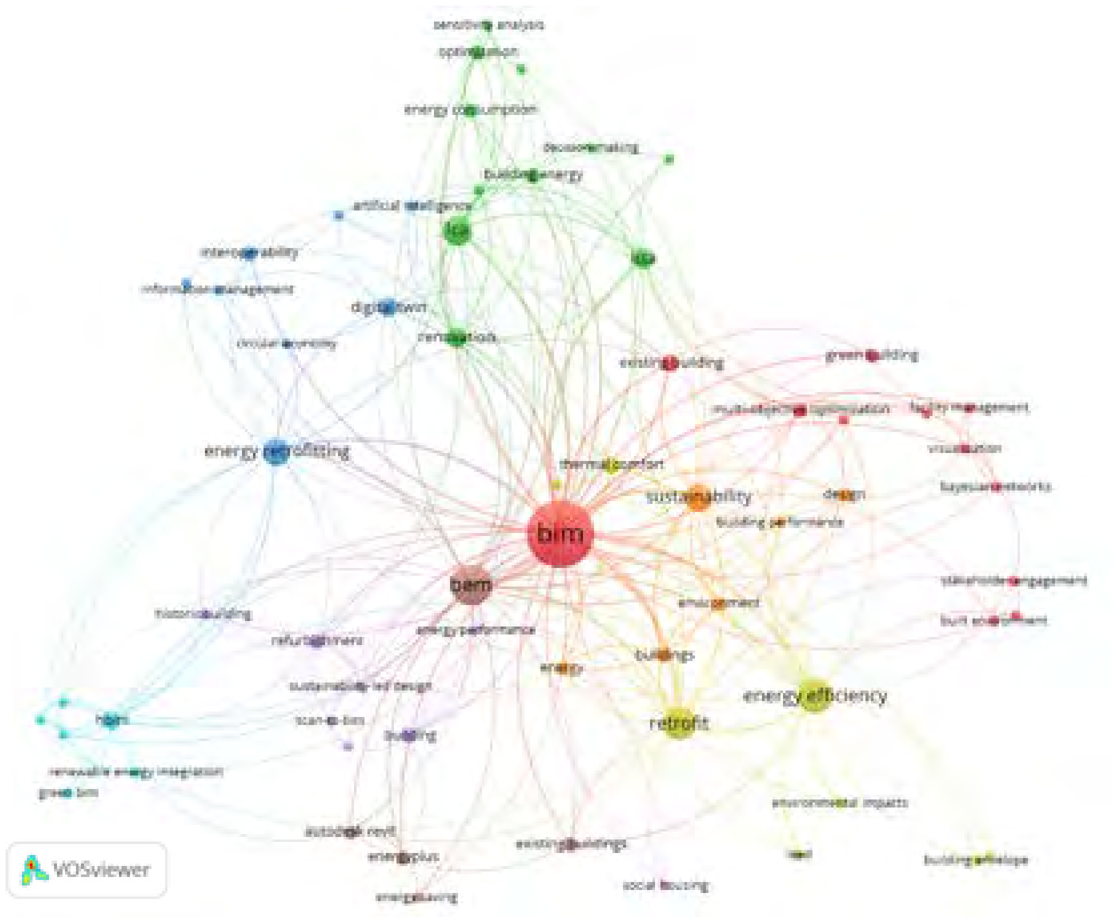

Figure 2: Keyword co-occurrence map.

3.2. Content analysis

In the next analysis, the content of the identified 64 studies was analysed based on the energy retrofit project cycle (Figure 3). At the pre-retrofit stage, the studies presented four main BIM adoption practices. Firstly, it was highlighted that the BIM information requirements and standards to be adopted should be selected and set before BIM is implemented for the energy retrofitting project. For example, D'Angelo et al. (2022) presented a BIM-based process model for retrofitting buildings. A key aspect of their model was to define the information requirements for proper BIM use by different stakeholders along the project's lifecycle (D'Angelo et al., 2022). Such information requirements are also defined in the ISO 19650 standards which allow management of information throughout the lifecycle by using BIM. Furthermore, the environment and contractual scope for the BIM implementation in retrofitting needed for proper collaboration is set. Particularly, studies have highlighted the need and use of Common Data Environments (CDE) that are necessary for effective collaboration.

Moving on, another important step at the pre-retrofit stage needed for successful scoping and implementation of BIM-ERFs is the collection of existing building data by energy auditing, surveying of existing conditions, and building documentation. All of these are crucial to develop a BIM model for the existing building with complete information required for the analysis stage. For example, Dauletbek & Zhou (2022) used monitored energy data for three years, estimates of building materials and building documentation to collect existing building data. Furthermore, a lot of development has been made in the automated digitisation techniques of existing buildings. For example, Marzouk et al. (2023) used 3D laser scanning to develop a BIM model of an existing building.

In the design and analysis stage, the studies have mainly focused on the interoperability between BIM and various software/methods for energy analysis, LCCA, and LCA, and touching upon optimizing the selection of retrofit solutions. In the construction and post-construction stages, the BIM-ERFs present the use of quantity take-offs to support the contractors and touching upon using BIM for the facility management and measurement and verification of the retrofit. However, most of the frameworks focus on the pre-retrofit and design stages of the cycle.

The frameworks in the 64 studies were mapped on to the retrofit project cycle to demonstrate where the frameworks focus in relation to the project's lifecycle and stakeholders. As seen in Figure 3, the mapping reveals that the studies are mainly focusing on the design stage. Typically, the frameworks start by gathering the existing building information and developing BIM models for existing buildings. Next, the data exchange methods and interoperability are discussed between BIM and the software/method that will be used for energy analysis, LCCA, and LCA. After that, the energy, economic, and environmental savings are calculated for the implemented EEMs. Some studies demonstrate optimization of the retrofit strategies to select the best scenario for the retrofit. This is where most frameworks end. A similar trend is seen in the keyword co-occurrence map where the keywords are revolving around analysis methods. While this establishes the theoretical framework of BIM-ERFs, several key areas are missing in the existing literature within the BIM-ERF space. One of the key areas that is lacking in the pre-retrofit stage is setting the information requirements. The requirements consider where and what type of information is required by the stakeholders at that stage. By setting the information requirements, the value of the BIM-ERF can be maximized for all the stakeholders. The lack of discussion around these areas forms a disconnect from the practice, and consequently discourages the actual adoption and use of BIM for energy retrofitting.

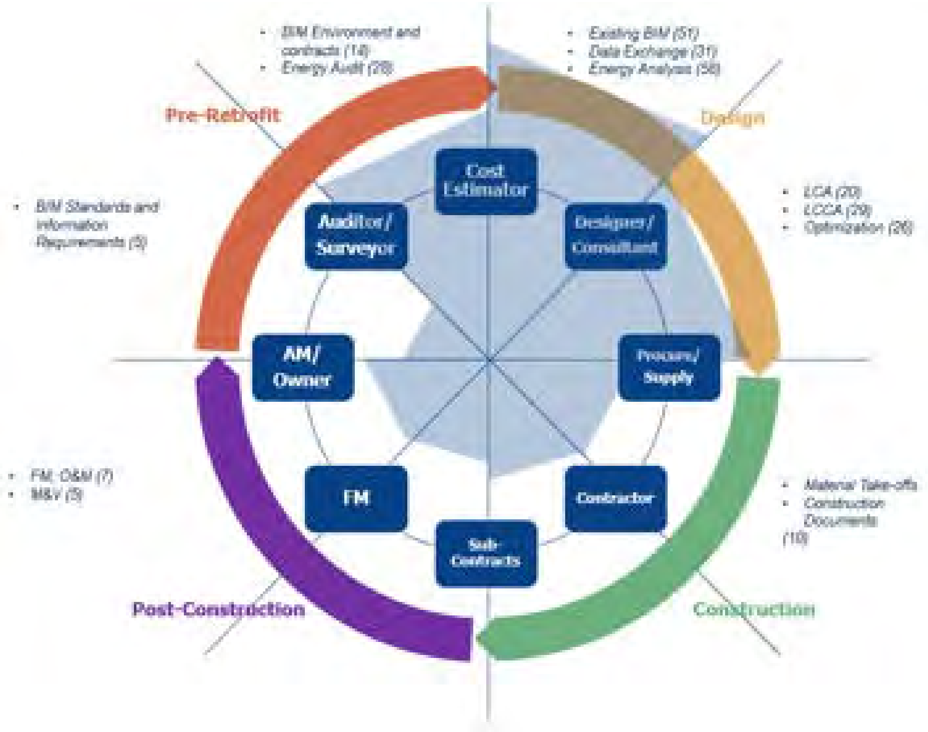

Figure 3: Mapping of studies on the retrofit cycle. *((#) indicates the number of studies addressing the topic).*

4. Conclusion and future work

This study presented a systematic review of BIM-ERF studies. The search identified 64 relevant studies that were used for bibliometric and content analysis. The bibliometric analysis reveals that the use of BIM for energy retrofitting is an increasingly trending research area and a multitude of frameworks for BIM use are presented in the studies. Furthermore, the content analysis reveals that BIM can be implemented in various ways along the project life cycle. However, from a critical perspective, the analysis reveals that there is a disconnect between the theory and application for the presented BIM-ERFs. Future studies need a more pragmatic shift and need to present the BIM-ERFs from a practical lens. Particularly, few areas where future studies should expand the BIM-ERFs include:

- Pre-retrofit stage: developing information requirements, standardization, and use of CDE, and contractual barriers while adopting BIM-ERFs. Using industry 4.0 techniques to improve developing of existing building BIM such as machine learning techniques.
- Construction stage: using the developed BIM in the construction management process.
- Post-construction stage: measurement and verification of the retrofitted buildings and using the developed BIM for facility management.

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Building a healthy, zero-carbon ecovillage: innovative homes meeting a high-performance building standard

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Abstract: The Council of Australian Governments (COAG) have set a trajectory towards net zero carbon buildings by 2050. This paper describes the design, materials and construction technologies of low carbon homes of members of a low environmental footprint ecovillage. Fifty homes in Stage 1 of Narara Ecovillage Co-operative (NEV) in NSW, have met a flexible, high-performance building standard, which required homes to have 1) a 2017 NatHERS rating of at least 7 stars, 2) solar power to meet their annual energy needs, and 3) sufficient reward points for items such as resource efficiency, good indoor environmental quality and low embodied carbon. The methods used included surveys of members and case studies comparing innovative buildings including an earthship home; a kit home with reverse-timber-veneer walls; an earthquake-resistant super-adobe walled art studio; homes with straw panel and strawbale walls; and those with CO_2-absorbing hempcrete wall infill. The paper describes the lessons learnt in Stage 1 that have improved the Stage 2 building standards, and considers the carbon life cycle for five homes. NEV has created a healthy, high-performance residential precinct with affordable, low embodied carbon homes, some built on difficult sites. This study provides a glimpse into the future of housing to 1) lower its impact on the electricity grid, 2) mitigate home operational and embodied carbon emissions for the climate emergency, 3) adapt homes for heatwaves, and 4) provide home energy storage as bi-directional charging becomes available for electric vehicles and they are charged from renewable energy.

Keywords: Zero energy ecovillage; innovative homes; construction technologies; life-cycle carbon analysis

1. Introduction

Greenhouse gas (GHG) emissions globally need to come down quickly and to reduce the impacts of extreme events related to climate change.

The recent dangerous weather of intense heat and devastating rainfall in the Northern Hemisphere summer has been attributed to human-induced climate change (WMO 2023). It has caused heatwaves, wildfires and floods with significant impacts on human health, agriculture, energy, water supplies, ecosystems and economies, including many thousands of excess heatwave deaths (Dickie, Abnett, and Dickie 2023).

Of Australia's total carbon emissions, residential buildings contribute around 13% of operational emissions from using appliances in the home (ASBEC, 2016, 26), and around 2.5% of embodied emissions, which are related to the home construction and manufacture of its materials (GBCA and thinkstep-anz 2021, 5).

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association *2023,* M. Dewsbury, D. Tanton (eds.), *pp. 148 - 153.*

The Council of Australian Governments (COAG) is aiming for net-zero operational carbon buildings by 2050 with more energy-efficient buildings and appliances, with new homes having renewable energy (Prasad et al., 2022). Existing homes can be operationally energy neutral since the cost of solar photovoltaic panels is falling.

To reduce their operational carbon footprint homes require more components for energy-efficiency and for solar power, increasing their embodied energy and emissions which are expected to dominate operational emissions in the building sector in 2050 (GBCA and thinkstep-anz 2021, 4). Therefore, the emphasis for new construction should be on creating low embodied carbon homes with net zero operational carbon.

1.1. Narara Ecovillage

This study describes homes in Narara Ecovillage (NEV), a community located at Narara in the NSW Central Coast aiming to live in healthy homes that have a low environmental footprint, by minimising energy, water and waste, while having strong social and financial sustainability values. The study compares seven innovative low carbon homes in detail and considers the carbon life-cycle of five homes.

NEV is a unique owner-developer of land co-operative, with 100 memberships and owing a 63-hectare (ha) site consisting of eleven hectares for residential development; a 45 ML irrigation dam with a freshwater river; a conservation forest of around 30 ha; and having 50 homes completed in Stage 1.

Sustainable precincts were reviewed to create the by-laws and the building standards, and these included Cape Paterson in Victoria for its renewable and embodied energy policy; Lochiel Park and Aldinga Arts Eco Village in South Australia for their proven home energy reduction and artistic, permaculture and environmental sustainability approaches; the NSW BEND Neighbourhood Association for community and management guidance; the Qld Ecovillage at Currumbin regarding reducing the number of managed precincts; and the Mullum Creek Development near Melbourne, Victoria for its sustainable materials.

1.1.1. Building standard and smart grid

NEV has been cited as an exemplar precinct for achieving net energy positive status since:

> “…Its building standards incorporate requirements for demand reduction, energy efficiency and on-site renewables... Each house is required to install sufficient PV energy on the roof to meet [its] needs [and is] connected to a Smart Grid that manages excess power and integration with the grid.” (Prasad et al. 2022, 186)

NEV initially won a NSW government Growing Community Energy Grant of $70,000 for a feasibility study that showed that a smart grid concept could work, where an embedded network balances its own internal loads and generation. This paved the way to win a $1.38m Advancing Renewables Program grant from the federal Australian Renewable Energy Agency (ARENA 2016) to help build it.

NEV members created their own building standard which had high energy efficiency and sustainability standards. It required homes to 1) gain at least 7/10 stars in the 2017 version of the Nationwide House Energy Rating Scheme (NatHERS) for home design, when the minimum was 6 stars and there were no limits on heating and cooling loads; 2) generate the solar power to meet annual needs; 3) achieve 70/100 points in an evaluation similar to Greenstar for small house size, reducing the use of water, energy, waste and their embodied carbon, and improving the indoor environmental quality (IEQ) for healthy homes.

NEV members updated the building standards in 2022 for Stage 2 that expanded the scope to also include member education and the review of the building stages from lessons learned in building Stage 1. This standard prepares homes for heatwaves by increasing the minimum NatHERS rating to 7.5 stars, while lowering the maximum BASIX cooling load by 50%. It also rewards Owners for undertaking an As-Built assessment to ensure important environmental design features other than in BASIX are checked during construction, and to record the As-Built NatHERS rating (or any Passive House blower door test result). The Stage 2 building standard rewards good ventilation and sealing as described in the 2023 National Construction Code (NCC) for better mould and other pathogen management, with extra points to achieve the minimum 70 points.

The Stage 1 members of the co-op also developed their own sustainable by-laws for the community association to minimise the use of energy, carbon emissions, water and waste, and encourage using electricity and renewable energy, and aspire to obtain the:

> "…target of purchasing, or generating, excess renewable energy, over a period of thirty (30) years, than the amount of embodied energy in the inhabited homes on the Lot." (NEV 2017, 44)

2. Method

The 55 home owners were surveyed about their home and family characteristics, appliance behaviour, special heating and cooling features, comfort levels and electric vehicle usage (ARENA 2016). The energy imported and exported to the grid by the village was recorded for the 2022/23 financial year.

Seven homes were selected for their innovative design and form, their materials or their construction method. The case study method was used to compare them for 1) materials used, 2) construction technologies, 3) energy assets, 4) thermal performance, and 5) health and amenity. This required a more detailed survey and analysis of the homes, owner appliances and behaviour, and detailed reviews of their construction methods.

An operational and embodied carbon analysis was conducted on five homes for which the appropriate data for energy and materials was available, and a projected life-cycle analysis (LCA) of their carbon footprint was performed.

3. Results & Discussion

3.1. Stage 1 homes

Figure shows the construction types of the 55 stage 1 homes showing 22 had innovative designs or materials, and the remaining 33 are traditional lightweight homes with either timber or concrete floors, or both.

Figure 1 - Construction types of the 55 stage 1 homes (Source: Author)

3.2. The design of innovative homes

The relative sizes, shapes and Northerly aspects are compared for the seven innovative homes in Figure .

The features of the innovative homes are compiled in

Figure 2 - Thumbnail sketches of relative plan sizes, shapes and orientations of the 7 innovative homes, numbered 1 to 7 from left to right (Source: Author)

Table which describes the home characteristics for: 1) an Earthship home; 2) & 3) two hempcrete homes 4) a reverse-timber-veneer kit home; 5) a family home with many biogenic (i.e. natural) and second-hand materials; 6) a super-adobe (walls made of earth bags with barbed wire between layers for earthquake-resistance) art studio with earthen floors; and 7) a home with strawbale walls and a reciprocal roof made from bamboo.

Figure 2 - Thumbnail sketches of relative plan sizes, shapes and orientations of the 7 innovative homes, numbered 1 to 7 from left to right (Source: Author)

Table also shows the cost ranges per square metre, the type of heating and cooling systems installed, and the NatHERS rating.

3.2.1. Discussion

Figure 2 - Thumbnail sketches of relative plan sizes, shapes and orientations of the 7 innovative homes, numbered 1 to 7 from left to right (Source: Author)

Table shows these homes comply with the building standards maximum size of 180m2, and have areas about half the average Australian detached home of around 245m2 (ABC 2015; ABS 2010). This greatly contributes to their affordability, and results from removing extra bedrooms, with other village accommodation available.

All homes have good thermal mass, with most having a concrete floor charged with direct sunlight in winter, while others have dense external walls: home 5 has a solid timber inner wall; homes 6 and 7 have compressed earth bricks CEB and earth floors (see

Figure 2 - Thumbnail sketches of relative plan sizes, shapes and orientations of the 7 innovative homes, numbered 1 to 7 from left to right (Source: Author)

Table). All have good insulation for their external walls.

Cold-bridging for the window frames was reduced by using timber, thermally broken aluminium or uPVC.

The home designs ensure good cross-ventilation in rooms; most having decks for outdoor living; and good ventilation features including utilising the convective stack effect (e.g. homes 1, 2, 3, 6 and 7 have openable upper windows and doors) aided by ceiling fans. While the costs per square meter are above average, the smaller village home sizes than average mean that the home costs are quite affordable and cost-effective, except for the homes which are particularly innovative.

3.3. The construction technologies of innovative homes

Details of construction materials, technologies and methods are shown in Table . All of the innovative homes use biogenic wall materials e.g. earth-filled tyres, strawbales, cob (earth, straw, lime and water), hempcrete (hemp husks, sand, a lime binder and water), a solid timber inner wall leaf, prefabricated strawbale panels, rammed earth, CEB, super-adobe, and light straw.

Figure shows the construction technologies of homes 1 to 4 It shows the earth-filling of home 1 tyre walls; a comparison of an Owner Builder hempcrete wall workshop and one built by a builder and the highly unusual Home 4 2-bedroom kit home with computer numerically controlled (CNC) laser solid timber wall being formed. The roof of the Octagon is an unusual reciprocal bamboo roof, and 3 of these homes have green roofs.

Figure 2 - Thumbnail sketches of relative plan sizes, shapes and orientations of the 7 innovative homes, numbered 1 to 7 from left to right (Source: Author)

Table 1: Design Features, Heating and Cooling Appliances and NatHERS ratings of Selected Innovative Homes (Source: Author)

Home	1	2	3	4	5	6	7
Description	Earthship	Hempcrete powerhouse	Sustainable hempcrete home	Reverse timber veneer modular kit	Natural family home	Hobbit style art studio	Bamboo & strawbale octagon
Drawings or Designer	Dr Martin Freney	Earlx2 Architecture	*	Mark Cassidy**	Kenney LeMire of IBD***	IBD's Will Eastlake	IBD's Will Eastlake
Gross Floor Area (m2)	82	143	113	79	83.6	53	104
Completed (year)	2019	2020	2020	2023 (expected)	2023 (upstairs)	2023 (expected)	2023 (expected)
Cost/area (AUD$/m2)	$4500 - $5000	$3,000 - $3,500	$5,000 - $5,500	$3,000 - $3,500	$4,300 - $4,800 (upstairs)	> 5,000	
No. bedrooms	2	3 and WIR	1	2	3 and study	1	1
Storeys	1	1 plus mezzanine	1 plus mezzanine	1	2	1	3
Ceiling insulation****	R5	R3	R5	R4	R6.5	R2.5	R4
Windows	Timber single and double glaze	Timber double-glazed	Thermally-broken, dble-glzd aluminium	Double glazed PVC	Local timber double glazed	Timber single-glazed	Timber single-glazed
Ext. Walls	Earth-filled tyres	Hempcrete	Hempcrete	Rvrs timber veneer	Prefab. strawbale	Super-adobe	Strawbale

Ext. wall insulation#	> R5	R4; R2.5 upper	R4; R2 upper	R2	> R7	> R5	> R7
Floor type(s)##	Concrete SOG	Concrete SOG	Concrete SOG	Steel-frame timber	Concrete part-suspended	Multiple	Multiple
Roof	Metal	Metal	Metal	Metal	Metal & green (plant) roof	Green roof	Metal & green roof
Eaves (m) ###	0.47	0.6 N&S, 1 E&W	0.3	0.1 N&S, 0.3 E&W	0.78	N/A	0.86
Ceiling Height (m)	2 to 3.6	2.7; 2.8 to 6.1	2.5 to 4.9	2.5 to 4.0	2.5	2 to 4	3 to 4.5 (3 levels)
NatHERS (design)	7.6	8.8	7.3	7.2	7	7.1	7.1
Heating and cooling systems####	Cooling tubes; inter-room fans; internal greenhouse	4 Laros Lunos e2 MHRV units	Air-conditioner; clerestory windows	Air-conditioner	Hydronic bathroom floor heating system	Openable cupola windows	Upper storey door for stack ventilation

*Not for publication; **Adapted a kit design; ***Integrated Biotecture (IBD); ****K.m2/W; [#](Acosta et al. 2010; Ahmed et al. 2022; Downton 2023); [##] Slab on ground (SOG); Multiple (Earth, timber & concrete floors); [###]North (N), South (S), East (E), West (W); [####] Mechanical heat recovery ventilation system (MHRV).

Figure 3 - Building technologies of homes 1 to 4. a. Compacting earth in tyres -earthship home 1 (Source: S. Bozkewycz); b. Home 2 volunteer hempcrete wall workshop (Source: G. Cameron): c. Home 3 hemp walls by builders (Source: M. Ong): d. Home 4 builders hammering together the solid timber wall (Source: P. Atkins)

Figure shows the construction technologies of homes 5 to 7. It shows the prefabricated straw panels; the art studio rock walls and arched doors; the art studio internal wall clay rendering of the super-adobe walls; installing the internal straw bale walls of the octagon home.

Figure 4 - Building technologies of homes 5 to 7. a. Prefabricated straw panel external wall for home 5 (Source: M. Lloyd); b. Home 6 art studio (Source: L. Scott); c. Home 6 art studio internal wall clay rendering onto super-adobe earth bags (Source: Will Eason); d. Straw baling the internal walls of the octagonal-shaped home 7, with the bamboo reciprocal roof at the top left blue cupola (Source: C. Oosthuizen)

3.3.1. Discussion

Except for homes 3 and 4, all were Owner-built with the help of the community, friends, relatives and others interested in learning during workshops, as well as professionals where needed. These workshops imparted valuable biogenic building skills on walls of hempcrete, earth-filled tyres, super-adobe, strawbale and rammed earth; and earthen floors; as well as for landscaping.

The kit home was sourced from Germany and manufactured in Lithuania, and had several delays resulting in late completion, including during the corona virus lockdown.

3.4. The health and amenity of innovative homes

Table shows the building materials are low in toxins, which should provide a healthy indoor environment. It also shows that the external walls of two of the homes were made of hempcrete, two had 450mm strawbale and one had a reverse timber veneer wall where the inner leaf was solid timber and the outer was colorbond. The internal walls of some homes included straw bales, straw panel and rammed earth.

For health and amenity two homes have hempcrete walls which have good environmental properties, and 4 have clay render while all have low VOC finishes and most have 2nd hand materials. The art studio and octagon homes have earth floors.

3.4.1. Discussion

The home air quality is high because owners used products with low volatile organic compounds (VOCs) or natural finishes e.g. earth floors had six oil coats taking many weeks to dry out. No carpets were used on floors, and the use of many second-hand materials and furniture items reduced fluorocarbon off-gassing effects.

Good natural ventilation was ensured as well as having active systems such as ceiling fans, mechanical heat recovery ventilation (MHRV) systems, buried cooling tubes activated with fans, and air conditioners to regulate temperature and humidity. These ventilation systems also reduce the risks of mould and can help reduce air-borne bacteria and viruses such as corona especially if using high-efficiency particulate air (HEPA) filters.

3.5. Village energy and carbon

Figure shows the Smart Grid's net annual export values, the grid connection via a 1MVA tap transformer regulating the voltage and frequency, and typical annual energy flows for homes with and without batteries.

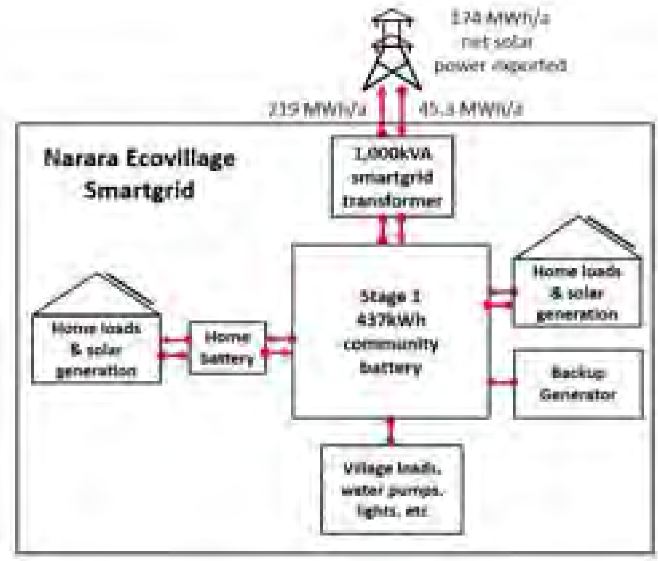

Figure 5 - Village and typical home energy assets, and annual exports and imports (Source: author)

The large community battery of 437kWh is charged by the village solar power with some homes having their own batteries, while there are village loads and an emergency diesel generator.

3.5.1. Discussion

The village is energy positive with the net energy exported in Figure of 174 MWh/a which is equivalent to an offset of around 135 t CO_2-e/a and is a significant renewable contribution to the grid from 50 homes. This is due to 1) the holistic approach to building standards, 2) energy generation and community battery storage, 3) peak power minimization and 4) other load demand management (ARENA 2016). The grid connection prevents the village from being operational zero carbon until it is decarbonised.

A few homes have electric vehicles (EVs) which can supply some power to the home. As EVs become more popular, NEV will encourage charging them with renewable energy and is looking forward to the imminent arrival of bi-directional charging where the EV can contribute as energy storage for the home (Teague 2023).

Table 2: Material details, construction methods and health and amenity of Innovative homes (Source: Author)

Home	1	2	3	4	5	6	7
Description	Earthship	Hempcrete powerhouse	Sustainable hempcrete home	Reverse timber veneer	Natural family home	Hobbit style art studio	Bamboo & strawbale octagon
Ext. Walls	Earth-filled-tyres; glass bottles; 450mm Strawbale; rammed earth; cob	Lower - 250mm hempcrete; Upper – lightweight wall	Lower – 300mm Hempcrete; Upper – lightweight wall	Reverse 80mm Nordic spruce veneer with colorbond	Lower – concrete, rammed earth, CEB & CEB veneer; Upper - Prefabricated 350mm strawbale panel; glass bottles	Double super-adobe with int. clay render & ext. lime render; glass bottles; cob	450mm strawbale; Light straw; cob; glass bottles
Int. walls	Rammed earth; cob walls	Timber frame with plasterboard	Timber frame & plaster-board	50mm solid timber	Straw-panel; Rammed Earth	Cob; double super-adobe with int. clay render	450mm strawbale; light straw; cob
Floor details	Concrete SOG with glass aggregate, polished 7 times	Concrete SOG	Burnished concrete SOG	Steel framed timber floor	Coloured low carbon concrete partly suspended	Mainly earthen with oil finish; timber; and concrete bathroom	Mainly earthen with oil finish; timber loft and concrete bathroom
Roof details	Light-coloured colorbond	Light-coloured colorbond	Light-coloured colorbond	Light-coloured colorbond	Light-coloured colorbond & green roof with plants	Green roof with plants	Bamboo reciprocal roof; Light-coloured colorbond & green roof with plants
Construction methods	Owner assisted in workshops with family & volunteers; local materials; skilled workers where required.	Owner build, with Local materials, workshops with volunteers; & skilled workers	Employed a local builder experienced in hempcrete building	Kit purchased from Germany, built in Lithuania, assembled by local organisation	Owner assisted by a local builder friend; volunteer workshops; skilled workers where required	Owner assisted by designers & builders for foundations & super-adobe workshops; skilled workers where required	Owner assisted by designers & builders for foundations & strawbale workshops; skilled workers where required
Health & amenity - avoiding toxins, and improving	Clay render on strawbale & low-toxic spray on rammed earth; low	Breathable hempcrete home; low VOC paints;	Breathable hempcrete home; thermally	Reverse timber veneer with solid Nordic	Natural wall materials and clay render finish including rammed	Natural wall materials & clay render finish for the strawbale	Natural wall materials & clay render finish (cob, strawbale

indoor environmental quality (IEQ)	VOC paints in greenhouse; lime render on bathroom ceiling and bamboo ceilings elsewhere; air cooled in buried tubes for cooling; good ventilation incl. inter-room reversible fans; many 2nd hand materials and furniture.	double glazed fire-resistant timber framed windows; good cross-ventilation; slow combustion heater; 4 small MHRV units	broken windows; good ventilation including stack effect; small air conditioner	spruce and colorbond mini-orb; low-VOC aquaclear paint; good cross-ventilation; small air conditioner.	earth, strawbale panels, cob walls with bottles; good cross-ventilation; many 2nd hand materials; low VOC paints	walls; good cross-ventilation; earth, timber and concrete floors; low VOC finishes; 2nd hand materials.	& light straw); good cross-ventilation; earth, timber and concrete floors; low VOC finishes; 2nd hand materials.

3.6. Home operational energy and carbon

Table shows the home details; the operational and embodied energy; and the carbon for five village homes where the full year of energy data were available. Three homes were from the above seven innovative homes and there are two additional ones. It shows the net operational energy exported and the carbon offset for supplying renewable energy into the grid for each home per year.

Table also shows the NatHERS star ratings, the solar panel size, any home battery, the 2 major home loads of 1) hot water system with their co-efficient of performance (COP) efficiencies and that use timers to use renewable energy and 2) the major heating and cooling systems. It also has the net energy exported and corresponding carbon offset, the home embodied carbon adjusted for the carbon-absorbing hempcrete.

3.6.1. Discussion

For thermal comfort Table shows that three of the five homes have air-conditioning installed. The village homes have 50% with air-conditioning due to higher NatHERS ratings or alternative approaches for heating or cooling (see

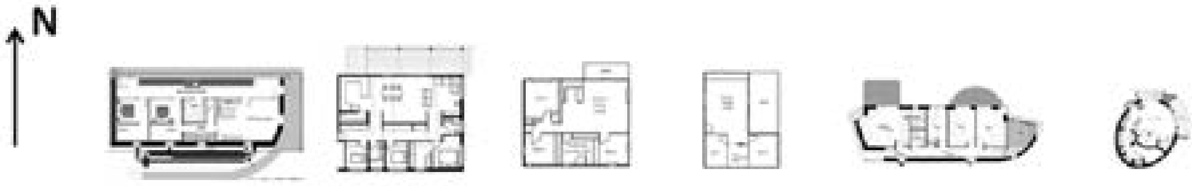

Figure 2 - Thumbnail sketches of relative plan sizes, shapes and orientations of the 7 innovative homes, numbered 1 to 7 from left to right (Source: Author)

Table), which eliminate temperature extremes. Two homes described in this section have MHRV systems to ensure proper ventilation, and assist with temperature and humidity stabilisation: home 2 having four small wall-inserted units that operated synchronously for a few hours per day; and home 8 having a large ducted system like that of a Passive House.

All homes have good thermal mass, but home 8 has an internal brick wall and a phase-change material called bio-PCM which releases and absorbs energy during the phase transition to assist with temperature control for the lightweight upper floor.

3.7. Home embodied energy and carbon

Table shows the embodied carbon using 1) NEV's embodied calculator in the Stage 1 building Standards and 2) using a current best practice value from Prasad et. al (NEV 2017, 24–25; Prasad et al. 2022, 130).

Table also shows the recurrent embodied carbon of the PV system (assuming that the renovation carbon is small in comparison), the total home embodied carbon after 90 years and the carbon capture calculations for the volume of hempcrete in two of the homes, with different wall thicknesses and perimeters. The table shows the calculations for offsetting due to solar panels and to hempcrete carbon capture, leading to an estimate of how many years each home would take to pay back its total embodied carbon (row 12 divided by row 14).

3.7.1. Discussion

NEV's embodied calculator in the Stage 1 building Standards was based on older overseas data, and only had the scopes of A1, A2 and A3 (raw materials supply, transport, and manufacturing, respectively), although it did include the solar panel and inverter embodied carbon and was a useful comparative measure. The best practice low value of Prasad et al (2022, p. 130) uses current Australian data and average values for the additional scopes of transport to site (A4) and construction carbon (A5), although it was assumed there was no solar panel embodied carbon calculation included, so the embodied carbon of the actual solar panel of each home was added when calculating the total embodied carbon for the five homes over 90 years.

The greatest challenge facing new housing is building homes with low embodied carbon. This is very difficult to achieve but successful strategies adopted by NEV members include 1) building smaller homes; 2) using biogenic materials like earth, timber, straw or hemp; and 3) using recycled and waste materials e.g. bricks, timber and cementitious materials for low carbon concrete.

All biogenic materials absorb carbon as they grow, but hemp grows particularly fast, and hempcrete captures carbon after setting since it reacts with lime to form limestone ($CaCO_3$), and so it has negative embodied carbon over its lifecycle. Hemp also has many other environmental features such as breathability, termite resistance, excellent insulation, good air-tightness and wastage recyclability. (Ahmed et al. 2022; Clarke 2018; Hempcrete Australia 2014). However, it has poor compressive strength, and so requires a frame.

The NEV by-laws have an aspiration to payback the for the home embodied carbon within 30 years, and there are three owners (homes 1, 2 and 3) who may achieve this (see Table). These homes use large solar systems, or moderate amounts of solar power with a battery, or have low energy consumption.

Home 3 has monitored its energy and carbon, and has abated 8.3t CO_2 in around 2 years, by using excess energy returned to the grid, without considering their hempcrete carbon capture. At this rate in 30 years, home 2 would only pay back around 120 tonnes of CO_2-e not the 167 tonnes estimated. However, this is a very interesting question for any future home carbon LCA and sustainability research, especially for hempcrete.

Table 3: Energy and carbon features of five NEV homes, with hempcrete carbon calculations (Source: Author)

Home	Details	1	2	3	8	9
Description		Earthship	Hempcrete powerhouse	Sustainable hempcrete home	Lightweight tightly sealed	Pre-fabricated 2 storey
NatHERS*	Stars	7.6	8.8	7.3	8.3	7.2
Solar panel size	kW	6.3	11.0	9.0	5.0	5.0
Battery	kWh	10.0	N/A	20.0	N/A	N/A
Hot water system	COP	5.0	5.0	5.0	4.0	17.0
Heating and cooling systems		Cooling tubes; inter-room fans; int. greenhouse	4 Laros Lunos e2 MHRV units	Air-conditioner; clerestory windows	Ducted MHRV system; air-conditioner	Air-condit-ioner
Net energy exports	kWh/a	4,567	12,013	7,692	4,674	3,325
PV carbon offset**	t CO2-e/a	3.6	9.5	6.1	3.0	2.6
Home embodied carbon***	NEV (2017)	62.9	74.0	61.0	50.8	58.6
	Prasad et. al. (2022)	62.5	109.0	86.1	87.6	114.3
PV system recurrent embodied carbon	t CO2-e every 30 years	18.9	33	27	19.8	15.6
Total home embodied carbon Prasad et al. (2022)	After 90 years (PV plus)	119	208	167	147	161
Hempcrete#	width (m)		0.25	0.30		
	area (m2)		50.0	80.0		
	Volume (m3)		12.5	24.0		
	Carbon capture (t CO2-e/a)		0.0119	0.0228		
Carbon offsets for PV & hempcrete##	t CO2-e/a	3.6	10.7	8.4	3.0	2.6
Total embodied carbon payback###	years	33.0	19.5	20.0	48.9	61.3

*Design NatHERS rating (2017 version) except for Home 8 (As-Built – NatHERS version 2019)

** Based on energy exported and the NSW electricity carbon intensity from National Greenhouse Accounts Factors (DCCEEW 2022)

*** (NEV 2017, 24–25; Prasad et al. 2022, 130)

#Hempcrete has a net sequestration range from 48.4 kg CO_2 per m3 to 137 kg CO_2 per m3 over 100 years (Jami, Karade, and Singh 2022, 229–30). So, the average of this range (95 kg CO_2/m3) was used to estimate the carbon capture per year.

##PV carbon offset from home PV net energy exported plus any hempcrete carbon capture

###Total home embodied carbon divided by carbon offset from home PV and any hempcrete carbon capture

4. Conclusion

Members of Narara Ecovillage in the Central Coast of NSW have created high-performance, healthy, energy-positive homes with low embodied carbon, and the village is known as an exemplar global precinct for achieving nearly net zero carbon.

Seven homes were compared for performance, construction technologies and health and amenity, and five others were compared for carbon imported and exported, embodied and their lifecycle carbon (LCA).

This study provides a glimpse into the future of housing to 1) improve home building with additional builder checks; 2) lower housing impacts on the electricity grid, 3) mitigate operational and embodied carbon emissions for the climate emergency, 4) adapt homes for heatwaves, and 5) prepare to rebalance home loads as a) the National Construction Code (NCC) increases its stringency for thermal performance, and b) electric vehicles replace home batteries as bi-directional charging arrives but require charging from renewable energy.

5. Acknowledgements

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Building resilience to climate change and mental wellbeing through eco-centric urban design

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Abstract: Climate change threatens more than just our physical livelihoods. In developed areas, urban heat island effects, flooding and coastal inundation - amongst other impacts of climate change – also trigger a psychological response. Recent terms such as *eco-anxiety, ecological grief,* and *nature deficit disorder,* have emerged associating the connection between climate change and mental wellbeing. Despite this, the dominant modes of urban design are not fit for purpose regarding our response to climate change and mental wellbeing and will only exacerbate the impacts of these issues moving forward. Ecocentrism, provides an alternative approach to problem solving. In comparison with the dominant models currently used which reflect anthropocentric thought, ecocentrism recognises the intrinsic link between the health of the ecosystem; and the health of people, who, are part of the ecosystem. This eco-centric thinking was applied to an existing neighbourhood sub-catchment in Māngere – Auckland, New Zealand and showed that when design decisions are driven by ecocentrism, it brings forth possibilities for our built environment that will better address the environmental and social challenges we face.

Keywords: Climate change, wellbeing, design

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Building tomorrow's buildings today – Assessing the climate resilience of a high-performing apartment building in Melbourne

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Abstract: It is well established that unabated greenhouse gas emissions will lead to warming of globe of at least 1.5ºC during the 21st century, and the resulting changes in atmosphere, ocean, cryosphere and biosphere that already have, and continue to occur, will alter perceived and measured indoor environment comfort levels. Despite the collective knowledge of building design mitigation strategies for climate change, relatively little is known about the future resilience of current high-performance apartments based on expected temperature rises and during extreme weather events. At present, we are still learning how to design for these future scenarios. This knowledge gap places building owners, operators and occupants at risk, and designers responsible for the thermal performance and resilience of buildings without a defined, evidence-based and common methodology. This research uses a calibrated computer simulation to predict future achievement of international comfort standards based on data collected from a recently built 8-star NatHERS apartment in Melbourne, Australia. These results show that a shift from a predominantly heating to a predominantly cooling scenario is likely for high-performance apartments that are designed for today's climate. These findings are significant for assisting designers to understand the need to balance the thermal performance of apartments in Melbourne both now and in the future.

Keywords: Building resilience; climate change; future proofing; indoor environment quality.

1. Introduction

The building sector has been identified as a substantial contributor to global warming, with 37% of greenhouse gas (GHG) emissions attributable to buildings globally (UNEP, 2022). Existing literature that addresses impact of the built environment on climate change often considers the Intergovernmental Panel for Climate Change (IPCC) predictions for temperature and sea level rise (de Wilde, 2014) with an overwhelming focus on mitigation strategies that prioritise the minimization of impacts from buildings on the environment. This mentality ignores the concept of adaptation and resilience, both of which address the inevitable occurrence of the predicted changes. 'Adaptation' describes the anticipation of the adverse effects of climate change and taking appropriate action to prevent or minimize the damage and adjusting to the current and future effects of climate change (European Environment Agency, 2023), which is of increasing importance when anticipating the impacts of the

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 168 - 183.

environment on our buildings (Jensen 2022). Resilience is the term used to define our ability to recover from these events when the occur (Swart & Raes, 2015). From an industry perspective, a resilient building is defined as “one that has been built to be more robust than required by minimum building standards and is thus able to better withstand natural disasters and future climate change conditions such as bushfires, flooding and heat waves” (GBCA). In Australia, multi-residential buildings (Class 2 in the National Construction Code (NCC)) are characterized by a lack of flexibility to modify the structure and envelope due to the multistorey nature of the typology, making apartments more susceptible to climate change than other residential building classes. This lack of flexibility to adapt places greater emphasis on the inclusion of climate resilience to be incorporated into a building’s design from the outset. Analysis of a building future climate performance is therefore critical for multistorey apartment buildings.

The benefits of the iterative design process using complex building energy simulation has been defined by others (Papamichael and Protzen, 1993; Papamichael, 2000), and the significance of the uncertainty analysed by Lee et al (2012). The design process for low energy buildings is improved by the knowledge developed by using a building simulation program for an existing building and “tuning” or calibrating the various inputs to the program so that predictions match closely with observed energy use (Reddy et al 2007). Bridging the gap between predicted and measured performance is crucial if the design is to provide serious input to the delivery of buildings that meet their ambitions now and into the future (de Wilde 2014). Despite this imperative, there is extensive evidence to suggest that buildings usually do not perform as well as predicted (Bordass et al 2004, Demanuele 2010), although others note that the inaccuracies can be due to the effect of the weather file (de Wilde 2014) and the behaviour of the occupants (Ryan et al 2012), each of which representing the dynamic variables in the otherwise static model. Gill et al (2010) found that occupant behaviour accounted for 51%, 37%, and 11% of the variance in heat, electricity, and water consumption, respectively, between dwellings. Other studies highlight meteorological variability as having an influential impact on building performance (Bhandari et al 2012, Hassan 2009). However, when considering that buildings have an operational life of 50 to 100 years, the use of historical weather data to assess their performance in a changing climate has been criticised as inappropriate (Watkins et al. 2011; Gupta, & Gregg 2012; Ren et al. 2011). However, there is sufficient scientific evidence and consensus of future climate prediction (Oreskes 2007) and these resources are now available to industry, to allow for the use of morphed future weather files in standard building simulation methods and protocols as part of statutory and voluntary certification requirements. Future weather predictions can also be used in building simulation used to optimise design and building services’ performance, and inform developers, building’s owners and occupants of the expected future efficiency of their buildings (de Wit and Augenbroe 2002). The ability to easily model using future weather files allows simulations ability to run multiple climate scenarios in design in order to optimise thermal comfort across multiple climate change scenarios and time spans.

2. Methodology

This research uses the case study methodology which included developing a calibrated computer model of the case study project using site specific recorded weather data and project specific indoor temperature data for the period August 2022 to July 2023, and then using modified weather files representing RCP8.5 in 2050 and 2090 as a variable for dynamic thermal simulation (see Figure 1). Case studies are appropriate to be used to test or generate theory and are particularly appropriate for areas where the research is still in its infancy, or formative stages where there are no solid theoretical foundations. It is preferred when “how” or “why” questions are being posed (Yin 1994).

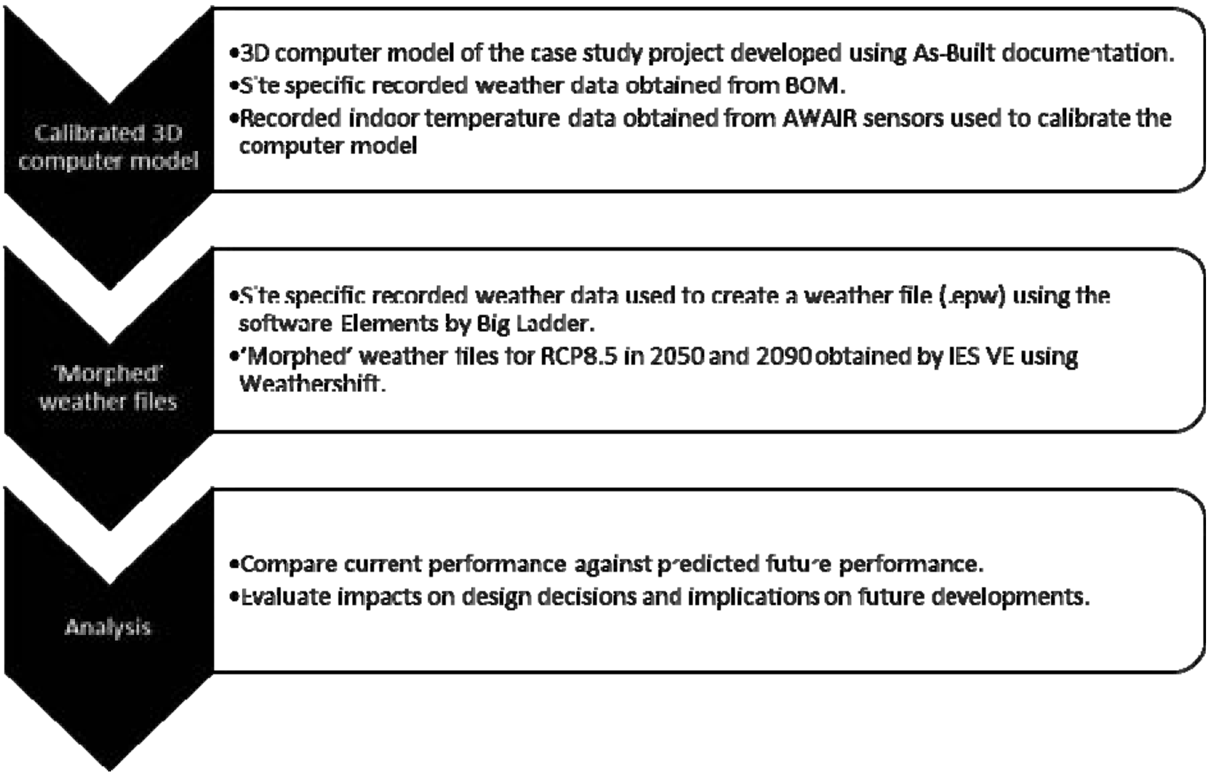

Figure 1: Schematic representation of research methodology

2.1. Case study computer model

The case study project (highlighted in Figure 2) is an apartment in a multi-storey building completed in August 2022 composed of 22 sole-occupancy units over five storeys with retail tenancy on ground floor located in South Melbourne, Victoria (Australia – NatHERS Climate Zone 21). Compared to the Victorian average NatHERS rating of 6.9-star for Class 2 dwellings (CSIRO 2023), the case study development can be considered of higher-than-standard thermal performance with an average NatHERS rating of 8.6-star and the lowest rating of 7.4-star. The reference apartment used as part of this research (Figure 3) was rated 8.1-star NatHERS. It is located on the fourth floor of the development, it is exposed to the outdoor on three out of four elevations, it has an exposed roof for approximately 50% of the floor area, exposed floors for approximately 13% of the floor area, and a window-to-wall ratio of approximately 26%.

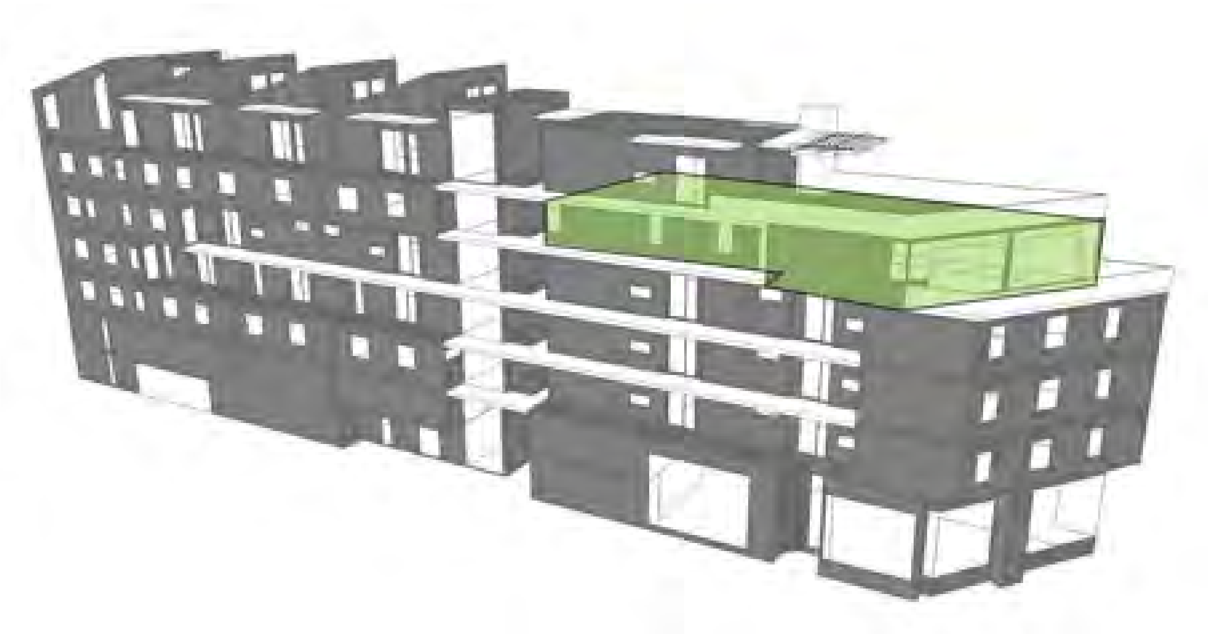

Figure 2: As modelled 3D geometry

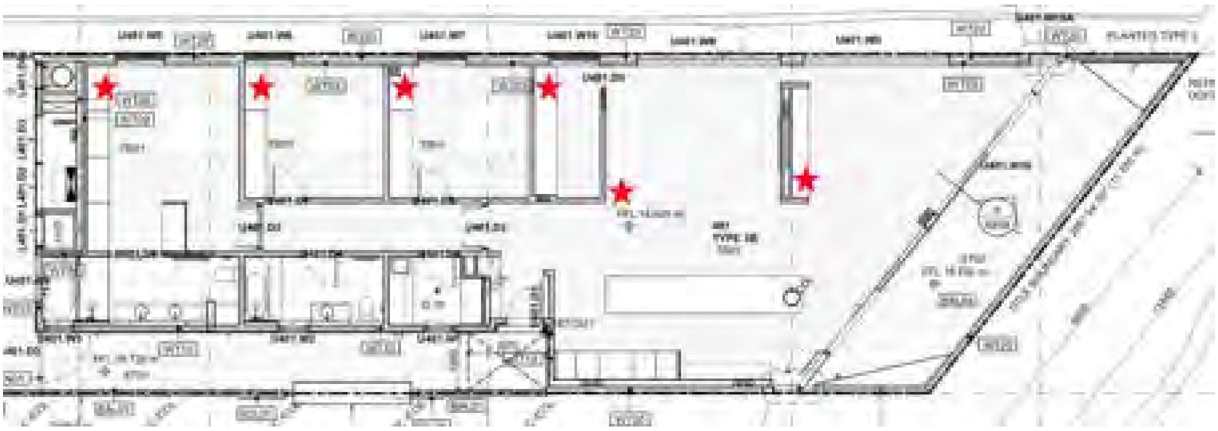

Figure 3: Case study apartment floor plan

The thermal performance of the construction assemblies, air permeability level, heating and cooling services and mechanical energy recovery ventilation design have been modelled as per As-Built documentation and test reports, thus providing a high level of accuracy and correlation to actual operational performance. Table 1, 2, 3, 4 and 5 outlines the parameter used in the model.

Table 1: Opaque thermal envelope assemblies

Assembly	Description	Total R-Value (m2.K/W)
External roof	200mm in-situ concrete, 70mm (R3.5) insulation, 290mm ceiling cavity, 13mm plasterboard	4.03
External wall	Perimeter concrete wall 150mm precast concrete, 20mm air gap (non-ventilated), vapour permeable membrane, 90mm (R2.7) insulation in 92mm steel stud (600 ctrs max.), 13mm plasterboard	1.86
	Lightweight wall 8mm fiber-cement sheet, 35mm furring channel (non-ventilated), vapour permeable membrane, 6mm (R0.2) thermal break, 16mm fire rated plasterboard, 90mm (R2.7) insulation in 92mm steel stud (600 ctrs max.), 16mm plasterboard	1.93
	Core & party wall 150mm precast concrete, 20mm air gap (non-ventilated), vapour permeable membrane, 75mm (R1.8) insulation in 64mm steel stud (450 ctrs max.), 16mm plasterboard	1.68
External floor	Floor covering (timber), 200mm in-situ concrete, 60mm (R3.0) insulation, 290mm ceiling cavity, 13mm plasterboard	3.73
Intertenancy floor/ceiling	Floor covering (timber), 200mm in-situ concrete, 350mm ceiling cavity, 13mm plasterboard	0.81

Table 2: Translucent thermal envelope assemblies

Assembly	Description	Total U-Value (W/m2.K)	Total SHGC
Tilt & turn window	4 clear / 20 argon warm edge / 4 iPlus in timber frame	1.50	0.313
Lift & slide	4 clear / 20 argon warm edge / 4 iPlus in timber frame	1.60	0.420
Awning	4 clear / 12 argon warm edge / 4 iPlus in timber frame	1.70	0.378

Table 3: Air permeability

Test method	Test Pressure (Pa)	Air permeability – negative pressure (m3/h/m2)	Air leakage – negative pressure (ACH)	Air permeability – positive pressure (m3/h/m2)	Air leakage – positive pressure (ACH)
AS/NSZ ISO 9972 Method A – Building in use test	50	2.33	2.72	2.36	2.79

Table 4: Heating and cooling

Type	Room served	Rated cooling capacity (kW)	Rated heating capacity (kW)	Airflow high (L/s)
VRF	Kitchen / living	7.1	8	350
VRF	Master bedroom	2.5	2.5	150

Table 5: Energy recovery ventilation

Type	Room served	Supply air (L/s)	Return air (L/s)	Outdoor air (L/s)	Exhaust air (L/s)	Static pressure (%)	Sensible efficiency (%)	Effective heat exchange capacity – heating (%)	Effective heat exchange capacity – cooling (%)
ERV	Bed 2 (SA) Bed 3 (SA) Pantry (SA) Ensuite (RA) Bath (RA)	7.1	97	97	97	150	81.4	73.4	54.1

2.1.1. Simulation software

The Virtual Environment building simulation software version 2023.1.0.0 developed by Integrated Environmental Solutions has been used to complete the dynamic modelling for this research. The Virtual Environment meets several approved international standards including ASHRAE 140: 2001, 2004, 2007, 2014, 2017; BEST TEST; CIBSE TM33; EU EN13791: July 200; ANSI/ASHRAE/ACCA Standard 183; and ISO 52000 thus making it an accurate software for detailed energy modelling simulations.

2.1.2. Weather data

The Melbourne Olympic Park 086338 weather station was selected as the most representative source of data for the case study project location. Hourly dry bulb temperature (˚C), wet bulb temperature (˚C), dew point temperature (˚C), relative humidity (%), wind speed (m/s), wind direction (˚true), and atmospheric pressure (Pa) were obtained from the weather station through the Bureau of Meteorology. Global horizontal solar irradiation (W/m2) and diffuse horizontal solar irradiation (W/m2) were not available from this weather station and have instead been obtained from the One Minute Solar Data through the Bureau of Meteorology. It should be noted that irradiation data was only available for Melbourne Airport 086282 weather station and recording stopped at the end of 2020. The raw data was converted into an EPW climate file using the software Elements by Big Ladder. The projected future climate EPW weather files were generated using the morphing technique (Belcher et al. 2005) by Integrated Environmental Solutions using Weathershift. These files are based on the Representative Concentration Pathway (RCP8.5) emissions scenario as defined by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report. Figure 4 illustrates the outdoor dry bulb temperature variations between the actual 2022-23 recorded data, and the projected future data in 2050 and 2090. The maximum recorded outdoor temperature in 2022 was 36.90 ˚C while the minimum was 0.9 ˚C. The projected future climate weather files feature a maximum temperature of 40.20 ˚C and 42.40 ˚C for the 2050 and 2090 timescales respectively and a minimum temperature of 2.50 ˚C and 3.60 ˚C for the 2050 and 2090 timescales respectively.

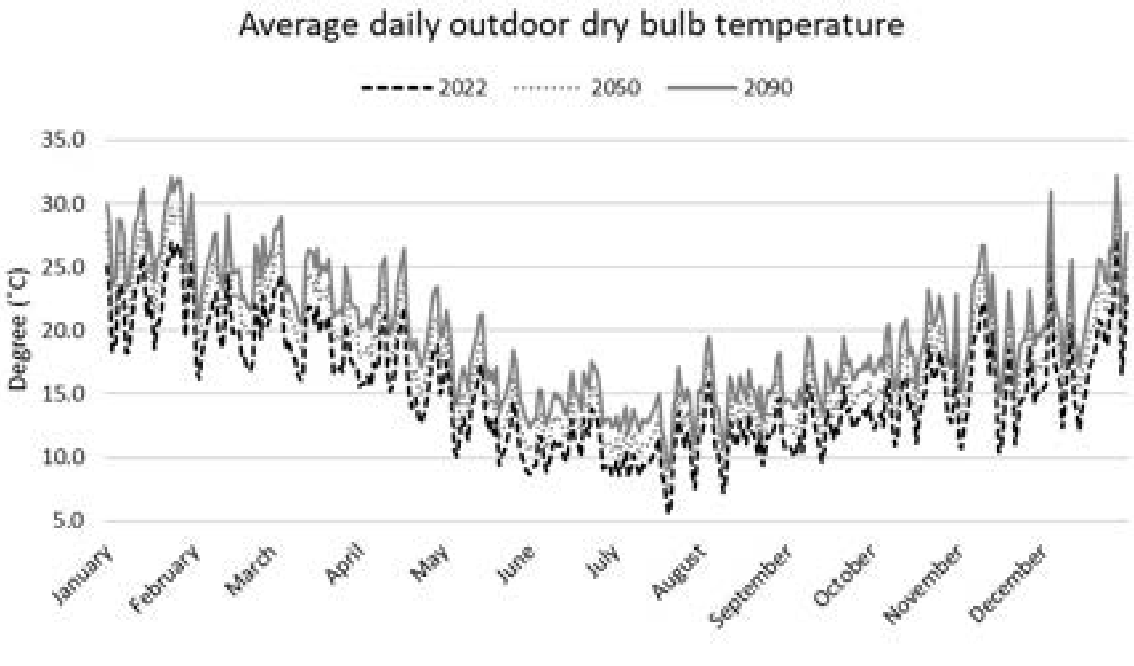

Figure 4: Average daily outdoor dry bulb temperature for 2022-23, 2050, 2090

2.2. Measured parameters

The dwelling was monitored with six factory calibrated IEQ AWAIR monitors located in each bedroom, study and living spaces (see Figure 3) over the period of August 2022 to July 2023. The monitors were located at desk height and recorded temperature, relative humidity, CO2, TVOCs, PM 2.5, noise and light at 5 minutes intervals. A representative summer and winter week were used for the calibration testing due to the overheating and overcooling risks and to represent the peak heating and peak cooling conditions.

2.3. Limitations

Several limitations have been accepted in this study. Firstly, predicted future weather files represent only one possible interpretation of the future climate. While uncertainty exist in this regard, the precautionary principle should apply in design and the worst-case scenario used as baseline. Further, IEQ monitors are sensitive devises and readings may be impacted by accidental movement of the devices. Finally, computer model represents a simplified and idealised version of a building that cannot fully account for all of the intricacies of buildings in operation. Therefore, the operational performance of buildings cannot be solely evaluated by computer models.

2.4. Calibration

The purpose of the calibration is to closely replicate the indoor temperature profile of the living room in the computer model with those recorded on site, thus allowing comparison between the two data sets so that the model can then be used to predict the performance of the dwelling under future climate scenarios with an acceptable degree of confidence. The key variable used for the calibration process was the indoor air temperature. This was selected as a key factor influencing thermal comfort and the heating and cooling systems energy demand in residential buildings. The key aspects of the model that have been modified include the operating profiles and set points of the heating and cooling systems; the efficiency of the heat recovery ventilation system; and user behaviours on natural ventilation as well as the operation of the hydronic floor heating in the evening and morning during winter to maintain comfortable temperatures overnight in the bedrooms thanks to the heat exchanger of the HRV unit. The calibration has been conducted for one heating week (6 to 12 August) and one cooling week (18 to 24 December) in the living room. The living room was selected as the main room where occupants spend a significant proportion of occupied hours, but also because this room contains a large glazed area, thus making it the worst-performing room in the dwelling from a thermal performance point of view. ASHRAE Guideline 14 (ASHARE 2002) has been referenced to establish acceptable variation tolerances in the calibration process. For the purposes of this research a coefficient of variation (CV) of less than 30% has been targeted. This accounts for variations due to occupants' behaviours, such as opening and closing windows randomly, which are difficult to account for in modelling and are outside of the designer's control. Table 6 lists the results of the calibration, while Figure 5 graphically represent the results demonstrating that the calibrated model is sufficiently accurate.

Table 6: Calibration results

Room	Period	Max. CV	ASHRAE max. CV targeted
Living	18-23 Dec (cooling week)	14%	30%
	6-12 Aug (heating week)	9%	

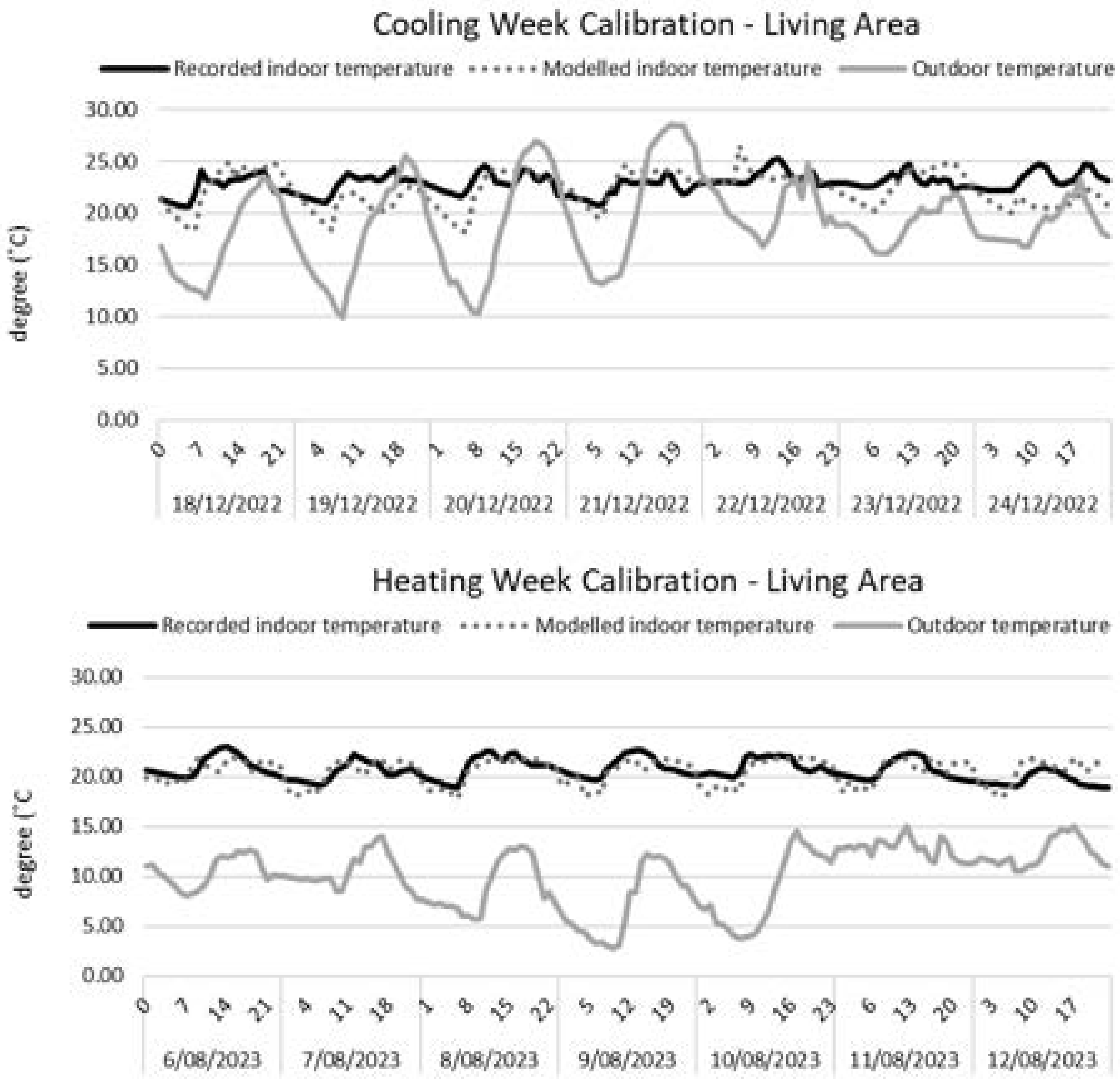

Figure 5: Cooling and heating week calibration

3. Results

3.1 Heating and cooling energy demand

The analysis of the heating and cooling energy demand shown in Figure 6 and 7 compares the modelled performance (2022) with the predicted changes in performance that the case study apartment is likely to experience during its operational life based on the RCP8.5 2050 and 2090 scenarios. Figure 6 shows that heating energy is predicted to decrease by 37% in 2050 and by 67% in 2090 under RCP8.5. In contrast, Figure 7 shows that the cooling energy is predicted to increase by 100% in 2050 and 198% in 2090, with the cooling season extended by approximately two months.

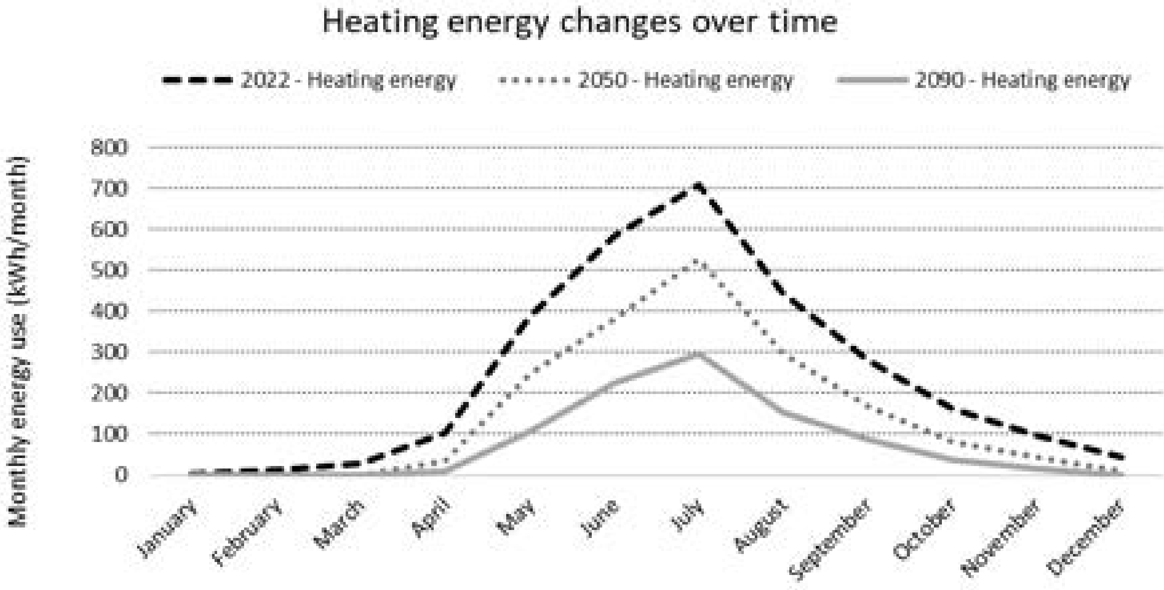

Figure 6: heating energy is predicted to decrease by 37% in 2050 and by 67% in 2090 under RCP8.5

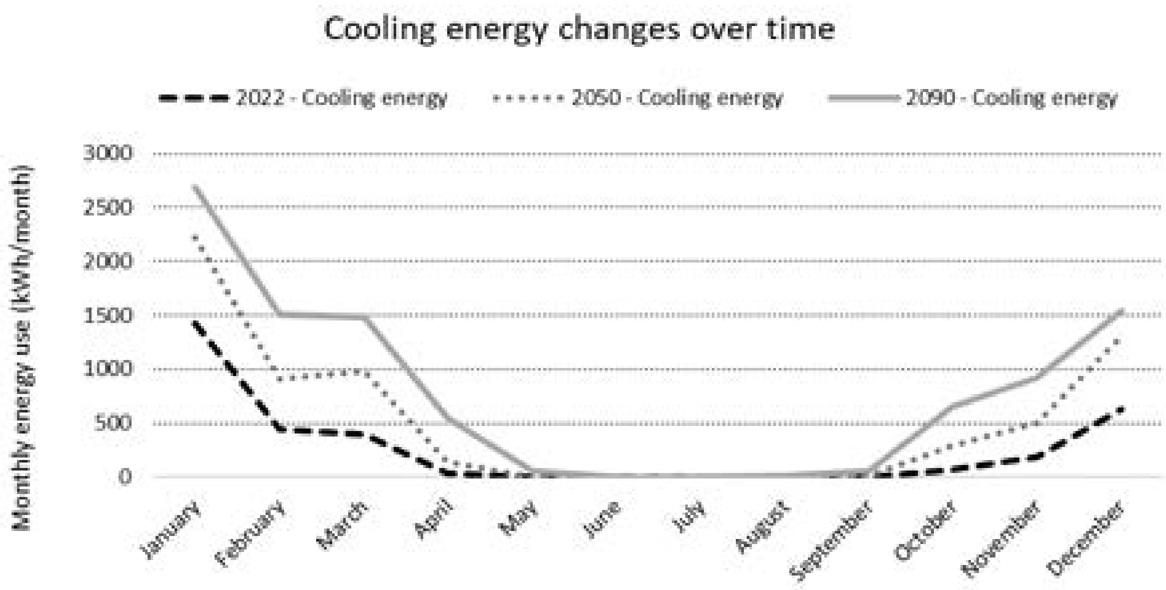

Figure 7: cooling energy is predicted to increase by 100% in 2050 and 198% in 2090

3.2. Thermal comfort

The analysis of the indoor temperature ranges in free-running mode is presented in Figure 8. The thermal comfort range of 18 ˚C and 24 ˚C has been used as recommended by the World Health Organization (2018) to reduce the risks of negative health impacts associated with prolonged exposure to cold and hot temperatures. As consistent with the energy results, the thermal comfort results indicate a shift from the majority of occupied hours remaining within comfortable temperature bands in the 2022 scenario to the majority of occupied hours exceeding the 24˚ C threshold in the 2090 scenario. On average the percentage of hours below 18 ˚C decreased by 51% in 2050 and by 92% in 2090 compared to the current 2022 levels. The percentage of hours within the 18-24 ˚C decreased by 3% and 8% respectively for the 2050 and 2090 scenarios, while the percentage of hours exceeding the 24 ˚C threshold increased by 58% and 111% respectively for the 2050 and 2090 scenarios.

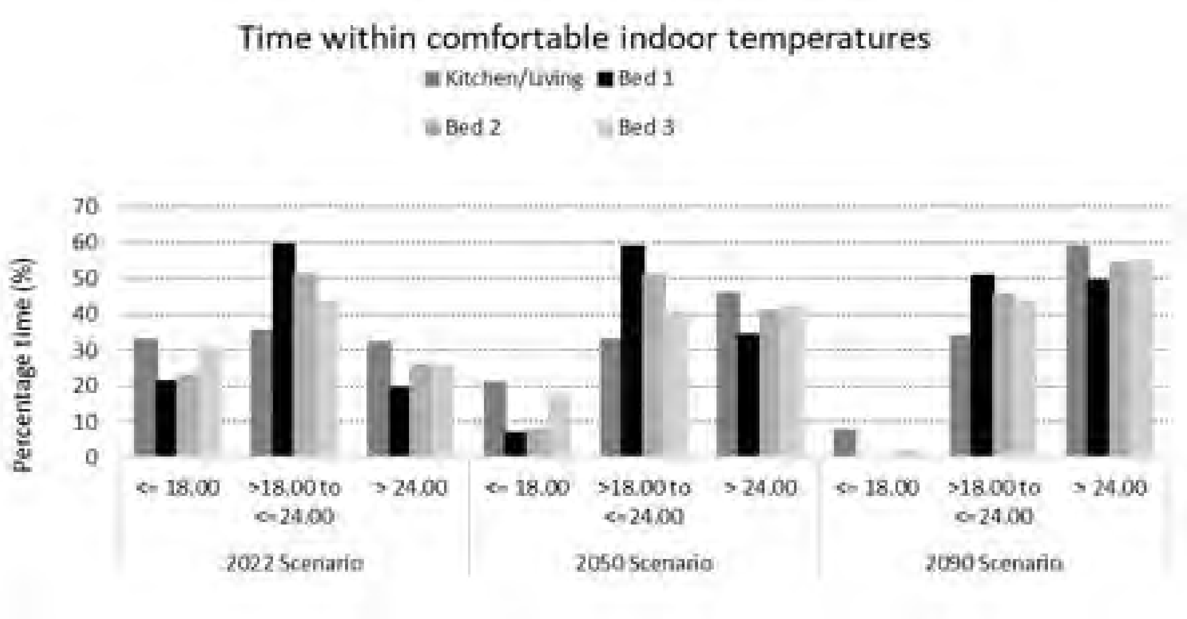

Figure 8: Current vs. predicted hours within indoor thermal comfort ranges

4. Discussion

The results of this research expose a key issue that is well-understood in academia (Wang et al. 2010; Karimpour et al. 2015; Chen et al. 2021) but not yet appropriately addressed in industry, including policy, statutory requirements, or modelling protocols. This is that by the end of the century, and assuming the worst in climate change projections, we are likely to experience a shift from a heating dominated to a cooling dominated climate for our residential building stock in Melbourne Australia, and the impact of this shift will impact multi-residential buildings that have limited flexibility for resilience and adaptation. As already highlighted by other research (Snow & Prasad 2011; Bamdad et al. 2021) such a shift can have significant implications to the operational performance of residential buildings and in turn how we design them. If we continue to design residential buildings for maximum solar heat gain and ignore the potential shift in heating and cooling requirements over the next 30 to 60 years, we may well be contributing to the construction of a residential building stock that is likely to become unfit for purpose half-way through its operational life. The shift from a heating to a cooling dominated climate may also have negative repercussions on greenhouse gas emissions (Wang et al. 2010). Using the data from this case study it can be possible to suggest that a shift from a heating to a cooling dominated climate may result in an increase in greenhouse gas emissions of 35% and 72% in the 2050 and 2090 timescales respectively compared to the 2022-23 baseline. This is a significant increase in national greenhouse gas emissions that will not support the global efforts to mitigate the impacts of climate change.

This research also highlights that buildings designed and constructed to a higher-than-standard thermal performance level today are not guaranteed to maintain the same level of performance in a period of climate change, thus raising concerns about the common assumption that high-performance buildings by today's standards are automatically going to be high-performance in the future. It is therefore increasingly important to approach buildings as dynamic rather than static objects, and to design them keeping their long-term operational performance and the factors that influence it the most, such as the climatic conditions in which buildings will operate, in the forefront of our minds. Most building simulation methods and protocols require historic weather files to be used to predict operational performance, highlighting the potential for weakness in buildings that target high-performance based on modelling with these weather files. These files are constructed using 20-40 years of historical data that exclude increasingly common extreme events and variation from current weather patterns. While simulation using this type of files is appropriate to establish a performance baseline for comparison purposes, it does not support an evidence-based design optimisation process. By using future weather files as part of sensitivity analysis and optimisation modelling, the industry will be better placed to future-proof buildings designed and built today to withstand the climatic conditions that we are likely to experience in the future. Relatively simple measures such as upgrades to the building thermal envelopes, window-to-wall ratios, external shading strategies can easily be evaluated and optimised to work today and into the future. Other design strategies, such as the need to make enough spatial allowances for plant rooms, risers, bulkheads, to allow for future upgrades of building services may also be cost-effectively evaluated and designed with the use of future weather files.

5. Conclusions

The extensive knowledge of climate change scenarios has yet to create a significant impact in the design of apartment buildings from the perspective of resilience rather than mitigation, which still promotes optimised solar gains for residential buildings in Melbourne. Analysis of a recently completed high performance apartment in Melbourne shows that current design practices may not appropriately address the future thermal performance requirements based on the RCP8.5 scenarios for 2050 and 2090, which show an overwhelming shift from a heating dominated climate to a cooling dominated climate. The modelling shows that indoor temperatures for the same apartment design shift from a balanced spread across the 18 – 24 degree range to being heavily stacked in the higher ranges in the 2090 scenario. Multi-residential apartments are likely to be especially affected as they are limited in their ability to be adapted to address these changes. Although further research is required, the results of this study indicate that high performance building designs are likely to be equally affected due to their design specific to the current climate. Further research is required to explore sensitivity analysis of future climate scenarios to design more resilient buildings, and how best to balance the current and future climate requirements in a single design. Future academic and industry-based research should focus on exploring how to best incorporate future weather prediction in typical modelling protocols part of statutory and voluntary certification requirements for different typology of buildings in different climate zones that may be more or less impacted by changes in weather patterns.

6. Acknowledgements

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Building with nature: The case of floating houses in Agusan Marsh, Philippines

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Abstract: Interest on vernacular and indigenous architecture is gaining more ground in search for socio-ecological approach to planning and design since urbanisation and climate change necessitates reframing the production of architecture as material expression of human-environment relation. Thus, this case study investigated the floating houses of Agusan Marsh in Sabang Gibong, Talacogon, Agusan del Sur, Philippines, home to the Manobo ethnolinguistic group. It documented the architecture, methods of construction, and factors that shape the dwellings and settlement of the community. Through direct observation and immersion, focus group discussions, and structured and key informant interviews, results revealed that there are four typologies of floating houses in the area referred in local dialect as *hapa*, *hanger*, *hapa-hanger*, and *dos andanas*. Further observation revealed that these typologies and settlement pattern are influenced by and in response to environmental conditions specific to Agusan Marsh, local materials available, and financial capacity of households. This indigenous practice reflective in the vernacular architecture maximizes environmental conditions as opportunities to produce man-made environment that complements the dynamism of marsh ecosystem. Thus, this study demonstrates the agency of the people in shaping the built and natural environment, which plays important role towards sustainability of the marsh landscape and its people.

Keywords: Indigenous, architecture, Agusan marsh, sustainability.

1. Introduction

1.1. Background of the study

The current challenges presented by urbanization and climate change resulted to the shift in the focus of inquiry to human-environment relations and the opportunities that can be presented by vernacular and indigenous architecture. As a result, studies relative to vernacular and indigenous architecture and the socio-ecological approach to design and planning has been gaining ground in recent years.

One of the pioneering works on vernacular architecture is that of Bernard Rudofsky (1964) and his publication of Architecture without Architects that highlighted human and nature-relations in shaping the built environment. He explained that vernacular architecture is communal architecture as they are produced not by specialists but by the spontaneous and continuing activity of a whole people with a common heritage, acting within a community of experience. Moreover, he provided an unconventional modern approach to architecture wherein

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he proposed learning from indigenous architecture sighting that they are 'unimprovable' as they are designed in 'perfection' to their environment (Rudofsky, 1964, p.1).

On the other hand, the socio-ecological model was first developed by a Russian-American Psychologist Urie Bronfenbrenner (1979) in relation to human development. He theorised that man is influenced by his ecological environment of nested structures they may or not be directly in. This theory was widely adopted not only in the social sciences and birthed among others the socio-ecological approach to architecture and design.

In relation to these theoretical developments, this study investigated the floating houses of Agusan marsh as vernacular and indigenous architecture under the lens of socio-ecological approach to planning and design. The study focused on architecture, methods of construction, and factors that shape the dwellings and settlement of the community.

1.2. Agusan Marsh and Sabang Gibong

The Agusan marsh located in the province of Agusan del Sur, Caraga Region, Mindanao, Philippines is one of the largest wetlands in the country serving as a catch basin of adjacent regions that is estimated to cover a total land area of 110,000 hectares including its floodplain. However, only 19,196.558 hectares was declared as protected area through Presidential Proclamation No. 913 Series of 1996 but was expanded to 40,954.745 hectares through Republic Act No. 11038 in 2018, spanning thirty-eight (38) barangays within six (6) municipalities of Agusan del Sur.

As one of the barangays located in Agusan marsh, Sabang Gibong, Talacogon is also a river barangay with 100 percent of its families residing in floating houses. Geographically, the barangay site is at the centre of Agusan Marsh Wildlife Sanctuary (AMWS) and within the Certificate of Ancestral Domain Title (CADT) 077, particularly at the junction of Gibong and Agusan Rivers. Currently, it has 248 total number of households, and population of 1,013 individuals, wherein 99 percent are identified who belong to the Manobo ethno-linguistic group (PGAS-CBMS, 2018).

1.3. Statement of the problem and research objectives

Urbanisation and climate change are two of the pressing issues of the 21st century. In the Philippines alone, the population increased from 26.27 million in 1960 to 111.05 million people in 2021, which is a gigantic growth of 322.7 percent within 61 years (World Data, 2022). Moreso, the ability of the environment to heal itself from natural calamities is dwindling and it is reported that the global water levels may rise from 10 to 12 inches by 2050, submerging majority of the coastal areas of the Philippines.

Recognizing the opportunities that may be provided by vernacular and indigenous architectures in response to pressing issues, this study documented the floating houses of Agusan marsh. Specifically, it investigated the knowledge and practices of the indigenous community, formally referred to as indigenous knowledge system and practices (IKSP), relative to the practice of floating houses, including but not limited to architecture, methods of construction, and factors that shape the dwellings and settlement of the community.

2. Methodology

This study employed varied qualitative data collection, processing, and analysis methods, and focused in the Sabang Gibong barangay site of 100 inhabited floating houses. Primary data were collected through direct observations and immersion, while three (3) focus group discussions (FGD) were conducted composed of five (5) to 11 informants per session using guide questions translated in local *Bisaya* language. Moreover, interviews were administered to further explore ideas and concepts gathered from the discussions; particularly with five (5) key informant interviews (KII) and 20structured interviews (SI) with the aid of prepared interview schedules in local *Bisaya* language. Each household was represented by one research participant as the key informant.

Additionally, secondary data were secured from government and non-governmental entities and researchers that served as baseline data and to support the literature review. These include studies relative to the subject matter, shape files and jpeg copy of maps, biodiversity assessment, and population statistics. The documents were appropriately referenced and recognized. Furthermore, this study employed data reduction and abstractions techniques (O'Leary, 2017, pp. 324-344). Particularly, raw data derived from FGDs, interviews, and observations were organized and reduced, interconnectedness were established, and themes were identified to ensure meaningful understanding of the result.

3. Results and discussion

3.1. The history of Sabang Gibong

Tracing the history of Sabang Gibong is necessary to understand the beginning of the floating houses of the area as a vernacular and indigenous architecture. For many thousands of years, Sabang Gibong is home to a community belonging to the Manobo ethnolinguistic group. Cruz-Lucero (2020) postulated that Manobo is an Islamized term for '*Manuvu*' or '*Minuvu*' which translates to 'people.' These groups are sometimes called '*Mansuba*,' literally referring to man (person or people), with '*suba' that means* 'river' since they usually reside along rivers (Cruz-Lucero, 2020, p. 1). In parallel, the locals refer the prehistoric Sabang Gibong as '*Sabangan'* or 'mouth of river' since it is where Gibong and Agdawan rivers meet the Agusan River. In another linguistic reference, the 'Manobo' refers to speakers of certain Philippine languages of Proto-Austronesian decent (Elkins 1974, pp. 1-2).

The floating houses of the area are a combination of outside influence and indigenous ingenuity. Archaeological digs at a community adjacent to Sabang Gibong revealed stone tools that may date back as far as 2.5 million to 5,000 years ago. Consequently, 15th century Vietnamese whiteware dishes were also recorded as unearthed and reported by locals in Sabang Gibong. These archaeological finds infer the existence of a thriving community way before contact with outsiders. In parallel, local history speaks of the arrival of the Spaniards in Talacogon (Poblacion) in the early 1800s. Eventually, they reached Sabangan to capture the natives, but majority of the leaders escaped to the upper part of Agusan del Sur and community members who were left behind were taken and brought to Talacogon (Poblacion) where many Visayan settlers resided. The Manobo were then baptized, and their children eventually intermarried with the migrant settlers. By 1892, the new generation of Manobo and Visayan descent escaped from the Spanish colony and returned to Sabangan. They developed the first floating house using logs as floaters, then divided the land per family or clan to manage and cultivate. With a combination of Manobo and Visayan cultures and languages, they became distinct from other Manobo communities of Agusan del Sur.

Figure 1: Sabang Gibong during the dry season in year 2019 with Gibong River at the foreground and Agusan River at the background

3.2. The architecture of floating houses in Agusan marsh

3.2.1. Anatomy and construction

The locals refer their houses as *ba'y*, closely associated with the *balai* of the Malay; or the *balay* of the Visayan and *bahay* of the Tagalog in the Philippines. As a technology developed by the people of Manobo and Visayan descents, the floating houses of Sabang Gibong is a combination of outside influence and indigenous ingenuity (Figure 2). Houses made of mostly soft or miscellaneous wood can last from 10 to 15 years, while houses made of mostly hardwood may remain up from 20 to 30 years.

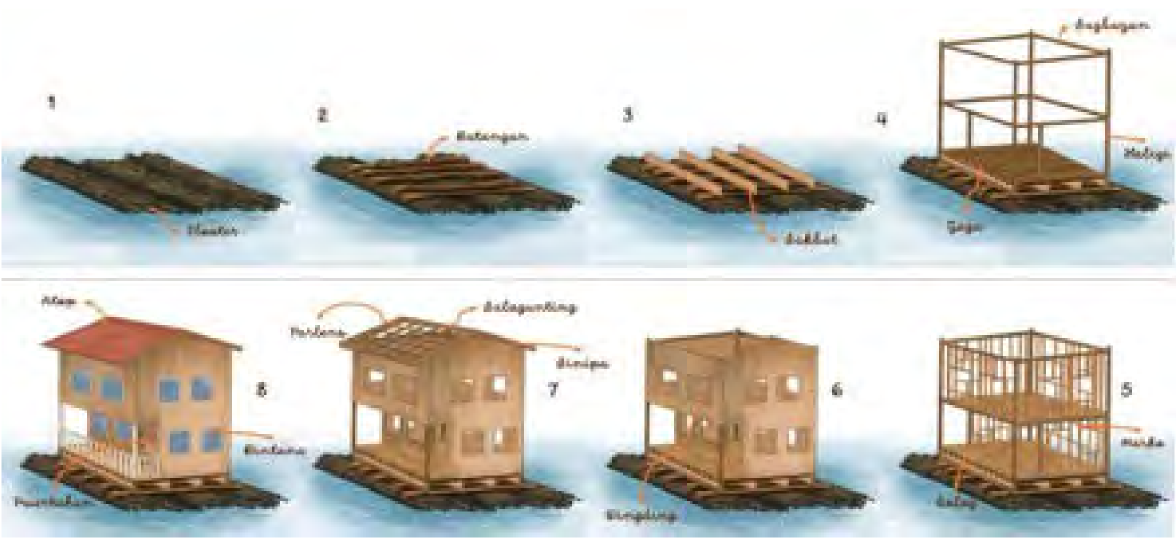

Figure 2: Typical anatomy of a floating house in Sabang Gibong

The anatomy of floating houses in Sabang Gibong is focused on functionality to ensure that the houses are kept afloat and intact despite the variability in weather conditions. A house, from bottom to top, typically has floater*, batangan, sakbat, gaga, salog, haligi, sagbayan, marko, dingding, salagunting, sinipa, parlens, atop, pwertahan, and bintana* (Figure 2). During construction, local carpenters are employed and assisted by the house owners. Construction activities are done regardless of season because the typical process require assembling the floaters first by making bamboo bundles each with 40 to 50 poles. For a house, bundles used may range from five (5) to 10 depending on the size of the house. Afterwards, *batangan* are placed above the floaters bounded together by ropes, then the *sakbat* follows. The rest of the sections of the house follow to complete building the entire structure.

Majority of the local materials used for floating houses are timber and bamboo. Timber used are mostly softwood tree species, but some would use hardwood when available. Moreso, timbers are processed as log or lumber depending on the diameter and the preference of the house owner. Furthermore, bamboo poles are either *kawayan* (spiny bamboo) or *damoan* (sweet bamboo) and although many would like to use the former because of its strength, the most abundant species and much easier to gather is the latter (Table 1).

Table 1: Parts and functions of a floating house

Part	Function	Material
Floater	– Keep the house afloat	Bamboo poles
Batangan	– Define the structural integrity of the house – Carry the pressure of the weight of the house – Ensures the upper layer is not reached by water	Round logs

	– Directly above the floaters	
Sakbat	– Base of the House	Round logs and/or lumber
	– Determine House Size	
	– Directly above the *batangan*	
Gaga	– Placed above the *sakbat* as the base of the flooring	Round logs and/or lumber
Salog	– Flooring	Lumber
Haligi	– House pillars/posts	Round logs and/or lumber
	– Directly connected to the *sakbat* up to the *sagbayan*	
Sagbayan	– Beams that support and hold the posts together	Round logs and/or lumber
Marko	– Skeletal frame of the house	Round logs and/or lumber
Dingding	– Wall of the house	Lumber, plywood, colour roof
Salagunting	– Rafter	Round logs and/or lumber
	– The base of the roof, supported by the beam and post	
Sinipa	– Roof walling placed at the edges of the *salagunting*	Lumber
Parlens	– Purlins	Round logs and/or lumber
	– Support the rafters	
Atop	– Roof	Leaves of Sago Palm Tree Corrugated roofing sheet
Pwertahan	– Door	Lumber
Bintana	– Window	Lumber, jalousie, or glass

3.2.2. Typologies of floating houses

There are four (4) floating house typologies in Sabang Gibong based on functionality (Figure 3). Out of the 100 houses inventoried and mapped in the barangay site of Sabang Gibong, 51 percent use Type 1, 32 percent use Type 2, 15 percent use Type 3, and (two) 2 percent use Type 4.

Figure 3: Illustration of the types of floating houses in Agusan marsh (from left to right – type 1 - hapa, type 2 - hanger, type 3 - hapa-hanger combination, and type 4 - dos andanas)

The typological choice of households is dependent on personal preference that is influenced by the benefits from the structures and financial capacity. *Hapa* is deemed the safest floating house typology in Sabang Gibong. It has been tested to provide safety against strong winds and typhoon. However, *hanger* provides better ventilation and ensures easier cleaning of the floaters, *batangan,* and *sakbat*. Some households would choose to enjoy the benefits of the first two types thereby combining the design although this also means experiencing the downside of both. An affluent few would choose to have *dos andanas* for bigger space, but transferring locations and safety against strong winds becomes a challenge. Further description, choice and relevance, and challenges of each type are presented and explained in Table 2 below.

Table 2: Description of the typologies of floating houses in Agusan marsh

Type	Description	Choice and Relevance	Challenges
Type 1 - Hapa	– *Hapa* means lying face down or prone position – Also called *dapat* referring to the proximity of the floor, the *batangan*, and the floater – Deemed the safest house design	– Personal preference – Wind and typhoon resilience	– Maintenance of floaters require removing the flooring thus more time, labour, and damage – Possible damage to the *sakbat*, *gaga*, and *salog* due to its proximity to water below
Type 2 - Hanger	– Translates to something that hangs or suspended – Taller than hapa, either by having two (2) or more layers of *sakbat* or by having a foot or more gap between two (2) layers of *sakbat*	– Personal preference – Easier cleaning, maintenance, and replacement of floater – Better ventilation	– Vulnerability to strong wind and typhoon due to its height and gap between the floor and floater
Type 3 – Hapa-Hanger combination	– Combined *hapa* and hanger characteristics – Usually *hapa* veranda and kitchen	– Personal preference – Better wind and typhoon resilience than the hanger type – Better ventilation	– Maintenance of floaters on *hapa* sections – Vulnerability to wind and typhoon on hanger section
Type 4 - Dos Andanas	– Locally adopted term from the Spanish which translates to “two layers” – Duplex	– Personal preference – Financial capacity – Larger space	– Vulnerability to Strong Winds – Heavy weight that may hinder relocation – Expensive

3.3. Factors that shaped the community and practice

3.3.1. Geography and settlement pattern

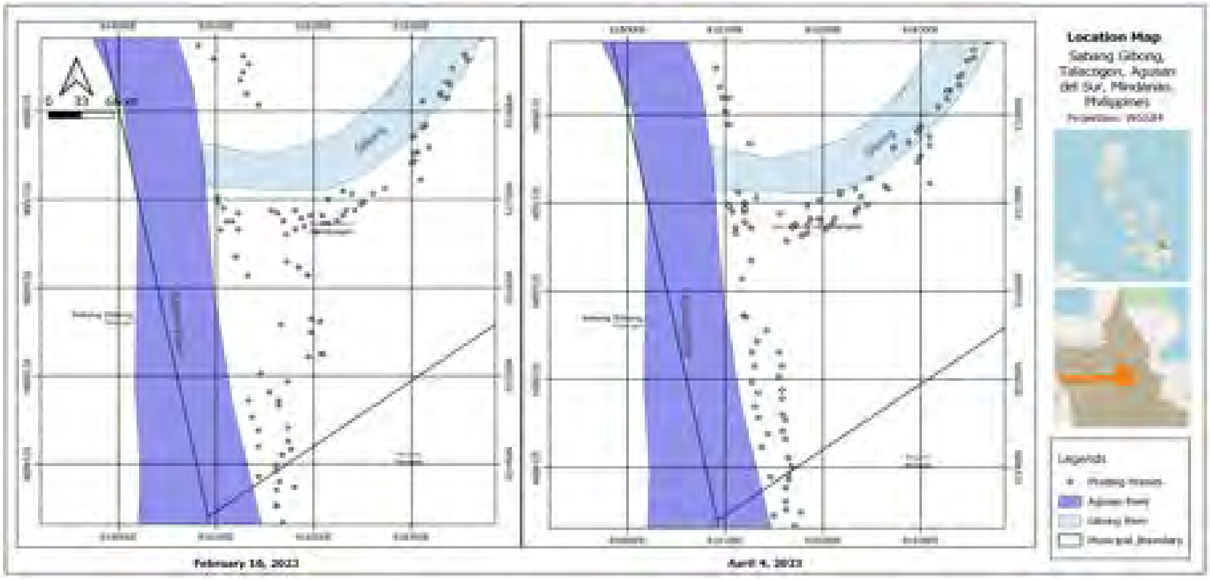

Figure 4: Settlement pattern and relative changes in Sabang Gibong as the water recedes between February 16, 2023, and April 4, 2023

Geography is one of the key influences in the development of the architecture and settlement pattern in Sabang Gibong (Figure 5). In particular, Sabang Gibong is at the centre of Agusan marsh with timberland or forestland land classification and elevation ranging between eight (8) to 18 meters above sea level. Since the marsh is a catch basin, all the water of adjacent regions converges in Sabang Gibong and since Agusan del Sur has a Type II climate, the locality has no pronounced dry season with a very pronounced maximum rain period from November to January. Nevertheless, the Agusan marsh has a micro-climate referred by communities as dry and flooding season, the former between March to September, and the latter between October to February. Dry season is the time of year that still has regular rain but no overflowing of rivers and lakes, while flooding season is the overflowing of water bodies and submersion of normally dry land. However, the effects of climate change already affected the area wherein there was non-stop flooding and high-water level between 2020 to first quarter of 2023.

The rivers are the defining factor of the settlement thus the community has a linear settlement pattern along Agusan and Gibong rivers. The houses are either within or adjacent to the rivers depending on the water level and strength of water current. During dry season, around 50 percent of the houses are within the rivers, close to the riverbanks where the tree anchors are located, while others are above ground. But all are afloat during flooding season and would move further away from the rivers as the water level and current rises.

The regular flooding and the strength of the current of Sabang Gibong also hindered the community from using other forms of housing such as bungalow and stilt houses. Flooding may sometimes reach as high as 30 feet (9 meters) and using stilts as high is not structurally feasible given the integrity of the marsh soil to support the structure, even if households use concrete posts. Moreso, the community find it unsafe and unpredictable since debris from the flood may get stuck along the stilts or damages on the wood cannot be observed when the water level is high thereby limiting maintenance and mitigating measures.

Figure 5: Situation of a hapa floating house during flooding (left) and dry (right) seasons

3.3.2. Marsh ecosystem and availability of raw materials

As a marsh ecosystem, the abundantly growing tree species in the area are soft wood or miscellaneous species particularly *Mambog* (*Mitragyna speciosa*), *Katmon* (*Dillena philippinensis*), *Kabak* (Nauclea orientalis), and *Bangiba* (common & scientific name unknown). But there are also hard wood species in the area, such as Banaba (*Lagerstroemia speciosa*), Anilao (*Bauhinia variegata*), *Bungyas* or Banyan Tree (*Ficus benghalensis*), and Sanganan (common & scientific name unknown). Nevertheless, trees do not grow as big or high compared to the terrestrial areas since the marsh ecosystem usually stunt plant growth. Also, only two (2) species of bamboo are present in the area, *Kawayan* or spiny bamboo (*Bambusa Blumeana*) and *damoan* or sweet bamboo (*Dendrocalamus latiflorus Munro*). Additionally, the abundance of Sago Palm Tree (*Metroxylun sago*) resulted to the use of its leaves as roofs called *sani* in the past, but majority of the households use synthetic materials due to the current rarity and limitations to access to the resource.

The above-mentioned materials served as the major raw materials for the floating houses. The same with geography in relation to the use of other forms of housing, the local materials cannot support them. Wood is easily damaged if regularly flooded in a bungalow type, and they cannot be used as stilts as high as 30 feet (9 meters) since they do not grow as tall compared to trees in terrestrial ecosystems. On the other hand, materials such as cement and sand and gravel for concrete posts can only be gathered from Talacogon (Poblacion). This would incur higher cost since the only transportation from the community to Poblacion are pump boats that will take around two (2) to three (3) hours and majority of the households cannot afford or will not take risk given the safety concerns.

Figure 3: Some of the local resources utilized for floating houses in Sabang Gibong (Right – bamboos along the Gibong River and Left - a bungyas tree at Tamboon Creek)

3.3.3. Financial capacity of households

Another necessary consideration in the practice of floating houses is the financial capacity of households. Although most of the local materials are free, payment for labour services is still required. In particular, the community practices a form of private yet communal ownership of land and resources. More than the existing political boundary, the community follows the traditional demarcation of their locality using the information passed down by the ancestors to each following generation. In fact, the barangay site is located outside its political jurisdiction and within the barangay Novele of the Municipality of Rosario and barangay Caimpugan of the municipality of San Francisco.

Access to the resources of an area outside one's land requires approval from the direct landowners or guards. Insiders or community members who express their intent to use the resources of another may be asked to pay or the resource may be gifted, depending on the agreement or economic situation of the receiver. Since the source of livelihood in the community are farming and fishing primarily for subsistence purposes, building a house is still considered costly. As such, houses are incrementally constructed. In such cases, the roofing shall be installed first while the *dingding* (walls), doors, windows, and even some *salog* (flooring) shall be completed gradually up to around five (5) years and sometimes more. Positively, this avoids unnecessary financial stress for the households given that their economic activities are very much influenced by unpredictable environmental conditions and changes.

As mentioned, the financial capacity of the households is also one of the key determinants in their choice of house type or dimensions. That while the first three (3) floating house types, depending on dimensions, may cost around PhP 100,000.00 to PhP 200,000.00 (AU$ 2,799.00 to AU$ 5,599.00) the last type may cost around PhP 300,000.00 (AU$ 8,398.00) or more.

Figure 7: A dos andanas floating house yet to be completed but already occupied by the owners

4. Conclusion and recommendation

The floating houses of Agusan marsh is a technology and practice developed in response to the dynamic environmental conditions of the area. Particularly, it is a vernacular and indigenous architecture that is adaptive to the challenges and opportunities presented by geography, availability of materials, and financial capacity of the households, currently confronted by climate change. By deeply understanding and taking advantage of the local conditions, the Sabang Gibong community was able to develop a floating architecture to adapt to the geography that is regularly flooded, using the local materials available, and aligned with their financial capacity. Further, the development of different house typologies reflects how the community was able to work around their dynamic environmental conditions suiting their preference. This resulted to the healthy and continued human-environment relation that continually shapes the built environment of the community.

In relation to the socio-ecological approach to planning and architecture and design, it is recommended to examine and apply the opportunities provided by floating houses while also considering the preconditions of the practice. In particular, urban areas limited of space may consider the applicability of floating houses and other form of floating architectures on their flood-prone areas, rivers, brownfields, among other water bodies. Aside from providing additional space and safer option, this can also re-frame the relations and mentality of man with water, especially with water bodies and areas deemed hazardous and of less utility.

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Child-friendly smart homes: An outline of possible challenges

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Abstract: Children's daily lives mainly occur in their homes. As technologies in residential environments constantly evolve, concerns about children's physical and digital safety are emerging. While the current literature highlights the influence by digital technologies and how smart home technologies might improve children's lives, there is a lack of critical appraisal of the relative pros and cons identified in the literature for children living in homes with smart home technologies. This paper asks what challenges are raised in the literature around using smart technologies in homes with children and what key knowledge gaps need addressing by future research. In this study, we conducted a scoping review to analyse and synthesise diverse research on the challenges of creating smart homes suitable for children. We followed a systematic process to gather a comprehensive scope of research relevant to the research question. As our prime aim was to identify knowledge gaps as a precursor to further research, we did not evaluate the data quality or findings. Key areas of research that need addressing to create child-friendly smart homes were identified through this analysis, including Safety Measures, Cognitive and Developmental Considerations, and Privacy and Data Protection. These findings aim to guide future research towards enhancing the development of safe and interactive smart home environments for children.

Keywords: Smart-homes, child-friendly-home, challenges

1. Introduction

Smart home technologies are becoming more prevalent in homes, but there is a lack of critical analysis on how they affect children's safety, privacy, security, and well-being. While digital risks are a concern, there is potential for enhancing children's daily lives. Smart home technologies, such as voice assistants, connected devices, and automated systems, offer numerous potential benefits for families with children (Wilson *et al.*, 2017). These benefits include increased convenience, improved energy efficiency, enhanced security features, and opportunities for educational enrichment. However, alongside these advantages, there are various challenges and risks arise for children in smart home environments (Demiris et al., 2009; Ding et al., 2011; Gentry, 2009; Stefanov et al., 2004a). Smart homes designed for children require a comprehensive understanding of these challenges. This understanding will help researchers, architects, IT designers, policymakers, and other industry professionals to develop strategies and guidelines that prioritise the well-being of children in smart home environments (Aldrich, 2003; Zhai *et al.*, 2014; Wilson *et al.*, 2015; 2017; Darby, 2018; Hargreaves *et al.*, 2018; Marikyan *et al.*, 2019; Li *et al.*, 2021; Sun *et al.*, 2021). To achieve this, a review has been conducted to synthesise current knowledge about child-friendly smart homes, analysing available literature and identifying gaps in

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knowledge for future research and policy development. Previous research has acknowledged the potential benefits of smart home technologies for children, such as enhancing educational experiences through interactive devices and promoting a sense of security through automated safety features. However, these studies have also highlighted several concerns and risks associated with children's use of smart home technologies, such as Privacy and Data Security, Safety Risks, Cybersecurity Risks, Lack of User Interface Design for Children, Health and Well-being Concerns, Parental Control and Monitoring, Developmental Implications, Ethical Considerations and so on (Aldrich, 2003; Zhai *et al.*, 2014; Wilson *et al.*, 2015; 2017; Darby, 2018; Hargreaves *et al.*, 2018; Marikyan *et al.*, 2019; Li *et al.*, 2021; Sun *et al.*, 2021).

2. Research Problem

The rapidly evolving landscape of technology in residential settings poses a challenge for families, who must navigate the potential benefits and risks these advancements present to their children's well-being. There is a need to analyse the literature to examine the existing evidence and identify the key areas of concern related to child safety, privacy, cybersecurity, social interaction, and autonomy in smart home environments (Balta-Ozkan et al., 2014; Coughlin & Pope, 2008a; Rialle et al., 2002). The concept of child-friendly smart homes is an important aspect of the broader smart home concept. Smart homes, as defined by Gram-Hanssen and Darby (2018), are modern residences equipped with advanced technologies such as sensors, networks, and intelligent systems. These technologies aim to create an intelligent environment that adapts to the needs of the inhabitants. However, despite the rapid development of the smart home concept since the early 1990s, there has been limited consideration of familial and children's concerns (Kim et al., 2022). While improving quality of life, security, and energy savings are key aspects of smart homes, there is also a growing interest in information flow, access to entertainment, and personalised living experiences (Chan et al., 2009; Kolokotsa et al., 2011). Despite its potential effectiveness, the adoption of smart homes has been slow, and obstacles such as a lack of empirical evidence, privacy concerns, and standardisation have been discussed (Coughlin & Pope, 2008a; Edwards & Grinter, 2001). Therefore, considering the interplay between smart home environments and children's needs, it is essential to consider how future homes should be structured and designed. This research aims to contribute to understanding child-friendly smart home challenges by comprehensively analysing the interplay between smart homes, built environments and children, providing valuable insights for future research.

3. Methodology

This research follows the PICO (population, intervention, control, and outcomes) framework recommended for scoping reviews by Arksey and O'Malley (2005) and Levac et al. (2010). Compared to systematic reviews, which answer highly focussed research questions, this review addresses broader conceptual issues across literature by asking: *What are the issues that make smart homes unfriendly for children?* To ensure an appropriate breadth of coverage around the topic, almost 400 preliminary search terms were identified by scanning the title, abstract and keywords of sources found through the search of the term *child-friendly smart home.* These search terms were refined to inform a final list structured into four groups: Population, Context, Intervention, and Outcome (table 1). Following Armstrong et al.(2011), three databases were used to search for articles: ProQuest Central, Scopus and Web of Science (Armstrong *et al.*, 2011). Searches using Google Scholar were also conducted. Inclusion criteria were established, which encompassed articles published within the last ten years, written in English, and focused solely on the impact of smart home technologies on children. Conversely, exclusion criteria were also introduced, which eliminated articles that did not provide substantial insights or were not peer reviewed. Throughout the process of data extraction, each selected article was read and analysed to identify key themes, arguments, findings, and recommendations. All the information gathered was then synthesised and organised in a logical and coherent manner, resulting in a comprehensive overview of the research topic.

Table 1. Search Term

Population	Context	Intervention	Outcome
Child *Children* *Kid* *Young adult*	*Design* *Built Environment* *Residential Building* *House* *Dwelling* *Home* *Home space* *Smart Home*	*Architecture* *Building Design* *Friendly design* *Family-friendly design* *Child-friendly design* *Design for children* *Design for family*	*Child-friendly home* *Child-friendly smart home*

4. Findings

Here, the findings are presented from 43 articles to elucidate smart homes in three contexts: design, built environment (cities and buildings), and homes via identification of key smart home issues for children. The analysis is organised into six sections, progressing in design scales from child-friendly cities to child-friendly homes and then on to smart technologies in those homes.

5. Child-friendly Environment (Cities/Buildings/Homes)

5.1.Child-friendly Cities

Research on creating child-friendly environments involves interdisciplinary studies that prioritise children's participation. Factors such as mobility, agency, community, adult presence, green spaces, traffic, and urban density are identified as crucial. Place friendship describes the reciprocal relationship between a child and their environment (Kruger and Chawla, 2002; Gill, 2008; Nordström, 2010; Kreutz, 2014; Jansson *et al.*, 2016; Kreutz and Beza, 2020). It is projected that by 2050, 70% of children will be living in urban areas, which has led to research on how this environment affects their physical, cognitive, and social development (Van Vliet and Karsten, 2015). It has been found that urban planning not only impacts cities but also the well-being of children who reside in them (Freeman and Aitken-Rose, 2005). Despite some provisions in the UN Convention on the Rights of the Child (CRC) related to city life, increasing urbanisation puts the rights of children at risk of being neglected (Malone, 2013; 2015). Research has shown that smart, green, and walkable environments are crucial for children's development (Riggio, 2002). Cities are working to become more child-friendly through research and practice (Brown *et al.*, 2019; UNICEF, 2019). Despite the increasing amount of research, child-responsive techniques have yet to significantly impact the urban built environment (Bishop and Corkery, 2017). Children have the right to explore safely and spontaneously (Homel and Burns, 1989; Coulton *et al.*, 1996; Taylor, 2007; Rakhimova *et al.*, 2022). UNICEF is leading the charge in promoting initiatives to make cities more accommodating for children (Mekonen, 2010). UNICEF defines a child-friendly city as a local governance system that prioritises the well-being and rights of children as outlined in the UN Convention on the Rights of the Child (Unicef, 2017).

5.2.Child-friendly Buildings

As city life evolves, the way children experience cities has also changed. This shift has been observed since the 1970s when participatory research with young people began (Gill, 2008). Nowadays, children in both developed and developing cities tend to spend less time on the streets and more time engaged in structured activities. They spend less time wandering around independently with friends and more time indoors using technology (Victoria *et al.*, 2018). While designing child-friendly buildings has been an aim for a while, it is hard to pinpoint its origin. The UN Convention on the Rights of the Child in 1989 granted children the right to a safe and healthy environment, education, healthcare, and play. The term "child-friendly building" may have emerged more recently as part of promoting sustainable and inclusive design practices for all occupants (Beheiry and Gabr, 2022). Architecturally speaking, child-friendly buildings are created to promote the well-being and happiness of children. These structures are designed to be easily accessible, safe, comfortable, and enjoyable for kids of varying ages and capabilities (Malone, 2013; 2015). Child-friendly building prioritises children's safety, emotional well-being, creativity, and learning opportunities. It accommodates diverse needs and cultural backgrounds through accessible, comfortable, and safe design elements (UNICEF, 2019).

5.3.Child-friendly homes

Recently, there has been a noticeable upsurge in the number of cities worldwide embracing child-friendly policies. These policies, for the most part, emphasise safety, play, and independent movement for children in public streets and spaces rather than in the design of residential areas (Tucker *et al.*, 2022). Even though children spend the majority of their time at home, there has been a significant lack of research on the role, function, design, and use of the family home. It is crucial to understand how families use their homes to ensure that they receive the most optimal living experience possible (Freeman and Tranter, 2011).

Table 8. Children's Housing Needs (Freeman & Tranter, 2011).

Adequate housing offers the following benefits	Sense of belonging Sense of identity Safety and security Healthy environment Independence Stability Private space Family space Play space – active and quiet play Access to other children and adults
Poor housing conditions can lead to the following issues	Poor physical health Poor mental health, stress, and depression Insecurity Learning and behavioural difficulties Higher accident rates Higher rates of child abuse Lower long-term life chances Poor school attendance and achievement Increased domestic strife Under-achievement Low aspirations Family breakdown

In the past, people had a more hands-on role in creating their homes. Today, some still build their own homes, while others pass them down and make modifications as needed (Freeman and Aitken-Rose, 2005; Freeman and Tranter, 2011). Historically, houses reflected the culture, values, and practical circumstances of the society. Today, most houses conform to universal international styles, failing to fully meet the context-specific needs of their inhabitants (Freeman and Tranter, 2011). Housing options vary depending on geographical and cultural context. In the UK, families prefer two-storey houses with gardens, while high-rise apartments are common in Asian countries like Singapore and Hong Kong. It is crucial to consider the needs of intended inhabitants when building homes (Freeman and Tranter, 2011; Freeman *et al.*, 2015). Different regions have different housing styles, such as uniform apartments in Eastern bloc states and suburban homes in Australia and the US (Freeman and Aitken-Rose, 2005). Housing options should prioritise the needs of families and children for a comfortable living space. Child-friendly amenities and thoughtful design can create an inclusive and welcoming environment. The needs of children are not limited to the type, style, or culture of their housing (Kreutz, 2015). While having a personal bedroom or a private outdoor space may seem essential, more fundamental requirements should be met. Cooper Marcus and Sarkissian's influential book, "Housing as if People Mattered," identifies the crucial physical necessities for a good living environment for children (Cooper Marcus and Sarkissian, 1986). These include a safe outdoor play area that does not require constant parental supervision, protection from traffic and pollution, natural spaces with flexible and adaptable materials, private open space that connects to communal areas, communal spaces for both adults and children to socialise, private play areas, effective management and

Source	Year	Definition
Lutolf	1992	[illegible]
Aldrich	2003	[illegible]
Chan et al.	2008	"A house which promises to provide cost-effective home care for the aging population and vulnerable users."
[illegible]	2012	[illegible]
[illegible]	2013	[illegible]
[illegible]	2014	[illegible]
Buildings performance institute Europe	2017	[illegible]
Wilson et al.	2017	[illegible]
[illegible]	2018	[illegible]
[illegible]	2018	[illegible]
Marikyan et al.	2019	[illegible]

maintenance, unique building designs that give each house an identity, and street connectivity that encourages independence and access to the wider environment (Freeman and Tranter, 2011) (Table 2).

6. Definition of Smart Home

In essence, a smart home is a dwelling that is furnished with advanced computing and information technology that is designed to anticipate and cater to the needs of its occupants. Through the seamless integration of technology and connectivity to the outside world, a smart home aims to enhance its inhabitants' comfort, convenience, security and entertainment (Aldrich, 2003). Managing technology within the home is paramount to ensuring that the occupants are provided with a safe, secure, and comfortable living environment (Aldrich, 2003). Numerous review articles on smart homes have been published in various scientific journals and by professional societies. These articles have been written by authors such as (Cook and Das, 2007; Chan *et al.*, 2008; Demiris and Hensel, 2008; Chan *et al.*, 2009)(Table 3). The focus on smart home technologies has mainly been on specific disciplines like electrical engineering, IT, computer science, gerontology, biomedicine, and robotics. However, architecture and town planning have not been extensively involved in this area despite their future responsibility. Smart homes can be described by a hierarchy of five levels of complexity and innovation, ranging from homes with intelligent objects to sophisticated homes that constantly register the activity and location of people and objects inside and outside the home (Madakam and Ramaswamy, 2014). The concept of smart homes has been around since 1980. Still, it has not gained widespread acceptance due to high device prices, limited consumer demand, long replacement cycles, and a lack of technology infrastructure (Paetz *et al.*, 2012). The focus on technology development has led to a failure to understand users' actual needs, and individual factors such as housing type, age, gender, region, income, prior experience, and environment can also impact a user's willingness to engage with smart home technology. Various names of smart homes are: Home network, Digital home, Home automation, and An intelligent home. Since 2010, there has been a shift towards combining Internet of Things (IoT) technology with a situation-aware smart home, resulting in a complete transformation from previous phases (Sági *et al.*, 2012) (Table 4).

Table 4. Different Smart Home Names and Their Features Over Time

Year	*Phase*	*Technical background*	*Main function*
1990s	Home automation	Broadband Internet	Household automation
2000s	Home network	Smartphone and apps	Remote monitoring & control
2010s	Smart home	IoT & AI	Content awareness

7. Smart technology in the home

"Smartness" is intense: it spreads beyond certain devices and places, including the home (Taylor, 2007; Wilson *et al.*, 2015). Although smart homes are now technologically possible and available (Sági *et al.*, 2012; Silva *et al.*, 2012; Sciuto and Nacci, 2014), and their attention in research and industry is rising (Adab *et al.*, 2013; Wilson *et al.*, 2015), their interest to the public is still low (Marikyan *et al.*, 2019). According to Maalsen and Dowling (2020), although perceived and potential benefits are still dissimilar, and adoption and spread rates are still limited, the COVID-19 pandemic may have hastened home technology adaptation (Maalsen and Dowling, 2020). Their advancement has still not been achieved due to the lack of the "socio-economic and technological constellation" (Friedewald *et al.*, 2005). The fact that most visions of smart homes are not grounded in the lived realities of real homes is a major problem. Rarely does the phrase "smart home" refer to a dwelling that is used for habitation; instead, it describes its technological capabilities (Madakam and Ramaswamy, 2014). Additionally, according to Strengers (2013), the design of smart homes frequently ignores the viewpoint of actual users and daily life (Strengers, 2013). Whether sterile, empty places that are at contrast with home realities (Wilson et al. 2015) can reflect the emotionally charged "invisible boundaries" that define the home context is debatable. Another challenge to the design of smart home systems is highly individual, diverging item combinations (Davidoff *et al.*, 2006), as is the investment and scope they represent—"instrumenting" a person's entire living environment (Mennicken and Huang, 2012). However, the context of the home could benefit specifically from smart home solutions because people spend a lot of time there and activities in the home have much room for improvement (Friedewald *et al.*, 2005). Smart home design could facilitate daily activities, support specific needs and domestic energy demand, meeting the challenges of digitalisation, and facilitating inhabitants' interactions (Friedewald et al., 2005;Wilson et al. 2015). Smart home technology might even imbue a home can be with identity and personality, an act which makes a house a home (Innocenti, 2017).

8. Smart homes in theory: features, expectations, and motivations

A smart home is defined by four essential components, according to Balta-Ozkan et al. (2013a): a communication network that links sensors (and devices); intelligent controls for system management; and smart features that react to user-, sensor-, or system (data) input (Balta-Ozkan *et al.*, 2014). In a smart home, devices can be accessed, managed, and controlled remotely. Accordingly, numerous researchers have examined the characteristics of "smart" homes, such as control preferences, energy feedback preferences, energy monitoring, and acceptance/perceptions of smart homes (Koskela and Väänänen-Vainio-Mattila, 2004; Balta-Ozkan *et al.*, 2014). In the context of the home, user-centred definitions of "smartness" frequently adopt a different, less feature-based approach, emphasising things like a good fit with daily life (Mennicken and Huang, 2012). A popular aspect of such as approach is home control, i.e., the central control of appliances and devices (Mennicken and Huang, 2012).

9. Smart homes in practice: approaches to domestication

The concept of smart homes promises a utopian future with the potential to become a reality for people who choose to reside in them. However, the feasibility and success of this vision are yet uncertain and subject to various factors that may influence its implementation and adoption (Strengers, 2013). Therefore, it might be more beneficial to shift the focus from features, expectations, and motivations towards experiences within and with smart homes. Participants in a study conducted by Mencken and Huang in 2012 found that the phases of planning, integration, and iteration had a greater impact on their experience with smart home technology than the actual use of the technology itself, once stability was achieved. These phases were found to be essential in the process of domesticating smart technologies for individuals who were planning or constructing a smart home, as well as those who were already living in smart homes, along with smart home providers. Technical infrastructure preparation was also found to be an important phase in the process (Kühnel *et al.*, 2011; Zhai *et al.*, 2014).

10. Challenges of Smart Homes

While there may be some consumer interest in Smart Home Technologies (SHTs), they have not yet gained widespread acceptance, according to GfK's 2016 report (Paetz *et al.*, 2012). The technical literature on smart homes lists the main technological and design challenges that need to be addressed. These challenges align with the social barriers to the adoption of smart homes, which were identified in deliberative workshops by Balta-Ozkan et al. (2013). These barriers *include concerns about loss of control, reliability, privacy, trust, and cost.* Additionally, there is a third set of challenges that investigates how and if SHTs can be effectively integrated into the home environment. It remains to be seen if SHTs can overcome these challenges and become widely adopted.

11. Acceptability and usability

The acceptability of smart homes among users is heavily influenced by concerns related to security, privacy, and trust, as well as practical issues concerning user-friendliness (Mayer *et al.*, 2011). The acceptability of SHT is significantly influenced by the level of awareness that individuals have regarding its existence. Recent studies have shown that a vast majority of individuals around the world are currently unaware of the existence of SHT and are therefore unable to utilise its benefits. This lack of awareness may be contributing to slower adoption rates of SHT technology in certain regions, as individuals are unable to make informed decisions regarding its use (Furszyfer Del Rio *et al.*, 2021). These challenges pose critical design considerations for how users interact with SHTs. Security concerns may cause hesitancy among individuals to adopt sensing technologies into their homes, as they are wary of leaving digital trails that others can monitor and use to their advantage, such as breaking in when the house is empty (Cook, 2012, p. 1578). Similarly, smart homes for assisted living raise privacy concerns since technologies that detect and monitor activity in the home may be viewed as intrusive violations in the domestic environment (Demiris and Hensel, 2008). Concerns around data security and the potential for utilities to monitor or control household demand have led to consumer backlashes against smart metering in energy smart homes (Darby, 2018; Abdullah *et al.*, 2019). While there is general support for the development of smart homes, a study on attitudes and values towards energy-system change in the UK found caveats around data sharing and a perceived loss of control through remote interference by utilities (Parkhill et al., 2013). Designing smart homes that ensure privacy, safety, and security is essential for their acceptability to prospective users (Cook, 2012). Furthermore, Paetz et al. (2012) suggest that smart home developers, particularly energy utilities, need to be more transparent and accountable and explicitly outline how all stakeholders may benefit from smart home development. Design challenges regarding the user-friendliness of smart homes are also highlighted in several studies. Creating intuitive and easy-to-use user interfaces is difficult due to the level of complexity and the number of user-control options that can potentially lie behind the interface (Park *et al.*, 2003; Demiris *et al.*, 2004; Koskela and Väänänen-Vainio-Mattila, 2004). User-centred design is a suitable response to smart home design challenges (Raei and Bouchachia, 2016). Engaging with a wide range of different stakeholders, even at the visioning stage for SHTs, can ensure that the widest possible range of interests and concerns are recognized and addressed. Different groups of users may require different design solutions, not just between households but also between cultures (Jeong *et al.*, 2010; Choi *et al.*, 2012).

11.1.Potential Challenges for Children in Smart technology Friendly Homes or Smart homes

Living in smart homes poses unique challenges and concerns for children, as highlighted by existing literature. These challenges and concerns include:

1. Privacy and Data Security: Smart home devices, such as cameras and voice assistants, have the potential to invade children's privacy by collecting and storing their sensitive data. This raises concerns about the security and protection of this personal information (Edu *et al.*, 2020).

2. Safety Risks: Although smart home technologies can enhance safety and security, they also present potential risks to children's safety. Children may accidentally activate or control devices that could be dangerous, such as stoves or doors, without adult supervision (Mennicken and Huang, 2012; Wilson *et al.*, 2017).

3. Cybersecurity Risks: The increasing connectivity of smart home devices creates a heightened risk of cyber-attacks and unauthorized access. This could lead to harm for children, such as hacking into baby monitors or accessing their personal information (Abdullah *et al.*, 2019).

4. Lack of User Interface Design for Children: Many smart devices are designed with adults in mind, resulting in interfaces that are not user-friendly or appropriate for children. This can make it difficult for children to understand and interact with these technologies effectively (Balta-Ozkan et al. 2013b; Cavoukian et al. 2010).

5. Health and Well-being Concerns: There are concerns about the potential impact of prolonged exposure to electromagnetic radiation from smart home devices, such as Wi-Fi routers. Additionally, excessive screen time from smart devices may negatively affect children's sleep quality, physical health, and social interactions (Van Zutphen *et al.*, 2007; Sequeiros *et al.*, 2021).

6. Ethical Considerations: The ethical implications of using smart home technologies with children are important to address. Issues such as informed consent, children's autonomy, and the potential for exploitation or manipulation through targeted advertising or behavioural tracking need to be considered (Bugeja *et al.*; Sharma and Giannakos, 2021).

7. Discrimination and Bias: The use of algorithms and artificial intelligence in smart home technologies can introduce biases and discrimination, potentially impacting children's experiences and opportunities and perpetuating existing inequalities (Raza, 2022).

8. Developmental Implications: Smart home technologies may impact children's development in several ways. For example, children may rely on voice assistants for answers instead of engaging in critical thinking and problem-solving. Excessive exposure to technology could also hinder social and emotional development (Beamish *et al.*, 2019).

9. Parental Control and Monitoring: Smart home technologies offer parents new tools for monitoring and controlling their children's activities, enhancing safety and supervision. However, this may raise concerns about autonomy, trust, and overparenting (Sun *et al.*, 2021).

It is important to note that the research on smart home technologies and children is still emerging, and more studies are necessary to fully understand the long-term effects and implications. Nonetheless, these challenges and concerns underscore the need for thoughtful consideration of how smart home technologies are implemented and used in homes with children. Effective policies and regulations are also necessary to safeguard children's privacy, security, and well-being in smart home environments.

12. Discussion

The integration of smart home technologies into children's lives presents both opportunities and challenges. Privacy, safety, cybersecurity, user interface design, health, ethics, parental control, educational implications, and policy considerations are all important aspects to address when researching and discussing the impact of smart home technologies on children. The following lists provide an outline of the challenges and interpretation of the findings:

12.1. Challenges in Implementing Child-Friendly Smart Homes:

a. Safety and Security: One of the primary concerns in child-friendly smart homes is ensuring the safety and security of children. This involves protecting them from potential risks such as electrical hazards, access to unsafe areas, and privacy breaches. The findings suggest that integrating robust safety measures into smart home technologies is crucial to address these challenges.
b. Age-appropriate Technology: Another challenge is designing age-appropriate technology that can engage and assist children effectively. The research shows that understanding children's cognitive and developmental needs is vital for creating intuitive interfaces, interactive games, and educational applications within smart homes.
c. Privacy and Data Protection: As children interact with smart home devices and systems, their personal data may be collected and shared. This raises concerns about privacy and data protection. The findings emphasize the importance of implementing comprehensive data protection policies and parental control mechanisms to address these privacy challenges.

12.2. Interpretation of Findings

a. Safety Measures: The research findings reveal the significance of incorporating safety features like child-proof locks on cabinets, automatic shut-off of electrical appliances, and monitored access to potentially dangerous areas. These measures ensure the well-being and physical safety of children within smart homes.
b. Cognitive and Developmental Considerations: The evidence suggests that smart home technologies should be designed with age-appropriate user interfaces and content. Understanding the cognitive and developmental stages of children aids in providing engaging and educational experiences tailored to their needs. This can promote learning, creativity, and social interactions.
c. Privacy and Data Protection: The findings highlight the need for robust privacy safeguards to protect children's personal information. Implementing strict data collection and retention policies, as well as offering parental control options, can enhance privacy and instil trust in child-friendly smart home technologies.

In summary, the challenges involved in implementing child-friendly smart homes revolve around safety, age-appropriate technology, and privacy concerns. By incorporating safety measures, considering cognitive and developmental factors, and prioritizing privacy and data protection, we can overcome these challenges and create a safe and engaging environment for children within smart homes.

13. Future Research

For child-friendly smart home design, as for child-friendly home design, it is important to understand the spaces that children commonly occupy, their personal opinions on these spaces, and the characteristics that make for an ideal home space for children. While it is clear that a poor home environment for children is one that does not meet basic housing conditions, such as adequate space, warmth, cleanliness, and furnishings, there is little research available on other aspects that may contribute to a good home environment (Freeman and Tranter, 2011). There is a lack of knowledge about basic questions such as whether children desire a separate play area or prefer to play in a communal meeting space, what type of furnishings are important to them, their relationship with the kitchen and eating areas, their preferred entrance, and the type of sleeping space they would like. Additionally, there is limited information on how space is designated, negotiated, and enforced. To inform child-friendly smart home design, it is important to address these knowledge gaps as well as the relationship between children and technology, computers, and other technological devices within the home.

14. Conclusion

In conclusion, this review aimed to analyse and synthesize the challenges faced in creating smart homes suitable for children. Our study highlighted the need for a critical appraisal of the pros and cons identified in the literature regarding children living in homes with smart home technologies. Through a systematic process, we gathered a comprehensive scope of research, identifying key areas of research that are required and possible research questions that need addressing. This will ultimately contribute to the design and development of child-friendly smart homes. However, it is important to note that while the literature highlights the potential benefits of smart home technologies for children, such as improved safety and convenience, there are also concerns regarding their impact on children's physical and digital safety. These concerns necessitate further research and investigation to ensure that the integration of smart technologies in children's homes is done in a responsible and safe manner. It is crucial to strike a balance between harnessing the potential benefits of these technologies and safeguarding children's well-being and privacy.

15. References

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Compliance strategies towards achieving net zero carbon emissions transition in the built environment.

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Abstract: The urgent need for a net zero transition of carbon emissions to safeguard the built environment from the devastating impacts of climate change has become a primary concern for the global community. To this end, various countries have developed different rules, regulations, and guidelines to achieve the United Nation's net zero emissions target based on the 2015 Paris Agreement. This study seeks to explore strategies for achieving compliance in the quest for a net zero emissions transition. An integrative literature review technique was adopted for this study to gain insights into relevant compliance strategies for transitioning to net zero carbon emissions within the built environment to achieve this goal. The results revealed that the different climate change response policies on greenhouse gas (GHG) emissions across the globe are time-based, with each country establishing transition strategies to regulate emissions while promoting alternative clean energy. However, the low compliance rate, cost, risks, and uncertainties surrounding these transition strategies have resulted in unintended resistance, despite the urgency and benefits of achieving net zero emissions. This study developed a compliance strategy that utilizes the PESTLE analysis factors to enhance adherence to net-zero transition regulations. The strategy monitors, evaluates, enforces, and encourages net-zero transition targets. Hence, it is imperative to adopt a collaborative approach that is more transparent and inclusive to facilitate the willingness to comply with the net zero transition regulations. These findings would guide relevant stakeholders and decision-makers with an improved compliance strategy towards net zero carbon emissions transition plans.

Keywords: Compliance; carbon emissions; net-zero transition; built environment.

1. Introduction

Reducing GHG emissions is a crucial step towards mitigating the effects of climate change on the built environment and stabilising global temperatures (Rogelj *et al.*, 2015; United Nations, 2015). Net-zero emission plans involve balancing out the GHGs produced in the built environment against the amount of GHGs taken out of the atmospheric temperature (Climate Council, 2023). GHGs comprise Carbon dioxide (CO_2), Methane, Nitrous Oxide, Hydrofluorocarbons, Perfluorocarbons, Sulfur hexafluoride, Nitrogen trifluoride, water vapour, and Ozone (EIA, 2022). Accordingly, CO_2 is the most significant source of GHG emissions within the built environment, primarily triggered by human activities such as burning fossil

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fuels for heating, transportation, and electricity generation (Davis *et al.*, 2018; EPA, 2023). According to (Liu *et al.*, 2022), the amount of CO_2 in the atmosphere is increasing rapidly, even though a temporary decline was recently observed during the Covid-19 lockdown period. In addition, the expansion of population growth, urbanisation, changes in household sizes, and industrialisation increases energy consumption which negatively contributes to the high intensity of carbon emissions, especially as economic growth continues to flourish (O'neill *et al.*, 2010; Sohag *et al.*, 2015; Acheampong, 2018).

The Paris Agreement declared climate change a global emergency requiring international cooperation across all nations in search of solutions with a legally binding international treaty, adopted on December 12, 2015 and later enforced on November 4, 2016 (UNFCCC, 2016). Accordingly, all 196 parties involved in the Paris Agreement have set up different rules, regulations, and guidelines towards achieving the net zero emissions transition target to mitigate the impacts of climate change and institutionalise sustainability (UNFCCC, 2016). The United Nations stressed the need to limit global warming to 1.5 degrees Celsius by ensuring that the GHG emission will unconditionally reach its peak before 2025 to achieve a notable 43 per cent decline by 2030 within the built environment (Rogelj *et al.*, 2016; UNFCCC, 2016). According to Erickson and Brase (2019), reducing global warming to 1.5 degrees Celsius relative to pre-industrial temperature would limit climate change impacts to an endurable minimum catastrophic level.

Each nation's circumstances and the impacts of climate change are unique, which has led to the adoption of different targets, approaches and regulations for reducing GHG emissions. However, to achieve these targets within the built environment, it is crucial to implement effective compliance strategies that can incentivise individuals, companies, organisations, and countries to comply with the relevant regulations. These strategies should be tailored to ensure relevance and practicality, ultimately encouraging the transition to a low-carbon future (Duan *et al.*, 2014; Nwadike and Wilkinson, 2021). Many nations have expressed their challenges to comply with the net zero emission target because of their dependence on fossil fuels to meet their economic developments, making non-compliance a significant issue (Limmeechokchai *et al.*, 2022). The compliance strategies could include reducing the emission of GHGs, calculating and accounting for the amount of carbon emitted, and purchasing appropriate carbon credits that will enable the capacity to meet climate change targets. Accordingly, non-compliance with the emission regulations comes with consequences that are not favourable to the emitters, government entities, and the built environment (Duan *et al.*, 2014; Zhang, 2015). Considering the consequences of non-compliance and the associated challenges, exploring strategies for achieving compliance in the quest for a net zero emissions transition is imperative.

This study explores compliance strategies for achieving a net zero emissions transition across relevant stakeholders and parties contributing to or regulating carbon emissions to enhance the reduction of GHG emissions in the built environment. In line with the objectives of this study, an integrative literature review technique was adopted to gain insights into relevant compliance strategies for transitioning to net zero carbon emissions. The study findings would guide relevant stakeholders and decision-makers with an improved understanding of net zero carbon emissions transition plans worldwide.

1.1. Research objectives

- To develop a compliance strategy to achieve a net zero emissions transition within the built environment.

- To provide innovative recommendations on encouraging compliance with net zero emissions regulations across the global built environment.

2. Climate change and greenhouse gas (GHG) emissions regulations

Sustainable Development Goal (SDG) 13 stipulates urgent action to combat climate change and its impacts across four targets focusing on reducing GHG emissions. Accordingly, the United Nations declared climate change a global emergency with a legal international binding treaty to devise measures to save the planet under the Paris Agreement (UNFCCC, 2016). All the 196 parties that signed the Paris Agreement were tasked with the responsibility of creating regulations, national policies and strategies, and adaptation plans (UNFCCC, 2016). The Paris Agreement is a legally binding treaty that helps ensure transparency, accountability, commitment, and willingness within the member parties to accelerate reducing GHG emissions (Kennard, 2020; GWA, 2023). Accordingly, the treaty provided legislation globally that established different statutory requirements and policies across member parties directed towards net zero emissions to enhance climate resilience in the built environment (GWA, 2023). Considering the global geopolitical and environmental differences, no single climate change regulation can provide valuable guidelines and procedures to achieve GHG emissions targets; each party was encouraged to draft suitable and applicable regulations with implementation strategies (Nachmany et al., 2014).

This stringent climate change regulation and implementation are significant, especially as the United Nations real-time data indicates that GHGs in the atmosphere have reached a new high and may continuously increase globally (UNSD, 2022). Among the GHGs, CO2 stays longer in the atmosphere and has the highest quantity released in the built environment, leading to an increase in ocean and land temperatures (Fair Supply, 2023). Hence, reducing CO2 emissions into the atmosphere will significantly contribute towards achieving the net zero emissions target. In line with the climate change mitigation strategy through reducing GHG emissions, the Paris Agreement has provided a standardised GHG reporting protocol system that guides organisations, countries, and other entities to access, measure, and calculate the amount of CO2 emitted within their respective operational activities (Wimbadi and Djalante, 2020; Fair Supply, 2023).

3. Compliance philosophy in net zero transitions

The GHG emissions regulatory system demands absolute compliance to mitigate direct and indirect climate change catastrophic impacts in the built environment. Mitigating this impact requires immediate action backed by operative transition plans, willpower, and financial support (Deloitte, 2022). Above all, a successful mitigation strategy for GHG emissions involves a detailed regulatory system and enforceable compliance strategies. However, achieving a high level of compliance requires stakeholder's cooperation with the regulators, understanding the significance of the regulations, and the associated implementation strategies (Nwadike and Wilkinson, 2021). In the context of this study, 'compliance philosophy' refers to creating a culture that stimulates the willingness of organisations, companies, countries, and other related entities to fully comply with all GHG emissions regulations towards meeting their net-zero targets. Furthermore, meeting the compliance target requires commitment from the policymakers and the emitters combined with a sound understanding of all parties (Nwadike and Wilkinson, 2021). Accordingly, the expectation of net zero transition is achievable through well-developed transition plans with implementation strategies (Deloitte, 2022).

Creating an excellent compliance environment would entail encouraging the inclusiveness of all relevant stakeholders where the opinion of both the regulators and the GHG emitters will count on the regulatory and compliance process (Lisa, 2010; Roshchanka and Evans, 2016; Nwadike and Wilkinson, 2021). The inclusiveness may initiate the involvement of regulators and GHG emitters in planning and formulating regulatory policies, dialogue engagement, and agreeable implementation strategies with actionable plans (Nwadike and Wilkinson, 2021). Engaging with GHG emitters is significant because all the relevant stakeholders come to the table with their respective diverse interests, meaning that inclusiveness and neutral dialogue reduces non-compliance while creating compliance values and cultures among the emitters of GHG emissions (Ahmed *et al.*, 2018; Nwadike and Wilkinson, 2021). In this study, a neutral dialogue means a deliberation void of any bias, where all parties' voices and viewpoints are considered. Achieving compliance with the net zero targets requires an action plan that incorporates the assessment of factors promoting and hindering compliance with an articulated solution agender comprising awareness, consultation, involvement, collaboration, and empowerment (Nwadike and Wilkinson, 2021). In addition, the net zero transition process helps identify and integrate compliance risks into a well-planned risk management framework aligned with the GHG transition plan (Deloitte, 2022). Hence, aligning compliance culture with incentives in a robust governance environment would facilitate net zero plans across the required strategies, plans, and risk management evaluation (Deloitte, 2022).

4. Research method

This study adopted a qualitative approach to gain insights into relevant compliance strategies for transitioning to net zero carbon emissions. An integrative literature review was conducted to evaluate the existing ideas and synthesise them to generate new perspectives using an in-depth analysis of key concepts to facilitate the assessment of the topic and construct novel knowledge (Torraco, 2016). The integrative literature review process consisted of problem formulation, literature search, data evaluation, data analysis, data interpretation, and presentation of research findings (Russell, 2005; Lubbe *et al.*, 2020). This research approach ensures that the study findings are incorporated into the existing literature to provide improved insights.

5. Results and discussion

This section delves into the various compliance strategies employed in net-zero emission transition plans within the built environment. The strategies used have been tried and tested to ensure a smooth transition towards net-zero emissions. Relevant recommendations and outcomes are also discussed in detail.

5.1. Compliance strategies towards net-zero emissions transition

To achieve a net-zero emissions transition in the built environment and reduce global warming, all actors in the value chain must collaborate on actionable plans (Patchell, 2018). Regulations that consider political, economic, social, technological, legal, and environmental (PESTLE) factors are necessary to ensure compliance with GHG emissions transition plans. Using the PESTLE factors as a data collection instrument can create a comprehensive framework for successful and sustainable transitions towards lower emissions. The impact of these PESTLE factors is crucial in shaping government and emitter compliance responses towards net-zero transition plans. Effective compliance strategies require urgent action to address climate change impacts and balance GHG emissions. PESTLE factors are interrelated but not interchangeable, and any unresolved factor has the potential to trigger non-compliance with GHG regulations.

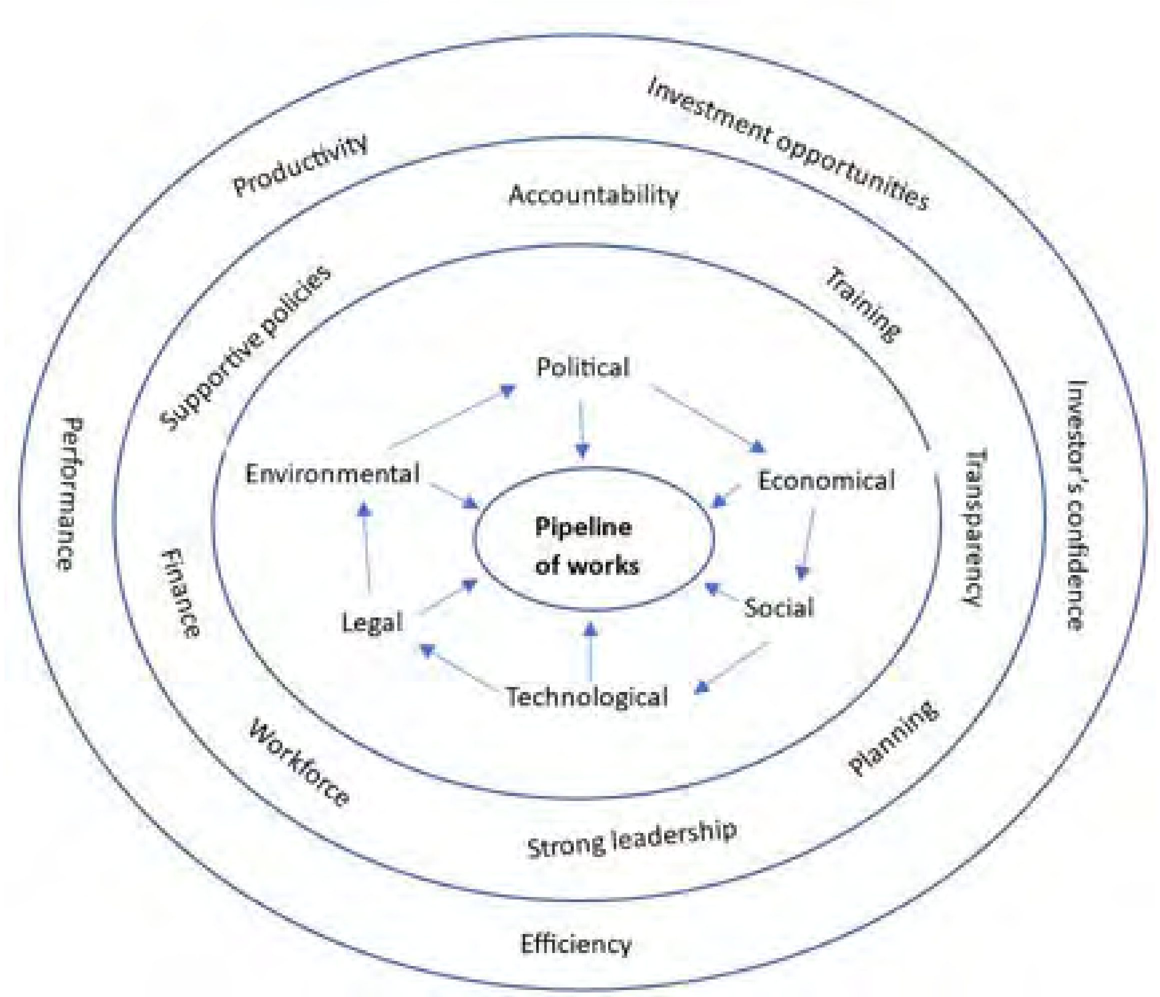

Figure 1: Compliance strategy concept.

In the context of this study, the PESTLE analysis provides a balancing tool to monitor, evaluate, analyse, enforce, and encourage effective compliance with global GHG emissions regulations towards achieving net-zero targets. Considering the significance of the PESTLE analysis, it offers strategic planning and decision-making tools that help to identify risk opportunities associated with the performance of compliance strategies towards net-zero transition plans in the built environment (Nicolette Bartlett *et al.*, 2016). These potential factors can influence a compliance process positively or negatively depending on the willingness of the government towards a net zero transition plan (Jordan *et al.*, 2022). For example, most of the political factors come from the government's roles in setting regulations, legislations, and implementable policies, as net zero emissions would require substantial government commitment and political will to enforce compliance (Jordan *et al.*, 2022; Dalirazar and Sabzi, 2023). Also, government policies shape and influence all internal and external policies across diverse organisations and the behaviour of the emitters towards complying with net-zero emissions (Brock *et al.*, 2022; Jordan *et al.*, 2022). Therefore, the government must legislate appropriate policies in conjunction with all relevant key players and stakeholders to make a sustainable compliance process that is favourable and implementable by all relevant parties (Nwadike and Wilkinson, 2021; Jordan *et al.*, 2022). Accordingly, Brock *et al.* (2022) believe that mandatory government policies geared towards net-zero emissions may reduce the consumption rate of emissions-generated goods and services and human activities, which may lead to less trading globally. However, changes in government, conflicts, and political elections may change countries' attitudes towards pushing for compliance with net zero emissions transition plans, mainly because politicians try to align and re-align their respective agendas while striving to secure re-election (Keefer, 2007).

Effective compliance strategies require viable economic growth and development capable of providing an enabling environment to finance the compliance process and allow GHG emitters to comply with the regulations willingly. The enabling economic environment should be devoid of weak financial schemes, high inflation and interest rates, and foreign exchange rates, among others (LOCO, 2018; Wang *et al.*, 2022). Wang *et al.* (2022) acknowledged that adverse economic shocks to the GDP may affect the level of compliance with carbon emissions regulations, especially where the laws guiding carbon emissions are strict. This signifies that developing nations may find it difficult to enforce compliance across GHG emitters towards achieving net-zero target. However, achieving compliance requires providing economic and non-economic incentives and reduced compliance cost to businesses, organisations, and entities that emits GHG (Nicolette Bartlett *et al.*, 2016). Societal influence maximally shapes individual behaviour towards complying with climate change policies and regulations geared towards reducing GHG emissions (Ela, 2009). The social influence may be difficult to quantify; however, it requires identifying how GHG emissions and their regulations may affect or better the value of people's life (Ela, 2009; Grayson and Robertson, 2020). This means maximum compliance may be achieved when the carbon emission targets and regulations align with the people's existing cultural values and norms.

Furthermore, Ela (2009) argued that any climate change policy that excludes the social influence in reducing carbon emissions may not be achieved. Hence, compliance with GHG emissions regulation is only effective when the compliance process and strategies are fully embedded in the socio-cultural values and norms of the people. The compliance strategy through socio-cultural values allows the people to view reasons for compliance through the lens of community structure, cultural trends, demographic, population, beliefs, and how climate change impacts may catastrophically affect their built environment (LOCO, 2018). This is necessary as social norms shape people's behaviour, and tailoring compliance strategies of GHG emissions to align with social norms facilitates people's willingness to obey regulations while guiding policymakers and carbon emitters towards a net zero emissions target (Ela, 2009).

The application of technology in compliance is drastically changing, shifting, shaping, and disrupting the traditional methods of compliance, especially towards net-zero transition. The use of technology such as Artificial Intelligence (AI) and machine learning to achieve compliance with carbon emissions regulation comes with positive and negative influences that affect the entire compliance process (CIAL, 2023). Incorporating and implementing a technological system into the compliance strategy process may be able to forecast, analyse, evaluate, and monitor how business, companies, and organisations emits GHG and provide various measures towards its reduction while maintaining service efficiency (CIAL, 2023). According to Villegas-Palacio and Coria (2010), a well-embedded technological system for compliance reduces the violation rate of compliance principles and the benefits of non-compliance. Furthermore, placing the merits of technology application with the associated compliance complexities, it is advisable to ensure compliance officers are adequately trained as the technological system evolves around GHG (Nwadike and Wilkinson, 2021; 2022). Harnessing the potentials of technological advancements system requires aligning compliance strategies with the objectives of net-zero transition plans and integrating the resultant outcome into driving risk management (Deloitte, 2017).

Nonetheless, efficient compliance strategies anchored around a legal framework and the rule of law help to enhance compliance with the outlined regulations surrounding net-zero transition plans. This is because legal influence is utilised to set out punishments for any breach of the net-zero transition regulations while helping to regulate people's behaviour towards compliance (Barker *et al.*, 2001). The urgency of climate change action necessitates involving an active legal framework that enforces enacted GHG regulations known and acceptable by all parties (Gerrard, 2007). Environmental factors directly or indirectly affect the efficiency of compliance strategies in reducing GHG emissions in the built environment. However, the (OECD, 2009) reported that many Organisation for Economic Co-operation and Development (OECD) countries find it challenging to comply with the GHG environmental regulatory requirements. Embedding implementable environmental policies into actionable strategies that promote compliance with regulations towards reducing carbon emissions (Guo et al., 2021).

Relevant compliance strategies to reduce GHG emissions require proactive and transparent accountability from the government regulatory agencies and the emitters across all sectors. This involves measuring and reporting all GHG emission activities. At the same time, the government provides supportive policies that can create an enabling environment with easy-to-understand guiding principles that will aid the measuring and reporting process. Effective utilisation of the guiding principles of measuring and reporting GHG emissions requires regular training on how to use GHG accounting tools, the significance of reporting, and various ways of minimising GHG in the built environment. Strong leadership in combating the challenges of reducing GHG emissions is necessary to ensure that stringent enforceable regulations are enacted with supportive policies that increase the emitter's willingness to account for their own GHG emissions. Accordingly, GHG regulators should provide accessible technical assistance as a compliance strategy to incentivise and increase compliance rates. However, providing financial incentives to alleviate the cost of compliance to some extent may help boost the compliance rate. Also, considering the urgency to reduce GHG emissions and the number of emitters in the built environment, it becomes imperative for the government to have functional accessors workforce with all the necessary knowledge and proper skills to assess and enforce compliance according to the established GHG emissions regulations. If well implemented, this compliance strategy may promote productivity, attract local and international investors, boost investors' confidence, enhance efficiency, and increase system performance.

5. Conclusion

It has become widely acknowledged that a crucial step in combating the negative impacts of climate change on our built environment is based on achieving a net-zero transition in carbon emissions to avoid the unfavourable prevailing consequences of climate change. This study explored strategies to boost and promote compliance with carbon emissions regulations among the emitters while pushing towards achieving a smooth net-zero emissions transition. An integrative literature review provided insightful techniques to develop a compliance strategy capable of transitioning to net-zero emissions in the built environment while boosting the emitter’s willingness to comply with carbon emissions reduction.

The study acknowledged the urgency of achieving the net-zero transition plans for carbon emissions and its profitability in safeguarding the built environment from the catastrophic climate change consequences. The findings from this study reveal that there are intended and mostly unintended non-compliance behaviour towards the carbon emissions reduction regulations, prompting the need for an active compliance strategy. The PESTLE analysis incorporated in compliance strategies provides a balance tool to monitor, evaluate, analyse, enforce, and encourage effective compliance to achieve net-zero transition targets. Also, the study findings show the inter-dependency of the PESTLE factors and their influential capacities in fostering compliance among the carbon emitters. It is crucial to consider all PESTLE factors when working towards carbon emission reduction and implementing the compliance strategy to avoid any potential setbacks or disruptions. This strategy's effectiveness relies on the government's willingness to make policies, regulate carbon emissions, enforce compliance and motivate the emitters to comply with carbon emissions regulations. This implies that a well-planned and implemented compliance strategy can drive carbon emissions regulations successfully through timely support policies and direct collaborative commitment between the government and the emitters. This necessitates proactive transparency and accountability from the government's carbon emitters and regulatory entities.

The research findings revealed how government policies and attitudes shape and influence CO_2 emitters' adherence to carbon emission protocols and regulations. Accordingly, adequate training of the emitters and the regulators is necessary as the environmental policies and technological innovations surrounding GHG emissions continue to evolve. Also, providing technical assistance to motivate and incentivise CO_2 emitters could significantly encourage and boosts their behaviours to meet the net-zero transition target by 2050. Although the net zero emission policies and responses may vary across countries, the time-based urgency on achieving climate change goal remains constant, as there are foreseeable environmental climate change impacts in the built environment. A limitation of this study is that it applied only an integrative literature review technique to drive the findings. Future research may consider incorporating a case study and interviews with subject matter experts to validate this study’s recommended compliance strategies. Also, future research is recommended to critically analyse and justify how carbon offsetting and credit will help to reduce GHG in the atmosphere and meet the climate change targets in the built environment.

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Cooling potential of C3 and CAM species of vegetative roofs for improving building thermal performance and surroundings urban environments

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Abstract: Urban growth presents challenges such as increased greenhouse gas emissions, the urban heat island (UHI) effect, and poor resilience to counter heat waves. Vegetative roofs can offer high cooling potential due to plants' transpiration, substrate moisture evaporation, and shading. Therefore, vegetative roofs can reduce building operational energy consumption and related CO_2 emissions, mitigate the UHI and make cities more resilient against global warming by lowering the surrounding air temperature of the urban environment. This paper aims to quantify the cooling potential of vegetative roofs in Melbourne (Australia) and Santiago (Chile). Six C3 and CAM species used in vegetative roofs are assessed using a New Linear Model (NLM) for the stomatal resistance (r_s) and a heat and mass transfer green roof model implemented in Matlab and validated in several climates. *Selliera radicans* (C3) outperforms the other species in terms of cooling potential; leaf area index (LAI) is the main plant characteristic that influences the substrate surface temperature due to the shading effect; r_s and LAI have a significant impact on the foliage temperature and evapotranspiration control. This research allows designers and urban planners to comprehend the importance of choosing suitable vegetative roof species to maximize their cooling potential.

Keywords: Green roof; cooling potential; C3 species; CAM species.

1. Introduction

The growth of the world population and the migration to urban areas have meant a considerable demand for new urban infrastructure and services. This urban growth brings an expansion of constructions to meet the great demand for housing, which creates a series of environmental problems, such as air pollution, the urban heat island (UHI) effect, and the lack of urban green infrastructure. Moreover, the building operational energy causes 28% of total CO_2 emissions (United Nations Environment Programme, 2020). Therefore, according to the Paris Agreement, the building sector is critical to accomplish CO_2 emission reduction goals and limit the global temperature increase to 1.5°C. Furthermore, buildings and

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their surrounding infrastructure is crucial to make cities resilient against overheating and heat waves caused by global warming.

Vegetative roofs, so-called green roofs, can reduce these problems by incorporating plants into the least valued urban spaces, such as buildings' envelopes (Garcia, 2010). They can decrease the building's operational energy because of reducing roof's heat gains by the following mechanisms: evapotranspiration, which is water evaporated from the substrate and transpired by the plants through their stomata (American Society of Civil Engineers, 2016; Boulet et al., 2020), shading effect produced by the foliage, and additional thermal inertia owing to the substrate layer (Besir & Cuce, 2018; Shafique et al., 2018). Moreover, vegetative roofs reduce UHI due to the vegetation's transpiration processes which are key to mitigating the effects of heat waves on people's health and comfort (Dwivedi & Mohan, 2018).

Vera et al. (2017) indicate that vegetation can be more effective than insulation in reducing cooling loads owing to evapotranspiration and the canopy's shading effect. Also, the authors show that vegetative roofs reduce heat gains through the roof and allow internal gains to flow to the outside in hot seasons.

Plants have diverse CO_2 fixation mechanisms and transpiration strategies (Taiz et al., 2015). There are three types of metabolic pathways for photosynthesis, C3 (most plants), C4 (tropical plants), and Crassulacean Acid Metabolism (CAM) (xerophytic plants) (Hartzell et al., 2018; Taiz et al., 2015). CAM plants are the most used in vegetative roofs in arid, semi-arid and Mediterranean climates due to their excellent resistance to drought periods (Blanusa et al., 2013; Cook-Patton & Bauerle, 2012). CAM species open their stomata at night to capture CO_2 and close them during the daytime to avoid water loss (Chen et al., 2002; Koch & Kennedy, 1980; Lüttge, 2004). While C3 and C4 plants capture CO_2 during the day, increasing water losses and, consequently, increasing the cooling potential (Cook-Patton & Bauerle, 2012). However, if water availability conditions are optimal, some CAM plants might behave like C3, which is helpful for cooling buildings' and the surrounding air (Starry et al., 2014).

According to several studies, stomatal resistance (rs) and leaf area index (LAI) are the most critical plants characteristics that influence the cooling potential of vegetative roofs (Monteiro et al., 2017; Saadatian et al., 2013; Tabares-Velasco & Srebric, 2011). rs is the resistance associated with gas diffusion through the stomatal pore (Taiz et al., 2015), and LAI is defined as the total leaf area per unit soil surface, measured in m2 m-2 (J. M. Chen & Cihlar, 1996). Pianella et al. (2017) found that LAI is essential to decrease substrate temperature and heat flux through the roof. They show that the highest LAI (5 m2 m-2) reduced the temperature up to 25°C compared to the lowest LAI (0.01 m2 m-2) during daytime and sunny days in Melbourne (Australia). However, they do not analyse evapotranspiration fluxes or foliage temperature. Thus, the cooling potential of the urban environment was not assessed.

Vegetative roofs include complex and simultaneous heat and mass transfer processes among the air, foliage, and substrate. Therefore, modelling these processes consists of a series of characteristics of the substrate, vegetation, and the roof's support, which try to represent the actual behaviour as accurately as possible. About 23 simulation models of heat and mass transfer through vegetative roofs have been developed (Vera et al., 2018). Tabares-Velasco & Srebric (2012) developed one of the most cited models and will be used in this study.

One way to analyse the cooling potential of vegetative roofs in building thermal performance is to compare the temperature at the substrate level of different alternatives. The reduction in substrate surface temperature reflects the vegetative roof's ability to decrease incoming heat fluxes through the roof structure, reducing heat gains across the roof, and hence, reducing cooling loads (Reyes et al., 2016; Vera et al., 2015; Vera et al., 2017). On the other hand, vegetative roofs could generate benefits in the buildings' surrounding urban environment. They contribute to mitigating UHI due to the evapotranspiration of the plant-substrate system. Therefore, the cooling potential of vegetative roofs could be indirectly evaluated by looking at their effects on the foliage and air temperatures (Jim, 2012; Razzaghmanesh et al., 2016; Yang et al., 2018).

Consequently, this paper aims to evaluate the cooling potential of six C3 and CAM species of vegetative roofs for improving building energy performance and urban environments in Melbourne (Australia) and Santiago (Chile).

2. Brief description of Tabares-Velasco & Srebric (2012) model and New Linear Model (NLM)

In this investigation, a modified green roof model of Tabares-Velasco & Srebric (2012) that we implemented in Matlab was used (Vera et al., 2017). This model has been analyzed and validated by Vera et al. (2018) and Vera et al. (2019). The general energy balance equation for vegetative roofs is presented in (1).

$$I_n = H + L + Q_{radiation} + Q_{cond} \quad (1)$$

where, I_n = solar radiation; H = sensible heat flux; L = latent heat flux (or evapotranspiration from substrate and plants); $Q_{radiation}$ = counts for the longwave and shortwave radiation exchanges (between the foliage and the sky, between the surface of the upper substrate and the sky, and between the foliage and the surface of the upper substrate); and Q_{cond} = heat flux by conduction through the substrate.

Thermal storage and metabolic storage are not considered in (1) because their contribution to the total energy sum is around 1-2% of the net radiation (Tabares-Velasco, 2009).

Regarding the vegetation modelling in Tabares-Velasco & Srebric (2012) model, the main parameters that represent plant characteristics are: (i) leaf area index (LAI), (ii) stomatal resistance (r_s) (iii) height of the plant, and (iv) coefficients of reflection and foliar emissivity. These parameters are fixed except for r_s. r_s equations used in the model present drawbacks such as overestimating r_s at low or null solar radiation, low substrate's volumetric water content (VWC), among others. Therefore, a novel r_s equation was obtained through field data collected for six species of ground covers (Figure). The new equation for stomatal resistance (2) was developed by Rojas et al. (2023) through a multiple linear regression analysis based on 586 measurements of r_s, LAI, minimum stomatal resistance ($r_{s,min}$), and environmental conditions of the six species obtained during December (2019) and January (2020) in Santiago, Chile, in a greenhouse of the Faculty of Agronomy and Forestry Engineering of the Pontificia Universidad Católica de Chile (33 ° 29' 47" S, 70 ° 36' 33" W) (Rojas et al., 2023) . Santiago's climate is BSk, according to Köppen-Geiger Climate Classification (Kottek et al., 2006).

$$r_s = 184.2 + 1.99r_{s,min} – 0.16R_{sh} – 247.12VWC – 34.59LAI +21.57VPD \quad (2)$$

where, $r_{s,min}$ = minimum stomatal resistance, (ii) R_{sh} = incident solar radiation on the surface, and (II) VPD = vapor pressure differential.

Figure 1: Selected species. C3 species: (a) *Glandularia berterii* (VER), (b) *Selliera radicans* (SEL), and (c) *Phyla reptans* (TIQ). CAM species: (d) *Aptenia cordifolia* (APT), (e) *Sedum palmeri* (SPA), and (f) *Sedum spurium* (SSV) (Source: adapted from Rojas et al. (2023)).

3. Methodology

The three-stage research methodology shown in Figure was carried out to evaluate the cooling potential of six C3 and CAM species of vegetative roofs. The first stage consists of preparing the data and case studies. The second stage consists of running heat and mass transfer simulations for two climates and six CAM and C3 plant species. The third stage consists of analyzing the cooling potential of the C3 and CAM species in both environments. This analysis focuses on two main aspects: quantify how plants affect the buildings' energy performance based on the substrate temperature and how vegetation species impact the buildings' surrounding air temperature based on the foliage temperature and evapotranspiration.

This study uses a dataset collected in previous research projects (Rojas, 2021; Rojas et al., 2023) for assessing the cooling potential of CAM and C3 species in an extensive vegetative roof located in Santiago (Chile) and a semi-extensive vegetative roof in Melbourne (Australia). Table indicates the climates according to the Köppen-Geiger classification (Kottek et al., 2006), the types of vegetative roofs used, and the season in which the datasets were obtained experimentally. Datasets include local climatic conditions (relative air humidity, global horizontal incident radiation, wind speed and direction, precipitation, and air temperature), substrate temperatures (from the surface and measurements every 50 mm, along with the vertical profile), and the substrate volumetric water content (VWC).

Stage 3 is based on analyzing the cooling potential of C3 and CAM species of vegetative roofs on buildings' energy performance and the surrounding urban environment. The evaluation is based on the simulated substrate surface temperatures, foliage temperatures, and evapotranspiration fluxes. The simulations are carried out using the characteristics of the species studied in the greenhouse (LAI and $r_{s,min}$) as individual species, groups of C3 and CAM species, and a set of all species.

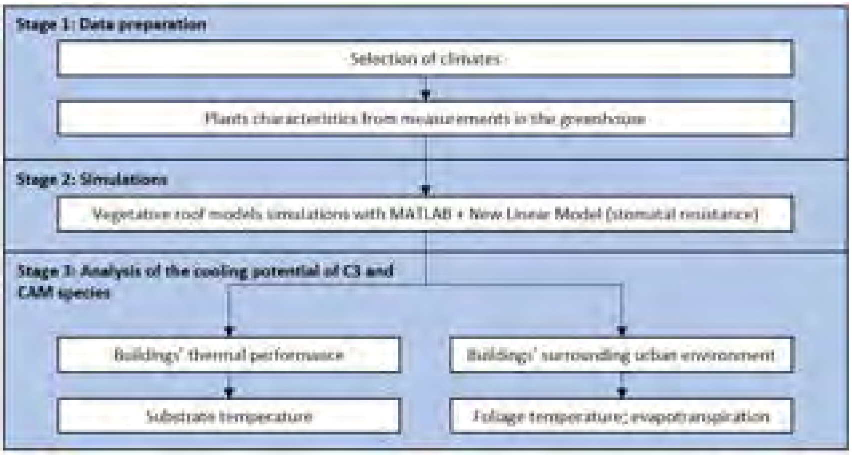

Figure 2: Methodology divided into three stages: stage 1 of data preparation, stage 2 of simulations and stage 3 of cooling potential of species analysis.

Table 1: Cities, climates, and type of vegetative roof.

City	Climate (Köppen-Geiger Classification)	Season	Type of vegetative roof
Melbourne	Cfb (temperate oceanic climate)	Summer (Dec – Feb)	Extensive
Santiago	BSk (cold semi-arid climate)	Winter (August)	Semi-intensive

3.1. Experimental dataset

The experimental vegetative roof data in Melbourne was collected from vegetative roofs (15 m^2) installed at the University of Melbourne, Campus Burnley (Pianella et al., 2017). The data from an extensive roof with a substrate depth of 100 mm were used. Measurements were taken between December and February, corresponding to summer.

The dataset collected in Santiago was carried out on a vegetative roof at the Laboratory of Vegetative Infrastructure of Buildings (LIVE, for the acronym in Spanish), located at Pontificia Universidad Católica de Chile, Campus San Joaquín (Herrera et al., 2017). Measurements were carried out during August (winter). The laboratory consists of four 2 m high modules composed by three modules of 25 m^2

vegetative roof and one module of 35 m^2 (Reyes et al., 2016; Viecco et al., 2018). The structure of these vegetative roofs is described in Vera et al. (2019), which consists from top to bottom of a vegetation layer, a substrate layer, a filter membrane, a drainage layer, a root resistance barrier, and a waterproofing membrane.

3.2. Vegetation

Table indicates the main characteristics of the vegetation and the values obtained from the measurements of a previous greenhouse study for the six species shown in Figure (Rojas et al., 2023). These values are used in the simulations, analysis, and comparison. The entire set of species, called "All species", considers the mean values for LAI, $r_{s,min}$, and height of the six species, while C3 and CAM groups consider the mean values of the respective groups.

3.3. Analysis method

The cooling potential of the C3 and CAM species is analyzed through substrate temperatures, foliage temperatures, and evapotranspiration fluxes, which are indirect metrics that allow inferring the cooling effect of vegetative roof species on the building's thermal performance and the surrounding urban environment. The following section presents box plots with the simulated variables, substrate surface temperatures, foliage temperatures, and evapotranspiration fluxes. Besides, scatter plots allow comparing a daily variation of these parameters.

4. Results and discussions

4.1. Substrate surface temperature

Figure shows the simulated data for the substrate temperature of the two vegetative roofs with different species and groups. The trend in all six species is the same for both climates. The species with higher LAI (> 2.8 m^2 m^{-2}) show lower substrate surface temperatures than species with LAI close to 1.0 m^2 m^{-2}. Therefore, in both climates, the substrate surface temperature strongly depends on the LAI and, to a lesser extent, depends on minimum stomatal resistance ($r_{s,min}$). Thus, the shading effect is critical in controlling the substrate surface temperature.

Table 2: Vegetation properties: species, leaf area index (LAI), minimum stomatal resistance ($r_{s,min}$) and height (m) (data from Rojas, 2021).

Group	Species	LAI (m2 m-2)	rs,min(s m-1)	Height (m)
Individual species	*Glandularia berterii*	1.00	30.06	0.18
	Selliera radicans	3.35	86.75	0.12
	Phyla reptans	1.16	44.50	0.15
	Aptenia cordifolia	1.59	164.87	0.18
	Sedum palmeri	2.83	221.75	0.15
	Sedum spurium	2.89	181.98	0.12
All species	*Glandularia berterii* *Selliera radicans* *Phyla reptans* *Aptenia cordifolia* *Sedum palmeri* *Sedum spurium*	2.14	121.65	0.15
C3 species	*Glandularia berterii* *Selliera radicans* *Phyla reptans*	1.83	53.77	0.15
CAM species	*Aptenia cordifolia* *Sedum palmeri* *Sedum spurium*	2.44	189.53	0.15

In Melbourne's vegetative roof, Figure (a) reports maximum substrate surface temperature values above 50°C in Phyla reptans and Glandularia berterii. Both species are C3 with 1.00 and 1.16 m2 m-2 LAI values, respectively. Aptenia cordifolia (CAM), which shows the lowest LAI (1.59 m2 m-2) among CAM species, reaches a maximum substrate surface temperature close to 47°C. In contrast, the Sedum palmeri and Sedum spurium (CAM), with high LAI close to 2.80 m2 m-2, show maximum substrate surface temperatures of 41°C. Selliera radicans (C3) shows the lowest substrate surface temperature among all species (around 40°C). This species shows a combination of high LAI (3.35 m2 m-2) and low rs,min (86.75 s m-1). Thus, substrate surface temperature is 12°C lower than Glandularia berterii, the C3 species with the lowest LAI. This trend is consistent in Santiago's vegetative roof (Figure (b)), demonstrating the importance of the shading effect. LAI is the main characteristic of the plants' species, which directly influences the thermal performance of the building, which aligns well with findings from other researchers (Monteiro et al., 2017; Tabares-Velasco & Srebric, 2011; Saadatian et al., 2013; Pianella et al., 2017).

"All C3 species" shows differences in maximum substrate surface temperatures up to 3°C higher than "All CAM species". The entire group ("All species") data reports values that are intermediate between those from "All C3 species" and "All CAM species" datasets. These results evidence species with higher LAI more successfully block solar radiation and prevent it from reaching the substrate of vegetative roofs. Therefore, the conductive heat flux through the vegetative roof decreases and reduces building heat gains across the roof, which reduces building cooling energy consumption. Designers could choose species with high LAI for a vegetative roof if the aim is to obtain lower substrate surface temperatures.

However, the potential cooling of surrounding ambient air temperature would be minimal. As such, appropriate plant selection should also consider species with low rs.

The plant species under which the lowest substrate surface temperature is found is Selliera radicans. Sedum species show differences in maximum substrate surface temperatures around 1–2°C higher than Selliera radicans. Therefore, sedum species could be an excellent option to be used on vegetative roofs in arid, semi-arid and Mediterranean climates.

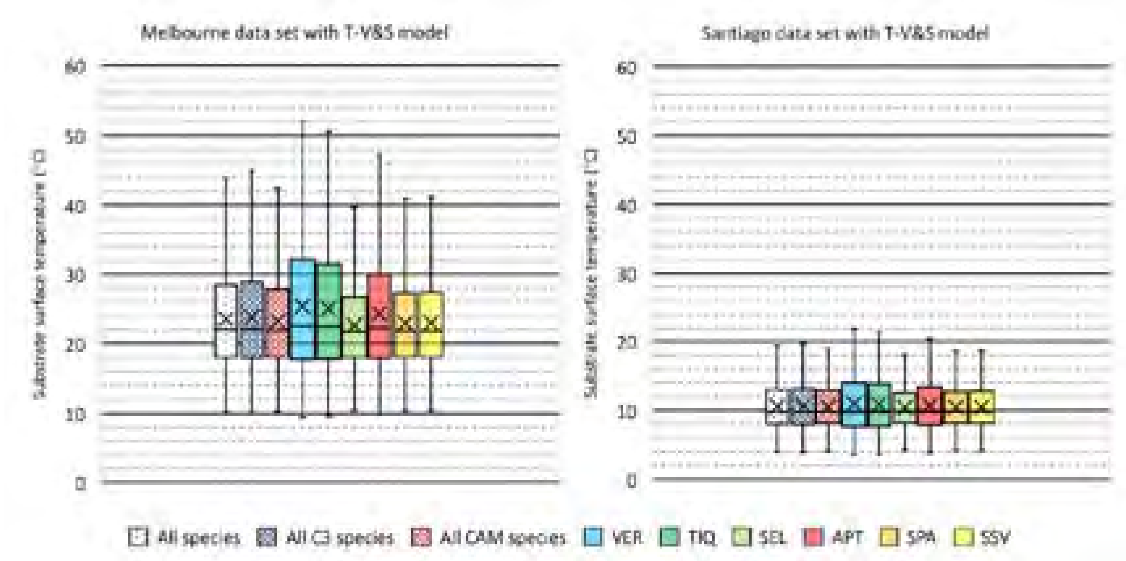

Figure 3: Substrate surface temperature (°C) simulated for: All species, All C3 species, All CAM species, *Glandularia berterii* (VER), *Phyla reptans* (TIQ), *Selliera radicans* (SEL), *Aptenia cordifolia* (APT), *Sedum palmeri* (SPA), and *Sedum spurium* (SSV), for two vegetative roofs with Tabares-Velasco & Srebric (2012) (T-V&S) model.

4.2. Foliage temperature

Figure shows the foliage temperature simulated for the two vegetative roofs with each species and group. In contrast to the substrate surface temperature, the $r_{s,min}$ through the transpiration process and LAI cause significant differences in foliage temperature among species and groups. The trend in the six species is similar in both evaluated climates. C3 species show lower foliage temperatures than CAM species because of lower $r_{s,min}$. However, high LAI helps increasing this effect and reduce even more the foliage temperatures.

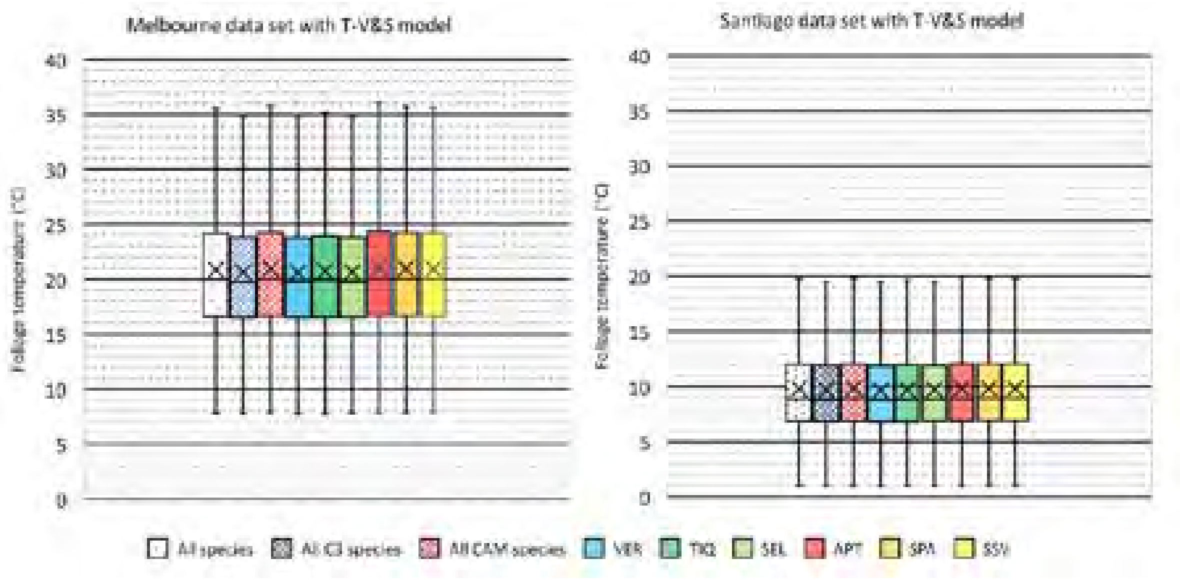

Figure 4: Foliage temperature (°C) simulated for: All species, All C3 species, All CAM species, *Glandularia berterii* (VER), *Phyla reptans* (TIQ), *Selliera radicans* (SEL), *Aptenia cordifolia* (APT), *Sedum palmeri* (SPA), and *Sedum spurium* (SSV), for two vegetative roofs with Tabares-Velasco & Srebric (2012) (T-V&S) model.

The species with the lowest foliage temperatures is *Selliera radicans* (C3), while *Aptenia cordifolia* (CAM) shows the highest foliage temperatures in both climates. Overall, CAM species show higher maximum foliage temperatures in the next order from the highest to the lowest: *Aptenia cordifolia*, *Sedum palmeri*, and *Sedum spurium*. Whereas C3 species show foliage temperatures in the following order from the highest to the lowest: *Phyla reptans*, *Glandularia berterii*, and *Selliera radicans*. The entire group of plants presents intermediate values between groups C3 (the lowest values) and CAM (the highest values).

Therefore, species with low $r_{s,min}$ and high LAI like *Selliera radicans* (C3, LAI = 3.35 m^2 m^{-2} and $r_{s,min}$ = 86.8 s m^{-1}) are the most likely to provide the greatest cooling potential. This agrees well with Ascione et al. (2015) research on optimizing the annual energy performance of an educational building with a vegetative roof of the University of Sannio, Italy. They reported that plants with high LAI (3.5 m^2 m^{-2}) and low $r_{s,min}$ (120 s m^{-1}) were the best plants option thata caused annual energy savings of 9% while electric demand for cooling was reduced by 10% during July and August.

4.3. Evapotranspiration flux

Figure shows significant evapotranspiration flux differences among the species in both climates. *Selliera radicans* (C3) and *Aptenia cordifolia* (CAM) species show the most significant difference. In Melbourne, *Selliera radicans* shows evapotranspiration rates up to 4.2 times more than *Aptenia cordifolia*. In Santiago, during the winter, the difference among species is close to 3.3 times.

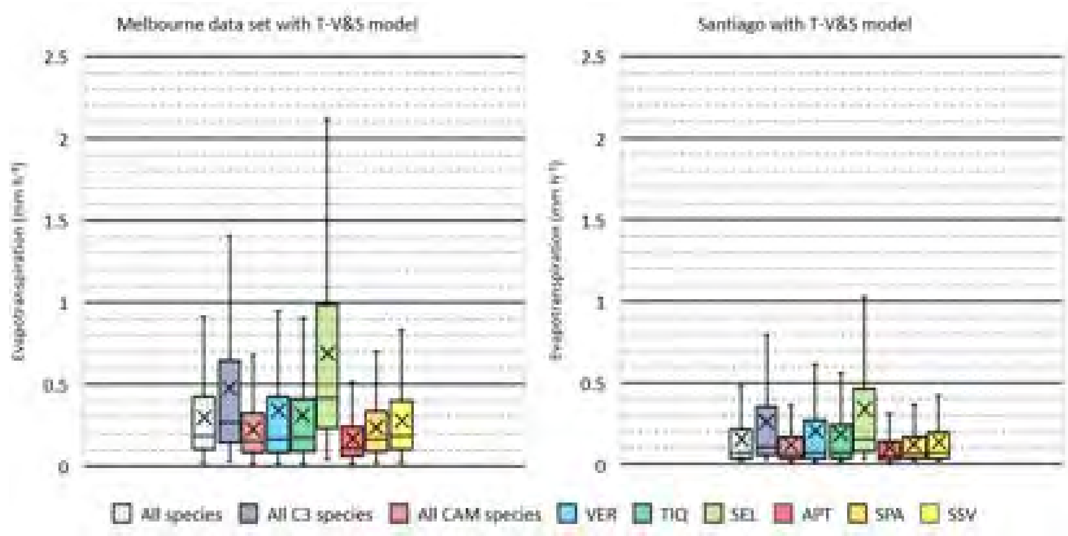

Figure 5: Evapotranspiration (mm h^{-1}) simulated for: All species, All C3 species, All CAM species, *Glandularia berterii* (VER), *Phyla reptans* (TIQ), *Selliera radicans* (SEL), *Aptenia cordifolia* (APT), *Sedum palmeri* (SPA), and *Sedum spurium* (SSV), for two vegetative roofs with Tabares-Velasco & Srebric (2012) (T-V&S) model.

Evapotranspiration is related to the foliage temperature owing to the transpiration process in the plant consuming energy, which comes from the heat absorbed by the vaporization of water (Taiz et al., 2015). Therefore, the species with the high evapotranspiration rate have the lowest foliage temperatures and highest cooling potential, such as Selliera radicans, whose performance is comparable in both vegetative roofs.

In Figure , the vegetative roof of Melbourne is presented for two simulation days (January 5th and 6th). This Figure shows the variation of the foliage temperature for each species and group. A difference of up to 3.4°C is seen between Selliera radicans and Aptenia cordifolia, reaching peaks of 33°C for Selliera radicans and 36.4°C for the case of Aptenia cordifolia.

Figure shows the latent heat flux or evapotranspiration for Melbourne's vegetative roof for two simulation days. A difference of up to 4.6 times between Selliera radicans and Aptenia cordifolia is observed.

Therefore, the potential of plants to reduce the building energy consumption for cooling is controlled by LAI owing to the shading effect offered by the foliage layer of a vegetative roof. However, evapotranspiration rates are essential to optimize the benefits of vegetative roofs in mitigating UHI effects and cooling urban environments.

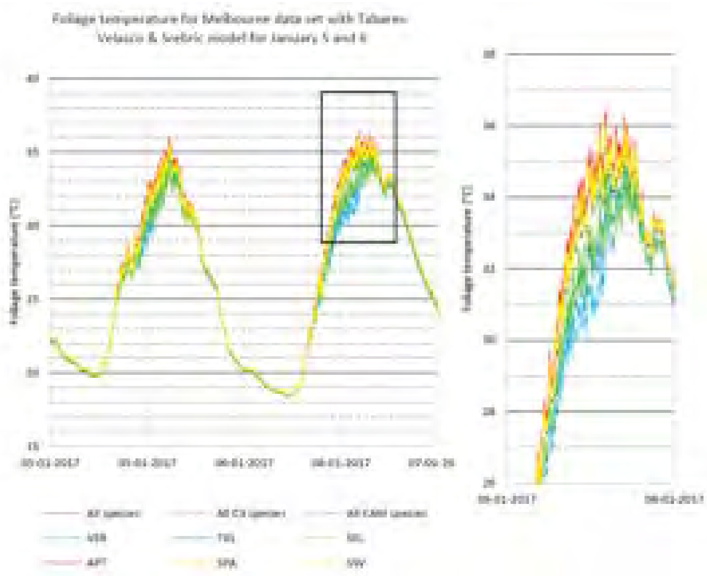

Figure 6: Foliage temperature (°C) simulated on January 5 and January 6 in Melbourne vegetative roof, for each species and groups: All species, All C3 species, All CAM species, *Glandularia berterii* (VER), *Phyla reptans* (TIQ), *Selliera radicans* (SEL), *Aptenia cordifolia* (APT), *Sedum palmeri* (SPA), and *Sedum spurium* (SSV) with Tabares-Velasco & Srebric (2012) (T-V&S) model.

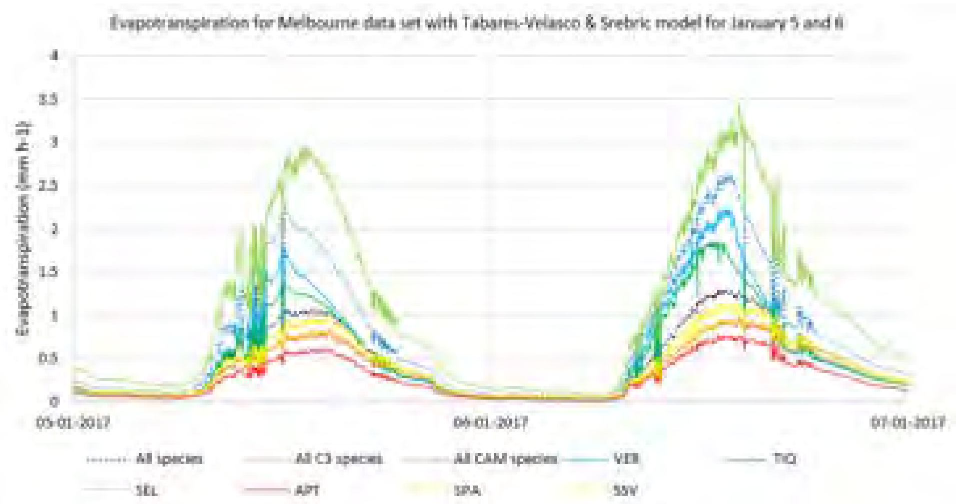

Figure 7: Latent heat flux or evapotranspiration (mm h^{-1}) simulated on January 5 and January 6 in Melbourne vegetative roof, for each species and groups: All species, All C3 species, All CAM species, *Glandularia berterii* (VER), *Phyla reptans* (TIQ), *Selliera radicans* (SEL), *Aptenia cordifolia* (APT), *Sedum palmeri* (SPA), and *Sedum spurium* (SSV) with Tabares-Velasco & Srebric (2012) (T-V&S) model.

5. Conclusions

The cooling potential of six species of groundcover vegetation used in vegetative roofs was evaluated by numerical simulations. The species tested were: *Glandularia berterii* (C3), *Selliera radicans* (C3), *Phyla reptans* (C3), *Aptenia cordifolia* (CAM), *Sedum palmeri* (CAM), and *Sedum spurium* (CAM). These plants are well suited for arid, semi-arid and Mediterranean climates. The cooling potential of these species on the building's energy performance was assessed through the substrate surface temperatures. At the same time, their effect on the surrounding urban environment was evaluated via the foliage temperature and evapotranspiration fluxes. The main conclusions of this investigation are:

- LAI is the main parameter of the vegetation to reduce the substrate surface temperature owing to its associated shading effect. The foliage layer absorbs solar radiation and reduces the heat absorbed by the substrate, decreasing the heat gain through the vegetative roof.
- The most significant variation of the simulated substrate surface temperature between two species is found between *Selliera radicans* (C3) and *Glandularia berterii* (C3), with differences up to 12 °C in Melbourne's vegetative roof. Therefore, *Selliera radicans* shows the best cooling potential to improve the building thermal performance.
- Stomatal resistance and LAI are relevant variables for changes in foliage temperatures and evapotranspiration rates due to the importance of the transpiration process to reduce foliage temperature and, consequently, the urban air temperature drops. In Melbourne, the highest difference among species was observed in *Selliera radicans*, which shows foliage temperatures up to 2 °C lower than *Aptenia cordifolia*.

This research allows designers or planners to understand the importance of choosing the species for vegetative roofs to obtain the greatest cooling potential according to the climatic needs of each zone.

Finally, the principal research opportunity that arises from this investigation is coupling the heat and mass transfers vegetative roof model with urban microclimate modeling tools to directly predict the impact of CAM and C3 species on the urban microclimate.

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Dynamic Embodied carbon BIM based Calculation tool: a User Experience Analysis Study

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Abstract: The integration of sustainability assessments, such as life cycle assessment (LCA), with digital construction workflow has become increasingly important in the architectural, engineering, and construction (AEC) sector due to global and governmental pressures to construct sustainable and low carbon buildings. Building information modelling (BIM) has revolutionised the AEC sector and has shown potential for integrating LCA into its platforms. However, there is still a need for testing and accessing early design and dynamic tools. To address this gap, the paper proposes a dynamic BIM based embodied carbon assessment tool and conducts a validation usability study to determine its ease of use and acceptability. The study employed mix between quantitative and qualitative method using online workshops with architects and sustainability assessors in UK to illustrate the use of the tool and collect feedback from participants through survey and semi structured interview. The results of the usability testing reveal the need to enhance the calculation model, visualisation and optimisation options, and develop a more advanced user interface for the tool. These results serve as a basis for future development to be addressed by researchers and practitioners to increase adoption of the new integrated approach. Overall, the paper highlights the significance of integrating sustainability assessments into digital construction workflow and the potential of BIM-based tools to achieve this goal.

Keywords: Building information modelling, Life cycle assessment, Embodied carbon, Usability study

1. Introduction

Sustainable buildings are designed to enhance the well-being of their occupants. Features such as improved indoor air quality, natural lighting, thermal comfort, and noise reduction contribute to occupant health, comfort, and productivity (Al horr et al., 2016). While sustainable building designs often focus on creating spaces that promote physical and mental well-being, the impact of long-term environmental performance of buildings is usually marginalized in research. The long-term performance is accounted for by the embodied footprint emissions of the building (Cabeza et al., 2013). The significance of this impact is derived from the fact that buildings currently account for 39% of all energy-related carbon emissions in the world: 28% come from their operating emissions, the remaining 11% come from their materials and construction(World Green Building council, 2019).

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 238 - 261. © 2023 and published by the Architectural Science Association (ANZAScA).

The embodied emission of the building is assessed using life cycle assessment (LCA) methodology which will be explained in detail later. In the digital construction era this methodology attempts to be integrated with Building information modelling (BIM) technology for efficient way to assess sustainable design decisions. Sustainable building practices that incorporate LCA data and BIM technology can result in buildings that perform better over their entire life cycle (Ayman et al., 2019).The integration of LCA research within BIM technology enables architects and designers to make more informed decisions regarding material selection and building design. This, in turn, can lead to the creation of sustainable buildings that prioritize the well-being of their users. However, there is a gap in literature in understanding the perspective of the architects and sustainability assessors on the efficiency of the approach. Therefore, the aim of this paper is to present a new model that overcomes the challenges of the current integrated approaches and suggest a perspective that consider users specific needs to enhance efficiency.

2. Literature review

The integration of LCA research within BIM technology enables architects and designers to make more informed decisions regarding material selection and building design (Ayman et al., 2018). This can therefore result in the development of low carbon buildings that prioritize the health of its occupants initially, encouraging healthier environment by reducing the footprint impact of the building. This section will define Life cycle assessment and Building Information modelling, then will analysis the current methods of the integration between them which will highlight the area of development.

2.1.Definition, standards, and boundary system

LCA is a methodology for evaluating environmental issues throughout the whole life cycle of the construction process (Naneva et al., 2020). It covers the entire life cycle of a material used in a building, from raw material extraction and processing to the production of building components to building use and deconstruction. It includes the extraction and processing of raw materials, the fabrication of building components, as well as the usage and end-of-life of the building. It also encompasses the whole life cycle of a product, system, or service utilized in a building. The LCA approach is standardized across publications to direct the quantification of the environmental effects of buildings (Lützkendorf & Balouktsi, 2022; Özdemir et al., 2022).

Material's life phases are divided into stages: preconstruction stage A0, product stage (A1-A3), construction process stage (A4-A5), use (B1-B8), end-of-life stage (C1-C4), and ultimately benefit and loads beyond (D1-D2). Also, multiple LCA environmental indicators can be assessed and calculated, such as: Global warming potential total (GWP - total), Depletion potential of the stratospheric ozone layer, ODP and Acidification potential, accumulated exceedance (AP). In this paper only Embodied carbon (EC) will be considered as part of Global warming potential total (GWP - total) indicator which is considered the factor under the impact category of climate change.

While LCA is commonly used in industrial production, it is more challenging to apply in the building industry due to its complex processes, as well as the time and effort it demands (Buyle et al., 2013). It is reported in several studies that LCA is complex and demanding in terms of time and effort, due to the considerable amount of information and processing needed ((Anand & Amor, 2017). The complexity of LCA in the AEC (Architecture, Engineering, and Construction) sector has led to researchers finding ways to simplify the assessment for structures. This includes creating a database of life cycle inventory (LCI) with functional units that represent the environmental impact of materials. In addition, digital integrated methods that combine BIM with LCA have been developed to improve the efficiency of the assessment process (Safari & Azarijafari, 2021).

2.2.Approaches and challenges

The digital building construction industry has proposed several methodologies and tools for integrating Life Cycle Assessment (LCA) calculations into the design process, which is addressed in previous studies ((Obrecht et al., 2020; Wastiels & Decuypere, 2019). The first approach involves using the BIM model to calculate the Bill of Quantities (BoQ), with dedicated LCA software or an Excel spreadsheet used for LCI (Life Cycle Inventory). This approach has shown to be time consuming and doesn't allow iterative assessment with design development (Cavalliere et al., 2019). The second approach involves exporting the IFC (Industry Foundation Classes) from the BIM model and importing it into LCA software, allowing for automatic mapping of the elements' quantities and structures (Forth, 2018). Although using IFC reduces the amount of time needed to manually insert data, this method is still less time-efficient, prone to error, and occasionally results in interoperability issues as a result of data being sent between platforms. Nevertheless, it is still preferable than the first one. The third approach uses a BIM viewer to map the LCI database, with the IFC model extracted from the BIM model and assigned materials using the BIM viewer (Apellániz et al., 2021). It is similar to the second approach but the use of the BIM viewer within the same environment eliminates the interoperability issues.

The most advanced method is the fourth one, which enables an iterative design process in the BIM environment and manages every stage using plugins in a Revit-approved BIM program (Bueno & Fabricio, 2018),. Examples of this method are tally and one-click LCA. The geometric model can display LCA results, providing a visualization of the most important impacts. The problem with those tools is that the user's choices are restricted by the material library provided within the tool. The fifth approach involves including the LCI database and BIM item data as parameters into the BIM model and use visual programming language (VPL) to automate all calculation and analysis process allowing for real-time LCA assessment (Alwan et al., 2021); Bueno et al., 2018; Hollberg et al., 2020). However, an adequate LCI BIM material library needs to be built first. This approach will be adopted & Fabricio in the proposed model discussed in the paper which will be explained in the next section.

3. Model brief

This model has utilized Dynamo (one of the VPL languages) coupled with Revit. The aim of this model is to provide a framework and tool that allows architects, sustainability assessors and structural engineers in the UK to create a suitable BIM material library and utilize (VPL) Dynamo to determine and visualize the embodied carbon (EC) of their design choices (Ayman Mohamed et al., 2023). This method facilitates the dynamic and iterative assessment of EC and allows for the reuse of this data in future projects. The framework involves the development of Dynamo scripts that connect the LCI database to the Revit material library using material ID. These scripts are then applied to the BIM model to perform the necessary calculations for Life Cycle Assessment (LCA), producing results that can be compared to benchmarks. Figure 1 provides an illustration of this concept, and additional details of the framework will be outlined in the subsequent sections.

The model is created in two stages, as shown in figure 1. In the first stage, a well-equipped BIM library is established using compliant databases and tools, and parameters are added to store the database and calculated results. This stage aims to create a ready-to-use Revit template file for the user to design. In the second stage, the template is utilized to model various design alternatives, which can be compared and visualized iteratively alongside design changes. The framework enables the reuse of generated data and provides a structure for building, reusing, and updating the BIM library for LCA. This entire process is automated using Dynamo visual scripts, eliminating the need for time-consuming manual tasks, as explained in the seps shown in figure 1. The only manual work required is the preparation of the standard Excel material file (step 2 stage 1), as displayed in figure 1. The user will prepare an Excel file containing information about all the materials.

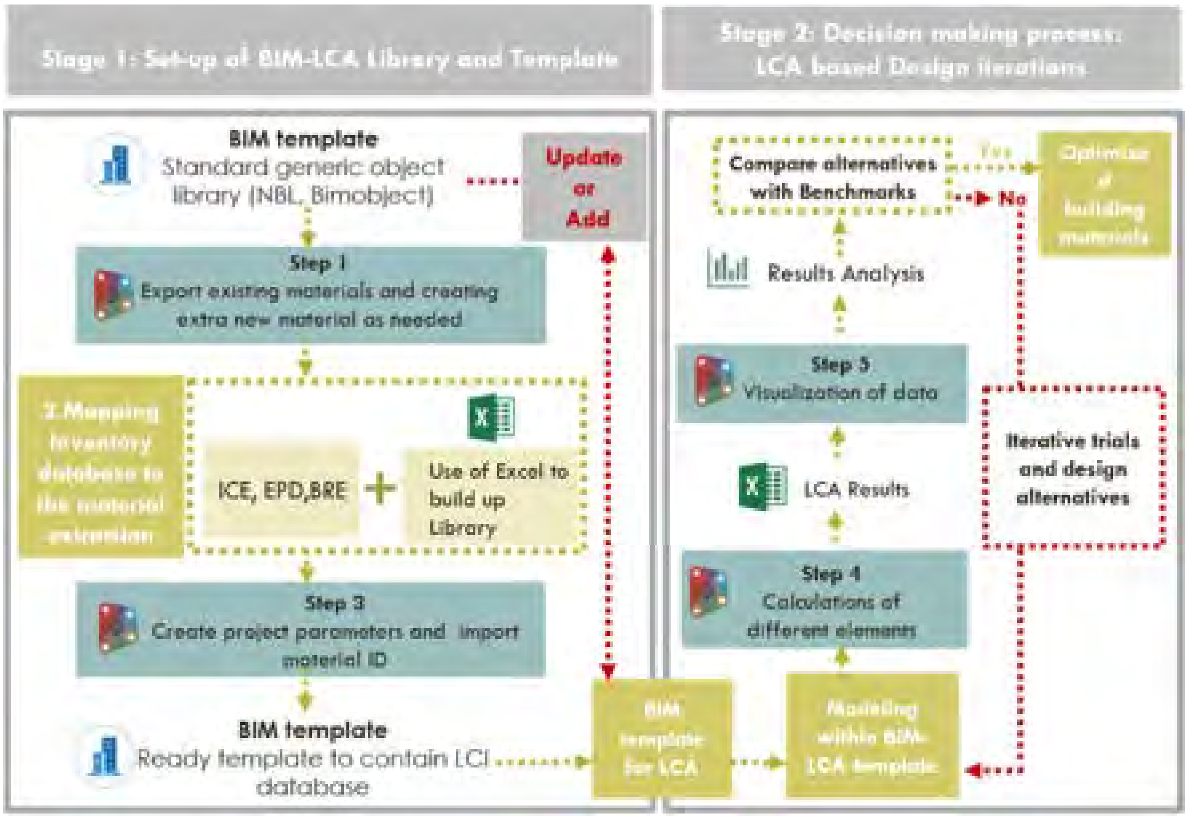

Figure 1 The proposed model framework (Ayman Mohamed et al., 2023)

The next section will explain the design of the usability study that was performed on this model. This test conducts a validation to determine its ease of use and acceptability of the model.

4. Research Method

This paper will demonstrate the participatory phase used to validate the proposed dynamo-LCA model. The framework and model are tested and analyzed from the user's perspective through usability testing. The next section will describe the methods and procedures used to design the evaluation, including workshops, questionnaires, and interviews in the participatory phase.

In order to design participatory phase , usability testing is used. To construct the usability test questions need to be answered to attain the output of structured, reliable and informative results through a rigorous process. The steps adopted in this study were guided by a similar study designed by (Cemesova, 2013) to evaluate a tool developed in the same field. Figure 2 illustrates the main steps of designing a usability test. This section contains a description and justification of the choices made in each step.

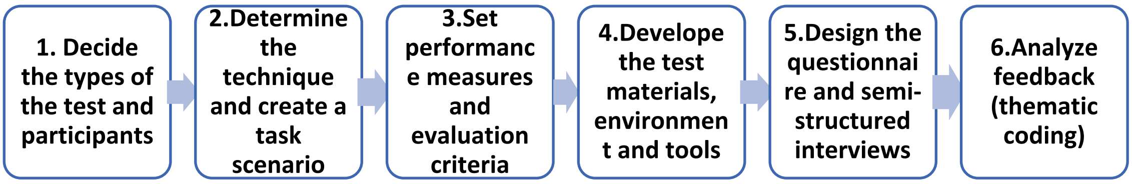

Figure 2 steps of designing and presenting a usability study.

Participant selection for this study involved recruiting 15 participants with experience in BIM software and knowledge of carbon LCA calculation in architecture projects. The selection criteria included different categories of BIM users (specifically Revit), such as innovators, early adopters, and conservatives. Non-users were excluded from the study.

The researcher used various data collection methods, including, online workshops, feedback questionnaires, and semi-structured interviews. Due to the pandemic, the workshops were conducted online. The questionnaire was completed anonymously on Google Forms, and data analysis was also done on the same platform. Triangulation of data was achieved by using mixed data gathering techniques.

Performance measures for the study were overall efficiency, effectiveness, and satisfaction. These measures were chosen because they were more suitable for the aim of the study compared to measures like time required to finish a task or number of errors made. The researcher defined effectiveness as the accuracy and completeness with which users achieve specified goals, efficiency as the resources expended in relation to goal achievement, and satisfaction as freedom from discomfort and positive attitudes towards product use.

The testing materials included a PowerPoint presentation, tool and scripts with video demonstrations, and a questionnaire, which can be found in Appendix 1. The testing was conducted remotely using Zoom application and Google Forms. The workshop consisted of a presentation and showcase, followed by a feedback interview. Participants were asked to provide feedback through a semi-structured interview and complete a questionnaire.

The questionnaire consisted of a mix of open-ended and scaled questions, as shown in Appendix 1. Quantitative analysis was done for the scaled questions, while qualitative analysis was done for the open-ended questions, user comments, and interviews. The questionnaire covered aspects such as BIM adoption status, LCA existing problems, system-related aspects, process-related aspects, and user satisfaction. A Qualitative evaluation is also included in the feedback from semi structured interviews that were conducted after each online workshop with the participants.

The next section of the study will present the analysis of the usability study, focusing on feedback related to system-related aspects, process-related aspects, and skills and satisfaction-related aspects.

5. Analysis and discussion

The usability test results will be discussed and analysed in this section. Findings from the analysis and reporting of the data collected from questionnaires, comments made in workshops and interviews will be presented together divided on the themes stated before.

Before presenting the core of the analysis, the first section of the questionnaire collected demographic information and aimed to identify the challenges and problems of repeating embodied carbon evaluations. The responses showed a variety of participants with different levels of experience. Most participants had 5-10 years of experience with implementing BIM and using BIM software. The inclusion of highly experienced participants added credibility to the study and their insights will be discussed using the group numbers assigned in Table 1.

Table 1 Participants profile

Participant group	Experience	Years utilising BIM	Number of participants
Group 1	1-5 years	1 -5 years	4
Group 2	6-10 years	5-10 years	5
Group 3	11-15 years	5-10 years	2
Group 4	16-20 years	More than 10 years	1
Group 5	24	ears	1

5.1 System related aspects

In the second part the participants were asked to rate how much they agreed that the system successfully supported each aspect, then further elaboration on the importance of the aspect and their opinions on the model/system features was discussed in the interviews and through comments in the workshop. These aspects were testing the ability of the system to:

1. Link the geometrical data and project quantities to the embodied carbon database.
2. Provide a procedure for mixing product database and create company library that can be reused.
3. Be able to track the source of the used material inventory data.
4. Minimise data input which is simple and intuitive.
5. Provide enough material library to overcome shortage.
6. Provide simple and visual output, which is easy to interpret and clear.

The results of the questionnaire and interviews showed that participants found the framework for linking geometrical data and model quantities to the embodied carbon database to be highly successful and efficient. Participants mentioned the benefits of flexibility, reduced labour, and decreased error through this framework.

For the second aspect, while participants expressed satisfaction with the concept of building a reusable library, they also highlighted the challenges and difficulties they faced in implementing it. Participants suggested starting with a template library and including a BIM manager for monitoring and maintenance. They also recommended providing resources and step-by-step guidance for this process. Regarding the feedback on the importance of the third feature, participants recognized the importance of tracking the source of material inventory and adding parameters for it in the BIM model. This feature was found to be effective and efficient in keeping records of the inventory source, facilitating reporting and verification processes.

The responses related to the input indicated that the proposed framework saves time and effort by minimizing input data. However, participants expressed the need for a component generic database to support early stages of design. The lack of such a database in the UK was seen as a limitation. The feedback on the material library showed that the framework provided a procedure and suggested resources to overcome the shortage of one source inventory database. Participants emphasized the importance of having control over adding materials to the system and recommended providing clear guidance and template files for easy adoption. Education and technical knowledge were identified as important factors for utilizing external and multiple resources.

Last was the feedback on the output which indicated that it was found to be simple, clear, and easy to interpret by most of the participants. Participants valued its support for design decisions and the link between the output and model elements stored in the BIM environment. The tool was recommended to be more visual, and participants suggested the development of a supporting database that includes all stages of the system boundary for future enhancement.

To conclude, evaluation of the system aspects revealed both the great potential of the system's integrated features, and deficiencies and problematic areas such as lack of generic database for UK, the building of a material library, and having flexible and easy to use system. Interestingly, a difference in interests has been highlighted between the different groups of participants. The younger participants with less experience were more concerned with details in the system and process that affected their day-to-day tasks, such as how the system affects their work efficiency and might ease their tasks. They also showed willingness to learn new skills if needed to maintain and expand the system. More highly experienced participants looked at how well the tool features might fit and adapt into their process, and were more concerned with management, consistency and value added as a result of using the tool. Overall, analysis confirmed the effectiveness and the efficiency of the tool in comparison with current available tools, despite the limitations in database and system bound.

5.2 Process related aspects

Following the same procedures in discussion as section 2.1, which provided insights related to the evaluation and user perspectives on the system features, this section focuses on process-related aspects. The themes used in analysis were initially informed by the literature review, with additional themes being generated through the process of qualitative data analysis. The aspects discussed in this area are ones affects in the process which discussed the model:

1. Provides a quickly and easily way to create and test alternatives which encourage design iterations.
2. Is adaptable to / in tune with design stages.
3. Is flexible and can accommodate additional indicators with the same concept.
4. Is suitable to different level of development models.
5. Provides the material library is reusable and buildable through projects.

The results indicated that participants agreed the framework process was easy to use and saved time. They also believed it allowed for dynamic assessment with changes in design iterations. Participants agreed that the framework successfully reduced manual mapping and repetitive tasks. This contributed to a reduction in errors during the process, validating the objective of the framework. However, some participants expressed concerns about difficulties with Dynamo and the stability of the tool as they highlighted the problem of dealing with the new versions of Dynamo and its effect on the model.

The feedback on the adaptability with design stages, participants agreed that the model was adaptable to different design stages and decisions. However, they mentioned drawbacks such as the inability to filter elements based on the project phase and the difficulty of modifying Dynamo scripts accordingly. This feedback emphasized the value of the tool's flexibility but highlighted that phase filters and element inclusion options are crucial for support of the assessment process throughout the design phases. In addition, the interviews showed that participants believed the model could accommodate other indicators as it was mentioned by multiple participants. However, the interviews revealed resistance to learning additional Dynamo skills among companies. It was suggested that younger architects may be more open to learning new technologies and that a hybrid approach of top-down adoption and bottom-up innovation may drive change in construction innovation processes.

In terms of the material library's buildability and reusability, participants acknowledged that the framework was an important asset throughout the design phase. They mentioned the ability to add materials at any stage and the depreciation of time and effort over multiple projects. However, maintaining the consistency and reliability of the library was seen as a necessity. The level of development of the model and its interference with calculations was also discussed. Participants agreed that the framework and details such as the correction factor and ontology of the material library added value to the feedback process, and it is considered novel contribution in dealing with model level of development. However, they highlighted the importance to consider the accuracy of results and validate them with integrating other tools.

Overall, the analysis of process-related aspects confirmed the potential benefit that the framework and tool provide to change the process of interaction between design development and EC performance assessment. The tool was found to enhance communication of sustainability aspects with clients and could potentially change the degree of contribution from clients in building performance decision making. Additionally, the tool could educate architects about the impact of material selection on embodied carbon. Overall, users found the tool to be a flexible and educational resource for evaluating embodied carbon in buildings and products.

However, it was also noted by more experienced participants that external factors relating to changing policies and more strict requirements for EC would also be likely to encourage architecture firms to adopt more tools like the proposed one, to be able to change their assessment process and make it more efficient.

5.3.Skills and satisfaction related aspects

The study focused on evaluating user skills and overall satisfaction through questionnaires, workshops, and interviews. Due to the difficulty of discussing skills directly, the analysis relied on questionnaire data, supplemented by insights from workshops and interview responses. The questionnaire provided participants with the freedom to express their views on overall satisfaction, which was challenging to address through interviews. The responses demonstrated user satisfaction with the system, supported by positive feedback comments emphasizing its intuitive nature and helpful visual representation, particularly within a Building Information Modelling (BIM) environment.

An exploration of the results revealed several insights. Positive correlations emerged between participants' perception of the system's simplicity and ease of use, as well as the perception of low demand for technical expertise. Additionally, high reliability and contentment with the system's integration into its functions were confirmed. Surprisingly, despite the favourable feedback on usability and reliability, only 55% of participants expressed an intention to frequently use the system. This observation suggested that the decision to adopt and utilize the tool might be influenced not only by satisfaction but also by the necessity driven by external factors, as indicated by a participant's comment regarding potential policy changes. Notably, certain questions yielded responses indicating participants had no strong opinion, suggesting the need for further testing, particularly concerning the system's ease of learnability and memorability.

Due to the impact of the COVID-19 pandemic, the workshops were conducted online, leading to limitations in the evaluation process. Moreover, time constraints prevented the full application of the tool across all phases of a real project, presenting another limitation. Consequently, the study acknowledged that the evaluation partially fell short in exploring the relationship between skill aspects and system learnability. The researcher recommended future testing to delve deeper into these aspects and provided an overview of skills-related aspects that warrant further investigation.

5.4 Summary of reported problems and recommendations for future improvements

The last two questions in the interviews explored the participants' perspective regarding general problems and recommendations to enhance the framework and tool. The purpose of these final two questions was to allow participants to add any additional opinions or ideas that had not already been covered. The final part of the analysis section will analyse and present these findings, which act as recommendations for future work.

5.4.1. Problems and limitations

Participants were asked if they encountered any issues with the framework and tool. The responses specifically mentioned technical problems, educational challenges, and management challenges. The technical issues raised were dealing with upgraded versions of Revit and Dynamo, lack of a guided interface, and the potential for errors without an expert to assist. One participant emphasized the educational challenge by stating, "The main challenge I see is educating our studio about EC as a calculation itself. It's fairly new to most people, and I don't think most architects have experience with it until this year." Another participant added, "It's important to keep the team informed about this process. There's an educational aspect that needs monitoring." These comments revealed both education and management challenges associated with using the tool. The results offered valuable insights and provided a comprehensive understanding of the problems and limitations in utilizing the tool. The main themes that emerged were technical issues, management concerns, skills and culture, limitations in the existing database, and education and resources, details are illustration in figure 3.

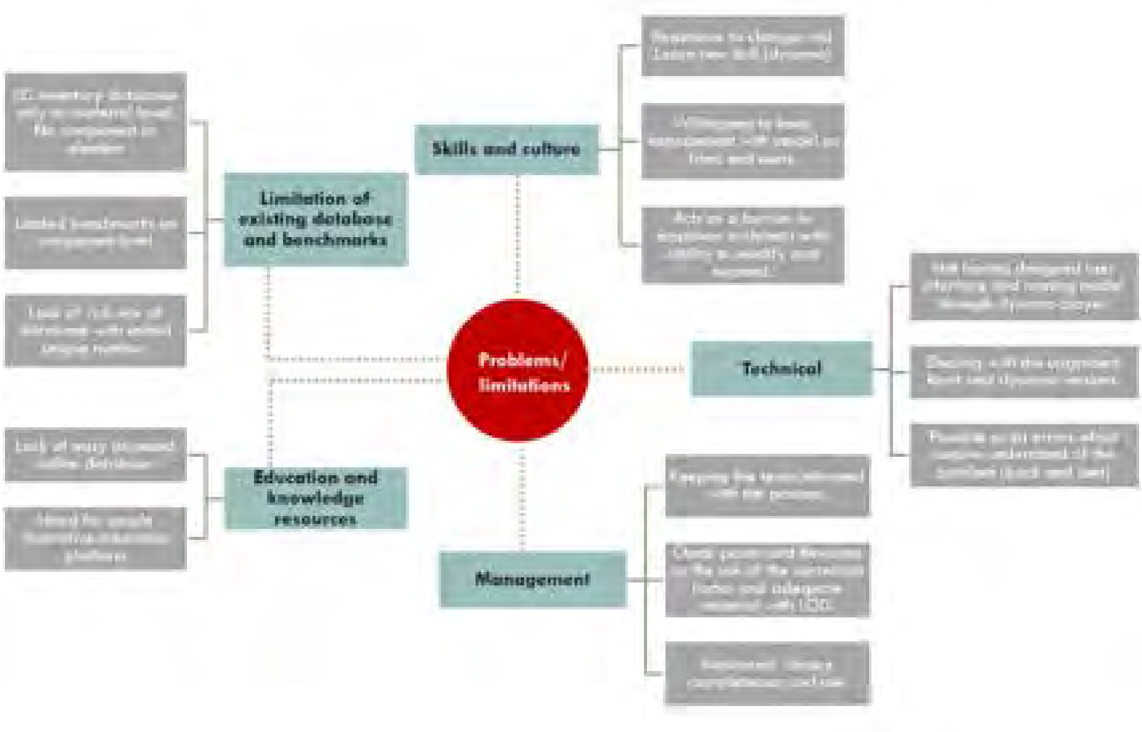

Figure 4 The problems and limitations themes feedback

5.4.2. Recommendations and potential recommendations

The interview included suggestions for improving the tool's usability. The first group of suggestions focused on adding functional features, such as capturing element phases and including more indicators within EC. Participants emphasized the importance of considering the whole carbon life cycle assessment rather than just EC. The second category of suggestions centred around designing a user interface that guides users through the assessment steps and allows them to include and exclude elements from the calculation. Participants also suggested filtering and sorting families in the BIM environment according to EC values and providing a material search window and recommendation feature.

The third category of suggestions involved adding visual features, such as color-coded feedback indicators and presenting results more visually on the model. Participants also wanted the output to be presented according to RICS categories and visual indicators to check model completeness. The final group of suggestions focused on creating an easily accessed online platform for guidance and resources, including educational materials and a combined material database linked to the BIM model. Detailed Thematic illustration of the recommendations is presented in Figure 4.

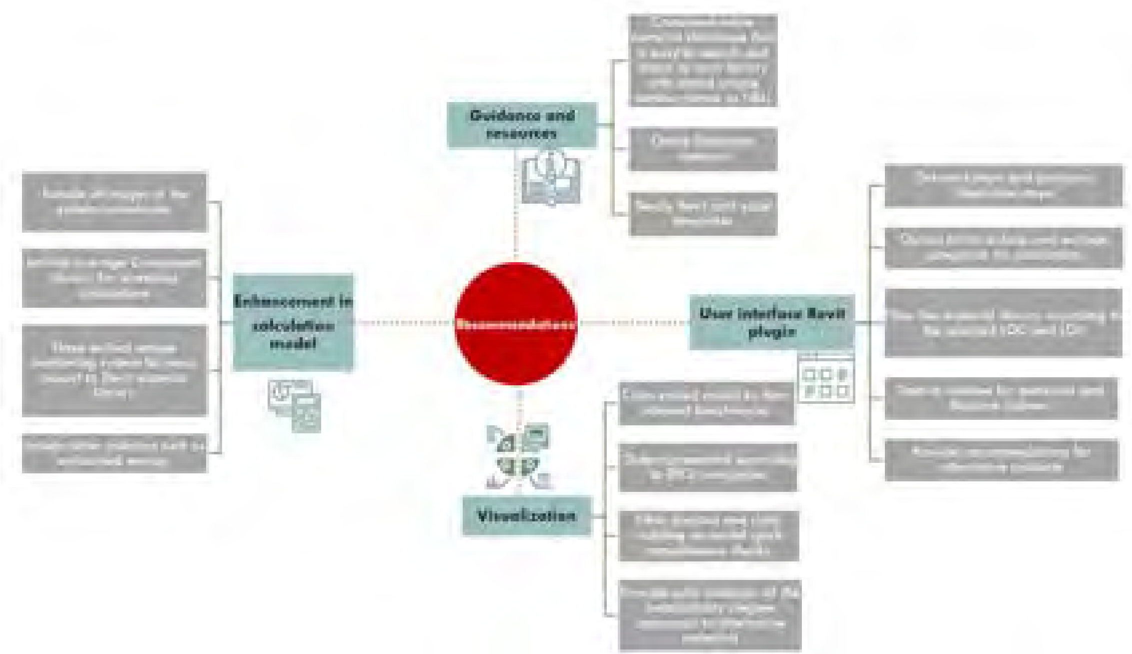

Figure 4 Summary of Recommendations

6. Conclusion

This paper introduces the Dynamic LCA assessment framework and its application through a usability test. The framework's potential impact on workflows and potential modifications were evaluated by users of varying experience levels using Dynamo scripts. The usability test utilized a user questionnaire and interviews aligned with research objectives. The study rigorously outlines sample size, participant types, and evaluation criteria, detailing the design process for the workshop, questionnaire, and interviews.

The analysis of participant feedback, encompassing questionnaire responses and interview content, was conducted using thematic analysis. System-related and process-related aspects, as well as overall satisfaction and skills, were examined. This discussion, along with the content analysis validate the proposed framework. The paper's conclusions draw on established performance criteria:

Effectiveness: The study effectively tackled issues in traditional EC assessment methods, the new framework and tool showed demonstrates significant potential in aiding iterative performance-driven design and impacting decision-making processes.

Efficiency: Although some reservations were expressed regarding the initial effort needed to develop the system, the suggested framework and tool shown proficiency in reducing time and effort. It was confirmed that using Dynamo to automate operations can reduce manual work and reduce the potential of human error.

Satisfaction: Overall feedback on the proposed tool was positive, with participants appreciating the added value. They found the tool's features well-integrated and useful for informing design decisions. However, concerns were raised about skill-related aspects. Further testing is needed to evaluate the learnability and memorability of the system, as the results did not reveal a clear trend. Participants emphasized the importance of testing the tool on a practical project to assess satisfaction.

The paper's recommendations for improvement focus on enhancing user interface design, the Revit plugin, and visualization to increase user appeal. The study emphasizes the potential of the Dynamic LCA framework, highlighting its positive impact on design and decision-making processes. It identifies gains in efficiency and user satisfaction while recognizing the importance of refining the framework based on user feedback and additional testing. Ultimately, this iterative process aims to achieve sustainable building design that promotes wellbeing on the long term through facilitating low carbon buildings design. Future work could include more hands on testing of the tools and running it though live projects which can be considered for future projects.

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Appendix 1- Usability Questionnaire

Usability of a dynamic BIM-LCA framework for Embodied carbon Evaluation

User Consent

Purpose
The Informed Consent Form is designed to confirm that the participant has been given all relevant
information about the research and their role within it, and how both the researcher and participant are
protected. Please read the following statements fully and carefully. By proceeding to take the
questionnaire, you are giving your consent.

Summary
I volunteer to take part in this PhD research questionnaire. I understand that the research aims to collect
data on user Evaluation of a dynamic BIM for LCA framework and model. The data collected in this questionnaire will be used in a PhD thesis and help expand the knowledge base for dynamic BIM for LCA software in AEC sector.

1. I confirm that I have been given a copy, and read, the Participant Information Sheet and fully
understood the information it contained.
2. I understand that my participation in this project is voluntary. I will not be paid for my involvement. I am
free to withdraw from the project at any time, without reason.
3. I have read and understood that all data provided will be treated in strict confidence, and that my name
and organisation will be anonymised. I understand that my data will be kept, securely, for a period of 5
years after the interview, in accordance with the Data Protection Act 1998. .
4. I understand that this research has been approved by Northumbria University Ethics Committee.
5. I have read and understood the explanation of the research project provided to me. I have had the
opportunity to ask any questions and they have been answered to my satisfaction.
By proceeding to take this questionnaire, I agree to take part in this research project and to the above
statements. Any statements I have concern with I will discuss with the principle researcher prior to
commencing.

This questionnaire is part of Phd research in Northumbria University

Northumbria University NEWCASTLE

Section 1- General User Information

This is a general section which will collect information about the user previous experience

1. How many years of experience do you have in practice?

Mark only one oval.

- ◯ 0-5 years
- ◯ 6-10 years
- ◯ 11-15 years
- ◯ 16-20 years
- ◯ Other: ____________

2. How many years have you been using BIM in your projects?

Mark only one oval.

- ◯ Less than 1 year
- ◯ At least 1 year but less than 5 years
- ◯ At least 5 years but less than 10 years
- ◯ 10 years or more
- ◯ Other: ____________

3. How many years have been using Revit or similar software?

Mark only one oval.

- Never used
- less than one year
- At least 1 year but less than 5 years
- At least 5 years but less than 10 years
- 10 years or more
- Other: ____________________

4. Did you use dynamo or dynamo player before?

Mark only one oval.

- Yes
- No

5. Have you been involved in project that involved assessment of Embodied Yes carbon?

Mark only one oval.

- Yes
- No

6. If yes what are the tools and material database used?

7. If Yes, At what stage did the Embodied carbon have been assessed? You can use more than one answer

Mark only one oval.

- Early Conceptual design stage
- Design Development stage
- Technical development stage
- Construction stage
- Post construction stage
- Other: ______________________

8. If yes, Approximately how many times the assessment was repeated?

____

9. What problems/challenges did you find in Embodied Carbon evaluation to be repeated to inform design decision? You can use more than one answer

Check all that apply.

- [ ] Time consumption
- [ ] Complex and Require expert
- [ ] Material database and library shortage
- [ ] Not reliable results
- [ ] Manual Mapping is prone to errors
- [ ] Results are not informative to design development
- [ ] All of the above
- [ ] Non of the above

Other: [ ] ______________________

Section 2- Overall Model Satisfaction

In this section user is evaluating the satisfation of the framework features.

Rate your experience and satisafation to use the system , by selecting how much do you agree with the statment.

1-Strongly disagree - to 5- strongly agree

10. 1. I think that I would like to use this system frequently.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly disagree

11. 2- I found the system unnecessarily complex.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

12. 3- I thought the system was easy to use.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

13. 4- I think I would need the support of technical person to be able to use this system.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

14. 5. I found the various functions in this system were well integrated.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	⬭	⬭	⬭	⬭	⬭	Strongly agree

15. 6. I thought there was too much inconsistency in this system.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	⬭	⬭	⬭	⬭	⬭	Strongly agree

16. 7. I would imagine that most people would learn to use this system very quickly.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	⬭	⬭	⬭	⬭	⬭	Strongly agree

17. 8. I found the system very complex to use.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	⬭	⬭	⬭	⬭	⬭	Strongly agree

18. 9. I felt very confident using the system.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

19. 10. I need to learn a lot before I could get going with this system

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

Section 3- Evaluation of Model Features

Using scale 1-not satisfied at all 5-fully satisfied evaluate the features of the tool, Also mention select is it important feature or not.

20. 1. Link the geometrical data and project quantities to the embodied carbon database

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

21. 2. Provide an ontology for mixing product database and create company library that can be reused

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

22. 3. Being able to track the source of the used material inventory data

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

23. 4. Minimize data input which is simple and intuitive

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

24. 5. Provide enough material library to overcome shortage

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

25. 6. The Output is Simple and visual, easy to interpret, and clear

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

26. **7. The output provides supportive information for design decisions suitable for early stage of design and design development**

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

27. **8. The output provides well segregated results on elemental and material level**

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

28. **9. The output can be compared to benchmarks**

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

Appendix 2- Post workshop usability interviews

Semi structured interviews:

- Do you agree that this tool provide a dynamic ability is efficient enough to save the user time and reduce error of manual material mapping?
- Do you agree that this tool provide a dynamic ability is efficient enough to save the user time and reduce error of manual material mapping?
- To what extend do you agree that the framework could instantly calculate the embodied carbon with the BIM model and would be effective in enhancing the design process?
- Could you predict a framework and tool such as dynamo for LCA being adopted in your practice? Why?
- Do you have any problem with the framework and use of tools?
- Do you have any suggestions for improvements?

Enhancing thermal performance: self-shading steel facades to reduce heat gain in hot to warm climates

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Abstract: Energy consumption for heating and cooling the space is affected by the building envelope design and detail including the roof, windows, walls, and other components. A potential optimization strategy for reducing energy demand is through self-shading. This paper focuses on the implementation of self-shading at the building components level and the impact of reducing heat gain in the facade. The pattern and shape of self-shading strategies to decrease the amount of heat absorbed by building envelopes will be investigated through a simulation and physical setup. To validate the simulation result, a test box is developed to isolate the self-shading façade from unwanted heat gain. Data loggers are used to gather the temperature data. The results from the simulation were initially analysed to make a comparison between profiles. The results show that the self-shading provides a reduction in both external surface and indoor temperatures, which is affected by the tilting angle and shape of the folded steel façade cladding. Additionally, the percentage of the sunlit area serves as a reliable predictor of external surface temperatures. However, this study also identifies limitations in the current simulation method, emphasizing the need for a validation process in self-shading studies.

Keywords: Energy consumption; façade component; self- shading; solar radiation

1. Introduction

The building envelope, which includes walls, roof, floor, and fenestrations, comprises components through which energy may transfer in or out of the system via heat transfer (McQuiston, 2005). One passive strategy to effectively reduce heat gain is through the implementation of self-shading techniques. Self-shading involves leveraging the building's form to provide partial protection against solar radiation, blocking direct sun rays while allowing for diffuse radiation (Capeluto, 2003; Kandar *et al.*, 2016). By incorporating self-shading, buildings can achieve annual energy savings, particularly in cooling loads (Mohsenzadeh *et al.*, 2021). However, the majority of studies primarily examine different overall building forms as means to self-shade, leaving a gap in the implementation of self-shading in façade components which may offer a more feasible and practical approach to the building façade design.

This study focuses on the implementation of self-shading through the design of the building facade components by exploring different morphologies and performance indicators in self-shading, namely

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surface temperature (Fleckenstein *et al.*, 2022) energy consumption (Alhuwayil *et al.*, 2019), and indoor air temperature (Lavafpour *et al.*, 2020). As the preliminary study, this paper explores the effect of steel façade cladding form on the heat gain of the façade through simulation and physical setup.

2. Research to date on self-shading facades

A larger portion of the literature studies self-shading in the form of building geometry. In the overall shape of the building, self-shading geometries are mostly shown through the inverted pyramid-shaped building, where the upper floor of the building provides shade to the lower floor (Guiping and Guangcai, 2011; Abdullahi *et al.*, 2017; Saifelnasr, 2019). A significant body of research also examines the intrusion and extrusion of building parts to form the self-shading effect. On a smaller scale, tilted walls are often used to achieve a similar effect (Kandar *et al.*, 2016; Freewan, 2022) and were used in a variety of buildings, namely in residential buildings (Lavafpour and Sharples, 2015; Lavafpour *et al.*, 2020), office buildings (Kandar *et al.*, 2016) and school buildings (Atthaillah *et al.*, 2022). By tilting building envelopes such as the wall, direct solar radiation, especially during the summer season can be reduced, resulting in a reduction of the electricity consumption in an HVAC building (Chan and Chow, 2014).

The effects of wall tilting are also shown to be effective when moderately used in the entire building envelope. In their study, Zerefos *et al.* (2012) analysed two identical buildings in terms of their location, number of openings, and materials. They found that making a minor alteration to the external envelope of both buildings, such as tilting the angle of the walls and adjusting the slope of the roof, could lead to an improvement in their energy consumption (with ± 0.7% area, ± 0.2% volume compared to the base case). Although it is limited in its conceptual design, a more complex tilted surface geometry like a crystal-shaped form is also examined for its effective self-shading effect (Adinugroho and Gadi, 2018). Another study by Jakica and Kragh (2020) explores building geometry by twisting a rectangular plane so that it affects solar irradiation.

Another distinct type of self-shading façade is that it does not involve the manipulation of building geometry. This classification is done on the basis that the particular self-shading strategy does not alter the floor and roof parameters and manipulates only the components of the envelopes. For example, a study by Bhai *et al.* (2022) explores the possibility of window wall protrusion while still maintaining the floor parameter. Aside from using glass, the self-shading effect is also examined through different materials. For instance, self-shading through the configuration of the brick walls (Molter and Chokhachian, 2020; Shahda, 2020; Fleckenstein *et al.*, 2022), shape memory alloy in the form of an origami shading (Mokhtar *et al.*, 2017) or shape memory polymer (Zupan *et al.*, 2020).

3. Methodology

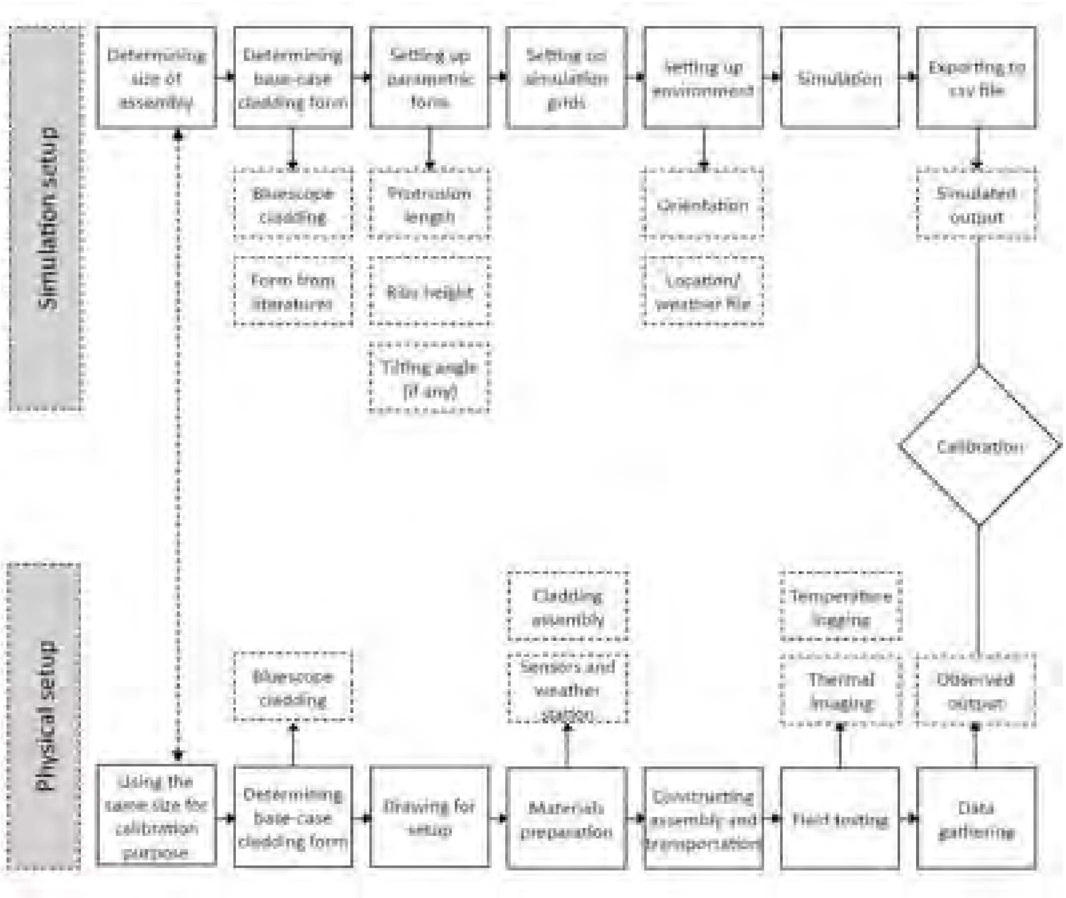

Figure 1: Simulation and physical setup process

This research focuses on the utilization of steel materials in self-shading façade assembly. In particular, the use of cold-formed steel is increasing steadily (Chen *et al.*, 2021). It has been extensively used in low-rise residential and commercial buildings (Roy, 2023), and offers several benefits including low maintenance costs, and increased structural and labour cost savings compared to other cladding options (Roy *et al.*, 2022). The primary objective of this research is to explore various profiles that facilitate self-shading through steel cladding. This exploration will be conducted using two distinct methods: simulation and on-site physical measurements. By combining both methods, a comprehensive analysis will be performed to evaluate the effectiveness and practicality of employing different profiles in steel cladding to achieve efficient self-shading solutions. To ensure practicality, this study adopts a small structure as a pilot study, rather than employing an entire building. The utilization of a small structure for investigating façade systems has been previously employed by Wonorahardjo *et al.* (2022) where the temperature measurement of 1 m x 1 m wall assembly was conducted using a thermocouple sensor and data logger. This approach serves to validate the results obtained from simulations and identify potential discrepancies and factors that may contribute to variations in performance indicators between the two sets of results.

Figure 1 illustrates the simulation setup process, which begins with determining an appropriate structure size based on considerations of time, cost, and ease of transportation. The cladding form parameters include protrusion length, rib height, and tilting angle. In terms of the environmental setup, particular emphasis is placed on orientations, particularly those facing west and north, to analyze their impact on self-shading efficiency. Then the simulated and observed output will go through the calibration process to ensure that models accurately depict real-world building performance (Chong *et al.*, 2021).

3.1. Simulation setup

Different simulation software was tested in this study, specifically analysing the surface temperature and indoor temperature resulting from solar radiation exposure. As one of the simulation methods, Finite Element Modelling (FEM) software, such as THERM and ANSYS, has limitations. It lacks the capability to simulate dynamic solar radiation patterns throughout the day and is not optimized for generating parametric architectural shapes. Furthermore, the accuracy of FEM also depends on the input boundary condition (Fokaides *et al.*, 2018). This factor makes Building Energy Modelling (BEM) such as IDA-ICE, IES-VE, and EnergyPlus remains the most used simulation method in the self-shading study.

Ladybug tools, commonly employed with the EnergyPlus engine, can be seamlessly integrated with the parametric tools within Grasshopper, making it easier to develop forms and conduct optimization. The utilization of Ladybug Tools and Grasshopper within the Rhinoceros software enables the division of a surface into separate grids, allowing a visual representation of individual grid surfaces. This capability proves advantageous in assessing the impact of ribs on surface temperature, as it allows for a more comprehensive analysis of the surface characteristics and temperature distribution. It can produce Surface temperature, Indoor temperature, Shading hours, and Solar Heat Gain Coefficient (SHGC). EnergyPlus model surface heat transfer in a one-dimensional manner along the temperature gradient from the interior to the exterior. Therefore, unlike FEM, EnergyPlus might not adequately account for thermal bridging (Schoplocher *et al.*, 2023).

Furthermore, in some self-shading literature such as the study by Shahda (2020), the profile/geometry that provides shading is considered solely as an adiabatic surface to block the sun, and the surface temperature as the performance metric only considers the other surfaces while the profile itself might have a contribution in the heat transfer. The potential impact of the profile's heat transfer has not been thoroughly explored in existing self-shading literature. While these simplified assumptions generally suit building energy workflows, they do raise questions about simulation accuracy. This concern gains particular significance in this research, as analyzing buildings at a component level requires a certain level of precision. Therefore, in this study, validating the simulation result with the physical measurement is crucial. Nevertheless, in the future direction of this research, coupling BEM and FEM may become imperative to add another degree of accuracy.

3.2. Physical setup

Physical setup is used to validate the results from the simulation. The self-shading façade physical setup will be monitored under real-life solar exposure conditions, mirroring the simulation inputs. The measurement period will start in the summertime in Adelaide weather conditions, utilizing the identical façade profile and orientation. If the cladding is tested without any treatment, the back side of the façade will experience a range of external influences beyond solar radiation alone. These factors encompass heat emitted by nearby HVAC systems (if any), heat reflection from the ground, and the introduction of cold air due to air movement. As a result, achieving a pure outcome solely from solar radiation may not be attainable.

Figure 2. Insulated box

Therefore, considering the influence of other elements on the back side of the façade, it is reasonable to consider the incorporation of insulation as a means of mitigation (Figure). Barbaresi *et al.* (2020) conducted an investigation into the thermal behaviour of various materials exposed to external elements by constructing a testing box. The box was constructed using a combination of Oriented Strand Board (OSB) and Expanded Polystyrene (EPS) to insulate the inner chamber. Additionally, to account for thermal bridges and considering the cost-effectiveness of their study, the placement of sensors was strategically chosen to ensure a considerable distance from the thermal bridging source, located at the corner of the test material. Several other studies using a low-cost hotbox utilize similar insulation properties with thicknesses between 100 -150mm (Zhao *et al.*, 2019; Kivioja and Vinha, 2020). Considering the study's size and materials, a new insulated box design was developed (Figure) based on the low-cost hotbox studies mentioned, incorporating several modifications as detailed below:

- The dimensions of the insulated box were slightly reduced to 850mm x 850mm x 850mm, for enhanced manoeuvrability and ease of experimentation.
- Unlike the previous design, no supplementary apparatus such as a heat source or small fan was included in this setup to distribute heat within the box.
- The study focuses exclusively on the heat generated by solar radiation.
- The updated design features thicker Expanded Polystyrene (EPS) insulation to achieve a minimum R-value of 2.8, aligning with the standard wall R-value requirements in Adelaide according to the 2022 National Construction Code (Australian Building Codes, 2022).

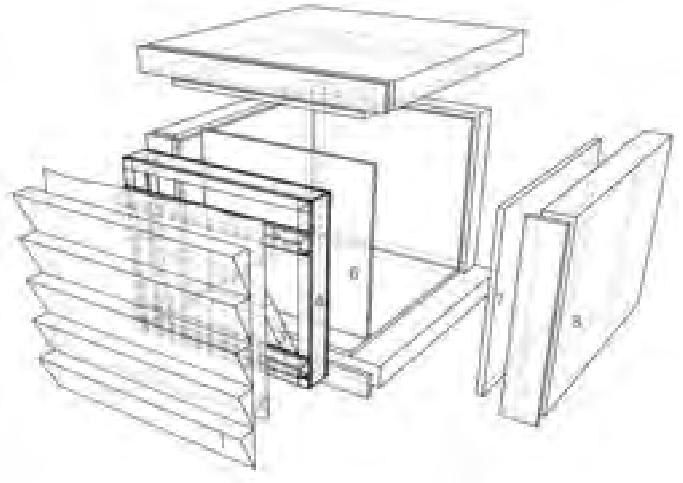

Figure 3. Structural assembly of the physical setup

The on-site measurement setup was conducted as shown in Figure, which incorporates a weather station to gather weather data such as outdoor air temperature, humidity, and horizontal and vertical solar radiation.

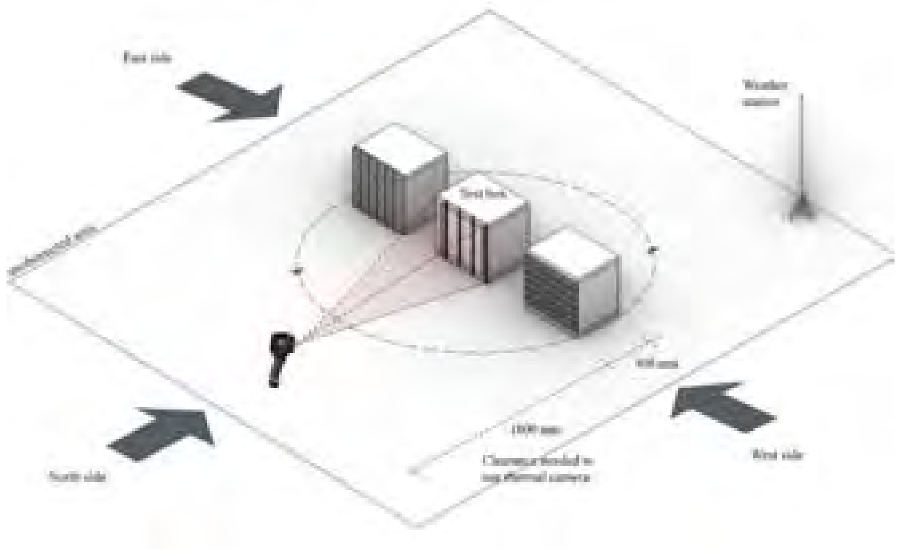

Figure 4: Field study setup

As previously shown in Figure , the physical setup is constructed to validate the results from the simulation. This is especially important since research on self-shading is often limited to simulation without considering validation, which can affect the reliability of the results. Therefore, for this study, which focuses on smaller building components, a physical setup is necessary to effectively differentiate and analyze the specific effects of the components' shape used in the façade assembly. The temperature sensor placement on the physical setup is done by aligning it with the simulation grid to enable a direct comparison between temperature readings from the simulation and those in the physical setup (Figure). The sensors utilise HOBO data logger with temperature probes, and a thermal camera is used to compare the temperature reading.

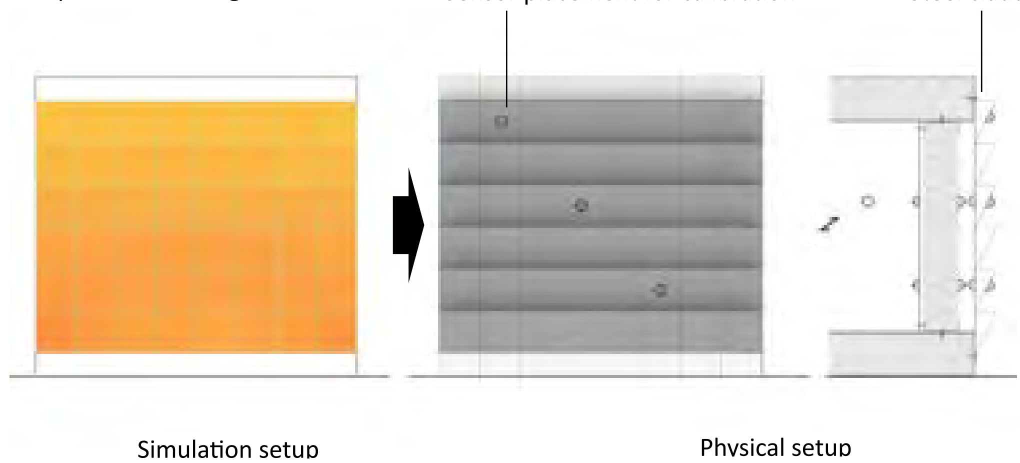

Figure 5. The sensor placement in the physical setup aligns with the grid in the computer simulation.

4. Results

The central investigation topic of this work is the applicability of self-shading in blocking direct solar radiation through facade components, reducing the facade heat gain and subsequently reducing energy consumption. Various geometries, encompassing the base case model and self-shading models from prior research, are parameterized for in-depth analysis to determine their suitability for the intended purpose. The study also explores the application of tilting angles in facade components. Existing literature (Capeluto, 2003; Kandar *et al.*, 2019; Lavafpour *et al.*, 2020; Freewan, 2022) states that when applied to the overall building form, self-shading can lead to up to a 20% reduction in annual energy consumption. Therefore, this study applies and tests the concept of tilting angles at the facade component level. For example, different tilting angles (20°, 25°, and 30°) in a horizontal direction were tested using the same rib height (100 mm) as shown in Figure . For this analysis, the performance metrics that are used include exterior surface temperature and the cavity temperature behind the steel cladding (referred to as indoor air temperature for this analysis).

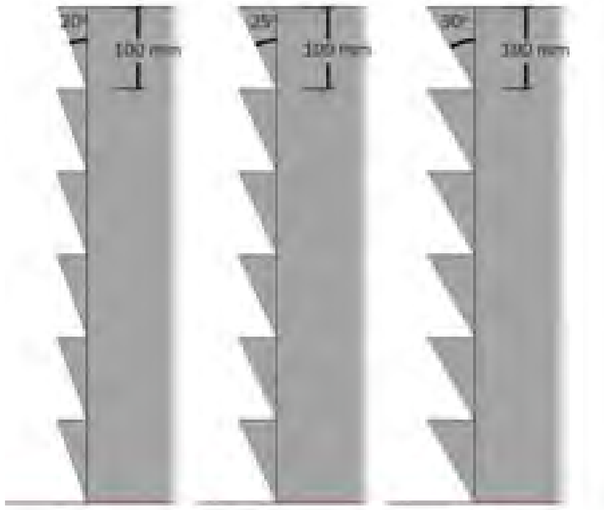

Figure 6: Tilting angles in the simulation study

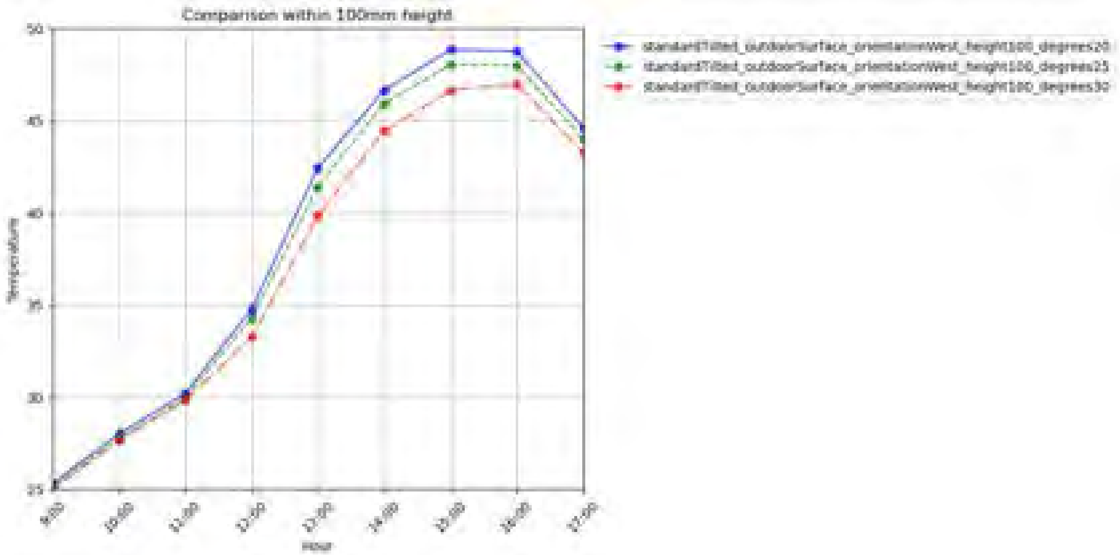

Figure 7: Comparison between different tilting degrees (20°, 25°, and 30°)

As shown in Figure , the application of a larger tilting angle to facade components in the west orientation effectively reduces the outdoor surface temperature of a steel cladding material (with a solar absorption value of 0.35). Notably, the self-shading effect becomes more pronounced after noon during the simulation period on December 22 (summer solstice), aligning with the onset of direct solar radiation onto the west facade. This, in turn, leads to a noticeable decrease in indoor air temperature at the larger tilting angle (Figure).

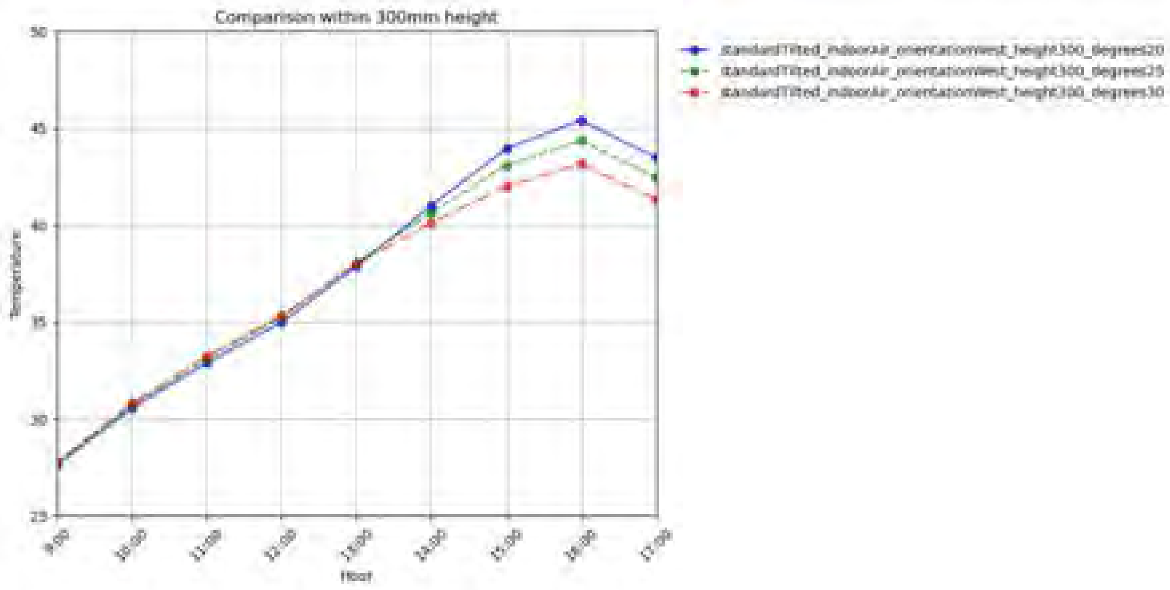

Figure 8: Comparison of indoor air temperature using different tilting angles (20º, 25º, and 30º)

However, when the 30º tilting angle was tested and compared to different ribs' heights, the results showed that larger ribs' height provides more temperature reduction after noon when the sun reaches the west façade, but inadvertently results in greater solar radiation exposure before the peak hour (Figure).

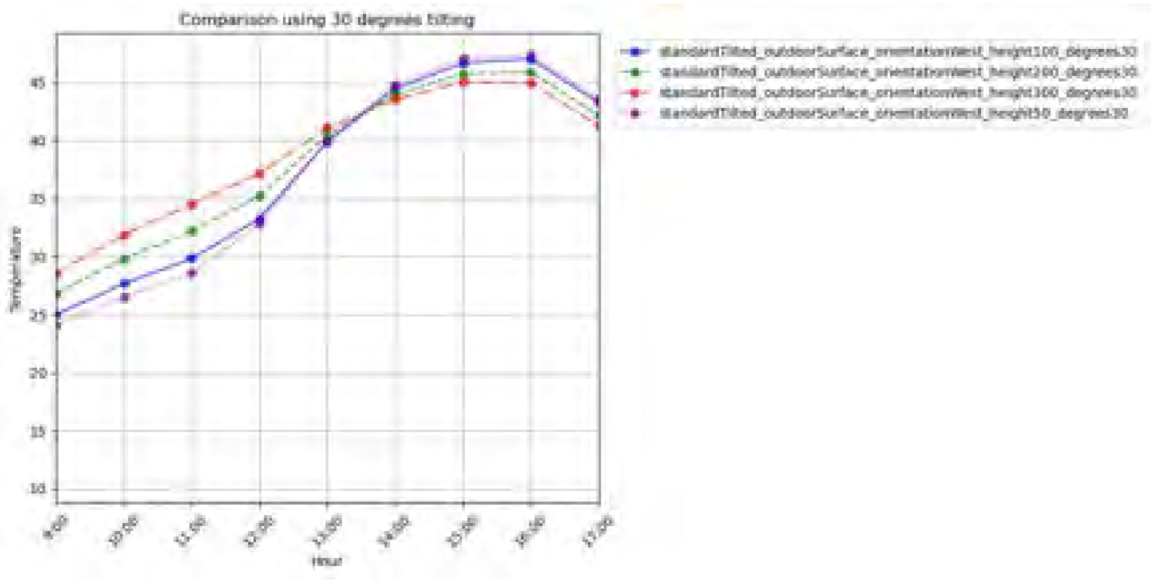

Figure 9: Comparison of outdoor surface temperature using different ribs height (50 mm, 100 mm, 200 mm, and 300 mm)

While maintaining a consistent tilting angle should theoretically yield the same sunlit area irrespective of rib height, this observation suggests the potential influence of other contributing factors. For instance, if the model exposes the topmost surfaces, that specific cladding might receive solar radiation throughout the entire day (

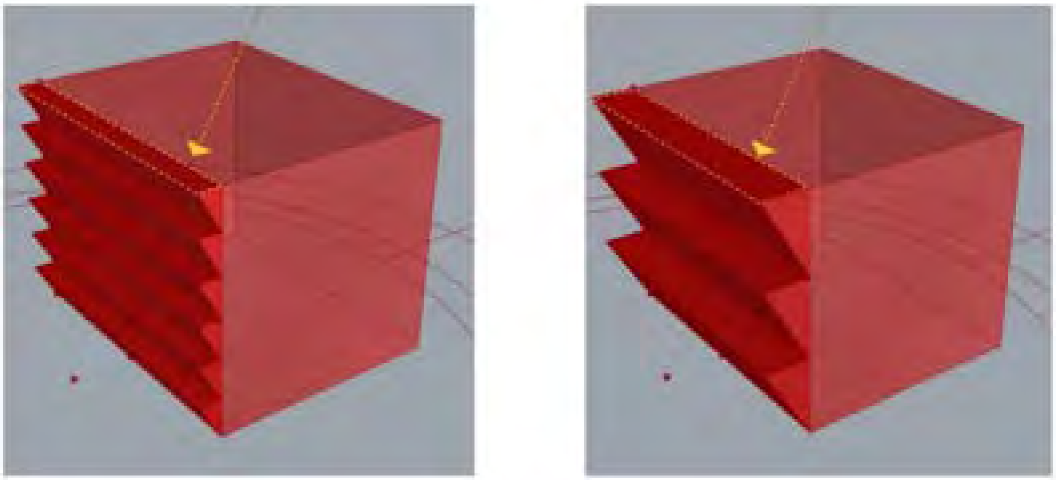

Figure). Another finding from the simulation process is that Ladybug tools fail to calculate a small surface area below 0.01 sqm in a façade component, excluding that specific area from the overall heat transfer calculations. Therefore, further treatment should be done before making a direct comparison, for example, as seen in

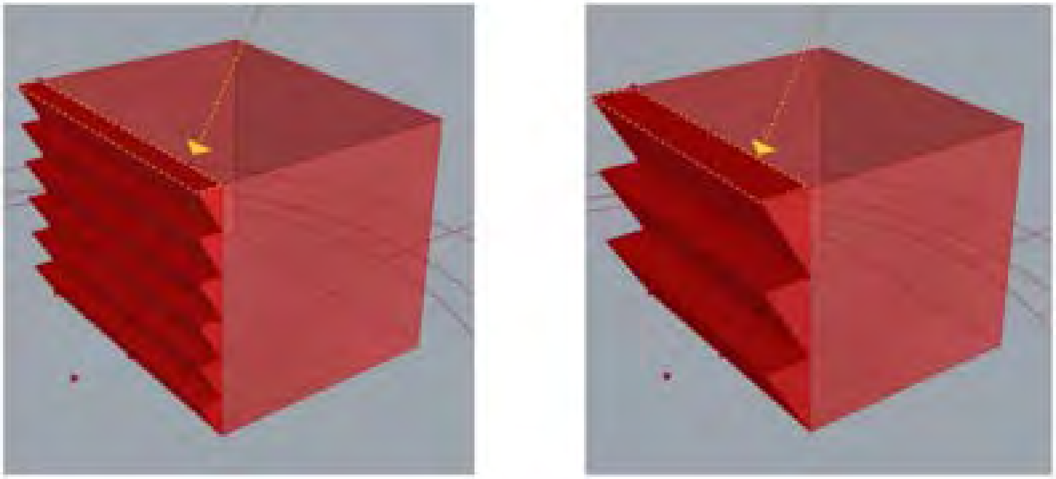

Figure , when a comparison was made, both yellow triangular area was omitted from the calculation.

Morning radiation Morning radiation

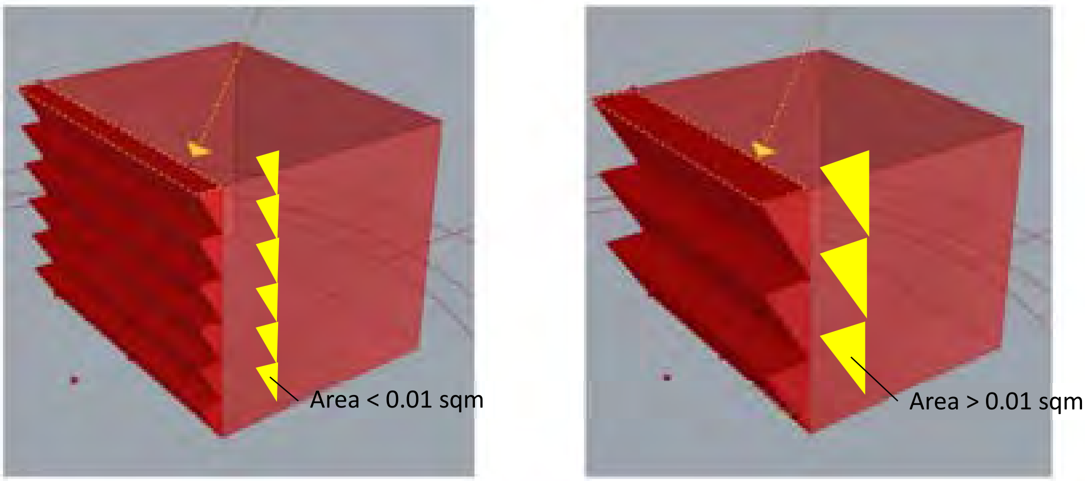

Figure 10: Comparison of the topmost area receiving direct solar radiation in the morning, between 100 mm ribs height (left) and 200 mm ribs height (right)

Further studies were conducted using different case study profiles to investigate the correlation between the sunlit area (the region directly exposed to solar radiation) and surface temperature during the week of December 22 to December 28. By excluding data with 0%-2% sunlit area (nighttime and early morning periods), Pearson correlation analysis revealed a statistically significant relationship between outdoor surface temperature and the percentage of the sunlit area ($r = 0.78$, $p < 0.01$).

Linear regression was also conducted to analyse the relationship between the independent variables-sunlit area percentage and outdoor air temperature to the surface temperature being observed. Several assumptions were also tested to confirm its validity, including normality, homoscedasticity, linearity and absence of multicollinearity by looking at the Variance Inflation Factor (VIF). The model that has the highest explainable variance is the model that used the combination of sunlit area percentage and the outdoor air temperature ($R^2adj = 0.486$), followed by the model that uses only the outdoor air temperature ($R^2adj = 0.339$).

The models that are proposed to be used based on this finding are:

Tout = 10.78 + Tair (1)

Tout = 6.765 + 0.9 Tair + 0.1 SunArea (2)

Where:

Tout= Outdoor surface temperature; Tair= Outdoor air temperature; SunArea = Sunlit area percentage

This result indicates that sunlit area percentage can be a good predictor of surface temperatures for the self-shading steel façade being tested.

6. Limitation

While this study investigates the potential of self-shading to reduce heat gain through the façade, it has certain limitations. At this stage, the simulation results have not been validated since the testing in Adelaide's summertime has not yet occurred. Therefore, the estimates in the self-shading model are based solely on the BEM. Furthermore, this research is limited to assessing the impact of self-shading component shapes on specific performance metrics, such as outdoor surface temperature, indoor surface temperature, and indoor temperature. As a result, factors like convection heat loss and cavity airflow remain untested in this preliminary stage of research.

7. Conclusion

This paper highlights the advantages of self-shading, a passive design approach that effectively reduces solar radiation exposure by partially blocking it from reaching the facade surface. Although recent years have shown an increased interest in exploring the potential of self-shading used in façade building components (as opposed to the overall building form), there remains a lack of studies on steel cladding. This research project involves the utilization of simulation tools and experiments to investigate the impacts of self-shading techniques towards the facade heat gain and to explore their applicability through the fabrication and testing of prototypes.

Initial simulations suggest that the concept of tilting angles, as explored in existing literature, holds promise for application to facade components. Incorporating larger tilting angles results in decreased average surface temperatures, accomplished by configuring shapes that shield against direct solar radiation. This, in turn, has the potential to lead to lowered indoor temperatures. Moreover, preliminary findings from the simulated models indicate that the percentage of the sunlit area as a result of self-shading can be used to predict the outdoor surface temperature when combined with outdoor air temperature. These early insights from the pilot study emphasize the significance of further investigation and analysis as the research progresses.

8. Acknowledgements

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Environmental impacts of digital platforms for building design: A case study exploration using scenario-based EEIO analysis

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Abstract: This study uses two building design platforms to investigate the environmental impact of an increase in the Australian construction industry's adoption of digital technologies. Environmentally Extended Input-Output (EEIO) analysis is used to trace the upstream and downstream environmental impacts of industries represented in the Australian national accounts' Input-Output Tables. Two intervention strategies are used to simulate tool adoption affecting two industry groups, i.e., an increase in the demand for Software Publishing and a decrease in Architectural, Engineering and Technical Services. Disaggregation of industry sectors was done using primary data and information from the Australian Bureau of Statistics, Labour Markets Insights, the Housing Industry Association and the National Skills Commission, among others. Iterative Proportional Fitting and Structural Path Analysis were used to rebalance the Input-Output Tables and trace the flow of environmental impacts, including proxy second-order effects. The results suggest a potential emissions reduction of 6.3 $MtCO_2$-e associated with embodied environmental impacts throughout the Australian economy under the explored scenario range. Within this range, the results show a maximum theoretical reduction of 0.0013% and 0.0026% for the case study tools. Under assumptions of wide-scale adoption and optimal efficiency gains, commercial objectives can be guided to capitalise on these results' potential magnitude and direction. The methodological limitations of this study and their implications on the results are discussed in detail, including uncertainty levels, data gaps, and ignored variables. Regardless of these issues, the study provides insights into the potential environmental benefits of transitioning to extensive digitalisation of building design services.

Keywords: Digitalisation; Scenario-based Analysis; Building; EEIO.

1. Introduction

Digital design platforms have the potential to significantly impact the environmental footprint of the building industry. Digitalisation can enhance efficiency and facilitate data-driven decisions, which can improve building performance and support the implementation of circular economy principles (Li et al., 2020). Digital design platforms refer to a set of automation tools and software that are developed to support design and construction processes. These tools aim to streamline and optimise various aspects of the construction process, from initial design and planning to project management and collaboration. By leveraging digital technologies, these tools enhance efficiency, improve communication and coordination among stakeholders, and enable real-time data analysis.

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Digital design platforms can increase efficiency by automating repetitive tasks, reducing the time and effort required for manual work. For example, they can generate 3D models and simulations, allowing architects and engineers to visualise and test designs before construction begins. This can save time and minimise the risk of errors and rework, leading to cost savings and improved project outcomes.

These platforms can also serve as the foundational infrastructure that enables the creation and deployment of product platforms for industrialised construction. This digital-enabled environment supports the development of standardised building modules or components that can be assembled in various ways to create a finished building (Gibb, 1999). Digitalisation facilitates the management of these modules and their design rules, which are critical elements of product platforms. These interfaces and design rules can guide the assembly of the building modules, ensuring that they can be combined in a variety of ways to meet different customer requirements. This iterative approach to product platform development can allow construction firms to respond more effectively to the complexities of customer requirements across multiple market segments.

While the benefits of digital design platforms have been demonstrated, their long-term impact on the construction industry is not well understood. As technology continues to evolve and integrate with emerging technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT), the majority of environmental impacts of the increased efficiency brought about by digital design platforms result from the benefits that may arise from their use, such as reduced material waste and improved energy use in buildings. However, it is important to note that digitalisation also has its own environmental footprint. Apart from the direct environmental impacts of information and communication technology (ICT) products and infrastructure, the numerous impacts on business models, lifestyles and consumption patterns also need to be considered (Gensch et al., 2023). While digitalisation can bring about positive environmental impacts, it is crucial to also consider its potential negative impacts and strive for a more sustainable implementation of digital technologies in the building industry (Horner et al., 2016).

Environmentally Extended Input-Output (EEIO) analysis is a suitable method for simulating the changes brought about by the adoption of building technology platforms. EEIO analysis is a technique that combines economic with environmental data to assess the environmental impacts of economic activities. It allows for the tracing of upstream and downstream impacts of industries, providing a comprehensive view of the environmental implications of technological changes in the construction industry (Kitzes, 2013).

We assess the potential of digital design platforms by modelling adjustments to specific sectors of the economy, assuming that increased platform adoption increases resource efficiency. In this study, we use EEIO analysis to trace the upstream and downstream environmental impacts of industries represented in the Australian national accounts input-output tables—a record of the supply and use of aggregated products and services in the Australian economy. Measuring the direct and indirect greenhouse gas (GHG) emissions intensity from platforms with EEIO presents opportunities for future research and commercial objectives.

2. Methods

We use EEIO to investigate an economic scenario in which changes to industrial activity are reflected in their GHG emissions against a baseline. EEIO is a method of evaluating the environmental impact of downstream and upstream production—in this case, GHG emissions from the Australian economy—

based on data describing activity between different industry groups, as recorded in Input-Output (I-O) tables.

2.1. Case study automation tools

2.1.1. uTecture

uTecture is a cloud-based virtual pre-construction platform that enables dynamic design presentation, documentation and workflow management. uTecture's platform business model focuses on linking individuals seeking housing with housing providers. This platform possesses the capability to visualise designs, offer personalised adjustments, create real-time cost estimates through live quantity assessments, and generate comprehensive documentation kits for both regulatory and on-site building procedures.

2.1.2. AirBuildr

AirBuildr is a cloud-based tool that enables the automation of structural design processes, including modelling, loading, building system selection, costing, project documentation, and process management. The building model can be visualised, modified and exported to other design tools. One of the key features of AirBuildr is it allows designers to iterate between different structural systems and optimise the outcomes for material and cost efficiency.

2.2. Evaluation scenarios

We evaluate two intervention strategies consisting of adjustments designed to simulate an increase in tool adoption affecting two industry groups (see Table and Figure).

Table 1. Intervention strategies used to model platform use and their corresponding adjustments to I-O values

Industry classification	Intervention strategy	Input adjustment	Output adjustment
Subdivision 54. Publishing (except internet and music publishing)	tool adoption	None	0 to 20% (to Professional, scientific and technical services)
Division M. Professional, scientific and technical services	Resource efficiency	0 to 20% (from Publishing, except internet and music publishing)	None

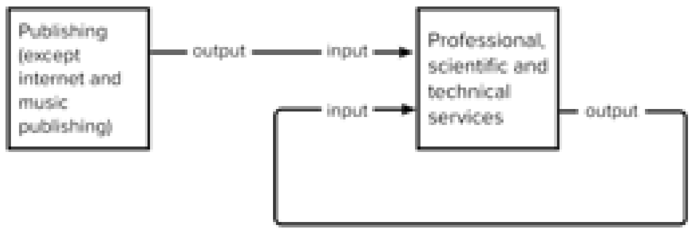

Figure 1. Adjustments used to model the effect of increased platform use and reduced operating costs

These adjustments represent relative changes in the production and consumption of goods and services, which express the financial and socio-economic factors underlying increased tool usage and the broader impact on Australian building design services. Based on monetary transactions flowing between industry groups, we can estimate the resulting GHG emissions per dollar of products and services. The result is a spectrum of possible GHG emission values associated with the intervention strategies designed to simulate Australian design automation tools.

The primary intervention is to increase resource efficiency due to process improvements and lower intensity of intermediate flows at the industrial level. The increase in platform adoption can be simulated by an increase in sales of software products to Professional scientific and technical services. This change is assumed to reduce operating costs for consultants and sub-consultants providing intermediate services in Professional scientific and technical services.

This combination of adjustments is translated into a range of quasi-random, uniformly distributed values and provided as inputs into a structural path analysis model to output a range of potential GHG emissions values.

Another set of adjustments (Scenario 2) is used to determine the weighted impact of building design automation tools. This estimate is designed to overcome the limitations of aggregate industry groups, products and services represented in the Australian national accounts I-O tables. The calculation of weights is described in Section 2.7.

We use the Python 3 programming language to process and analyse data, including several open-source libraries—two of which are particularly useful for EEIO analysis: pyspa (Stephan and Bontinck, 2023) and ipfn (Forthomme, 2021).

2.3. I-O tables and carbon satellites

I-O tables are part of the Australian national accounts, complementing the quarterly and annual series of national income, expenditure and product aggregates. They provide information about the supply and use of products in the Australian economy and the structure and interrelationships between Australian industries. These tables depict all of the yearly monetary transactions between actors in the economy.

We use Table 5—Industry by industry flow table (direct allocation of imports)[1] in EEIO analysis for the 2019 accounting year (i.e., pre-COVID).

I-O tables are combined with sector-based environmental data, known as 'satellites', to conduct EEIO. The first step is to select economic sectors and their emissions reporting, which reflect the consumption ratio among different industry sectors. We use Electricity generation, Electricity transmission, Electricity distribution and Electricity market operation, and Gas supply. The total expenditure for these activities was used as a proxy to allocate the GHG emissions reported for Australian and New Zealand Standard Industrial Classification (ANZSIC) sectors from the National Inventory by Economic Sector data (NIBES, 2020).[2]

We performed a sensitivity analysis to understand how changes in industry inputs/outputs contributed to the variance of their direct intensity of GHG emissions. It shows how sensitive the model is to changes in adjustment values and changes in the relationship between adjustment values and their output GHG emissions intensity. Variance-based sensitivity indices (Sobol' indices) were computed for two adjustment parameters, whose output was determined by the Structural Path Analysis (SPA) method outlined below.

2.4. Iterative proportional fitting

After adjustments to the scenario, I-O values are changed, and their sum totals are modified. We 'rebalance' the table of I-O values through an iterative proportional fitting (IPF) algorithm (i.e., bi-proportional fitting, 'raking' or the RAS algorithm). IPF adjusts values across all columns and rows to ensure their marginal totals are preserved in an iterative process until they converge to the 'maximum likelihood' estimate. The main purpose of rebalancing the I-O tables is to preserve equal production and consumption between industry groups. However, the motivation behind using the IPF method is to preclude second-order effects that were not explicitly modelled.

2.5. Structural path analysis

SPA is a statistical technique that traces back interactions between industry groups, thus unveiling their supply chains. This is a statistical technique that allows for the decomposition of a consumption-based account into the sum of an infinite number of production chains, also known as paths (Owen, 2016). This process is described as "unravelling the Leontief inverse using its series expansion" (Wood and Lenzen, 2003, p. 371). The SPA technique was first introduced by Defourny and Thorbeck (1984) and Crama et al. (1984), and it can be used to identify those production chains that contribute most to a particular consumption-based account.

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1 Australian Bureau of Statistics (2019-20), Australian National Accounts: Input-Output Tables methodology, ABS Website, accessed 28 March 2023.

2 The National Inventory by Economic Sector 2020 provides information on national emissions by economic sector. The Energy sector is made up of many different sources. Stationary energy is mainly GHG emissions from the production of electricity and other direct combustion of fossil fuels in industries such as manufacturing and construction. Transport comprises GHG emissions from air, road, rail and shipping transportation. Fugitive emissions comprise the GHG emissions from the extraction and distribution of coal, oil and natural gas.

The paths in SPA are categorised according to their length. For instance, a zeroth order path represents an industry's direct on-site emissions arising from the final demand for the product produced by that particular industry. A first-order path has one further step in the supply chain, representing the emissions from an industry that are used to make a final demand product in another industry (Owen, 2016).

Most SPA studies rank these production chains or paths in order of their importance. Because there are an infinite number of paths of decreasing importance that sum to the total consumption-based account, most authors will display the top 20 chains (Peters and Hertwich, 2006). This method allows for the tracing back interactions between industry groups, thus unveiling their supply chains and providing insights into the environmental and economic impacts of different industries (Lenzen, 2003), including the production of hybrid life cycle inventory coefficients (Treloar, 1997; Crawford et al., 2022) used for impact assessment modelling of the built environment (Stephan et al., 2022).

The SPA technique is particularly useful in environmental economics, where it can be used to analyse the path of spillover effects of economic, environmental, and energy factors. It provides a detailed understanding of the complex economy and the energy environment, making it a valuable tool for policy formulation and decision-making.

We use SPA here to examine the flow of environmental impacts within the national economy by quantifying the transactions involved in the interaction between different economic activities and mapping their value chains.

2.6. Software application

To generate intervention strategies and automate counterfactual economic scenarios, we developed a user-friendly software application in Python and the Streamlit web application framework (Figure 2). Computation is cached, and results are stored in a real-time database and can be shared via the Streamlit cloud-based application server.

The application fetches Input-Output Table data from the Australian National Accounts (Australian Bureau of Statistics, 2021), which is used in subsequent processes, including the calculation of the Leontief inverse matrix.

A user-defined alignment of industry groups and economic sectors is presented to the user to easily allow GHG emissions reported for ANZSIC sectors to align with the National Inventory by Economic Sector data (NIBES, 2020).

Scenarios are then defined by the user who defines which industries to modify both inputs and outputs in this scenario, e.g., a -0.5 means a 50% reduction in both inputs and outputs (sales and expenditure). Industries purchasing or selling to the industry with modified I-O values are then chosen.

Figure 2. Screenshots of the web application showing scenario building and sensitivity analysis results

Once scenarios are defined, an IPF algorithm is used to modify the table of I-O values so it maintains the sum total of I-O values after the adjustments made under the chosen scenarios. EEIO analysis and SPA are then performed to a user-defined number of maximum stages, accumulated coefficients are evolved, and the final demand associated with the supply chain is determined. Finally, we use Sobol' sensitivity analysis to examine the sensitivity of the output with respect to the input variables. Sobol' method estimates first-order and total sensitivity indices and verifies individual parameter impacts and interactions using quasi-random uniform samples of the parameters in sector adjustment. An interactive contoured heatmap is produced for each scenario, showing the resulting GHG emissions intensity for the explorative range of adjustments.

2.7. Disaggregation of Industry Groups

One of the main limitations when constructing scenarios for EEIO analysis is the lack of specificity of products and services. Aggregating industry sectors, products and services implies they have the same emissions sources and prices (see Table 2).

Table 2 List of aggregated products and services within two subdivisions under Division M Professional, Scientific and Technical Services

Subdivision 69 Professional, Scientific and Technical Services (Except Computer System Design and Related Services)	Subdivision 54 Publishing (except internet and music publishing)
691 Scientific Research Services 692 Architectural, Engineering and Technical Services 693 Legal and Accounting Services 694 Advertising Services 695 Market Research and Statistical Services 696 Management and Related Consulting Services 697 Veterinary Services 699 Other Professional, Scientific and Technical Services	541 Newspaper, Periodical, Book and Directory Publishing 542 Software Publishing

To disaggregate industry groups 542 and 692 and estimate the impact of building technology platform adoption, we produced a series of weights. We combined data from the Australian Bureau of Statistics (ABS),[3] Labour Markets Insights (LMI) and the Housing Industry Association (HIA) with automatability scores per occupation released by the National Skills Commission (NSC), IBIS World and PwC data.

2.7.1. Workforce size

First, we identified the representation level of Group 692 in Subdivision 69. This was done using the total workforce per group as a proxy, where Group 692 accounted for 25.02% of the total (322,800 out of 1,290,000), according to LMI.

[3] Australian Bureau of Statistics (June 2021), Building Activity, Australia, ABS Website, accessed 28 March 2023.

2.7.2. Task automation

Second, we estimated the maximum potential impact that task automation can have on Group 692. We used the automatability scores reported by the NSC, where Construction, Architecture and Design scored 2.89 of a maximum of 4.0 (completely automatable) and a minimum of 1.0 (not at all automatable). This is a potential for automation of 62% of the activities done in the sector. From this, it is possible to infer that the maximum theoretical impact of platforms on Subdivision 69 is a reduction of 15.51%.

2.7.3. Platform scope of impact

Third, we focused on AirBuildr and uTecture, where AirBuildr enables automation of engineering design and documentation tasks for portal frame steel structures, and uTecture enables automating design, documentation and sales tasks for the homebuilding industry. We used the total value of the construction work done both in the private and public sectors—as reported by the ABS for the latest four available quarters (i.e., Q4 2021 and Q1–3 2022)—as a proxy for the total value output of Group 692 (i.e., AUD217.906 billion). This was used to estimate the potential impacts of AirBuildr and uTecture based on the value of the construction done for their target building types.

For AirBuildr, we extracted this figure from the value of warehouses built by the private sector as reported by the ABS for the latest four available quarters (i.e., Q3–4 2021 and Q1–2 2022) (i.e., AUD5.658 billion), representing 2.59% of the total. As the maximum theoretical impact of platforms on Subdivision 69 is estimated to be –15.51%, and the impact of AirBuildr on this total is 2.59%, the maximum market-wide theoretical impact of AirBuildr on Subdivision 69 was assumed to be –0.40%.

For uTecture, we addressed the lack of granularity in ABS data by combining it with data extracted from HIA's 2019-20 Top 100 Homebuilders report. According to the ABS, the total number of houses completed in the private sector over the last four available quarters (i.e., Q3–4 2021 and Q1–2 2022) is 115,367, with a total value of AUD39.537 billion. Of these, according to the HIA, 69,679 units were completed by the top 100 homebuilders, meaning uTecture could potentially impact 60.39% of the total dwellings built in the private sector or AU23.876 billion, representing 10.95% of Group 692's total. Then, because the maximum theoretical impact of platforms on Subdivision 69 is estimated to be –15.51%, and the impact of uTecture on this total is 10.95%, the maximum market-wide theoretical impact of uTecture on Subdivision 69 was assumed to be –1.69%.

2.7.4. Revenue of software publishing

After defining the potential impacts of platform adoption on Subdivision 69, the next steps focused on identifying the level of representation of Group 542 (Software Publishing) in Subdivision 54 (Publishing (Except Internet and Music Publishing)). According to IBIS World, the total revenue of Subdivision 54 is AUD2.631 billion, whereas Group 542 accounts for 57.79% of the total (AUD7.300 billion).

We used the revenue evolution of digital and printed media (PwC) as a proxy to estimate the impacts of automating Architectural, Engineering and Technical Services (Group 692) tasks on the demand for Software Publishing (Group 542). For this, the PwC revenue data was normalised from 0 to 20 and used for regression analysis. This resulted in predictions of 1.99% for AirBuildr and 2.34% for uTecture for Group 542, hence of 1.15% and 1.35%, respectively, for Subdivision 54.

3. Results and Discussion

3.1. Scenario 0 – Baseline

This baseline scenario provides a measure of GHG emissions of all industries without any intervention strategies to model increased building technology platform adoption or resource efficiency. The total GHG emissions of the entire Australian economy is 528.9226 $MtCO_2$-e.[4]

3.2. Scenario 1 – Explorative range of platform adoption and resource efficiency

The contoured heatmap in Figure 3 visualises the GHG emission intensity of the Australian economy for a range of adjustment values for the two industry groups under analysis.5 The difference between minimum and maximum values across the gradient (in the direction perpendicular to the contours) is 6.292 $MtCO_2$-e.

The baseline value is shown in the light-coloured band. The near horizontal contour lines illustrate the dominant effect of reduced economic output on GHG emissions intensity in the Professional, Scientific and Technical Services industry. In this scenario, the increase in software publishing outputs consumed by the Professional, Scientific and Technical Services industry has a marginal effect on GHG emissions of the complete economy.

Table 3 presents the sensitivity analysis results for the adjustment range under analysis. The total-order indices show that approximately 100% of the variance in GHG emissions intensity is caused by Professional, Scientific and Technical Services adjustments. There are no significant higher-order interactions between these two adjustment parameters, as confirmed by equivalent values (1.000) for total- and first-order indices. The range of GHG intensities explores adjustments that help determine the sensitivity and the presence of second-order effects.

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[4] GHG Emissions values are carbon dioxide equivalent (CO_2e or CO_2eq); the standard metric measure to compare the global warming potential of various GHGs over a specified timescale. It expresses a 'carbon footprint' consisting of different GHGs as a single number.

[5] The x-axis and y-axis are labelled with zero adjustment value located on the bottom right.

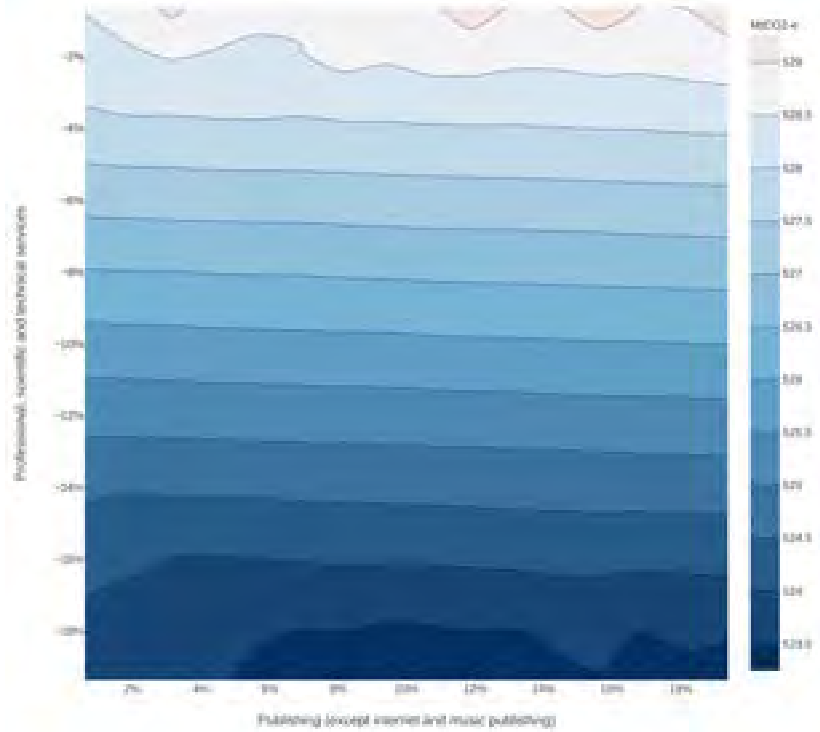

Figure 3. GHG emissions intensity for the explorative range of tool adoption and resource efficiency

Table 3. Sensitivity analysis results for the adjustment range of Scenario 1

Adjustment **parameter (industry group)**	Total-order (CI 95%)	First-order (CI 95%)
Publishing (except internet and music publishing)	0.002 (± 0.03)	0.015 (± 0.001)
Professional, Scientific and Technical Services	1.000 (± 0.25)	1.000 (± 0.311)
		First-order (CI 95%)
(Publishing (except internet and music publishing) & Professional, Scientific and Technical Services		0.000 (± 0.03)

3.3. Scenario 2 – Impact-weighted platform adoption and resource efficiency

The table below presents GHG emissions reduction estimates specific for AirBuildr and uTecture, within the explorative range presented in Figure 3 and based on the disaggregation procedures described in Section 2.4. According to the assumptions of these impact scenarios, widespread adoption of AirBuildr and uTecture in the Australian market can potentially lead to a maximum theoretical reduction of 0.1393 $MtCO_2$-e and 0.6184 $MtCO_2$-e, respectively (Table 4).

Table 4. Maximum theoretical GHG emissions reduction estimates for the case study platforms

Platform (weighted IO)	GHG emissions ($MtCO_2$-e)	% change from baseline
AirBuildr	528.7833	↓ 0.0026 % (0.1393 $MtCO_2$-e)
uTecture	528.3042	↓ 0.0013 % (0.6184 $MtCO_2$-e)

4. Limitations

Below, we describe some of the limitations of the EEIO analysis affecting reporting and decision support.

4.1. Methodology

The utility of EEIO analysis when applied to a single product, service or platform is constrained by the quantity and specificity and alignment of multiple classifications. This is due to industry groups being too coarsely aggregated to trace the environmental impact flows of a singular productive activity. EEIO analysis within the Australian economy must assign GHG emissions reported in the National Inventory by Economic Sector (Australian and New Zealand Standard Industrial Classification - ANZSIC) to align with the I-O industry group classifications used in I-O tables (Table 5). The concordance (mapping) required may lower the accuracy due to the ambiguity of alignment between classifications and, in turn, their GHG emissions intensities.

Table 5. Alignment between ANZSIC and I-O Industry Group classification for ANZSIC Division M Professional, Scientific and Technical Services

ANZSIC sector	I-O industry group
M Professional, Scientific and Technical Services	1. Professional, Scientific, Computer and Electronic Equipment Manufacturing 2. Professional, Scientific and Technical Services 3. Computer Systems Design and Related Services

Further, EEIO analysis assumes homogeneity of products such that all products in a sector have the same emissions sources. This can be problematic for EEIO analysis in the building industry because varying sources of GHG emissions intensities are aggregated into a single category defined by the I-O industry groups and the activities bundled within them. This lowers the accuracy of GHG emissions intensities according to the diversity of goods and services and the variability of emissions sources upstream.

EEIO assumes industry groups do not differentiate prices of different services and products. For platform businesses and professional services operating in different markets, this can lead to inaccurate GHG emissions intensities based on monetary flows that can vary between sectors.

4.2. Explorative scenarios

Adjustments to individual industry group I-O values introduce discrepancies in outputs used by other industries that must be accounted for. To achieve this, we 'rebalance' the table of I-O values through an IPF process. IPF is an algorithm used to modify I-O values so they maintain the sum total of I-O values for every industry after adjustments are made. However, this assumes the prices of goods and services change proportionately. This assumption diminishes the veracity of counterfactual scenarios because it ignores factors that influence the relationship between price and quantity demanded, which are held constant. EEIO presents a snapshot of the time of inter-industry flows within the economy. The lack of specificity and control over second-order effects and exogenous factors also applies to the composition of industry groups, where heterogeneous activities are assumed to be evenly distributed and their output undifferentiated.

5. Conclusions and Future Work

Building technology platforms have the potential to reduce the environmental impacts of the Australian building industry. Under a scenario of wide-scale platform use, our EEIO analysis explores the range of potential GHG emissions reduction of 6.292 $MtCO_2$-e associated with upstream and embodied environmental impacts throughout the Australian economy.

Within the 20% explorative adjustment range, this reduction would be achievable only if subsequent gains in resource efficiency effectively lower—by up to 10 times as much—goods and services consumed and produced by the Professional, Scientific and Technical Services industry.[6] However, under the assumptions of wide-scale adoption and efficiency gains of platforms, commercial objectives can be guided by the magnitude and direction of these results to advance the environmental credentials of building technology platforms. Within this explorative range, the results show a maximum theoretical reduction of 0.0026 % and 0.0013% for AirBuildr and uTecture, respectively.

Given the present methodological challenges that limit the application of results and, ultimately, decision support, assessing the environmental impacts of digital platforms for building design, such as AirBuildr and uTecture could be improved by creating systems more capable of responding to complexity. Real-world systems and scenarios feature nonlinear and second-order effects, uncertainty and unexpected events of considerable magnitude. To this end, knowing the shape of the curve is arguably more important than knowing the value of y at time x.

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[6] According to our sensitivity analysis, the variance in GHG emissions intensity is due to lower production and consumption activity associated with Subdivision 69, not increases in software publishing associated.

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Evaluation of the illuminance and thermal conditions of perforated facade prototypes for a tropical humid climate

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Abstract: According to the Köppen scale, the Colombian territory presents a wide spectrum of climates, being the tropical humid climate the predominant condition, occupying an area equivalent to 27.89% of the national extension. This climate is characterized by having temperatures that oscillate between 18 and 30 °C and relative humidity levels above 60%, issues that cause an increase of the thermal sensation. Due to the requirement of a regulation in the ingress of daylight and wind, the implementation of passive control strategies such as Windows and openwork walls turns into a major necessity (The last being a vertical enclosure system composed of masonry elements equipped with one or multiple openings). With the premise of enhancing the conditions of indoor spaces, 4 openwork-wall prototypes were developed. The present study aims to evaluate the illuminance and thermal performance of the developed prototypes in a residential Building Located in the City of Medellin using an analytical, deductive-comparative methodology, based on the use of computer simulations parallel to on-site measurements. The results show the differences in the wind shadow between the rectilinear and the cylindrical alternatives as well as the increment of the indoor illuminance levels associated with the opening percentage of the prototypes.

Keywords: Openwork Walls, Tropical Humid Climate, Colombia, Evaluation

1. Introduction

Due to its proximity to the equator line and factors like the abrupt terrain changes and its wide hydrographic network, the Colombian territory presents a diverse range of climates throughout tall its extension. According to the Köppen climate classification, the Colombian territory presents 5 different climate conditions (Rumney, G.R. 2022) listed below:

- The Tropical Humid Climate (Af) prevails mainly in the Pacific, Caribbean, and Amazon regions.
- The Tropical Savannah Climate (Aw) Found in the Llanos/Orinoquia region.
- The Subtropical Mountain Climate (Cwb): present in the Andean region, along the Eastern Cordillera.
- The Temperate Mountain Climate (Csb) found in the central mountain range and the Sierra Nevada de Santa Marta.
- The Desert Climate (BWh) present in the northern part of the territory, on the La Guajira Peninsula.

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Despite the diverse array of climates mentioned above, the prevailing climatic condition in Colombia is the tropical humid climate (Af). According to the Köppen scale map, it covers approximately 27.89% of the national territory. This climate condition is characterized by temperatures ranging from 18 to 30 °C throughout the year, along with high relative humidity percentages often exceeding 60%, which amplifies the thermal sensation. Precipitation is constant, exceeding 2500 mm, and distinct dry seasons are not observed.

The characteristics of the tropical humid climate pose a significant challenge to the design and construction process, particularly when aiming for high comfort standards. The biological and climatic conditions of the region demand a profound understanding to avoid erroneous architectural and construction practices. Inappropriate utilization of these elements can lead to the creation of indoor environments that can adversely affect the Indoor Environmental Quality or IEQ.

IEQ is a comprehensive concept that encompasses various aspects of indoor environmental conditions, including thermal comfort, air quality, lighting, and acoustics. In the context of Colombia's tropical humid climate, achieving good IEQ is crucial to providing occupants with comfortable and healthy indoor environments. (Nasir, A.R.M. et al, 2011)

To address the challenges related to IEQ, several authors concur that the implementation of passive control strategies is an effective way to enhance indoor conditions in the tropical humid climate (Arango-Díaz, L., 2016; Quirós-Lacau, C.E., 2005; Salazar-Trujillo, J.H., 2015; Vieira, A. et al, 2012). These strategies encompass design guidelines, architectural criteria, and devices that improve various aspects of IEQ, including temperature, natural light, and acoustics, without significantly increasing energy costs.

Among the most commonly employed passive control strategies are skylights, windows, chimneys, openwork walls, material selection based on thermal properties, and building orientation to minimize direct sunlight exposure.

In the context of Colombia's tropical humid climate, the implementation of passive control strategies becomes a critical necessity, given that the combination of high temperatures and humidity can result in uncomfortable and unhealthy indoor environments. Among these strategies, the "Openwork wall" emerges as a prominent and widely adopted option throughout the country. Whether constructed from concrete or ceramics, this type of block features surface openings that facilitate the ingress of air and natural light into interior spaces. In addition to its practical functionality, the perforated block harmoniously complements the architectural aesthetics of the buildings (Garcia-Cardona A., 2020).

With the imperative of creating buildings that offer comfortable and healthy indoor environments in the context of Colombia's tropical humid climate, this research seeks to evaluate the luminous, thermal, and acoustic performance of four prototypes of perforated blocks as a viable alternative for facades in this region.

2. Methodology

An analytical-comparative-deductive methodology was employed in this study. The process involved the evaluation of four openwork block prototypes as an alternative facade option for a residential building located in Medellin. The evaluation encompassed both illuminance and thermal performance and was conducted through a combination of on-site measurements and computational simulations.
The selected building was a four-level residential project situated at 2A#55-29 on Santa Fe Street in Medellin.

Figure 1. building localization

2.1 Prototype Description

Four openwork block prototypes were developed for this research, featuring two with conical/cylindrical geometries and two with rectilinear configurations. Each block had dimensions of 60 cm in length, 60 cm in height, and 15 cm in thickness, and all were constructed with concrete, featuring nine openings.

Each prototype incorporated interior devices made from recycled materials designed to alter wind trajectories and enhance the entry of natural light into spaces. The construction of these prototypes consisted of two concrete pieces that assembled to create an interior serving as thermal insulation, thereby improving their performance.

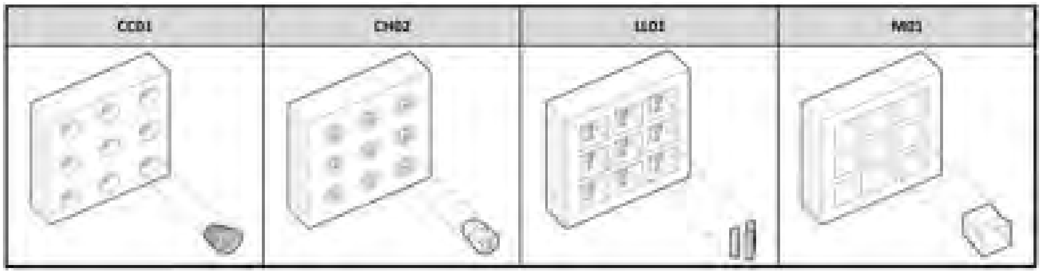

Figure 2. Protoype Codification

- CC01 Prototype: This prototype adopted a conical shape derived from commercial circular openwork blocks. Tubular filaments were designed to modify wind trajectories by introducing obstacles, and PVC pipes were used in its fabrication.
- CH02 Prototype: The base form of this prototype featured a truncated cone with a diameter variation of 3 cm between the front and back openings, intended to modify wind trajectories and speeds. Disposable cups were employed in this design.
- LL01 Prototype: This prototype had a rectilinear shape derived from commercial square openwork blocks and featured three hollow filaments or traps designed to modify wind trajectories. Translucent tiles were used as the material choice to increase the entry of natural light into the space.
- M01 Prototype: Like to the previous one, this prototype has a partially rectilinear shape derived from commercial alternatives. Inclined surfaces aim to create a funnel effect, modifying indoor wind speeds and preventing rainwater from entering. Aluminum-brass was chosen as the material to reflect more natural light into the evaluated spaces.

2.2 Experiment Description

The prototypes were assessed between June 21 and 25, 2022. Each prototype was evaluated on a different day, between 10 am and 8 pm, as authorized by the construction site personnel for data collection. Four HOBO Dataloggers were utilized for this purpose. The first three HOBO Dataloggers, positioned at 0, 1, and 3 meters indoors, were used to capture indoor measurements. A fourth HOBO Datalogger was placed outdoors to monitor external conditions, including wind speed, Illuminance, and temperature, providing reference measurements to assess the facade behavior of each prototype.

HOBO Dataloggers are sensors that simultaneously measure environmental factors such as temperature, wind speed, and illumination at 5-minute intervals.

Figure 3. Floor plan and Datalogger distribution

2.1.2 Computational simulations

For the computational fluid dynamics simulation, or CFD Simulations, the intention was to emulate the prevailing conditions of the particular city sector where the research was conducted., to achieve this, data was extracted from meteorological station # 198 using a local online platform called SIATA. This way, it was determined that the average wind speed in that zone is 0.90 m/s, coming from the northwest direction. With these data, the three-dimensional modeling of the building was made using Autodesk Revit, and subsequently exported to Autodesk CFD using the following parameters:

- Wind speed: 0.90 m/s
- Wind direction: Southwest
- Building material: Brick
- Surrounding building material: Brick
- Number of interactions: 100.

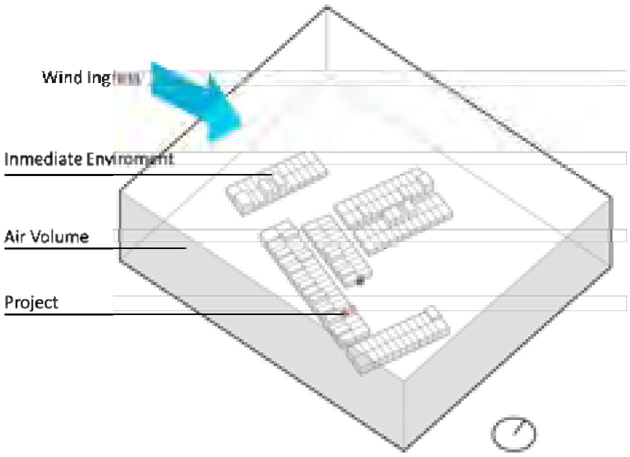

Figure 4. CFD Model representation

The Illuminance simulations were elaborated using the ClimateStudio plugin for Rhino using the parameters listed below:

- Climate file: Medellin. epw
- Distance from work plane: 70 cm
- Node distance: 30 cm
- Floor material: White ceramic tile
- Wall material: Brick wall
- Glass material: Clear glass

The simulations use the Useful Daylight Illuminance (UDI) metric, which accounts for the percentage of the evaluated area falling within the range of useful illuminance. This means the percentage of area that, throughout the evaluated year, presents illuminance levels between 100 and 3000 lux.

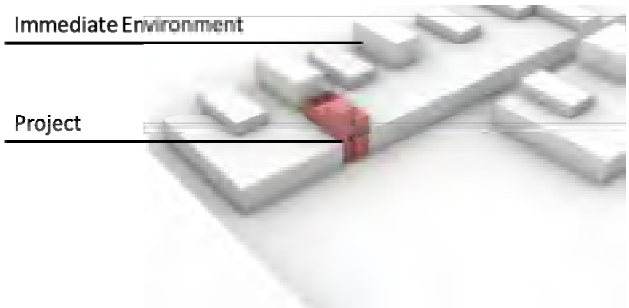

Figure 5. UDI Model representation

3. Result Treatment

3.1 On-Site Measurement Result Treatment

Data from each of the HOBO Dataloggers set up in the assembly were extracted using Hoboware software. Once this was done, the data was imported into Microsoft Excel, and the study was limited to the data collected between 10 am and 8 pm on the evaluated day.

3.2 Computational Simulation Result Treatment

For the CFD Simulations, A weighted average of the ventilation vectors provided by Autodesk CFD Softare was calculated using Microsoft Excel. In the specific case of the UDI Simulations, the percentages from the illuminance reports generated by the Climate Studio program were extracted and manually entered into Excel to compare the performance of the four studied prototypes.

Since the measurements of the datalogger sensors are recorded every 5 minutes, hourly averages were made in order to facilitate the data understanding.

4. Results

4.1. On-Site Measurements

4.1.1. Wind speed

The CC01 prototype exhibited consistently low wind speeds, measuring less than 0.1 m/s, indicating limited air circulation within the analyzed housing unit. Wind speed readings were slightly higher in the morning/noon hours compared to the evening, with minimal variation.

In the case of the CH02 prototype, wind speeds were generally less than 0.2 m/s at all distances evaluated. The highest wind speeds were observed at the sensor located 2 meters from the façade when the prototypes were arranged in a row. This phenomenon can be attributed to turbulence generated by the spatial layout of the housing unit.

Similarly, the LL01 model displayed higher wind speeds at the sensor positioned 3 meters from the façade, potentially due to turbulence resulting from the housing unit's spatial distribution. Overall, this prototype recorded higher wind speeds compared to the M01 rectilinear alternative. Despite having a lower effective opening area percentage, the narrowing of the internal aperture contributed to wind acceleration and increased speed.

Prototype M01 registered elevated indoor wind speeds at the sensor located 3 meters from the main façade, potentially linked to turbulence generated by the housing unit's spatial distribution. However, it's worth noting that the external wind speed showed noticeable reductions, up to 1.6 m/s, due to the presence of hexagonal obstacles inside, disrupting the continuity of the wind flow.

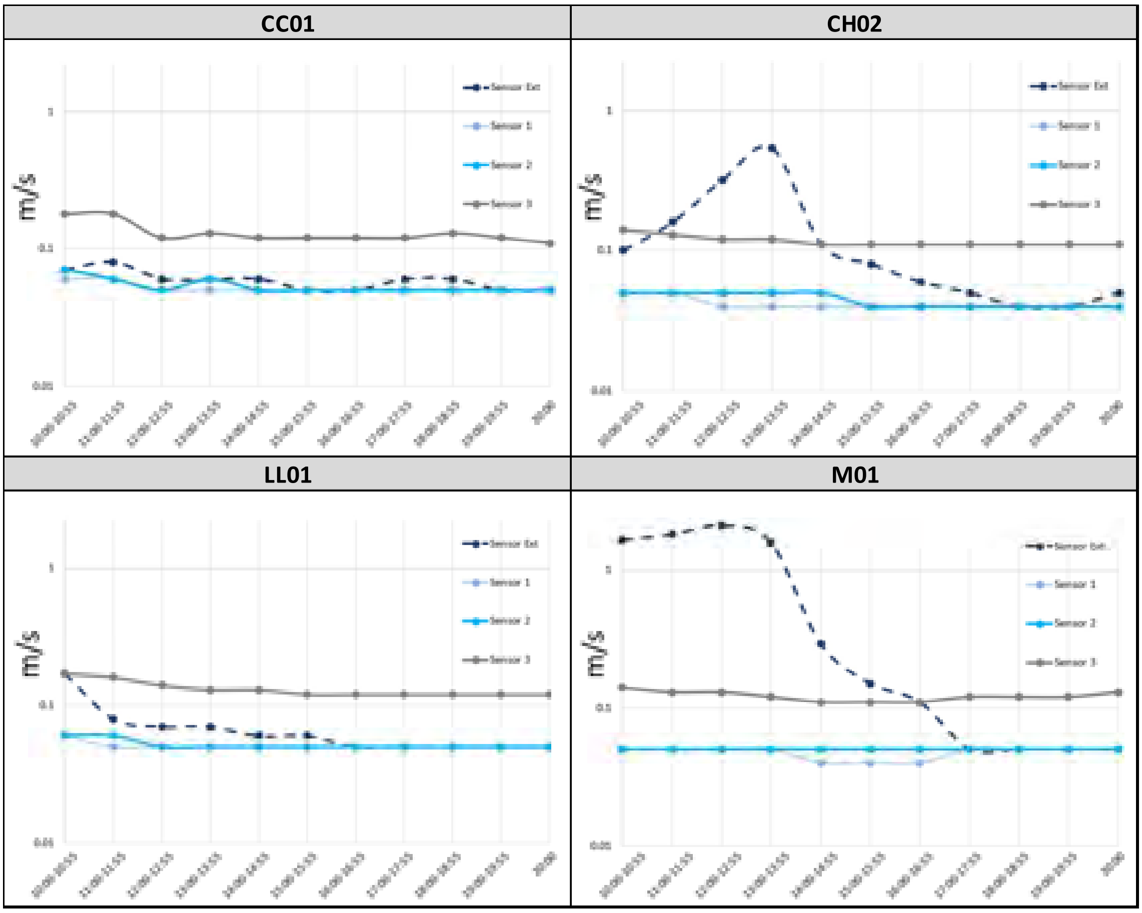

Figure 6. Wind Speed Performance graphics

4.1.2. Illuminance

The CC01 prototype demonstrated relatively low illuminance levels, primarily attributed to its limited opening percentage, with readings ranging from 7.19 to 26.93 lux. In general, the prototype exhibited higher illuminance levels at a 1-meter distance from the façade, with a limited range of lighting qualities. For the CH02 prototype, illuminance values ranged from 3.9 to 28.39 lux, with peak values occurring between 10 AM and 12 PM. Illuminance decreased as the sensors moved away from the light source (the exterior), with the highest values at sensor number 1 and the lowest at sensor number 3.

The LL01 prototype's inclined surfaces created smaller openings, resulting in reduced natural light entry compared to the rectilinear alternative (M01). This caused a decrease in lighting performance, with illuminance values ranging between 3.9 and 197.73 lux, marking the prototype with the widest range of illuminance.

The M01 prototype registered illuminance values ranging from 3.9 to 80.82 lux at distances of 1, 2, and 3 meters. It demonstrated higher illuminance values closer to the light source (exterior) due to its larger opening area and the use of translucent materials inside, resulting in greater illuminance than the cylindrical alternatives proposed.

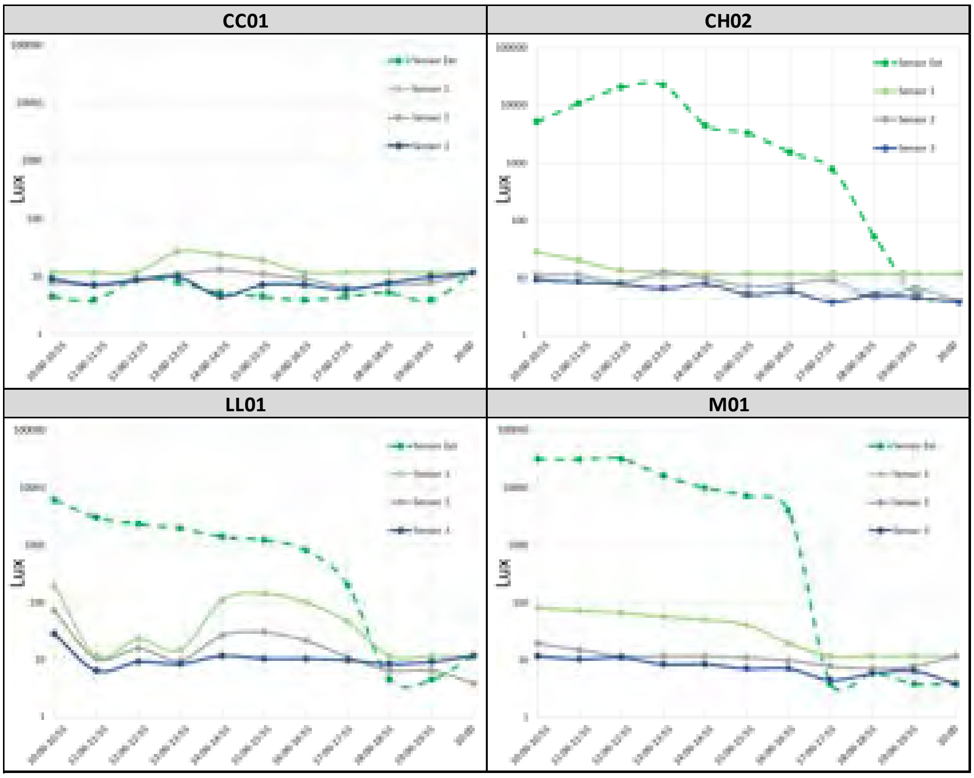

Figure 7. Illuminance Performance graphics

4.1.3. Temperature

In The CC01 prototype displayed temperature values quite similar to those recorded externally, indicating its limited thermal effectiveness, with maximum differences of less than one degree centigrade.

In contrast, the CH02 prototype exhibited significantly lower dry bulb temperatures compared to the external readings, with specific differences of up to 4.6 degrees, making a notable contribution to the tropical wet climate context.

The LL01 prototype demonstrated adequate thermal performance during the period with the highest external temperature values, with temperature decreases of up to 5.8 degrees at the sensor located 3 meters from the façade. Internal conditions fluctuated between 24.95 and 27.13 °C, with more substantial thermal reductions around noon and less perceptible changes in the afternoon/night hours.

The M01 prototype achieved noticeable temperature reductions in the morning and early afternoon, with differences of up to 7 degrees compared to the exterior at sensor number 3. However, as the day progressed, the thermal reduction effect decreased, with temperature differences not exceeding 0.5 °C by 8 pm (the last hour evaluated).

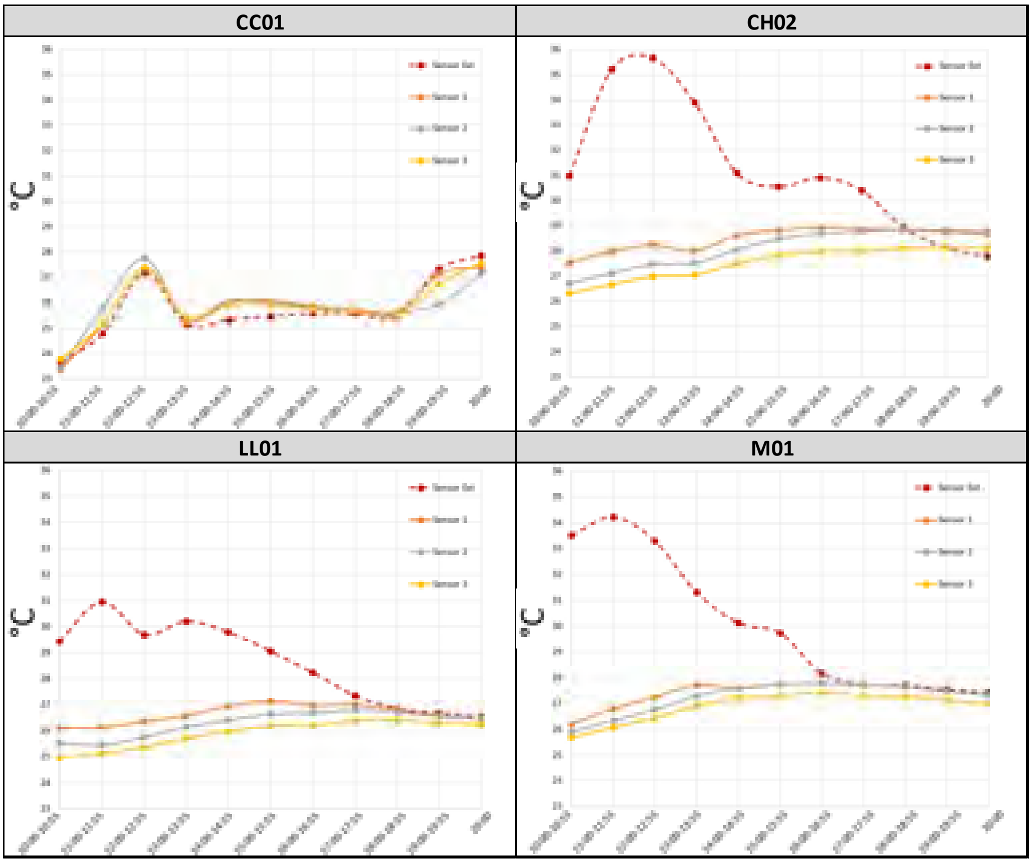

Figure 8. Temperature Performance graphics

4.2. Computational Simulations

4.2.1 CFD Simulations

The ventilation inside the building is very low with the CC01 prototype, since it presents less than 0.01 m/s. The CH02 prototype, since it presents less than 0.03 m/s, which is also a low value. LL01 module shows a cross ventilation with a wind speed of up to 0.1 m/s in the social area of the house and in the rest of it, 0.4 m/s was evidenced.

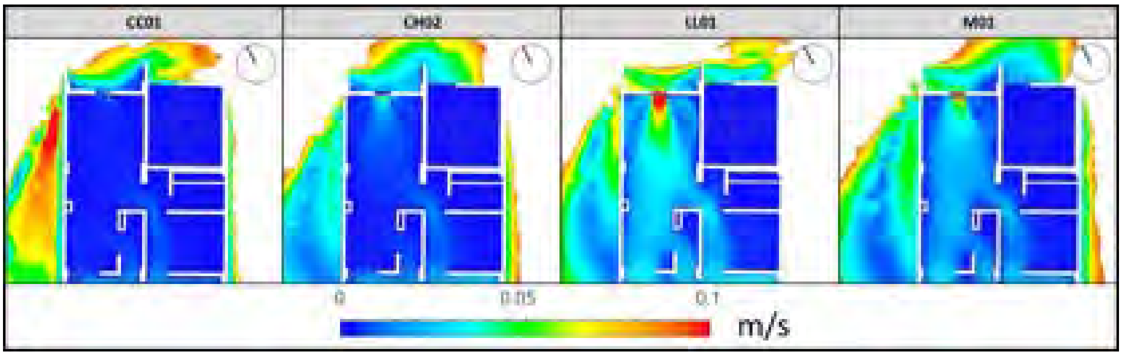

Figure 9 . CFD Simulations

To properly analyze the results from CFD, additional analyzes were carried out on the generated simulations, evaluating 3 new parameters: the R.W.D or relevant windspeed distance, which measures the depth of the wind spectrum with speeds between 0.05 m/s and 0.1 m/s; the R.W.A O relevant windspeed area, which aims to calculate the plan area of the wind spectrum with speeds between 0.05 and 0.1 m/s, and M.I.W or Mean internal windspeed which corresponds to the average speed recorded inside the building.

According to this analysis, the simulations show the prototypes LL01 and M01 as undisputed winners, being the ones with currents with greater depths (2.60m and 1.25 respectively), larger areas of influence and higher average speeds.

Table 1: Indoor Windspeed Analysis

Prototype	R.W.D	R.W.A	M.I.W
CC01	0.40 m	0.19 m2	0.005 m/s
CH02	0.45 m	0.25 m2	0.010 m/s
LL01	2.60 m	2.55 m2	0.040 m/s
M01	1.25 m	0.80 m2	0.035 m/s

In general terms, a better behavior of the solutions with rectilinear geometries (LL01 and M01) is evident, since they present higher opening percentages and facilitate the entry of a greater amount of air into interior spaces.

4.2.1 Illuminance Simulations

As a result of the comparison, slight differences are observed in the contribution of natural light from each of the depths, the maximum being difference of 1.3% between models CH02 and LL01. There is evidence of a greater contribution of natural light from the two prototypes derived from the commercial model with a square opening, being LL01 with 14% and M01 with 13.4%.

Models CH02 and CC01 present lower percentages of useful Illuminance, due, among other causes, to a lower percentage of perforated area

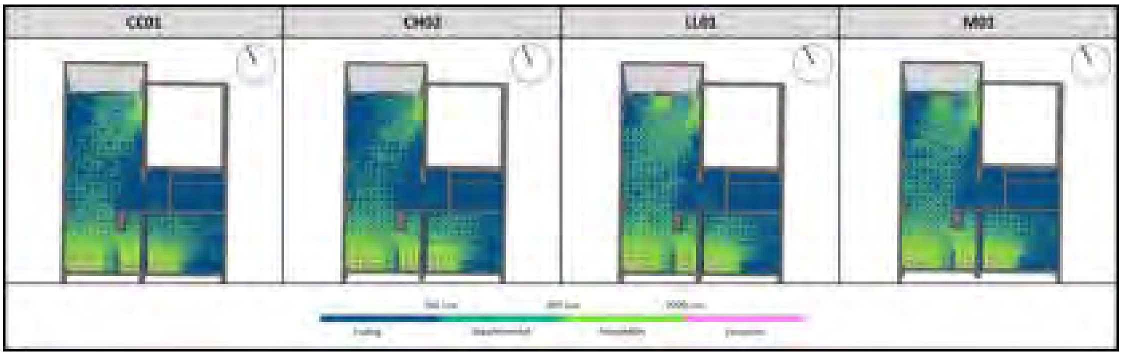

Figure 10. Useful daylight illuminance simulations

As in the CFD simulations section, for the illuminance section, an additional sub-analysis was generated that allows contrasting the graphic information provided by the simulations, collecting the average lux inside the House with each of the prototypes used, in addition of the percentage of area of the House that is in the useful illuminance range.

The results in question did not present significant variations, being that in terms of UDI, all presented percentages between 13 and 14%, a fact that corresponds with the almost null variation evidenced in the average lux analysis, which presents a range between 233 and 250 lux.

Table 2: U.D.I Analysis

Prototype	**U.D.I**	**Average Lux**
CC01	13.0%	235 Lux
CH02	12.7%	233 Lux
LL01	14.0%	250 Lux
M01	13.4%	244 Lux

5. Discussion

It is important to emphasize that limitations in financial resources impacted the scope of the study. The small number of constructed prototypes (16 in total, with 4 units per model) restricted the evaluation to only a third of the facade area. This condition significantly influenced the presented results, altering the elastic behavior of the wall and consequently affecting its ventilation and illuminance responses. The comparison between computational simulations and in-situ measurements reveals a significant disparity in assessing building performance. In terms of ventilation, the in-situ measurements consistently indicated indoor wind speeds well below 0.1 m/s for all prototypes, with specific measurements ranging from 0.05 m/s to 0.08 m/s.

In contrast, the computational simulations suggested an average facade wind speed of approximately 0.04 m/s, highlighting a notable discrepancy. This disparity can be attributed to the complex interplay of real-world factors, including site-specific wind patterns, neighboring structures, and local terrain effects, which are challenging to fully replicate in a simulation. Moreover, the illuminance measurements emphasized this difference, with the LL01 and M01 prototypes yielding the highest percentages of useful illuminance, at 14% and 13.4%, respectively, specific to the building's geographical location and climatic conditions. These data underscore the necessity of integrating localized empirical data for a comprehensive understanding of building performance and making informed design decisions.

6. Conclussions

Over the course of the project, the prototypes revealed indoor wind speeds below 0.1 m/s. These values indicate low air volume movement inside the evaluated building. However, it's essential to recognize that this result cannot be solely attributed to the use of the prototypes in the facade. Indeed, various factors such as location, surrounding constructions, wind direction, and speed influence the results. However, it's relevant to mention that the CFD simulations revealed average facade wind speeds of 0.04 m/s.

Considering the specific conditions of the selected building, the implementation of the CH01 and CC01 prototypes is not recommended, as their use would not improve the air circulation. In contrast, the LL01 and M01 openwork walls are suggested, combined with other passive control strategies like Windows to maximize airflow into habitable spaces.

In terms of illuminance evaluation, the prototypes derived from the square commercial reference (LL01 and M01) show the highest percentages of useful illuminance, with values of 14% and 13.4%, respectively. These results consolidate these alternatives as the most suitable for the tropical humid climate. These rectilinear geometries, with their high opening percentages, outperform cylindrical strategies with smaller openings.

These conclusions emphasize the importance of considering not only prototype design but also specific environmental factors when optimizing ventilation and illuminance in building design. By selecting the right prototype and integrating passive control strategies, architects and designers can significantly improve the comfort and energy efficiency of residential buildings in tropical climates.

7. Acknowledgements

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Experimental investigation of vibration performance of cross-laminated timber floor constructed from fibre-managed *Eucalyptus nitens* with various surface treatments

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Abstract: Cross-laminated timber (CLT) floors made from fibre-managed plantation *Eucalyptus nitens* (*E. nitens*) have raised a lot of research interests recently due to their sustainability and higher value than producing woodchips. However, their serviceability performance is not yet fully understood. Investigating vibration behaviour of timber floors is necessary because the inappropriate control of structural vibration would finally lead to human discomfort. In this study, seven CLT samples were analysed, consisting of six *E. nitens* CLT panels with different structural grades (modulus of elasticity) in each layer, and one spruce CLT with constant structural grade used as a control sample. The vibration performance of all CLT panels were investigated under different scenarios including the utilisation of residential carpet, hardwood overlay and a soundproofing material. A ball-dropping method was used as an excitation for the vibration test, and an accelerometer was used to collect the acceleration-time data. Calculations of natural frequency and damping ratio were performed by MATLAB. The results have demonstrated the reliable serviceability performance of *E. nitens* CLT via comparing the vibration properties of spruce CLT. The variations in structural grade within different layers of CLT, as well as the inclusion of carpet, timber overlay and soundproofing material have demonstrated different vibration performance of CLT panels.

Keywords: fibre-managed *Eucalyptus nitens*; vibration; serviceability performance; hardwood CLT.

1. Introduction

Cross-laminated timber (CLT) is an innovative type of engineered wood product, constructed by a minimum of three orthogonally bonded layers of timber boards, using structural adhesive to laminate longitudinal and transverse layers (*ANSI/APA PRG 320-2012*, 2012). This structure provides reliable in-plane and out-of-plane carrying capacity, which makes it suitable for the use of walls and floors.

In Tasmania, *Eucalyptus nitens* are the main plantation hardwood species, which are typically used for pulp production (*ABARES*, 2021). There is a growing interest to explore the potential utilisation of this underutilised hardwood species in Tasmania. Similar research goals are also existed in other parts of the world, including the studies of chestnut in Italy (Callegari *et al.*, 2010), large-leaf beech (Essoua and Blanchet, 2017) in Canada and low-grade yellow-polar in the United States (Thomas and Buehlmann, 2017). Recent research has proven that

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fibre-managed *E. nitens* species are mechanically reliable for structural products, such as finger-jointed sawn boards (Hou *et al.*, 2022) and CLT (Ettelaei *et al.*, 2022, Gutierrez *et al.*, 2023). Nevertheless, further research is necessary, particularly related to the vibration performance of CLT constructed by this species.

Investigating vibration performance of timber floors is necessary, especially when they extend to larger and longer span. That is because uncontrolled structural vibrations can lead to annoyance of occupants and negative impact on their quality of life. The common sources of vibration annoyance include people walking, jumping children, service equipment, domestic appliances, traffic, wind and other sources from domestic appliances (Zhang *et al.*, 2013). In order to control the vibration annoyance occurring, some standards such as Eurocode 5 (*EN 1995-1-1:2004*, 2004) and AS/NZS 1720.1 (*AS1720.1* 2010) have been widely used for the design of timber structures. These standards include serviceability limit state criteria, focusing on the control of deflections and natural frequency. It has been found that low-frequency floor vibration problems have been observed in typical softwood CLT floors, when the floor resonates due to walking excitation, and finally lead to human discomfort (Breneman, 2020). Hardwoods CLT tends to have higher stiffness and strength than CLT manufacturing with softwood (Pangh *et al.*, 2019, Ettelaei *et al.*, 2022, Nero *et al.*, 2022); however, the performance of CLT made from plantation *E. nitens* still exists knowledge gap, especially for the investigation of its required serviceability performance.

Several methods exist for assessing the vibrational characteristics of timber floors. Typical experimental approaches would include accelerometers and sensors to determine the dynamic response of timber floors, and different sources of excitation such as foot traffic (Opazo-Vega *et al.*, 2019), brushing (Weckendorf *et al.*, 2006), bouncing ball (Kan *et al.*, 2017, Taoum *et al.*, 2019), impact hammer (Faircloth *et al.*, 2021, Giordano *et al.*, 2023) and vibration shakers (Jarnerö *et al.*, 2015, Robertson *et al.*, 2018). Finite element analysis is another common method for modelling and predicting vibration properties of timber floors. This method allows the simulations under different situations such as different boundary conditions (Huang *et al.*, 2020) and loading conditions (Wang *et al.*, 2021).

The vibration performance of hardwood cross-laminated timber floors remains novel due to the limited number of literatures so far. The research on *black locust* CLT (Crovella and Kurzinski, 2021), *E. nitens* nail-laminated timber (NLT) (Derikvand *et al.*, 2019) and CLT (Liang *et al.*, 2023) have demonstrated that the high stiffness of hardwood could improve the vibration performance, and potentially be able to have longer span compared to softwood species. These studies only focused on the vibration performance of bare timber floor, and the influence of implementing carpet, timber overlay and soundproofing materials on vibration performance is still unknown and necessary to be investigated. This knowledge gap forms the main objectives of this study, which include:

- To determine the vibration performance of *E. nitens* CLT panels incorporating residential carpet, timber overlay and XYLOFON.
- To compare the results of first-mode natural frequency and damping ratio between different *E. nitens* CLT configurations.
- To compare the results of first-mode natural frequency and damping ratio between different surface treatments
- To compare the overall vibration performance of *E. nitens* CLT panels with spruce CLT.

2. Materials

In this section, the mechanical properties of *E. nitens* sawn boards and CLT panels will be discussed, including the values of modulus of elasticity (MOE) and density. In addition, Section 2.2 will discuss the characteristics of different surface treatments and the introduction of XYLOFON.

2.1 Properties of CLT samples

Fibre-managed *E. nitens* sawn boards were sourced from CUSP Building Solutions, Wynyard, Tasmania, with original size of 110 mm × 38 mm × 3100 mm (width × depth × length).

The non-destructive edgewise four-point bending tests (linear elastic range) were performed on the sawn boards to determine the values of MOE in accordance with Australian Standard (*AS/NZS 4063.1-2010* 2010)

The boards were then categorized and arranged into three groups: high-MOE, medium-MOE and low-MOE. The average MOE values of the sawn boards in this study (Table 1) were reported in previous study (Liang *et al.*, 2023).

Table 1. Average stiffness (MOE) of the sawn boards

Name	Abbreviations	MOE (GPa) ± StdDev
High-MOE	H	13.1 ± 0.81
Medium-MOE	M	10.6 ± 0.67
Low-MOE	L	8.3 ± 0.17

Three configurations of three-layered *E. nitens* CLT panels were constructed by CUSP Building Solutions. Each configuration was designed with different MOE values on the outer and inner layers. Additionally, a spruce CLT panel was included as a controlled sample. The spruce CLT acted as a benchmark to compare the experimental results of *E. nitens* CLT. The dimensions of all CLT panels were 300 mm × 90 mm × 2000 mm.

The MOE values of CLT were determined through non-destructive four-point bending tests. The density of the CLT panels was determined according to Australian Standard AS 1080.3 (*AS 1080.3*, 2000). Table 2 includes a summary of their overall characteristics.

Table 2. Properties of CLT configurations (Liang *et al.*, 2023)

Lamellas from top to bottom	Acronyms	Replicates	MOE of CLT (GPa)	Average density at 12% MC (kg/m^3)
High-MOE Low-MOE High-MOE	HLH	2	11.6	523.3
Medium-MOE Low-MOE Medium-MOE	MLM	2	9.0	515.5
Medium -MOE Medium -MOE Medium -MOE	MMM	2	9.4	507.1
Spruce Spruce Spruce	S	1	8.3	413.7

2.2 Properties of Carpet, Timber Overlay and XYLOFON

Three supplemented materials located on top and between timber and support (GLT as bearers in this study) were considered in this study. The supplemented materials include a residential carpet (Figure 1a), a timber overlay (Figure 1b) and a soundproofing material (Figure 1c) between timber and support. The residential carpet was sourced from Dunlop Springtred with a carpet underlay, which is meeting with Australian Standard AS 4288-2003 (*AS 4288-2003*, 2003) for soft underlayers. In addition, the timber overlay is a commercial product, constructed by Tasmanian Oak with density of 605.1 kg/m^3 and moisture content of 11.98%. In addition, XYLOFON 35 with 6 mm of thickness and 3.22 N/mm^2 of compressive modulus was applied between the CLT panels and the glulam supports. XYLOFON, a high-performance resilient soundproofing material designed to reduce structural noise, was sourced from Rothoblaas Solutions for Building Technology. In this study, the objective of applying XYLOFON was to investigate its impact on vibration performance of CLT panels.

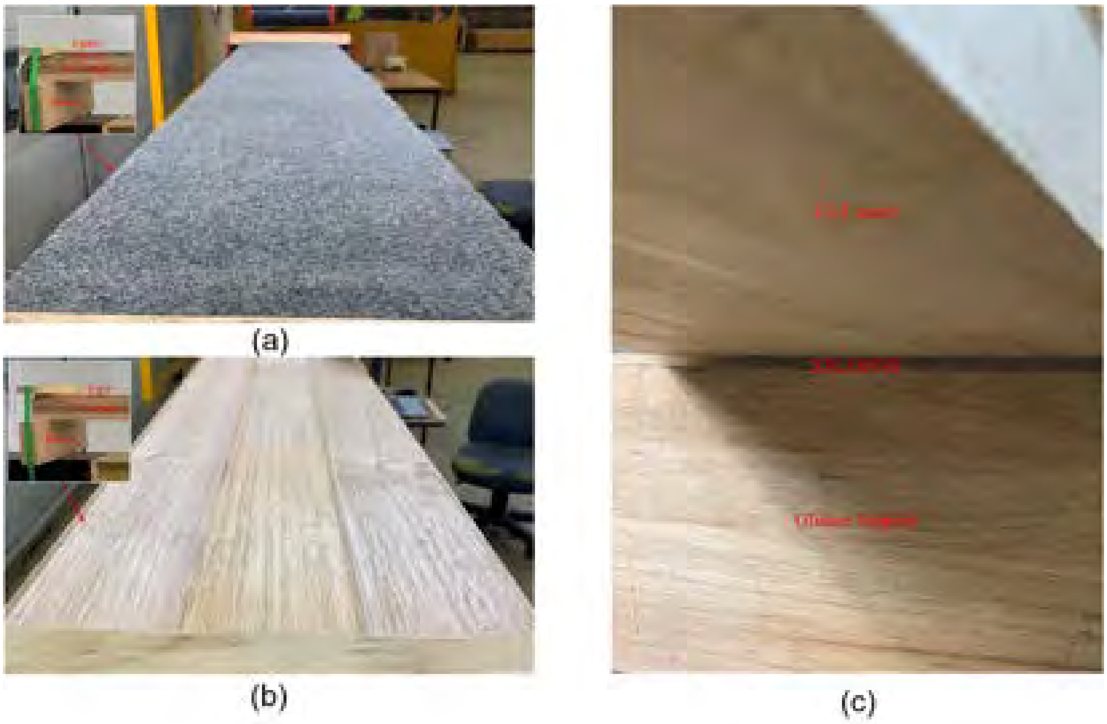


Figure 1. (a) CLT with carpet, (b) CLT with timber overlay and (c) CLT with XYLOFON

3. Methods

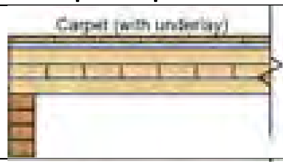
3.1 Experimental setup

In this study, an accelerometer and a basketball were used to determine the dynamic responses of CLT panels. Mid-span vertical acceleration of samples was measured, utilizing the Crossbow CXL04LP3 accelerometer, which has a sensitivity of 500 ± 25 mV/g. The accelerometer was secured at the bottom layer, located at the mid-span of the CLT panels. A basketball with a weight of 600 g was dropped from constant height of 300 mm, acting as the excitation source of the vibration. For each panel and each setup (Figure 1), five excitation locations were chosen (Figure 2), and each location was excited three times. All CLT panels were placed onto two glulam beams with dimensions of 70 mm × 200 mm (cross section). Two ratchets were used to secure the edges of CLT panels firmly onto the bearers. This setup ensured that the CLT panels were securely held in place during the basketball excitations, preventing any potential bouncing or displacement that may influence the results. Furthermore, the ratchets also provided a practical solution for temporarily securing carpet, timber overlay and XYLOFON on the CLT panels without the need of permanent adhesion.

In this study, four different scenarios considering supplemented materials on CLT samples including carpet, timber overlay, XYLOFON and two combinations (e.g., with XYLOFON and Carpet, XYLOFON and timber overlay) were included, and summarised in Table 3.

Figure 2. Experimental setup

Table 3. Different Scenarios

Scenarios	Name	Graphic explanation
A	CLT + carpet	
B	CLT + timber overlay	
C	CLT + XYLOFON + carpet	
D	CLT + XYLOFON + timber overlay	

3.2 Data Analysis

In this study, first-mode natural frequency and damping ratio are two important factors for assessing the impact of applying different materials on CLT panels. Fast Fourier Transformation (FFT), an efficient method for computing discrete Fourier transform (DFT), was used to convert the time-domain signal to frequency-domain (considering first-mode natural frequency only) data (Bergland, 1969) through coding in MATLAB.

Then, the values of damping ratio were calculated using the following sequence:

$$x = Xe^{-\zeta\omega t}\sin(\sqrt{1-\zeta^2}\omega t + \varphi) \quad (1)$$

Where:

ζ = damping ratio (%); ω = undamped angular frequency (rad/s), which is equal to $2\pi f$; f = natural frequency (Hz); t = time (s); X and φ = arbitrary phase and amplitude constants defined by initial conditions.

Equation 1 assumes the displacement of vibration system with a linear stiffness and damping response (Thomson, 1998).

As the maximum value of sine term is equal to 1, Equation 2 can then be reformulated to Equation 2.

$$y = Xe^{-\zeta\omega t} \quad (2)$$

Finally, the curve fitting tool from MATLAB was used to fit the exponential decay curve to general model equation:

$$f(x) = ae^{bx} \quad (3)$$

The values of b will be determined by fitting the exponential curve, so the damping ratio can be determined by:

$$\zeta = \frac{b}{\omega} = \frac{b}{2\pi f} \quad (4)$$

4. Results and discussion

4.1 Vibration test results

Typical acceleration-time graphs were plotting in Figures 3 (a-d). FFT was used to transfer the acceleration-time data into frequency-domain data. In this case, since the accelerometer was located at the mid-span of the CLT panels, only fundamental frequency was considered.

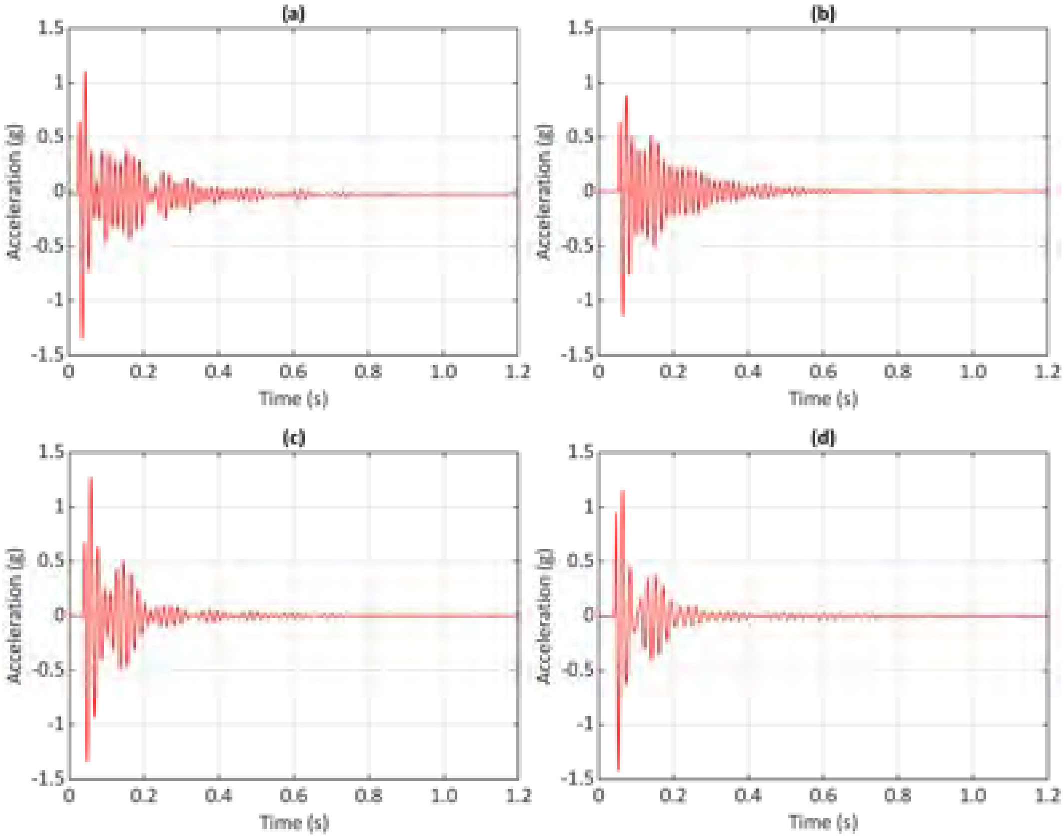


Figure 3. Typical acceleration-time plots for (a) CLT (HLH1) in scenario A, (b) CLT (MLM2) in scenario B, (c) CLT (MMM2) in scenario C and (d) CLT (Spruce) in scenario D

Table 4 and Table 5 present the results of natural frequency and damping ratio for different CLT configurations and scenarios. For the results of natural frequency, it shows that HLH CLT panels consistently exhibit the highest values across all scenarios, while MLM and MMM CLT panels demonstrate comparable results with each other. All the *E. nitens* CLT showed higher results of natural frequency compared to the controlled spruce CLT for all scenarios. On the other hand, there is not obvious relationship between CLT configurations and results of damping ratio.

The inclusion of carpet (Scenario A) has lower results of natural frequency comparing to the implementation of timber overlay (Scenario B) but has higher results of damping ratio comparing to the implementation of timber overlay. The introduction of XYLOFON under Scenarios C and D did not influence the results of natural frequency but increased the results of damping ratio by 18.9% and 35.7%, respectively.

Table 4. Results of first-mode natural frequency

Average results of first-mode natural frequency (Hz) ± StdDev				
Name	**Scenarios**			
	A	**B**	**C**	**D**
HLH1	48.4 ± 0.3	62.2 ± 0.1	47.3 ± 0.1	62.2 ± 0.3
HLH2	48.5 ± 0.3	61.9 ± 0.1	47.3 ± 0.1	60.7 ± 0.1
MLM1	45.0 ± 0.1	59.6 ± 0.1	46.3 ± 0.1	57.8 ± 0.1
MLM2	45.0 ± 0.0	59.4 ± 0.2	46.8 ± 0.3	58.3 ± 0.1
MMM1	46.2 ± 0.1	58.9 ± 0.1	46.4 ± 0.1	58.4 ± 0.1
MMM2	45.3 ± 0.1	58.2 ± 0.1	47.0 ± 0.1	58.7 ± 0.4
Spruce	44.8 ± 0.0	56.3 ± 0.3	46.0 ± 0.1	56.1 ± 0.1
Average ± StdDev	46.2 ± 1.6	59.5 ± 2.1	46.7 ± 0.5	58.9 ± 2.0

Table 5. Results of damping ratio

Average results of damping ratio (%) ± StdDev				
Name	**Scenarios**			
	A	**B**	**C**	**D**
HLH1	3.0 ± 0.12	2.2 ± 0.15	4.8 ± 0.23	3.9 ± 0.19
HLH2	3.2 ± 0.12	2.3 ± 0.15	4.3 ± 0.03	4.2 ± 0.18
MLM1	4.0 ± 0.05	3.0 ± 0.21	4.1 ± 0.04	4.1 ± 0.13
MLM2	3.4 ± 0.10	2.6 ± 0.14	5.3 ± 0.11	3.7 ± 0.24
MMM1	4.2 ± 0.16	2.8 ± 0.13	4.0 ± 0.03	3.5 ± 0.14
MMM2	4.2 ± 0.08	3.1 ± 0.13	4.4 ± 0.09	3.4 ± 0.18
Spruce	4.3 ± 0.05	3.3 ± 0.15	4.4 ± 0.05	4.0 ± 0.14
Average ± StdDev	*3.7 ± 0.54*	*2.8 ± 0.41*	*4.4 ± 0.45*	*3.8 ± 0.31*

4.2 Discussion of natural frequency

In this study, CLT configurations based on different MOE values on different layers showed significant effect on the results of natural frequency of *E. nitens* CLT panels. To sum up, the experimental results have suggested that using higher MOE timber boards in outer layers could increase the results of natural frequency, while using higher MOE timber boards in inner layers has no or minor effect on the results of natural frequency. In terms of different species, the average results of *E. nitens* CLT are higher than those of spruce CLT, considering all scenarios. In detail, HLH *E. nitens* CLT has significantly higher results than spruce CLT, while MLM and MMM CLT have slightly higher results compared to spruce CLT. This phenomenon can be explained by the following basic frequency equation:

$$f_n = \frac{\lambda_n}{2l^2}\sqrt{\frac{EI}{m}} \quad (6)$$

Where:

f_n = undamped natural frequency for the nth vibration mode; λ_n = frequency constant; l = span length (m); EI = apparent stiffness of the samples ($N.m^2$), and m = mass per meter (kg/m).

When using higher-MOE timber boards as outer layers, the CLT panels would have higher overall MOE, and while using higher-MOE timber board as inner layers, the overall MOE of the CLT panels have no significant difference (as shown in Table 2). According to the equation (6), higher E-value will increase the value of natural frequency. On the other hand, Spruce CLT has lower MOE compared to *E. nitens* CLT (much lower than HLH CLT and slightly lower than MLM and MMM CLT). However, its density is lower than *E. nitens* CLT (Table 2). While density of samples will contribute decreasing results of natural frequency based on Equation (6).

The results of this research also suggested that CLT samples with timber overlay exhibited higher results of natural frequency than with residential carpet. The results indicated that the employment of timber overlay may increase the stiffness of the whole system. In the prior study (Derikvand *et al.*, 2019) on Eucalyptus nailed-laminated timber (NLT), it was found that adding a layer of concrete can impact the structural vibration performance. However, whether this results in an improvement or not depends on factors such as the timber-concrete configurations and connection systems, which were suggested to further investigation. On the other hand, employing XYLOFON as soundproofing material did not show any influence on the results of natural frequency, when comparing to scenarios with the same coverings.

Furthermore, all CLT configurations and different scenarios exhibited significantly higher results when compared to the 8 Hz of minimum frequency, which has been stated in the serviceability requirement of the Australian standard (*AS/NZS 1170.0*, 2002). It is worth noting that these results are based on a span length of approximately 2 meters for CLT panels. As the span length increases, the natural frequency will decrease. Consequently, it becomes necessary to investigate the maximum span length of CLT under different scenarios above the specified 8 Hz of minimum frequency for the future research. Nevertheless, the results obtained in this study include comprehensive results for *E. nitens* CLT with different finishes, which have built a cornerstone for further research.

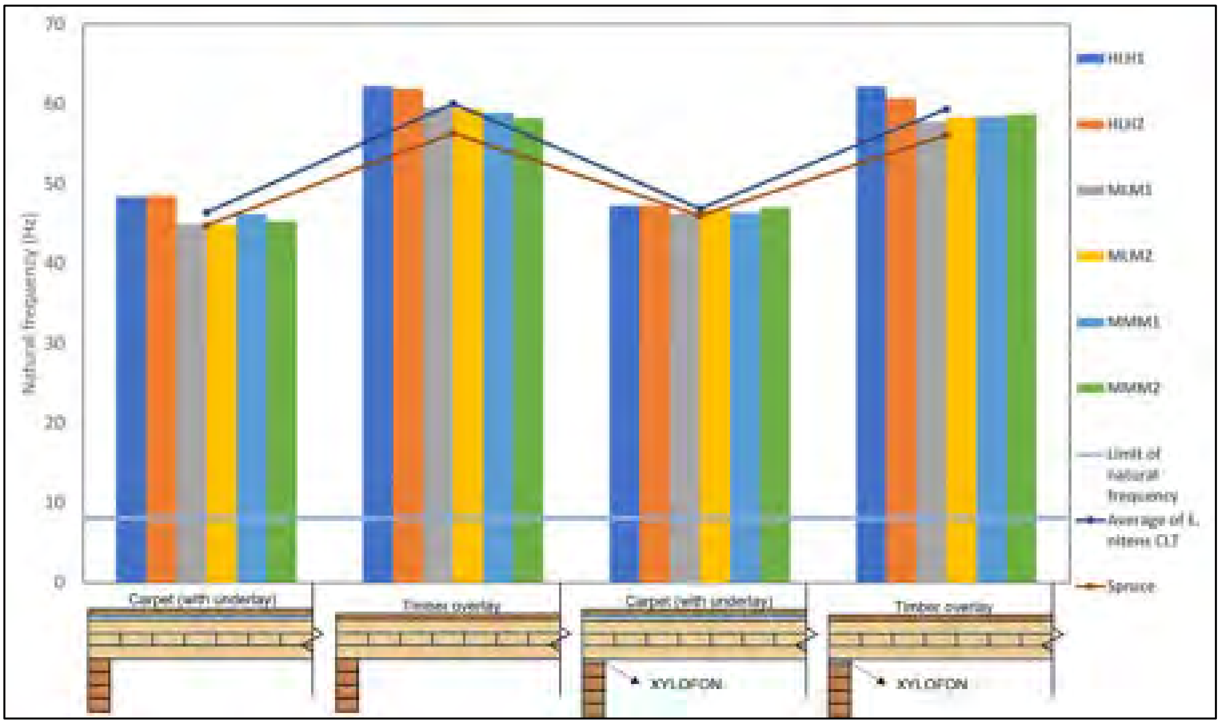


Figure 4. Comparison of results of natural frequency

4.3 Discussion of damping ratio

Damping ratio, on the other hand, has not been found any relationship between the stiffness of CLT from the obtained results in this study. However, the results have suggested that the implementation of a residential carpet (Scenario A) has higher results when comparing to the CLT samples with timber overlay. In addition, the use of XYLOFON can also increase the values of damping ratio by average of 28.6% comparing to the scenarios with the same coverings (Table 6).

It should be noted that XYLOFON is specifically designed as a soundproofing material to reduce structural noise, and it has been applied to CLT buildings by Rothoblass Solutions for Building Technology. The objective of applying XYLOFON in this study is to investigate the potential effect of it on vibration performance of CLT floors. The results in this study have indicated that the use of XYLOFON not only does not compromise the vibration performance of CLT samples, but also increase the values of damping ratio to a certain extent. Nevertheless, it is important to keep in mind that there is a wide range of available options for soundproofing materials in the industry, it is necessary to further investigate the impact of different soundproofing materials on the vibration performance of CLT.

According to Canadian CLT Handbook (Erol Karacabeyli, 2020), 2% of damping ratio is suggested for wood buildings without finish, and 3% of damping ratio is advisable for wood buildings with finish. In this study, most of the scenarios showed higher results of damping ratio than the reference number for wood buildings with finish (3%), except the one with timber overlay, which is slightly lower than the reference number. However, it is crucial to know that damping ratios in laboratory conditions may be much lower than real world situations. That is because the method of construction and workmanship have a significant influence on the values of damping ratio (Murray *et al.*, 1997, Dolan *et al.*, 1999). This study confirms this theoretical knowledge because the results of damping ratio showed significant variation when different supplementary materials were applied. Therefore, this study not only contributed the results of damping ratio from *E. nitens* CLT, but also provide insights for supplementary material selection for improving vibration performance of CLT floor.

Table 6. Comparison of results of damping ratio

CLT configurations	**Scenarios**				**Increase or decrease (%)**		
	A	**B**	**C**	**D**	**A - B**	**A - C**	**B - D**
HLH	3.1	2.3	4.5	4.0	-26.6	47.8	78.2
MLM	3.7	2.8	4.7	3.9	-24.1	25.8	37.9
MMM	4.2	2.9	4.2	3.4	-29.8	-0.5	16.3
Spruce	4.3	3.3	4.4	4.0	-21.7	2.9	20.4
Average	3.8	2.8	4.4	3.8	-25.5	19.0	38.2
COV (%)	14.3	15.6	4.8	7.4			

5. Conclusion

This study employed the conventional ball-dropping method to investigate the vibration performance of *E. nitens* CLT as well as the impact of using surface coverings and soundproofing materials. First-mode natural frequency and damping ratio were considered as the important parameters in this study. This is due to the fact that the first-mode natural frequency is the most important parameter in analysing the frequency response spectrum of a vibrated floor (Hassan and Girhammar, 2013), and also, damping ratio is highly related to the energy dissipation of the vibration.

The main objective of this study is to investigate the vibration performance of *E. nitens* CLT panels under different configurations and scenarios. These scenarios include the utilisation of residential carpet, timber overlay and XYLOFON. In addition, a spruce CLT with identical dimensions with *E. nitens* CLT is also included in this study, acting as a benchmark for reference purposes. The key findings of this study include:

- For *E. nitens* CLT panels, using higher-MOE timber boards in outer layers increased the values of natural frequency, while using higher-MOE timber boards in inner layers had no influence on the results of natural frequency.
- HLH *E. nitens* CLT has significantly higher results of natural frequency compared to spruce CLT, while MMM and MLM *E. nitens* CLT panels showed comparable results with spruce CLT. The overall results have shown that *E. nitens* CLT has better vibration performance than spruce CLT.
- The configurations of CLT showed little relationship with the results of damping ratio but different supplementary materials on CLT exhibited significant impact on the results of damping ratio.
- The natural frequencies were higher when implementing timber overlay as a surface treatment compared to using a residential carpet for all tested CLT samples. However, the damping ratio values exhibited the opposite trend between these two scenarios.

- The implementation of XYLOFON did not significantly influence the results of natural frequency, but it increased the results of damping ratio by 26.4% on average, when comparing to the same topping conditions.

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Heat in the streets

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Abstract: Heat stress from rising temperatures in the workplace is an urgent public health issue. The absence of canopy cover, excessive built-up areas with heat-reflective materials such as glass facades and concrete paving, the absence of shade provided by surrounding buildings, the width of streets, and traffic occupancy often aggravate heat stress in cities. This paper presents the outcomes of a research study to map, analyse, and visualise the lived experience of climate-exposed outdoor workers. The project sought to understand how experience data of heat-exposed urban workers can be communicated using digital tools and environmental sensors to derive evidence-based suggestions for developing heat-sensitive urban environments. Focusing on bicycle delivery couriers and outdoor council workers, the project draws on quantitative (temperature, humidity, and geo-location) and qualitative data (time worked and psychophysiological responses to heat) from outdoor urban workers. Minnow sensors, Strava (geo-location mapping), analogue intake and exit interviews, Google Street View, and online surveys were deployed for data acquisition, correlation, and prototyping of a real-time updating digital dashboard that served as a visual narrative of summer heat stress experienced by Sydney's essential outdoor workers. The dashboard is instrumental in revealing heat stress hotspots and corresponding opportunities for urban interventions (e.g., heat refuges, shade, landscaping) to mitigate urban heat effects while simultaneously revealing the lived experience data of the participant outdoor workers. A citizen science initiative, the research is instrumental in communicating the impact of the spatial, social, and policy landscape on critical climate emergencies to a broader audience.

Keywords: Heat stress; Vulnerable population; Qualitative and Quantitative research; Digital dashboard.

1. Introduction

At the time of writing, the publication of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2023) IPCC report and recent heat waves in the northern hemisphere (Copernicus Climate Change Service, 2023 Zachariah et al., 2023) reinforce the reality that climate change is already resulting in extreme heat events with concerns and has grave consequences for human mortality and morbidity as well as serious impact to society livelihoods and economies. Based on similar predictions for the future here in Australia and experience (Hill, Cumpston and Quintana Vigiloa, 2021), the question of heat stress and urban heat remains extremely relevant for the Australian context.

Against a backdrop of concerns about rising temperatures and urban heat, Zander et al. (2015) conducted studies in Australia focusing on heat stress, work, and productivity. They found major threats for many occupation classes. Climate heat is now recognised as posing 'immediate and pressing risks' for

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Australia (Stanley et al., 2017). In 2011, Hanna et al. addressed physiological impacts and policy responses and pointed to the need for more qualitative work. Qualitative research on the issue remains relatively weak. An important exception is Xiang et al. (2016) qualitative study in South Australia, which found that 30% of people working outdoors had experienced heat-related injuries (37% had experienced 'heat illness'). With no minimum national standard to address heat illness, the research found that only 20% of employees stated that work would cease when the temperature exceeded 40°C. Half of those surveyed had concerns about extreme heat and strongly favoured training, regulation, and workplace changes to address the problem.

Heat stress is an important factor in working conditions indoors (A.Y. Jia, D. Gilbert and S. Rowlinson 2018.) and outdoors. A substantial body of public health, industrial relations and occupational health and safety research reveals direct connections between working arrangements and worker health and safety outcomes (Quinlan, 2013). There are wider concerns about livelihood and productivity, with agriculture most clearly affected (Gornall et al., 2010; Kjellstrom et al., 2016). Insecure and underpaid outdoor workers are likely more vulnerable to heat stress than counterparts with better employment conditions. One US study found heat-related fatality 20 times more likely in the agriculture industry than in other sectors (Jackson and Rosenberg, 2010). Workers in these sectors are often self-employed or on piecework, and heat stress impacts livelihood and health.

Strong linkages exist between heat stress and the built environment regarding how cities are planned and constructed (Petkova et al., 2014; Smith and Levermore, 2009; Bulkeley et al., 2016). Exposure to heat is heavily stratified both across workplaces and in social contexts (Harlan et al., 2008). Reliance on home or work air conditioning and private transport can shape expectations for upper echelons; those unable to afford home cooling, who work in outdoor occupations and are dependent on public transport, can be much more exposed and, at the same time, more vulnerable. Inequity at the social, spatial, economic, and work flexibility front equally shapes our experience of heat stress. At the macro level, the emergence of satellite cities with large distances across suburbs only exacerbates exposure (Stone et al., 2010). Urban planning is also significant at the 'micro' level, such as access to water fountains and shaded and cooled resting spaces, preferably with foliage (Norton et al., 2015). Addressing such issues can be central to ensuring sociality in the city, enabling the city's connectivity and cultural vibrancy.

Within this context of heat stress, the paper presents the findings of the 'Heat in the Streets' research project funded by the City of Sydney in 2019. The project aimed to understand how the lived experience of heat-exposed urban workers can be collected, analysed, and communicated using digital tools and environmental sensors to derive evidence-based suggestions for developing heat-sensitive urban environments. The paper intends to provide urban planners and designers with evidence-based suggestions on developing contextually embedded heat-sensitive urban environments, subsequently enhancing accessibility and participation to and in the urban open spaces by the wider public, especially by outdoor urban workers. The research accordingly investigated the perspectives of heat-exposed workers on how infrastructure planning in the city, alongside workplace policies, could be improved. Heat-exposed workers as a vulnerable demographic were particularly chosen since their nature of work enables them to experience and reflect upon urban attributes such as the absence of tree canopy cover, excessively built-up areas with heat-reflective materials such as glass facades and concrete paving, the absence of shade provided by surrounding buildings, the width of streets, and traffic occupancy in certain urban zones of the city.

2. Methodology

The research primarily intended to create a participatory platform for gathering data on heat stress while adopting a citizen science methodology where participants socialise their experience of heat stress in a bottom-up, evidence-based manner. Citizen science resources such as citizenscience.org, citizensciencealliance.org, citsci.org and the 'Commons Lab' (Bonney et al. 2014; Bates et al. 2016) were referred to during the formulation of the citizen science-driven methodology. The research meticulously focused on mediating scientific data and participant experiences (Hochachka et al. 2012). Motivating participants to participate and making engagement accessible and simple via electronic devices based on common templates and interfaces were some of the mediation strategies involved in the project.

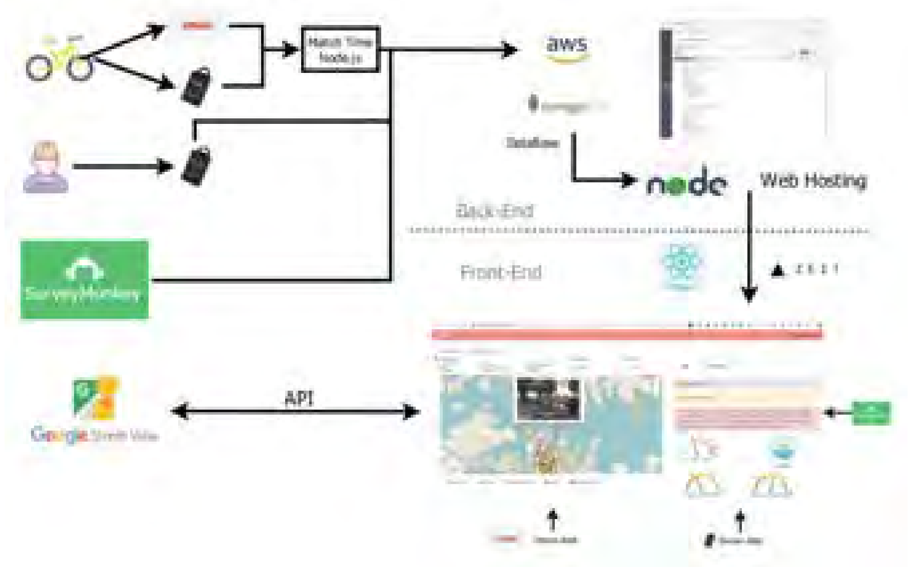

Figure 1 System architecture underlying the research.

Figure 1 illustrates the overall system architecture developed for the research and outlines the back-end computational processes (outdoor urban worker data collection using specific hardware and software, time-stamps-based data assimilation and data filtering, database development and web hosting), and front-end data visualization (Google street view and digital dashboard). Components comprising the system architecture are elaborated upon in the following sections:

2.1. Recruitment of urban workers

Urban workers, typically exposed to urban heat while conducting two distinct categories of work, are engaged in the study as citizen scientists:

- Workers in ongoing work for a government body (council outdoor workers): Six workers from the Parks Maintenance Unit in the City of Sydney and one worker from the road maintenance unit were identified to participate in the study.

- Gig workers working as subcontractors (bicycle delivery couriers): Eleven participants, eight document delivery courier workers and three food delivery workers, were recruited via a Facebook group for Sydney bike couriers.

2.2. Tools for Quantitative and Qualitative data collection

- Quantitative data: Heat stress data for each participant (bike couriers and council workers) was collected using a temperature and humidity data logger, namely, the Minnow Sensor 1.0 (Figure 2 - left). Minnow 1.0 offers accurate and repeatable logging for temperature and humidity. The device measures temperature to an accuracy of +/- 0.3 degrees centigrade over 5 - 60 degrees centigrade range and humidity to +/- 2.0% over the 20-80% humidity range. The geolocation of the participants is tracked in real-time using the Strava application (Figure 2 – right). Strava is a free social fitness application primarily used for tracking dynamic fitness activities such as cycling and running using mobile networks' GPS data.

Figure 25 Minnow Sensor 1.0 is used for temperature and humidity data (left), and the Strava application (right) tracks geo-location in real-time during on-field investigations.

- Qualitative information pertaining to the amount of time worked and physiological responses to heat, including a post-activity reflection, are captured via a five-minute survey using the SurveyMonkey application installed on each participant's mobile phone. Additionally, intake interviews, as well as exit interviews, were conducted with each participant to extract their subjective opinion and mitigation suggestions as regards heat stress. As a precautionary measure and as a nudge, both groups of participants were sent a text message prompting them to complete the survey about their experience of heat stress during mid-day. Participants were additionally sent an SMS the evening before each day reminding them to carry their Minnow sensors during work hours. Bike courier riders were also instructed to log in to their Strava application (on their mobile phones) while performing their job.

2.3. Data collection

As a pilot initiative, five hot days (identified via BoM environmental predictions) during March 2019 were selected to deploy and collect heat stress sensor data, Strava-based location data, and SurveyMonkey-based experiential data. Intake and exit interviews were conducted on-site, transcribed, and stored on secure cloud storage.

2.4. Back-end and front-end computing

Amazon web services and a MongoDB database store data collected from the Minnow sensors, Strava, SurveyMonkey, and transcribed interview sources. The disparate data sets were cleaned and filtered before database storage through a custom program developed using Node.js. OpenStreetMap (OSM) is used specifically as the underlying map layer in the dashboard's front end, on top of which heat stress-related geo-location data is plotted in conjunction with the integration of panoramic Google Street View.

3. Research Results

3.1. Digital heat-stress data visualisation prototype platform production

A prototype digital platform for indexing, analysing, and visualising quantitative and qualitative data sets collected during the research term was developed to intuitively communicate quantitative and qualitative aspects of heat stress. The data relating to heat stress measurement and geo-location were collected in addition to the digital survey and physically conducted interviews. The role of the dashboard was thus to aggregate the collected datasets and visualise all associated parameters relating to the experiences of each participant. These parameters included Temperature and Humidity to derive the Heat Index (a measure of how hot it feels when relative humidity is factored in with the air temperature (https://climate.ncsu.edu/climate/heat_index_climatology), the speed at the point of the collected measurement and the distance covered by the participant at the point of the acquired reading (for bike couriers). Besides this, salient features extracted from the interviews about the perception and experience of urban heat and how the workers cope with the same are also displayed (Figure 6). This adds a qualitative dimension to the otherwise quantitative datasets and enables comparison of on-ground environmental conditions with the participant's lived experience.

3.1.1. Data extraction

Both temperature and humidity were logged at a user-configurable logging rate (set to a reading rate of 1 minute in the case of this study), via a PC application program: Sensonics. Raw data relating to temperature and humidity was registered in the Sensonics platform and was automatically converted to a CSV file format for ease of transfer to a custom Mongo database through a custom program written in Node.js.

Bicycle Courier participants were instructed to download the Strava application and log in using accounts created for this research. Each participant’s recorded log was geo-spatially mapped using OpenStreetMap (Figure 3). These data sets are downloaded directly from the respective Strava accounts of each of the participants as GPX files. A custom program written in Node.js eventually extracted and transferred the geolocation and associated datasets to the custom-made Mongo database.

Figure 3 A screenshot from the Strava website showcasing geolocation and associated time segment (point-to-point) data plotted on OpenStreetMap.

3.1.2. Data filtering and correlation

An algorithm was further developed to extract matching data entries between Strava's geolocation data and the Minnow sensor's heat stress data. Data was obtained from both collection sources and was filtered with respect to time, date and participant id. The matching sets of heat stress and spatial data were subsequently stored in a custom MongoDB database developed for this research.

3.1.3. Data visualisation

The prototype digital dashboard visualises the correlated datasets in two distinct sections (Figure 4) with an operating menu bar at the top of the dashboard window. The menu bar allows intuitive navigation and selection of the following:

- Selection of participant type: Bicycle Couriers or Council Workers
- Selection of the Heat Index caution level
- Selection of individual participants and the day the data had been recorded.

Activating the Filter button after making the aforementioned selections results in the display of relevant data. Besides this, a Download option is also provided to extract the chosen selection-based data in an Excel worksheet format. A provision to see the plotted heat stress data in full screen is also made available in the dashboard (Figure 5). Below this section, a provision to visualise the Heat Index value per participant plotted in relation to the day of the selected data is made.

The primary visualisation section below the menu bar is divided into two halves: the left half displays a geospatial mapping of the filtered and correlated datasets. The matching data is plotted using OpenStreetMap in the dashboard's geospatial visualisation section. The visualisation is in the form of Heat Index plots at an interval of 5 minutes on the route taken per bike courier. The colour variation in these plots reflects heat-index caution levels (Figure 4). The right half of the screen is a real-time feed from the survey completed on the day, showcasing quantitative responses and open-ended, lived-experience-based comments.

Figure 4 Screenshot of the Dashboard Front-end with the Menu bar on top and two distinct Left and right data visualization sections.

Each plotted Heat Index point (in the OpenStreetMap section) can be clicked to activate a Google Street View pop-up window of the location to reveal the 3-dimensional nature of urban space in the immediate vicinity of the geolocation. This helps determine aspects such as the amount of tree cover, the height, material, and nature of buildings that could shade or produce heat in the streets, traffic conditions, land use, permeable vs. impermeable surfaces etc., at that location (Figure 6 Left). Furthermore, clicking on any participant data opens an interactive visual mapping of the Heat Index Reading progression compared with the actual Temperature changes for the chosen day.

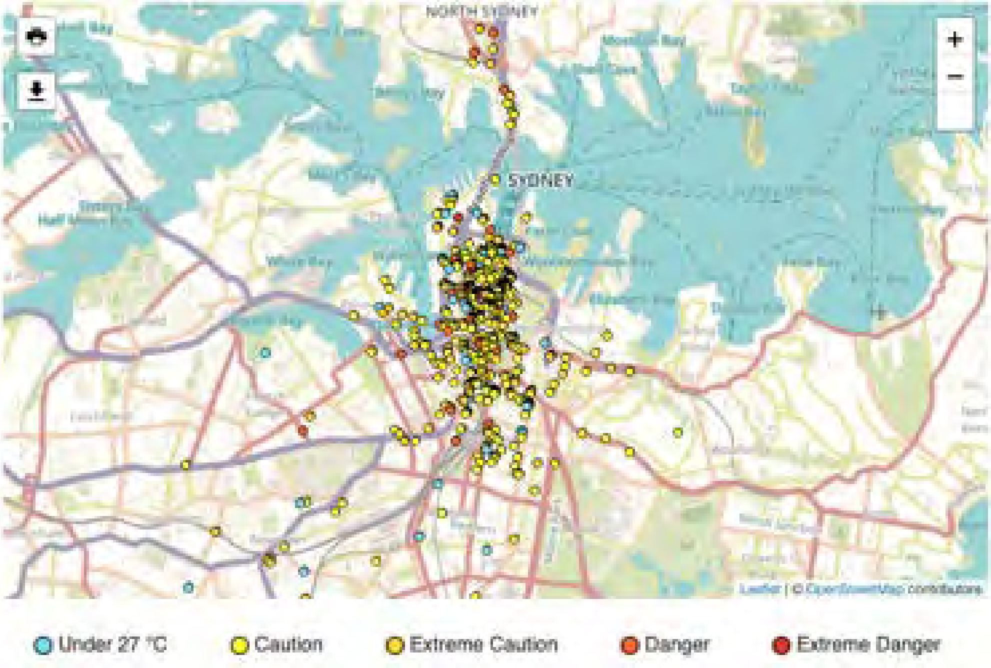

Figure 5 Left: Screenshot showcasing Google Street View corresponding to the selected Heat Stress Point Right: Screenshot of the right data visualization panel showcasing qualitative and quantitative datasets of a participant.

Figure 6 Screenshot showcasing Heat Index visualization on geolocated datasets of all participants on a given day and time interval.

The right side of the dashboard is coded for additional information display: In the home page view, the right side of the dashboard pane displays information graphics summarising the qualitative feedback (pertaining to experienced responses to thermal conditions, physiological response, and overall perception of temperature conditions during the term of the research) provided per participant. This data is collated from the survey forms and is based on the responses provided by actual participants in the study. Selecting a participant from the menu bar transforms the visual display on the right pane and showcases data relevant to the chosen participant: Participant ID, Survey data (quantitative and qualitative), excerpts from any interview conducted with the participant, Heat Index measurement and humidity measurement (Figure 6 Right).

3.2. Multi-domain research deductions

With its integrated quantitative and qualitative data correlation and visualisation ability, the digital dashboard prototype served as a rich platform for extracting multi-domain deductions contributing to urban heat stress. Initial data comparison demonstrated the well-established nexus between outside temperature/ humidity and work effort in producing heat stress. For ease of comprehension, the multi-domain deductions are categorised as follows:

3.2.1. Public health deductions

Psychophysiological impacts: Through the SurveyMonkey survey, it became apparent that heat stress had a similar impact on bike-courier and council workers. Almost half of all respondents stated they experienced heat stress at work, with three-quarters acknowledging they felt thirsty. A quarter to a third of bike-courier deliverers and council workers also felt overly fatigued, resulting in difficulty concentrating, and subsequently faced trouble completing assigned tasks (including a small proportion experiencing fainting or dizziness). Differences between how the two user groups attempt to mitigate heat stress became apparent from the salient feature extraction section of the dashboard. Two-fifths of the courier delivery workers resorted to extra breaks during hotter conditions; three-quarters of the courier delivery workers rehydrated more often; 10% had taken on lighter duties; and 4% stopped work. Only a fifth of the Council workers had taken extra breaks; two-fifths had otherwise changed how they did their work or where they worked; almost all Council workers rehydrated more often; 15% undertook lighter duties, and 9% stopped work. This inherent flexibility in how and when work is conducted during hotter conditions must be considered and translated into public health and wellbeing policies.

3.2.2. Policy deductions

Workplace policy: Exit transcribed interviews showed that the flexibility in work scheduling allowed council workers to reallocate the most physically exerting tasks. However, even though the bike delivery couriers could take more breaks (between deliveries), they could not take on lighter tasks due to their work schedules' non-flexible nature. Work policy for such vulnerable gig-economy workers thus needs to be revisited, and collaborative solutions involving private organisations, worker unions, and public policymakers need to be initiated accordingly.

Urban context and design features: Courier delivery workers, when provided with the opportunity to plan routes autonomously, took advantage of the available infrastructure of the city to mitigate the impacts of heat. Reported strategies included choosing to work in the CBD, where streets were shaded by the tall buildings in the middle of the day, or finding refuge in air-conditioned lobbies, cycling along tree-lined streets, or relegating strenuous or inclined routes to cooler parts of the day. Other key factors determining the choice of routes were the presence or absence of dedicated bicycle paths, the amount of congestion, and traffic density at different times of the day. Policies regulating the provision of supportive infrastructure, such as cycling routes, water fountains, tree canopy, etc., should be integrated and communicated with urban planning and development bodies.

3.2.3. Data deductions

OpenStreetMap-based plotting of heat index: The colour-coded plotting of heat stress in combination with the Google Street View images allows one to correlate the physical features of the built environment, such as the height, material, and density of the built fabric, the nature of surfaces (permeable vs. non-permeable), the nature of urban green (tree canopy, sky view), the nature of the activity (traffic flow, pedestrian flow, land-use), self-shading (building's shadows). For instance, in Figure 6, the blue plot depicts a temperature of under 27 degrees Celsius, even with the absence of tree cover and heavy traffic can be attributed to the degree of self-shading created by the proximity of high buildings, the non-reflective nature of the stone surface of the surrounding buildings, and the additional sun-shading enclosures. The nature of surfaces is, however, impermeable and could certainly be improved by adding urban green as a mitigation strategy for further heat reduction. Integrating three-dimensional visualisation of the urban context alongside two-dimensional statistical data is thus considered to add value while helping otherwise siloed domain-specific (transport, health, urban planning, environment) interpretations of tackling heat stress in the urban environment.

3.2.3. City council deductions

Lived-experience-driven advice to local councils: The lived-experience-based results from the research gathered irrefutable evidence-based data and can serve as a vital channel for communicating on-ground user needs to respective city councils. Exit interviews gathered valuable suggestions about how the council could minimise heat stress: sufficient infrastructure provision and adequate maintenance in the form of access to cold water, the introduction of working bubblers, and clear communication of public water access points across the city. Council workers suggested workplaces provide hydrates for mitigating humidity, non-polyester clothing, and roofing for shading on ride-on machines. Courier delivery workers suggested increasing natural and artificially produced shading on streets and rest areas, including installing water misters in specified public areas. Additionally, the provision of dedicated cycling lanes, a call to educate drivers and the use of slip-proof paint for cycleways were suggested to improve infrastructure quality. These are quintessential bottom-up feedback from the everyday citizen that could enrich the urban environment and positively improve health and wellbeing.

4. Conclusion

The project aimed to combine a citizen science approach to understanding the impacts of heat stress on heat-exposed urban workers with data analysis and visualisation techniques to create a digital platform for communicating the lived experience of such a vulnerable demographic. The digital platform and the underlying system architecture can process and visualise multiple forms of qualitative and quantitative data capable of data filtering and producing data correlation-driven informative visuals pertaining to various aspects of heat stress experienced by the participants. The prototype platform is fully scalable and can drill down to an individual participant level to extract personalized heat stress-related contextual determinants. Besides this, the ability to spatialize the received data alongside embedding Google Street View imagery per geospatial heat stress point allowed the information to become easily accessible and comprehensible to a larger audience while allowing one to study the determinants of heat stress in a contextually embedded manner.

The prototype can be further refined to stream real-time data that can be made freely available to view by city councils and residents alike. The platforms could also be enriched by developing a mobile application version built on the same platform footprint wherein survey forms, note-taking and commenting, and geolocation are combined into one seamless package. It would also be possible to integrate real-time temperature and heat stress data at fixed points within the city through smart poles/bus stops, etc. A network of such sensors (IoT devices) would allow for the development of a temporal understanding of key places of interest — public parks, public spaces, bus stops and other areas where citizens are exposed to the vagaries of climate.

The research also demonstrated the well-established nexus between temperature, humidity, and work effort in producing heat stress. The capacity to minimise exertion during the hotter times of the day and allocate work requiring more effort during cooler days/times can be critical. The research findings also suggest the importance of workplace autonomy in determining the pace and type of work, thus shaping the experience. Besides this, the role of the built environment, especially mitigation-focused urban infrastructure development such as providing cold water, bubblers and misters at strategic locations, tree canopy and shading, dedicated cycling lanes etc., was brought to the fore via this evidence-based citizen-driven research.

Overall, the research successfully prototyped a digital tool for communicating the lived experience of heat-exposed urban workers. In doing so, multiple mitigation strategies ranging from flexible work policies, urban infrastructure, lived-experience-driven advice to local councils, and a reflective evaluation of the potential and possible development of the prototype were bought to the fore.

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6. Research ethics

The University of Technology Sydney Human Research Ethics Committee granted research ethics for the project (UTS HREC ETH17-1817).

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Hempcrete housing: a preliminary evaluation of the relationship between housing typology and demand on agricultural land

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Abstract: At a time when awareness of the need to accelerate the uptake of low carbon construction practices is at an all-time high, it is critical to reflect on the rich histories of such already existing materials. Industrial hemp is a plant with a troubled history, but one with the potential to alleviate the troubled future that the world faces, staring down the barrel of climate change. Hempcrete is an example of a low-carbon material which has struggled to permeate into mainstream construction. Through visualizing the impacts that an accelerated uptake of hempcrete for medium-density housing may have on agricultural land use, it is possible to envision what a future of hemp-based construction looks like in Aotearoa New Zealand. These insights are further contextualised by comparisons to the agricultural land use of different diet types, acknowledging the concerns for food safety that rise with discussions of transition to a bio-based economy. The case study undertaken demonstrates that the quantity of adjoining housing units directly influences the volume of hempcrete required for construction, when adjusted for the number of units provided or people housed. Furthermore, the data implies that the required agricultural land, adjusted per occupant, is equivalent to that required to sustain one person on a plant-based diet for one year.

Keywords: hemp-based construction; carbon-neutral construction; barriers; stigma over time.

1. Introduction

It is possible to build healthy, carbon negative buildings at scale today, using hemp-based construction materials – but that is not a common practice. Why is that? At a time when awareness of the need to accelerate the uptake of low carbon construction practices is at an all-time high, it is critical to reflect on the rich histories of such already existing materials. This paper reviews the social and technical history of industrial hemp, and its roles in construction, with the aim to start understanding the impacts that a wider uptake of hempcrete construction may have on agricultural land use in Aotearoa New Zealand.

In order to better understand the impacts of a hypothetical increase in use of hempcrete, a case study investigation is undertaken using five sample buildings – two different two-storey townhouses, and three different three-storey walk-up apartments. Preliminary estimates are made for the volumes of hempcrete required by these buildings, which are then discussed in relation to agricultural land use and resultant housing density. This paper offers a preliminary visualization of the relationships between bio-based material consumption, demand on agricultural land and effective housing density, further contextualised by comparisons to the agricultural land use of different diet types.

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2. A brief history of industrial hemp

Hemp fibres have recorded uses in construction as early as 500AD (Özdamar, 2021). The Pont de Saint-Céneri-le-Gérei bridge in France was built around 500AD, and utilises a mortar comprised of at least 10% hemp fibre. The Rustem Pasha and Sultan Ahmed mosques in Istanbul, built in the 1550s and 1610s respectively, also used hemp-based mortars in their construction (Özdamar, 2021). These structures have lasted so long in part because the cellular structure of hemp fibres allow them to effectively absorb and release moisture, reducing the impact of moisture-based corrosion over time. The practice of mixing hemp fibres with earth or clay also appeared throughout history. Constructed in the 6th century AD (around the same time as the Pont de Saint-Céneri-le-Gérei bridge in France), the sacred Ellora Caves in India utilise an earthen plaster reinforced with hemp fibres, which in recent years has been attributed to the longevity of the caves (Singh et al., 2018). Hemp rope was another common use for hemp in construction, and hemp stalks have also been used in place of straw for thatched roofs. Built in 1698 and still standing today, The Nakamura Family Residence in Miasa-mura, Japan employs a thatched hemp roof, internal partitions made from hemp stalks and timber structural members tied together using hemp rope (Özdamar, 2021).

The fibres of the hemp plant (Cannabis sativa) have been used in textile production for domestic and industrial applications for centuries, with estimates as early as 8000BC (Özdamar, 2021). The seeds of the plant have been used in food production since approximately 3000BC (Li 1974; Cerino et al., 2021). Rope and canvas derived from hemp was used for shipbuilding in Europe as early as 600AD, and hemp production continued to be a major industry for the British Navy well into the 1700s (Fike, 2016). This affinity for hemp-based textiles continued into the early days of the United States, where the first American flag was woven from hemp, and the Declaration of Independence drafted on hemp paper (Crini et al., 2020). Industrial usage of hemp, particularly in the Western world, would later decline throughout the twentieth century. Competition from cheaper natural fibres such as cotton began to impact hemp cultivation in the mid-nineteenth century, with competition from synthetic fibres occurring in the early twentieth century (Crini et al., 2020).

The social stigmatization that often plagues hemp today originated in the 1920s and 1930s, during prohibition in Western society, namely in the United States (Chasteen, 2016). The 1920s saw an increase in campaigning for the restriction of hemp-based products due to the biological relation with marijuana, as both were derived from the Cannabis sativa genus. The 1930s brought a wave of legislative action, resulting in hemp cultivation being outlawed or severely restricted in most Western nations (Crini et al., 2020; Özdamar, 2021). In the United States, hemp production for industrial usage dwindled until a significant peak occurred during World War Two, due to shortages of other fibres (Johnson, 2014; Fike, 2017). This would decline to nothing by the late 1950s, as anti-narcotic sentiments moved to the forefront of Western politics (Johnson, 2014). The late 1980s and 1990s brought a renaissance of sorts for both industrial and agricultural use of the hemp plant. The first form of hempcrete was patented by Charles Rasetti in 1986, and hemp-based concretes were used often in France throughout the 1990s as an alternative to wattle and daub, for the restoration of historic buildings (Crini et al., 2020).

The opportunities for wider adoption of bio-based materials in the building industry are considerable, as global economies shift in favour of lower carbon emissions (Bennich and Belyazid, 2017; Pittau et al., 2018). Industrial hemp is well positioned to play several roles in this ongoing transition. Given this long and varied history of hemp use in construction, it is relevant to evaluate if besides stigma there might have been other reasons to avoid extensive use of hemp. Only, if no such reasons can be identified, it would be valid to propose a substantial increase in use of hemp in contemporary construction.

3. Agriculture, hemp and bio-based construction

3.1. Agricultural context

Before intensifying the use of hemp for construction, it is important to consider any issues that increase may be presented for agriculture, in terms of agricultural practices needed to grow industrial hemp. There is an extensive body of literature detailing the unique bio-remediation properties of the hemp plant. Hemp is a fast-growing hyperaccumulator plant, typically reaching maturity in 3-4 months, which can absorb considerable quantities of heavy metals from contaminated soils (Ahmad *et al*., 2016). In the New Zealand context, hemp has been considered as an alternate solution to restoring the soil health of land used for landfarming. Landfarming is an agricultural practice common in the Taranaki district, where drilling waste contaminated with hydrocarbons from fossil fuel exploration is spread through soil and sown with a pasture crop to facilitate bioremediation of the soil (Kerckhoffs *et al*., 2015).

The use of land-farmed soils for dairy farming and other means of food production is currently prohibited due to public concern over health risks (Kerckhoffs *et al*., 2015), but research is ongoing into whether the fibres and hurds from hemp grown on land-farmed soils would pose risks to human health as construction materials. A report by Cavanagh (2015) found that the concerns regarding the use of landfarmed soils for food production were unnecessary but acknowledged that some further research would be beneficial. This opportunity highlights one potential avenue for the expansion of the hemp industry, with a particularly appealing sentiment of circularity in growing carbon-negative building materials from soils tainted by the fossil fuel industry.

3.2. Implications for food production

While the multi-faceted benefits of industrial hemp in a changing agricultural economy have been discussed at a surface level, it is also important to consider how might an increase in land use to grow our buildings impact the land needed to grow food. There is the previously discussed nuance that some land, such as land-farmed soils, is unsuitable for food production. Reasonable caution has been expressed in literature that the transition to a bio-based economy, including the wider uptake of bio-based construction materials, may pose a threat to food security (Langeveld et al., 2010; Osseweijer et al., 2010). This is an important consideration. Because hemp is fast-growing, it is possible to achieve 3 harvests per year from the same land if the local climate permits it. However, to consider more directly how an increase in consumption of industrial hemp might impact food production, it is useful to consider the land footprint of different diets is considered. Peters et al. (2016) provide a well-detailed overview of the impacts of different recommended diets on agricultural land. The data is based on recommended diets in the United States but is considered relevant and reasonably transferrable to the New Zealand context also (see Table 1), and clearly shows very significant improvements which are possible by moving towards plant-based diets

Table 1: Relationships between typical diets and agricultural land use. (Based on: Peters *et al*., 2016)

Diet Type	Agricultural land required per person, per year (ha)	Number of people fed by 10 hectares, for one year
Vegan	0.13	76.92
Vegetarian	0.14	71.42
Omnivorous	0.93	10.75

Dietary changes are often posed as strong individual actions which people can make to reduce their carbon footprint. According to Alexander *et al*. (2016), New Zealand has the least sustainable diet in the world. Their study found that if every country were to adopt the typical New Zealand diet, 191.2% of the land used globally for agriculture would be required to sustain it – which is simply not possible, let alone sustainable.

4. Hempcrete for medium-density housing

4.1. Technical performance of hempcrete

Hempcrete is a bio-based building material with a range of attractive sustainable qualities. At face value, these materials are carbon negative due to the hemp plant's high capacity for carbon sequestration, theoretically enabling zero-carbon buildings (Ingrao *et al*., 2015; Arehart *et al*., 2020). Hempcrete is also particularly attractive as it uses hemp hurds, the byproduct of hemp cultivation, rather than the hemp fibres – a primary product, which are used in textile applications and other hemp-based materials, such as hemp-wool insulation (Promhuad *et al*., 2022). The seed of the hemp plant also has various applications in food production, including hempseed oil and hemp flour (Promhuad *et al*., 2022). Therefore, all major components of plant can be efficiently utilised. Furthermore, hempcrete is a non-toxic material – once cast, it does not off-gas or release any volatile organic compounds (VOCs) (Magwood, 2016).

Hempcrete tends to be promoted based on five key benefits: carbon negativity, thermal insulation, moisture capacity, fire resistance and durability against most forms of corrosion or decay. The effectiveness of the material is greatly influenced by the mix ratio of the hemp hurds, binder and water, with lighter densities typically exhibiting more favourable properties (Walker and Pavia, 2014; Florentin et al., 2017; Arehart et al., 2020). While the embodied carbon of hempcrete will naturally fluctuate based on the sourcing of raw materials, as well as emissions due to manufacturing and transportation processes, lower density hempcretes (i.e., those with less binder) generally have lower embodied carbon (Arehart et al., 2020). Extensive research (Sassoni et al., 2014; Pochwała et al., 2020) has demonstrated that hempcrete is fire resistant, however product testing and certification has lagged behind this knowledge, particularly in Australasia. Some fire exposure tests have been undertaken in Australia in recent years, with a test on a 300mm thick Tradical® hempcrete wall being certified (Tradical and OzHemp, n.d.). In terms of durability, hempcrete is resilient against reasonable levels of moisture and does not support mould growth or attract insects, in large part due to the lime binder (Walker et al., 2014; Magwood, 2016).

4.2. Industrial context in New Zealand

The twenty-first century has brought an accelerating series of reforms internationally, in favour of hemp-based products. In New Zealand, The Misuse of Drugs (Industrial Hemp) Regulations 2006 and the Food Regulations 2015 were both amended in late 2018 to allow the sale of hempseed products as food (MPI, 2018). The quantity of hemp grown in New Zealand would subsequently quintuple between 2018 and 2020, from 259 hectares to 1,335 hectares of cultivated land (Venture Taranaki, 2022). In 2022, a report by Venture Taranaki provided the most comprehensive overview to date of New Zealand's market potential to grow hemp for construction, positioning Taranaki as a suitable region to expand within. Key uptake barriers identified included: the cost and process of licensing for farmers (annual renewal of licences is required to grow hemp, under the Misuse of Drugs (Industrial Hemp) Regulations 2006), the lack of clear building code compliance pathways for hempcrete buildings, transport logistics for the processing of hemp hurd and the limited number of processing facilities in New Zealand (Venture Taranaki, 2022).

4.3. Thermal performance of existing hempcrete products

The thermal properties of different hempcrete mixtures have been well documented (Magwood 2016; Arehart *et al*., 2020). The porous structure of hemp particles enables the material to have a high moisture capacity, while the air pockets trapped in the aggregate make it an effective insulator (Walker and Pavia, 2014). Lighter-density mixes of hempcrete typically have lower thermal conductivities, however commercially available products are generally limited to somewhere between the light and medium densities listed in Table 2. IsoHemp and BIOSYS are two European hempcrete block products, each with thermal conductivities of 0.071 (CSTB, 2018; IsoHemp, 2023), landing them within the light-medium range discussed by Arehart *et al*. (2020). For the purposes of this study, a hempcrete mix ratio of 1 part hemp hurd, 1.5 parts binder and 1.75 parts water will be assumed, as a midpoint between the light and medium densities listed in Table 2.

Table 2: Insulating properties of different hempcrete densities (adapted from Arehart *et al*., 2020).

Hempcrete density	Thermal conductivity (W/mK)	R-value per 140mm	Parts hemp hurd	Parts binder	Parts water
Very light	0.032	R4.3	1	1	1.5
Light	0.053	R2.6	1	1.25	1.75
Medium	0.085	R1.6	1	1.75	1.75
Heavy	0.137	R1.0	1	2.5	2.25

4.4. Reflection

Hempcrete can be detailed in several formats, such as pre-cast blockwork or panels, or cast in-situ. The limited number of hempcrete builds in New Zealand to date have tended to be cast in-situ in layers, using similar methods to rammed earth construction (Venture Taranaki, 2022). For larger scale buildings, such as medium-density housing, prefabricated methods are likely to be optimal both for consistency of performance and for on-site construction time. While there have been a variety of developments for the deployment of such techniques overseas, the New Zealand market is still limited in its options.

5. Case study: relating housing typology to hemp and agricultural land requirements

5.1. Method

In order to better understand the impacts of a hypothetical increase in use of hempcrete, a case study investigation was undertaken using five sample buildings. The buildings sampled in this study are based on plans submitted at the resource consent phase of the Kāinga Ora Arlington housing development in Mount Cook, Wellington (Designgroup Stapleton Elliot, 2019). The plans were adapted, assuming timber framing in accordance with NZS 3604, and incorporating high-performance hempcrete external walls (Figure 1).

An approximate figure for the amount of agricultural land needed to supply the hemp hurd for one 150m^2 house is 3 acres, or 1.2 hectares (HBANZ, n.d.; Venture Taranaki, 2022). However, these sources do not clarify some of the assumptions made to achieve this figure, such as the wall thickness, hempcrete composition and whether or not the figure is limited to the external walls. Nonetheless, it serves as a base point for comparison with the results of this research. The following evaluation will offer insights as to how reliable this figure may be.

The calculations made in this section approach only the external walls of the building envelope, all other envelope components and internal partitions were assumed to be retained, as in the existing plans, and therefore have been excluded from the scope of this study. An initial net wall volume is calculated by multiplying the total wall area by the thickness of hempcrete in the wall (280 millimetres), excluding other layers of the wall, with an assumed timber fraction then subtracted from the resultant volume. Acknowledging that this is a much thicker wall composition than standard practices, and that timber framing is only present in one of the two 140-millimetre layers of hempcrete (Figure 1), a timber fraction of 17% is assumed – half of the 34% figure reported by BRANZ studies (Ryan et al., 2020).

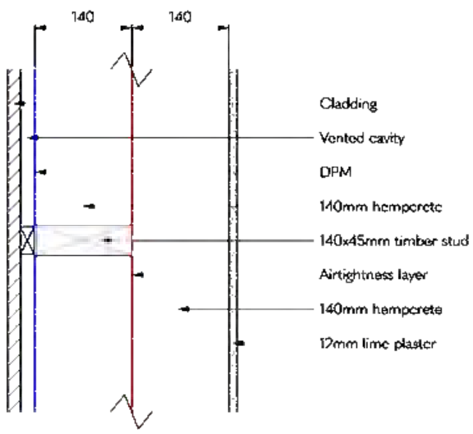

Figure 1: Typical hempcrete wall composition for case study. (Source: Author)

The indicative hempcrete volume is subsequently used to calculate the approximate volume of hemp hurd required – assuming a light-medium mixture ratio (by mass) of 1 parts hemp hurd, 1.5 parts binder and 1.75 parts water, as previously discussed. The volume of water present in the mix is not counted in the calculations, only the 1 parts hemp hurd and 1.5 parts binder, and a maximum density of 160kgm^{-3} is assumed for the dry hemp hurd (Delhomme *et al*., 2020). The following equation is used:

$$C = \frac{(0.4(xy))}{z} \quad (1)$$

Where:

C = volume of hemp hurd; x = volume of hempcrete; y = density of hempcrete; z = dry hemp hurd density.

5.2. Overview of results

Table 3 summarizes the calculations made to determine the indicative volumes of hempcrete required for the buildings sampled in this research. Further details of the sampled buildings are as follows:

- **Walk-up type 1** – three floors, each with four two-bedroom apartments. Two open-air access stairways separating pairs of apartments, with intertenancy walls between the innermost apartments.
- **Walk-up type 2** – three floors, each with two three-bedroom apartments. One open-air access stairway at the centre of the building, separating pairs of apartments.
- **Walk-up type 3** – three floors, each with two two-bedroom apartments. One open-air access stairway at the centre of the building, separating pairs of apartments.
- **Townhouse type 1** – two-storey townhouses. Two five-bedroom units adjoined by an intertenancy wall.
- **Townhouse type 2** – two-storey townhouses. Five four-bedroom units with adjoining intertenancy walls.

Table 3: Indicative hempcrete requirements for sampled buildings.

Building	Housing units	Envelope wall area	Net wall volume	17% timber fraction	Approximate hempcrete volume	Approximate hemp hurd volume
Walk-up type 1	12 (2-bed)	880.58m^2	246.56m^3	41.92m^3	204.64m^3	127.9m^3
Walk-up type 2	6 (3-bed)	636.1m^2	178.1m^3	30.28m^3	147.82m^3	92.39m^3
Walk-up type 3	6 (2-bed)	539.4m^2	151m^3	25.67m^3	125.33m^3	78.33m^3
Townhouse type 1	2 (5-bed)	233.5m^2	65.37m^3	11.11m^3	54.26m^3	33.91m^3
Townhouse type 2	5 (4-bed)	484.7m^2	135.72m^3	23.07m^3	112.65m^3	70.4m^3

Table 4 further analyses the data from the previous table, correlating the indicative hempcrete demand with the number of people housed. From this data preliminary observations can be made regarding the relationships between medium-density housing typologies, in terms of both quantities of people housed and of land used, and the demand for agricultural land to provide the hemp. Figure 2 summarizes the data from Table 4, adjusting for the differing sizes of the five sampled buildings.

One New Zealand grower reported that they would expect to harvest up to 6 tons of hemp hurd per hectare, on a good year (Venture Taranaki, 2022). Hemp hurd typically comprises 60-80% of the plant’s stalk (Magwood, 2016). Zvirgdzs *et al*. (2023) report that between 5 and 15 tons of hemp stalks may be harvested per hectare.

Assuming a midpoint of 70% hemp hurd, this would translate to between 3.5 and 10.5 tons of hemp hurd per hectare. The 6 tons reported by Venture Taranaki (2022) fits comfortably within this range, which when divided by the previously assumed dry hemp hurd density of $160kgm^{-3}$, gives an approximate yield of $37.5m^3$ of hemp hurd per hectare. While one grower reported this figure as the harvest from a good year, the literature reinforces the figure as reliable, especially as practices and infrastructure improve. Figure 3 summarizes and adjusts the data from Table 4, comparing the approximate area of agricultural land needed to provide the required hemp hurd for each building, to the number of people housed.

Table 4: Correlation between housing typology and material requirements.

Building	Housing units	People housed	Building footprint	Approximate required hemp hurd volume	Approximate land area to provide hemp
Walk-up type 1	12 (2-bed)	36	$374.4m^2$	$127.9m^3$	3.41ha
Walk-up type 2	6 (3-bed)	24	$248.5m^2$	$92.39m^3$	2.46ha
Walk-up type 3	6 (2-bed)	18	$219.4m^2$	$78.33m^3$	2.09ha
Townhouse type 1	2 (5-bed)	12	$177.6m^2$	$33.91m^3$	0.9ha
Townhouse type 2	5 (4-bed)	25	$343.5m^2$	$70.4m^3$	1.88ha

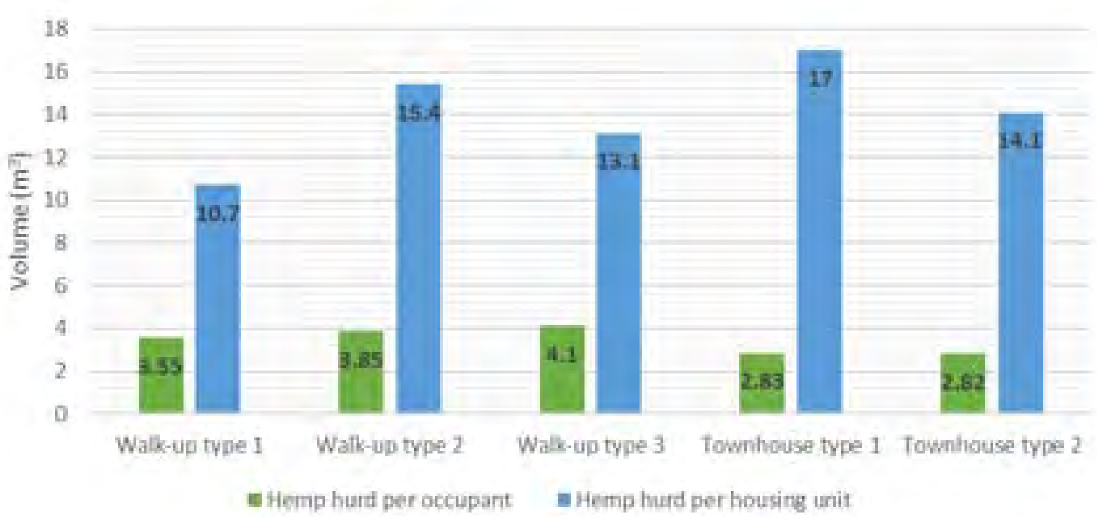

Figure 2: Adjusted correlation between housing typology and material requirements. (Source: Author)

Figure 3: Adjusted correlation between agricultural land use and people housed. (Source: Author)

6. Discussion of results

The preliminary results indicate that higher-density three-storey walk-up apartments generally required less hempcrete per housing unit, but the lower-density two-storey townhouses required less hempcrete per occupant. This observation is in part due to the varying occupant densities of the housing units, where the townhouses in the sample were four of five-bedroom units, and the walk-up apartments were two or three-bedroom units. In the sample buildings, hempcrete is used only for the external walls of the building envelopes. Walk-up type 1 was the largest building in the sample, and had the lowest hempcrete requirement per unit, and a lower hempcrete requirement per occupant than both other three-storey walk-up apartment buildings. This is due to the increased number of adjoining units, with four apartments per floor, as opposed to two apartments per floor in the other three storey walk-ups. This also applied to the two-storey townhouses sampled. Townhouse type 2 had five adjoining units and required notably less hempcrete per housing unit than townhouse type 1, which only had two adjoining units.

It is worth re-iterating that the sampled buildings are all from a Kāinga Ora social housing development, and that by nature Kāinga Ora buildings tend to have more compact plans and building footprints, particularly when compared to 150m2 detached single dwellings. Returning to the previous statistic that 1.2 hectares of land provides the hemp hurd for a single 150m2 house (HBANZ, n.d.; Venture Taranaki, 2022), some comparisons can be drawn with the data from this study. Two key assumptions to note, however, are that the walls of this hypothetical detached dwelling are likely to have been thicker than the 280 millimetres considered in this study and some internal hempcrete walling is likely to have been included. If one were also to assume three bedrooms and a nuclear family unit of four people, there would be an agricultural land requirement of 0.3 hectares per occupant. Even when considering the assumptions noted above, this is significantly higher than walk-up type 3, which had an agricultural land requirement of 0.12 hectares per occupant – the highest in the sample.

7. Further discussion: relating agriculture to architecture

Bringing things full circle, Table 5 further summarizes previously reported data from the case study, to be comparable with Peters *et al.*'s (2016) data regarding the agricultural land use of different diets, which was previously reported in Table 1.

Table 5: Correlation between people housed and land required to supply hemp.

Building	People housed	Agricultural land required per occupant (ha)
Walk-up type 1	36	0.09
Walk-up type 2	24	0.1
Walk-up type 3	18	0.12
Townhouse type 1	12	0.08
Townhouse type 2	25	0.075

The data indicates that for all sampled building types, less agricultural land is required per occupant or per person housed, than is required to sustain one person on a plant-based diet for one full year. However, given that meat-eaters' diets are more than seven times more intensive in terms of need for agricultural land, this shows that using hempcrete to build lasting housing for people consumes less agricultural land than feeding those people for only one year. This is especially relevant for New Zealand, considering research showing that New Zealand has the least sustainable diet globally (Alexander *et al., 2016*). This observation seriously challenges the notion that there should be competition between agricultural land use for food production and for growing building materials – especially given that if just a proportion of meat-eaters were to shift to plant-based diets, there would be enough land to supply a significant number of hempcrete buildings. Taking this together with other advantages associated with hemp, it is difficult to see why hemp generally and hempcrete specifically are not more frequently used in contemporary construction.

The fluctuations between the designs of each sampled building provide a range of results. This range is useful, enabling further comparison of the agricultural land demand of hempcrete housing to that of different diets. Walk-up type 1 and both types of townhouses sampled required less than 0.1 hectares of agricultural land per occupant. Walk-up types 2 and 3 both required 0.1 hectares or more agricultural land per occupant. None of the sampled buildings required more agricultural land per occupant than that needed to sustain one person on a vegan or vegetarian diet for one year, which would be 0.13 or 0.14 hectares, respectively (Peters *et al.*, 2016). The 150m^2 detached dwelling considered as a base point for this study (HBANZ, n.d.; Venture Taranaki, 2022) required 0.3 hectares of agricultural land per occupant, making it more intensive than the ranges discussed, but less intensive still than the 0.93 hectares of agricultural land needed to sustain one person on a typical omnivorous diet for one year (Peters *et al.*, 2016).

However, it is also important to acknowledge the limitations of this analysis. Due to the nature of the assumptions made in this study, it is critical to acknowledge that some of the data used here is likely to fluctuate for a range of reasons. It is possible that in some instances, when growth conditions are not ideal or other growth limitations are encountered, more land will be needed to produce the assumed quantities of hemp. This analysis points at another really important variable being in the design of the units. It showed that many aspects of design will influence the final quantities of hemp needed for construction both per unit and per occupant. This being said, the hope is that this data will inspire similar future analyses and research, gradually increasing the quantity of data in this important field of study.6. Conclusion

For the example of hempcrete, this research has explored a range of factors relevant to consider when looking to accelerate carbon neutral practices in construction. The long history of hemp usage in a range of industrial applications was considered, as were issues of social stigmatization and Western anti-drug rhetoric. Performance properties were also evaluated, and particular attention was given to the importance of the agricultural land needed to grow hemp and its possible competition with the agricultural land needed for food production.

The case study undertaken has demonstrated that the number of housing units directly influences the volume of hempcrete required for construction, in comparison to the number of units provided or people accommodated. Although a future study with a broader more systematised housing sample would be beneficial in order to further understand these correlations, this range shows that hempcrete compares well against common lifestyle choices. This research has shown that the area of agricultural land required per occupant, to supply the required volume of hemp for their part of the house, is approximately equivalent to the area of agricultural land required to sustain one person on a plant-based diet for one year. Of course, the houses would last significantly longer than one year. Therefore, this paper presents preliminary findings on the relationship between the agricultural demand of food production and that of bio-based building materials, using hempcrete as the case study. It also explored the impacts of increasing housing density and material consumption across different housing typologies and scales. The results are striking, with long lists of advantages for using hempcrete, and generally a hundred-year-old stigma presenting obstructions to a greater uptake of hempcrete in contemporary sustainable construction.

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Hygrothermal and bio-hygrothermal risks to architecture: moisture accumulation, indoor mould growth, and energy efficiency

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Abstract: Hygrothermal and bio-hygrothermal risks within buildings are commonly acknowledged to be synergistic effects of the interrelated factors of the outdoor climate, envelope material selection, indoor climate, and operational profiles. This paper provides a summary of a literature review of hygrothermal (heat and moisture) and bio-hygrothermal (mould growth) risk analyses of buildings. Responding to Australia's industry and government needs to inform ongoing enhancements to the national building regulations, the aim of this review is to bring together the current research, methodologies, evidence on prevalence, and risk factors in this field, and to explore the implications that may be caused by Australia's intermittent conditioning requirements and the major reliance on occupant operated ventilation to manage interior relative humidity within old and new residential buildings. This research has applied a two-step research approach, namely a bibliometric analysis and a systematic literature review. Using bibliometric techniques, 7194 documents regarding the theme were analysed that were published from 2008 to 2023, and then further limited to articles with the occurrence of keywords, analysed papers of key research clusters to further unpack current knowledge of this area. This systematic literature review focuses on the factors, causes and mitigations of the hygrothermal and bio-hygrothermal risks in energy efficiency buildings, to identify that the research gaps are still significant. For temperate climates, impact from intermittent occupation and conditioning and the reliance on occupant managed interior relative humidity control haven't been adequately captured in the regulations, standards, or simulation processes.

Keywords: hygrothermal, bio-hygrothermal risk, sustainable building design, bibliometric research, indoor air quality, sick building syndrome, dampness of building, literature review, VOS Viewer

1. Introduction

Sustainable buildings are the focus of the 21st century architectural profession in response to actions needed to mitigate global climate change. The amount of future warming the Earth will experience depends on how much carbon dioxide and other greenhouse gases are emitted in the coming years. (Global ABC, 2019) The design, construction, operation and demolition of buildings are responsible for more than 40% of energy consumption and greenhouse gas emissions (Global ABC, 2019). Actions that reduce the energy consumption and emissions associated with buildings are among the most cost-effective, greenhouse gas mitigation measures available (Zhong et al., 2021). However, energy-efficient

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buildings can offer favourable conditions for mould growth in terms of more ideal temperatures, increased nutrients and higher interior air moisture content (Brambilla and Sangiorgio, 2020). Advanced sustainability guides advocate the use of bio and renewable materials, such as timber, agricultural bioproducts, and natural fibres. Generally, these materials are particularly sensitive to moisture and mould that can be easily decomposed by fungi, instead of historically high carbon emission emitting materials like concrete and steel. However, natural materials are more sensitive to moisture and mould (Austigard and Mattsson, 2020; Hoang et al., 2010; Mensah-Attipoe et al., 2015; Spiegel and Meadows, 2010). Mould not only feeds on the susceptible substrates, but the reproductive spores are easily carried by air currents to new sites (McGinnis, 2007). Recognising that Australia's temperate climates have led to the development of intermittent conditioning regimes, the review of literature will also explore publications that explore this additional layer of complexity.

This research is being conducted within the broader hygrothermal research that has been occurring at the University of Tasmania, since 2008, which has explored and analyzed hygrothermal simulation methods and low to medium rise building envelope construction systems. Nath and Olaoye (Nath et al., 2020b; Olaoye et al., 2020) have identified significant differences in the hygrothermal simulation method that may be needed for buildings located in temperate climates. Whereas the guidelines from many northern hemisphere countries require permanent conditioning for human health reasons, countries like Australia which have a predominantly temperate climate may only need intermittent conditioning for human health and comfort. Recognising the evolution of hygrothermal research in the last decade, the first stage of this research was to conduct an updated and comprehensive international literature review that examines links between energy efficient-building design and the presence of moisture or mould.

The visual presence of mould on interior and interstitial surfaces has been identified as a hazard affecting indoor air quality and is recognized as an important risk factor for human health (WHO. Regional Office for Europe, 2009), and a cause of premature deaths worldwide (Valavanidis, 2023). Mould spores and excessive relative humidity are classified as airborne pollutants (WHO, 2021). Furthermore, the mental and social impacts of exposure to mould within houses are generally underestimated, with indoor mould as a sign of poor, irresponsible housekeeping, or living practices within social housing (Diaz Lozano Patino and Siegel, 2018). IAQ issues could lead to sick-building-syndrome (SBS) such as mucous-membrane irritation, skin rash, asthma, cough, increased low-birth weight and even death of infants (Gray et al., 2015; Lu et al., 2022; Redlich et al., 1997; Weinmayr et al., 2013). The medical treatment of human health conditions associated with moisture in UK buildings has been estimated at £1 Billion per annum (Rickaby, 2021).

Uncontrolled moisture, mould and bacterial growth can occur as a result of structural building faults, moisture ingress, inadequate heating, thermally broken insulation, or inadequate ventilation (WHO, 2021). Dampness and mould risk are related to all states of water, (gas, liquid and solid), and in all locations within the building fabric. Interstitial moisture, surface condensation, relative humidity (RH), the adsorption of liquid water, and freeze-thaw effects are conditions that interact and should be considered together, not separately, as they often are in standards and regulations (May and Sanders, 2017). Internationally, recent research has identified that dampness and indoor mould indicators affect up to 55% of buildings (Cai et al., 2019; Coulburn and Miller, 2022; Haverinen-Shaughnessy, 2012). A study of buildings in Victoria (Australia) observed that of the 2,178 moisture-related claims analysed, 92% (1,995 claims) had a least one water-related defect (VBA, 2023). Remediation costs associated with moisture in buildings have cost the New Zealand economy more than NZ$48 billion since 1995 and in Germany, the annual remediation costs have been estimated to be €300 million per year(MBIE, 2022). The human health and building remediation costs highlight this as an international problem that needs to be adequately addressed during in the design process.

Figure 1 shows the history of publications that included the keywords shown in Table 1, within ten journals that are published in English. Despite international research on this topic for nearly a century (ASHVE, 1937), the first research publication within the selected journals occurred in the 1970s, with a significant increase in the number of articles published after 2007. The prevalence of articles since 2007 may in part be correlated to increased building energy efficiency requirements in the United Kingdom and North America, and a greater awareness of indoor environmental quality and its impact on human health(“World health statistics 2009,”) . However, the diversity of research factors and supported disciplines are not able to offer a clear and accurate approach to confronting the risks yet, due to various challenges including but not limited to the sophisticated knowledge of multiple research gaps and information advancement among various challenges (Coulburn & Miller, 2022). This study has utilised the bibliometric method to analyse previous publications. VOS Viewer 2023 was used to process a large volume of publications, to achieve a better understanding of the phenomenon, and mitigation strategies, and to identify gaps and limitations within the emerging field of architectural science research.

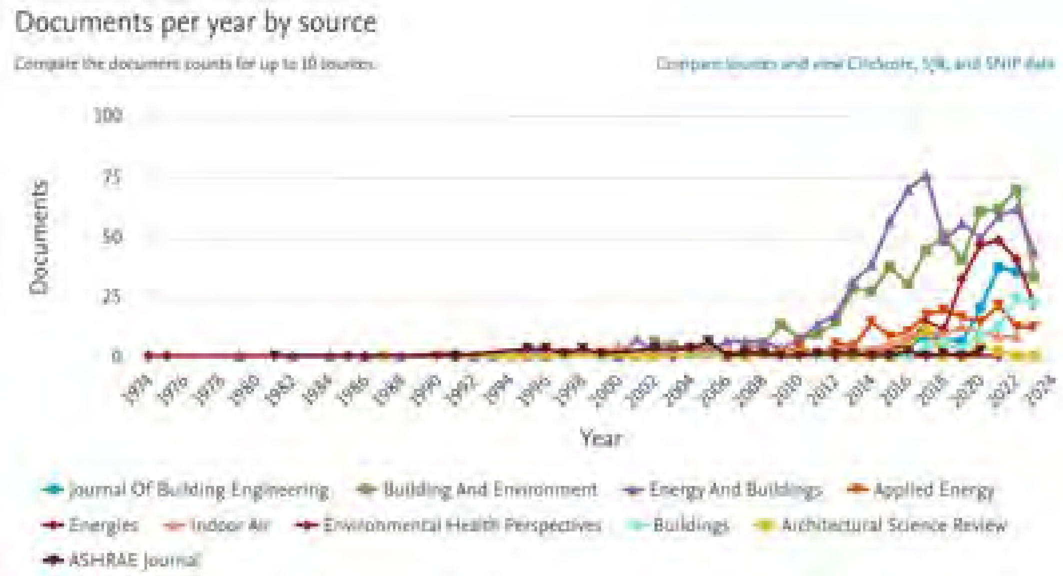

Figure 1: The History Publication Data of relevant to hygrothermal and bio-hygrothermal research of buildings (Source: Scopus 2023, graph created by author).

Even though the literature review included both English and non-English-speaking countries. It is unclear if the frequency of publication may have begun earlier than the 2000s. As an example, the German standard DIN4108 was first established in 1952, the British Standard 5250 was first published in 1975, and the CSIRO published three notes on the science of building regarding the need to consider moisture in 1964.

2. Research on bio-hygrothermal and hygrothermal risk of buildings---data analysis and visualisation

This paper used the Elsevier Scopus database to find publications on hygrothermal and bio-hygrothermal risks of housing. The search was processed by searching the key terms listed in Table 1 below and limited to papers and articles. Initially, 7194 articles were recognised for the period from 2008 to 2023. Subsequently, manual data selection was completed, which excluded unrelated research. These excluded items often included three main topics of articles, namely Food, Agriculture and Bio-chemistry disciplines. Therefore, a total of 3268 keywords were selected for research analysis and data map visualization.

By making a conscious decision based on the intention of visualisation, the text-mining and thesaurus function of VOS Viewer (2023) generated a range of maps to illustrate the network among articles, key terms, and authors. The outputs included Network Visualization, Overlayer Visualization and Cluster Density Visualization maps.

Table 1: The keywords used for this literature review.

Search with in: Article title, Abstract Keywords	Keywords applied “or”	Keywords applied “and”
	"Hygrothermal risk”; “Bio-hygrothermal risk”; Condensation; Indoor; “Mo?ld risk” "Moisture accumulation"; "Mo?ld growth"; “Dampness condition"; "WUFI simulation"; “Moisture Safety”; “Sustainable design”; "Energy efficiency”; “Airtightness"; “Indoor ventilation"; “Building performance"; "Sick building syndrome"; "Interstitial Mo?ld "; "Energy efficiency "; "Sustainable building"	Building Housing

The number of articles revealed a brief history of the research field. Alarmingly, when there is mould-growth in housing, occupants may not be aware of its presence until the indoor air quality affects conditions like coughing, allergies and asthma (Brambilla et al., 2022). Significant health effects on building occupants have attracted the attention of scholars to find out why. The damp condition within a building is the key. The dampness may include high interior relative humidity, linings and structural elements that have adsorbed moisture and the visual presence of moisture. The dampness can be a consequence of the architectural design. Construction methods, building operation or occupant behaviour. In several countries, the occupant behaviour was initially blamed, but these same countries have since regulated facade construction systems and ventilation to manage interior generated water vapour and moisture and mould growth within the external envelope. As a more detailed analysis of publication dates was undertaken, it was revealed that from 2022 to 2023 there are more than 400 papers published those focusses on hygrothermal and bio-hygrothermal aspects of existing and new buildings. Based on the volume of data, a few separate sub-databases were established, which explored links to energy efficient-buildings and indoor and interstitial mould, mitigation methods and simulation limitations. The key steps taken in this analysis comprised:

- The minimum keyword occurrences were 5, filtering from the author’s keywords set.
- Binary counting was used, only the keywords from the title and abstract of the paper are considered.
- A thesaurus file was applied to combine similar words and phrases. Such as “Mold” and “Mould”, “air- flow” and “airflow”, “home” and "building”, “method” and “methodology”,” high humidity” and “high moisture” and so forth.

2.1. Mould growth in energy efficient buildings

Figure 2 shows the results of the analysis with the greatest breadth of keywords. In the network visualization map, keywords are represented by their label and by a circle (Nees Jan van Eck, 2023). The size of the circle and label indicates the occurrence of the research keywords. Clear research connections and gaps of the research items were illustrated from the co-occurrence keywords map from 2008-2023. A total of 895 out of 15210 articles were identified to shortlist. The top three highest-weight items are "Energy efficiency" in blue, "Thermal comfort" in purple and "Indoor air quality" in red, representing the most intensively researched clusters. The lines between terms display relatedness and co-citation (Nees Jan van Eck, 2023). Energy-efficiency was identified as the item that has the highest weight and is intensively connected to a large amount of other research clusters, becoming one of the key research aspects of hygrothermal and Bio-hygrothermal risks of building.

Energy efficiency in buildings balances many aspects to reduce the energy to heat and/or cool a building to within accepted thermal comfort bandwidths, by providing an optimized mix of passive solar-design strategies, energy-efficient equipment, high performance building envelopes and sources of renewable energy (Ionescu et al., 2015). Indoor environmental quality (IEQ) further establishes limits for acceptable interior conditions, regarding temperature, lighting, noise and moisture (Gupta and Chakraborty, 2021). This has promoted the popularity of green buildings, bio-materials and massive timber architecture (Cover, 2020; Ilgın et al., 2022). However, the singular focus on energy efficiency has been identified as problematic (Santos et al., 2013). The enhancement of the building envelope, thermal insulation and air tightness has been found to reduce the air exchange rate (Marszal et al., 2011), may stop the passive removal of interior generated water vapour, and affect indoor air quality (Brambilla and Sangiorgio, 2020; Dewsbury et al., 2016; Nath et al., 2020).

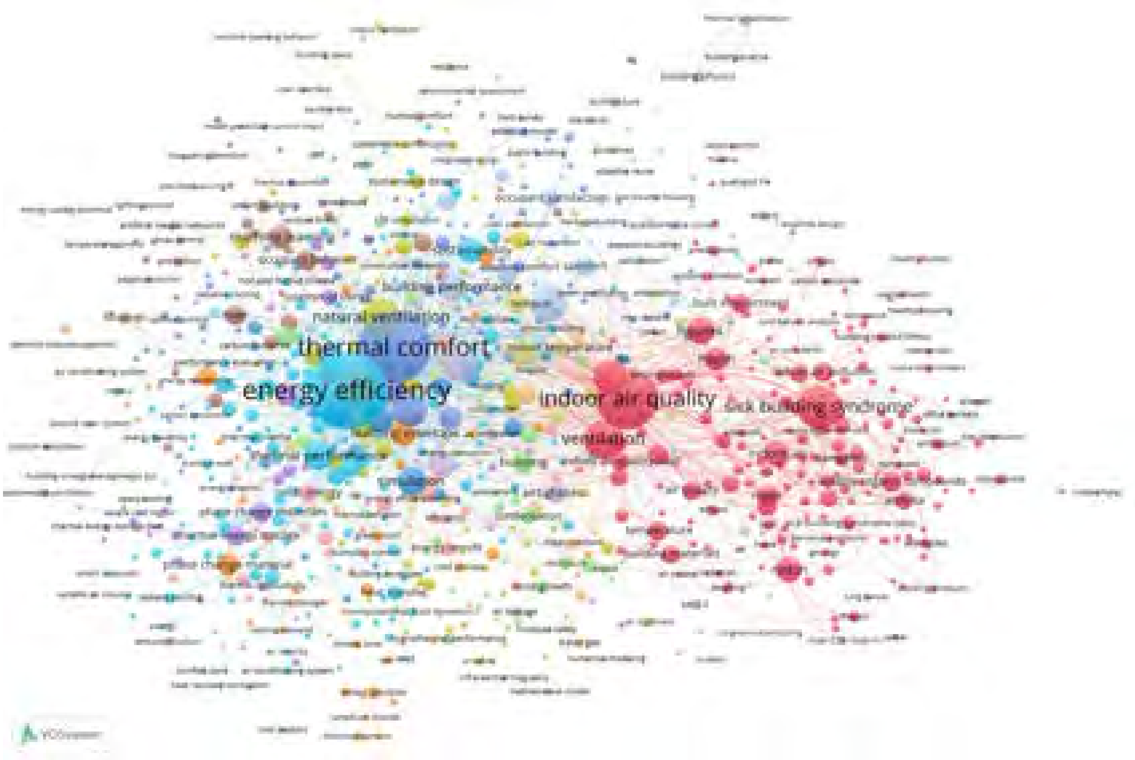

Figure 2: The Network Map of co-occurrence of author keywords for 2008-2023. (Source: VOS Viewer 2023, Map generated by author.)

Previous studies have attempted to reveal the correlation between indoor environment quality and energy consumption (Guo et al., 2021; Ma et al., 2023), and have debated links between hygrothermal comfort and energy efficiency (Asere and Blumberga, 2018; Boardman et al., 2023). The inconsistency between the methodologies to obtain a simulated moisture accumulation and mould growth index, and a Building Energy Rating (BER) has led to the incapability to fully capture the risks from Energy-efficient building design, their associated regulations, and the increased potential for excessive moisture and mould in new buildings. Therefore, this bibliometric analysis has further confirmed that energy-efficient buildings can offer favourable conditions for moisture accumulation and mould growth. Energy efficient buildings offer reduced operational energy demands; however, they may also provide unhealthy interior environments. Hence, the need to develop energy efficiency principles that also balance the need for healthy and safe indoor environments is required.

2.2. Indoor mould and Interstitial mould research review

There are two types of mould evident in the literature namely; indoor mould and interstitial mould (Cai et al., 2016; Mendell et al., 2011). The conditions to support surface or interstitial mould depend on the design and construction of building envelope elements and building operational characteristics, which could lead to either one or both to occur. Meta-analyses and systematic reviews have provided consistent evidence of relationships between immunologically sensitized mould spores exposure and asthma, rhinitis, and allergic symptoms (Cai et al., 2019; Caillaud et al., 2018; Kanchongkittiphon et al., 2015).

Indoor mould most often occurs on the inside surface of a poorly insulated wall or on the inside surface of walls, floors, and ceilings of uninsulated buildings. This results from the interior surface having a high moisture content or dew point conditions occuring at the inside surface of external envelope elements. The combination of warm indoor conditions and unmanaged internally generated water vapour can raise the interior surface moisture condition, which is favourable to generating fungi (Xue et al., 2022). It is well documented that when the indoor relative humidity (RH) is greater than 70% in well-ventilated or above 60% in a poorly ventilated space, mould growth and sporing may occur, directly polluting the indoor air quality (Menneer et al., 2022).

The insolation of walls could be an efficient solution to reduce the heat or cold losses of uninsulated and poorly insulated buildings yet is not risk-free. In the same manner as building interiors, a well-insulated wall system with some air-tightness measures would be classed as a poorly ventilated space, indicating opportunities for mould growth to occur within these interstitial spaces when the relative humidity is above 60%, and when the temperature is suitable and a food source, like timber framing is available. Interstitial moisture may accumulate due to the selection of building envelope materials that do not consider climatically appropriate water vapour diffusion (Dewsbury et al., 2022). Additionally, there is a strong correlation between the coverage of mould behind the wall lining, sampling periods and airflow rate (Efthymiopoulos et al., 2020). Therefore, avoiding interstitial mould growth in wall-insulated external envelop systems should be a significant design criterion (Alev and Kalamees, 2016).

2.2.1. Factors of moisture accumulation and indoor mould growth

The relative humidity (air moisture content), air and surface temperature, airtightness and construction materials and furnishings which provide nutrition are the three main factors that contribute to Indoor Mould growth (Clarke et al., 1999). It is also a consequence of multiple factors including design defaults, outdoor climate, environment, rates of ventilation, and occupancy behaviours (Winkler et al., 2018). The moisture affecting the external envelope may come from the interior and /or exterior of the building.

Research has shown that the moisture load of the façade depends highly on wind-driven rain (Finken et al., 2016). Data has shown that the façade attacked by driven rain can affect the indoor air quality by increasing the amount of mould spreading via infiltration and their genus representation. Water leakage or intrusion from roof or drainage systems can rapidly lead to mould growth problems. Similarly, variations in the operational profile of occupants can have a non-negligible impact on overall building performance, especially the indoor relative humidity (Winkler et al., 2018; Bui et al., 2019). This includes but is not limited to different living activities, hours of usage and density, which would have quite different impacts on indoor mould risks. In temperate, cool temperate and cool climates, the difference between indoor and outdoor humidity in winter reaches a maximum due to the increased indoor activities and reduced ventilation (El Diasty et al., 1992). The building envelope may be unable to passively manage moisture control and ensure adequate ventilation occurs, which can be further compounded by occupant economic concerns about heating and cooling energy consumption (Ginestet et al., 2020)**.**

2.2.2. Indoor mould impact

Moisture accumulation and mould growth have become a major concern of buildings, as they affect indoor air quality, the duality of materials and durability of the building, as well as building thermal performance and energy efficiency. It could be summarised into three aspects. Firstly, indoor environment quality (IEQ), Indoor air quality (IAQ), and indoor health and safety could be seriously affected by mould exposure (Bone et al., 2010). Secondly, the sustainability of a building is greatly impacted by excessive moisture and mould, as they can significantly decrease the service life of building materials and components, due to the process of biodeterioration (Verdier et al., 2014). Consequently, a building with excessive moisture and mould may need major costly renovations. Thirdly, environmental response and energy efficiency as heating and cooling caused energy loads are often raised as a major conflict with the need for ventilation to remove interior pollutants including water vapour.

3. Mitigation of condensation and mould risks for buildings

The architectural design approach needs to be the first strategy. Contemporary architectural building design and typology can compromise water-tightness, the ability to deflect water ingress, poor design documentation, non-compliant balcony design, water vapour diffusion, interior relative humidity management, and unresolved penetrations (Law and Dewsbury, 2018). It is critical for Architects to be aware of the significance of building design for a specific climate (Albatayneh et al., 2018). Applying envelope design systems like Integrating Climate Based Design Modelling (CBDM) and natural ventilation parameters into the design process would be beneficial (Zoure and Genovese, 2023). Furthermore, with better awareness of more options using untreated natural materials, vapour control layers, and mass air transfer methods to remove interior moisture must be considered in relation to mould growth risks and energy consumption. As mentioned above, the envelope may not passively be able to manage the interior generated water vapour, and occupants may not wish to operate ventilation systems due to undesirable outdoor conditions, raising the need for other forms of ventilation.

Increased resources to educate the public could mitigate moisture accumulation and could also significantly increase the potential to prevent indoor mould growth. The occupant's behaviour and regular activities occurring in the home such as drying clothes indoors contribute to the water vapour impacts on hygrothermal risks. The causes and threats are often unknown or ignored by homeowners (Law, 2023). Educating the public to use their homes and offices wisely is crucial. Similarly, the ability progress, scrub the shower to minimize moisture vapour sources, and know to identify the risks at an early stage, helps to avoid health hazards and major renovations. The advantages of mechanical options like Also learn to use available low-cost mechanical ventilation solutions when needed, such as Wall Recuperator Enthalpy Heat Recovery Ventilators (ERV or HRV), needs to be communicated to the broader community WIFI Control for Home Ventilation. These actions may stop the potential for moisture accumulation at the manageable low-cost stage.

Finally, to mitigate risks, the call for greater resilience or architectural design details, including sufficient construction details and the support and guidance of related construction regulations and standards. The Code of Conduct for Building Surveyors often limits their capacity to minimum regulatory compliance, rather than 'better-than-code' actions that can eliminate moisture risks (Dewsbury et al., 2016). More detailed requirements towards the problematic areas, like balcony design, internal and external wet spaces, parapet design, flashings, and gutters, would assist in reducing moisture accumulation and ingress (Defo et al., 2022; Hejazi et al., 2019).

4. The limitation of research results from hygrothermal simulation

Hygrothermal simulation-based research faces two main challenges, namely the quality of user inputs and the need for ongoing software calibration based on real world experiences. Condensation and mould growth phenomena in buildings are highly correlated to relative humidity, ventilation, and air and surface temperatures. There are indoor and outdoor sources for these three main aspects. Typically, hygrothermal calculation tools like WUFI®2022 (“Release WUFI® Pro 6.6 and WUFI® 2D 4.4 | WUFI,” 2022). use hourly average weather datasets like wind and rain, which obfuscates peak climatic conditions (Cambray et al., 2022). Current simulation results may be further thwarted by the effects of climate change. Changes to average temperature and atmospheric moisture may provide improved conditions for sustained mould growth in a wall assembly where such a problem does not currently exist (Diaz Lozano Patino and Siegel, 2018). This emphasises the importance of further research with consideration of climate impact in both the short and long term (Camilleri et al., 2001; Nik, 2017).

Transport of water through hydrophobic cracks of both treated and untreated external walls could be significant, and it is highly relevant to include peak gusting wind pressure (Cambray et al., 2022). Without accurate inputs for climate data and occupant moisture-generating activities, the hygrothermal calculation results may be compromised (Crawley, 2008). More accurate input data of moisture source will improve the reliability of the results. It is important to note that based on international regulations many software simulation tools, like WUFI, include a cap on the interior relative humidity. However, in Australia, there is no quantified regulation regarding the control of interior relative humidity conditions.

Computer simulation-based research cannot replicate real life scenarios due to the combination of uncontrolled variables regarding how the building’s external envelope is exposed to different patterns of interior and exterior environmental variables. However, software calibration allows for these variations to be reduced. The best way to inform software calibration is to collect data from a building that includes temperature and moisture sensors inside, within interstitial zones and outside the building. A comparison of simulation and measured data can then occur (Dewsbury, 2015). Indoor Air Quality is assessed by calculating the mould Index (MI), which represents the amount of visible mould. However, the calculated mould index may only partly support the assessment remediation urgency, due to many other factors that inform IAQ (Tähtinen et al., 2018; VBA, 2022). Future research must consider standard methods of air sampling, analysis and laboratory testing to quantify building IAQ performance. This could suggest the need for the development of early detection strategies that could minimise the health hazards to building occupants, to assist laboratory study, thereby preventing the need for any major renovations (Brambilla et al.,2022).

5. Future Trends of these Research

Many current Architectural design strategies still really on ISO13788 compliant-non-transient simulation tools. In a similar manner to the development of transient Building Energy rating tools since the 1990s, transient hygrothermal simulation tools have also been developed since the 1990s. There is a need for the international community to require transient hygrothermal simulation tools as a minimum requirement. Furthermore, these tools need to not only simulate ‘average’ climate data but also need to simulate extreme weather events, such that the design profession can provide robust and durable building envelopes.

A key function of the systematic literature review was to establish if there were knowledge or knowledge gaps regarding hygrothermal simulation for temperate climates that include intermittent conditioning. Most publications referred to simulation methods that focused on continuous interior conditioning, often to a minimum temperature ≥21°C. Currently, there is no requirement for Australian Class 1 and Class 2 building interiors to be maintained at or above 21°C. Furthermore, based on the requirements for interior relative humidity control in most developed nations, the hygrothermal simulation tools include a 70% interior relative humidity cap. In a similar situation to the minimum temperature requirement, there is no requirement within current building regulations in Australia to limit interior relative humidity to ≤70%.

Material engagement trends are present in the most impact as new bio-materials ever emerging to satisfy the requirements of sustainable buildings, Materials like cross Laminated Timber (CLT), hempcrete, green concrete, and the water vapour permeability of construction materials (Alqahtani et al., 2023; Bennai et al., 2022; Piot et al., 2017; Satone et al., 2023).

6. Conclusion

This paper has documented a systematic literature review on hygrothermal (moisture and heat) and bio-hygrothermal (mould growth) risks of buildings. This has included, moisture, mould growth risks and energy efficiency. Succinctly, the dilemma of sustainable architecture between thermal comfort, moisture accumulation and energy efficiency has been researched for almost half a century (from the 1970s to 2023). Either from the empirical experiences of buildings and occupants, or manual and computer-based calculation methods research has consistently identified the unresolved conflict between energy efficiency and hydrothermal safety. A novel method or perspective may need to be developed coherently the hygrothermal performance and energy efficiency in buildings harmoniously address building durability, energy efficiency, thermal comfort, and healthy building interiors. Nath (Nath et al., 2020) identified that the first step for hygrothermal simulation in Australia was to complete multi-year transient simulations applying the methodology described in ASHRAE Standard 160. Nath also identified that this may be too onerous for buildings located in Australia's temperate climates. The aim of the literature review was to explore what new knowledge has been published in the last decade and to look specifically for research that explored matters regarding temperate climates, intermittent conditioning, and relative humidity control.

Alarmingly, the literature review identified more than 700 articles published in the last decade. The literature showed a progression from Sick Building Syndrome to a focus on Indoor Air Quality, followed by Energy Efficiency as the cause for excessive moisture and/or mould in new buildings. This demonstrates that there is still an international problem exploring methods to mitigate excessive moisture and mould within buildings.

More specifically, the research identified that most articles were from northern hemisphere nations where forms of permanent conditioning have been required for many years due to the human health affecting cold winters. The International standard, nation-based guidelines for hygrothermal and bio-hygrothermal simulation, and the simulation tools have default settings for permanent conditioning. This has resulted in most published research applying the permanent conditioning mode to simulations. This identifies that there is a significant knowledge gap regarding hygrothermal and bio-hygrothermal simulation which applies an intermittent mode of conditioning, which is most prevalent in Australia. The second aspect that was explored in detail was the matter regarding interior relative humidity control. In a similar pattern to the requirement for interior conditioning, the standards, guidelines and reported simulation research had adopted the simulation methodology that includes a capped interior relative humidity of 70%. This knowledge gap will now be applied to the next stage of this research, where a methodology will be developed that explores what the impacts of intermittent conditioning and uncontrolled interior relative humidity, within new energy-efficient homes, may have on hygrothermal and bio-hygrothermal simulation.

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Impact of indoor environmental quality satisfaction on guests' rating of Australian tourist accommodation

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Abstract: Numerous studies have shown that indoor environmental quality (IEQ) plays a significant role in occupant satisfaction in office buildings, yet insufficient research has been done on how IEQ factors affect customer ratings of hotels and serviced apartments. This study analyzed 543,213 guest reviews from 1,397 Australian hotels and serviced apartments with 2-5 stars on Booking.com using web-mining, natural language processing, and the Three-Factor Theory of customer satisfaction. The sentiment polarities for nine IEQ factors were calculated to estimate the IEQ satisfaction. The Three-Factor Theory and mixed effects models were applied to model the asymmetric effects of IEQ factors on guests' rating scores. All IEQ factors except for exterior view were considered Basic Factors of customer satisfaction, meaning that customers expect satisfactory performance of these factors. Exterior view served as an Excitement Factor in accommodations with 3 stars and lower, a Performance Factor in those with 4 stars, and a Basic Factor in 5-star guest homes. When IEQ performance was deemed satisfactory, the most influential factors in determining overall satisfaction were exterior view, cleanliness and maintenance, and acoustics. When IEQ performance was unsatisfactory, the most influential IEQ factors were cleanliness and maintenance, indoor air quality, and acoustics.

Keywords: Indoor environmental quality; Three-Factor Theory; natural language processing; sentiment analysis

1. Introduction

The Australian tourism industry contributes significantly to the nation's economy. During the 2018–2019 financial year, the industry generated $61.9 billion in revenue, representing 3.1% of Australia's gross domestic product (Australian Bureau of Statistics, 2022). Customer satisfaction towards tourist accommodations plays a critical role in the success of the hospitality industry. On the one hand, satisfied customers are more likely to recommend the hotel to their friends and family, leading to increased bookings and revenue. On the other hand, disgruntled travellers are more likely to leave unfavourable online reviews of the hotel, which not only undermines the hotel's brand and image, but also reduces hotel revenue by scaring off new customers (Li et al., 2020). In a competitive market, maintaining high levels of customer satisfaction in hospitality buildings is crucial for the continued growth and success of the hospitality industry in Australia. Therefore, the industries must have a thorough understanding of the factors that influence the guests' satisfaction and rating of the guest homes.

1.1. Indoor environmental quality and overall satisfaction

Indoor environmental quality (IEQ) refers to the physical and psychological conditions within a building that can affect the health, well-being, and productivity of the occupants (U.S. Green Building Council, 2014). Factors that contribute to IEQ include temperature, humidity, lighting, air quality, acoustics, to name a few. Employing a post-occupancy evaluation approach, numerous IEQ studies investigated on the association between IEQ factors and the overall satisfaction of office employees. These studies have revealed that IEQ plays a significant role in determining the overall satisfaction with the workspace (e.g., Kim and de Dear, 2012; Cheung et al., 2021).

Recent review studies (Zhao and Li, 2023; Roumi et al., 2022) indicate, however, that the combined effects of IEQ satisfaction on overall satisfaction are complex and nonlinear, as different IEQ factors may exert varying degrees of influence on satisfaction. Tang et al. (2020) discovered that the impact of a specific IEQ factor on occupants' overall IEQ satisfaction varied based on its relative level in comparison to other factors; the IEQ factor with the lowest level of satisfaction will have the greatest impact on the occupants' overall IEQ satisfaction regardless of the perfection of the other IEQ factors. Cao et al. (2012) also found that unsatisfactory thermal and acoustic conditions can override satisfaction with other IEQ factors, resulting in a substantial decrease in overall satisfaction. However, this non-linear relationship between individual IEQ satisfaction and the overall satisfaction has been neglected in many previous studies where a linear relationship was assumed.

1.2. The Three-Factor Theory

The Three-Factor Theory originated from the Kano Model (Kano *et al.*, 1984). In 1984, Professor Kano and his colleagues proposed the Kano model of attractive quality, which postulated that the individual quality attributes of a product have an asymmetric effect on overall customer satisfaction, and that different attributes have varying effects. In 2008, Füller and Matzler (2008) proposed the "Three-Factor Theory of Customer Satisfaction" as a modification of Kano's theory, suggesting that customers have different levels of satisfaction with products or services based on three factors: Basic Factors, Performance Factors, and Excitement Factors.

- Basic Factors: also known as dissatisfiers, refer to the minimum requirements that customers expect from a product or service. The absence of these factors may elicit dissatisfaction; however, their presence does not guarantee satisfaction.
- Performance Factors: satisfaction is proportionally influenced by performance factors whereby high performance elicits satisfaction and low performance results in dissatisfaction. The effects of these attributes on overall satisfaction are linear and symmetrical.
- Excitement Factors: also known as satisfiers, are the extra features or characteristics that customers don't expect, but when present, result in a significant increase in satisfaction. However, their absence does not necessarily result in dissatisfaction.

1.3 Bridging IEQ satisfaction and guest ratings in hospitality buildings

Kim and de Dear (2012) introduced the Three-Factor Theory (Kano model) to the built environment studies for the first time, where they examined the impact of individual IEQ factors on overall workplace satisfaction. It was found that Basic Factors included temperature, noise level, amount of space, visual privacy, adjustability of furniture, colours and textures, and workspace cleanliness, with the negative impacts of these factors outweighing their positive counterparts in determining the overall satisfaction; Proportional (Performance) Factors included air quality, amount of light, visual comfort, sound privacy, ease of interaction, comfort of furnishing, building cleanliness and maintenance. These factors are proportional to the overall satisfaction. There were no Bonus (Excitement) Factors detected. However, the paucity of research on IEQ in hospitality establishments leaves us uncertain about the potential asymmetric impact of IEQ on customer satisfaction in hotels and serviced apartments, and the nature of this asymmetry.

In hospitality industries, there are numerous research studies that have applied the Three-Factor Theory to understand the asymmetric relationship between the product/service attributes and overall customer satisfaction. According to the findings of Albayrak and Caber (2015), the Basic Factors that contribute to customer satisfaction of a hotel included animation, child amenities, cleanliness, food and beverage, personnel, pool, and room decoration. Performance Factors were determined by beach access and the technical capabilities of hotel rooms. In a similar vein, Matzler et al. (2006) found that Basic Factors, such as reception, friendliness, service, and hotel room, played a crucial role in customer satisfaction. Additionally, the presence of a wellness area was identified as a Performance Factor, while the hotel restaurant and breakfast offerings were considered Excitement Factors. However, due to their discipline-specific focus, these studies did not examine the impact of IEQ factors on guests' overall ratings.

1.4 Aims of the study

This study constitutes an early endeavour to investigate the suitability of the Three-Factor Theory in elucidating the IEQ impacts on overall satisfaction in hospitality buildings, employing online reviews as a data source. This project aims to gather guest reviews from Booking.com on hotels and serviced apartments in Australia and examine the association between guests' satisfaction with various IEQ factors and their ratings of the tourist lodges. By applying web-mining, natural language processing (NLP), and the Three-Factor Theory, we aim to answer the following questions:

- Do IEQ factors in Australian hotels and serviced apartments have asymmetric effects on guests' ratings?
- Which IEQ factors are Basic Factors, Performance Factors and Excitement Factors, respectively?
- How much variance can IEQ satisfaction account for in the guests' ratings?

2. Methods

2.1 Dataset

A crawler was created to scrape guest reviews from the Booking.com website spanning from May 2019 to May 2022. The crawler had filters for city, property type, and star rating. The cities included Sydney, Melbourne, Brisbane, Gold Coast, Sunshine Coast, Perth, Adelaide, Hobart, Darwin, and Canberra. The property types were limited to hotels and apartments. The star ratings ranged from 2 stars to 5 stars and excluded the "unrated" category. A total of 1,470,709 reviews were collected and written into a CSV file and included details such as accommodation name, suburb, city, star rating, overall guest rating, nationality of the guest, room type, duration of stay, check-in month, check-in year, individual guest rating, positive comments, and negative comments. Reviews written in languages other than English were translated into the English language. Data pre-processing removed positive and negative reviews that were both fewer than five words. The resultant dataset consisted of 759,877 reviews from 1,402 Australian hotels and serviced apartments.

2.2 IEQ classification

The dataset was expanded from the reviewer level to sentences level, allowing multiple rows per review. A semi-supervised word-embedding model categorized guest review comments into nine IEQ factors—thermal environment, indoor air quality (IAQ), lighting, acoustics, available space, facilities, exterior view, cleanliness and maintenance, and layout & design. The nine IEQ factors were derived from the Building Occupancy Survey System Australia (BOSSA) (Candido et al., 2016), an Australian post-occupancy evaluation tool designed for office buildings but modified to meet the unique requirements and characteristics of tourist accommodations. This study excluded IEQ factors that were mentioned infrequently in online reviews or that could not be reliably identified by words or phrases, e.g., individual control, colour and textures.

For each IEQ factor, we manually selected seed words frequently mentioned in the reviews, shown in Table 1, and fed them into a bespoke semi-supervised NLP model (Zhang et al., 2023) to detect IEQ-related sentences. We discarded sentences that were not associated with any IEQ aspect. Despite this, the sentences mapped to IEQ aspects contained numerous non-IEQ comments because IEQ vocabulary was used in a variety of polysemous contexts. For instance, “large” can refer to the size of the room or other objects; however, only the former is relevant to IEQ. After mapping review sentences to IEQ factors, sentences with non-IEQ contexts were filtered out with the help of a manually curated lexicon of phrases irrelevant to IEQ contexts. These irrelevant phrases were modified based on previous studies (e.g., Qi et al., 2017) with a similar focus.

Table 1: Seed words for nine IEQ factors (Source: Zhang et al., 2023).

IEQ factors	Seed Words
Thermal Environment	warm, cold, freezing, chilly, hot, heat, scorching, sweltering, melt, sweat, humid, muggy, clammy, steamy, draughty, drafty, temperature, cool, snow, snowy
Indoor Air Quality	air, air circulation, ventilation, aerate, breeze, smell, smoke, stuffy, stink, stunk, stench, reek, airless, stale, odour, airtight, musty, mould, air purifier, air flow, airy
Lighting	bright, dark, glare, dazzle, dim, dusky, light, glow, lamp, block out, shady, lighting
Acoustics	noise, loud, quiet, sound, sound insulation, soundproof, disturbance, silent, hear, overhear, rowdy, roaring, rattling, blaring, racket, earphone, earplug
Available Space	spacious, space, large, huge, small, enough room, tiny, cramped, compact, congested, poky, size, roomy
Facilities	facilities, gym, equip, sauna, microwave, amenities, broken, damaged, cracked, not work, holes, chipped, air conditioner, air conditioning, aircon, AC, lifts, elevator, bed, furniture, fridge, tv, toilet, balcony, kitchen, laundry, towels, hot water, shower head, fly screens, faulty, pool, Wi-Fi, internet
Exterior View	view, overlooking, facing, outlook, scenery
Cleanliness & Maintenance	clean, cleanliness, (un)hygienic, (un)tidy, spotless, dirt, disgusting, dusty, filthy, dingy, grubby, stain, wash, scrub, leaking, cockroach, bugs, insects, cobwebs, rubbish bin, housekeeping, maintenance, maintained, renovated, renovation, refurbished, updating, modern, décor, decoration, decent, dated, old, run down, dilapidated, rusty, art deco, scum
Layout & Design	layout, design

To validate the IEQ classification method, a comprehensive and systematic test set has been curated. Most review sentences addressed one to three IEQ factors. During the curation process of the validation dataset, we ensured that the proportions between sentences mentioning only one IEQ factor and sentences mentioning two or three IEQ factors were maintained similar to that of the entire dataset. The sentences in the validation test set were manually categorised into various IEQ factors. These manually generated categorisations were then compared with the categorisations generated by the AI Classifier to evaluate the accuracy of the AI-generated categorisations. The validation process is described in detail in Zhang et al. (2023).

2.3 Sentiment analysis

This study employed aspect-based sentiment analysis to evaluate the sentiment polarities of nine pre-determined aspects wherein each aspect referred to a distinct IEQ category. A bidirectional Long Short Term Memory (BI-LSTM) deep neural network model (Graves & Schmidhuber, 2005; Yadavilli & Seshadri, 2022) was utilized for this purpose. A BI-LSTM-based deep neural network classifier was trained to classify each review-IEQ factors combination into a 3-point sentiment polarity scale of "satisfied", "neutral", and "dissatisfied". A "neutral" category was assigned in cases where the sentence did not make any explicit reference to the IEQ factor in question. The classification accuracy for all IEQ factors ranged between 92% and 96%. The details about the architecture, training algorithm adopted, optimization objective and hyper-parametric settings used by the BI-LSTM model can be found in Zhang et al. (2023).

2.4 Data analysis: regression models with dummy variables

Prior research has extensively employed regression analysis with dummy variables to investigate asymmetric relationships across diverse contexts (Li et al., 2020; Kim and de Dear, 2012; Füller and Matzler, 2008). The basic logic is to divide the performance of a product or service attribute into three groups, high, medium, and low (Figure 1), and then compare the **absolute** differences in overall satisfaction between these groups. If the difference in satisfaction between the mid-performance and low-performance group is greater than that between the mid-performance and high-performance group, the attribute is identified as a Basic Factor (the bottom curve in Figure 1), as low performance has a greater impact on dissatisfaction. If the difference in satisfaction between the mid-performance and high-performance groups is greater than that between the mid-performance and low-performance groups, the attribute is identified as an Excitement Factor (the top curve in Figure 1), as high performance leads to high satisfaction. If the difference in satisfaction between the mid-performance and high-performance groups is roughly equivalent to the difference between the mid-performance and low-performance groups, the attribute is identified as a Performance Factor (the middle line in Figure 1), as performance changes proportionally to satisfaction.

Figure 1 The Three-Factor Theory (adapted from Matzler et al., 2004)

To examine the IEQ impacts on guest ratings, this study categorised IEQ performance levels into three groups based on the sentiment polarity values of each IEQ factor. To be specific, a "satisfied" sentiment polarity was deemed as high IEQ performance, a "neutral" polarity deemed as medium performance, and a "dissatisfied" polarity deemed as low performance. Dummy coding is a way of representing groups of people using only zeros and ones. In accordance with existing literature, two dummy variables were created, and a 0 and 1 binary coding scheme was applied. We chose the medium IEQ performance group as the reference group because we were interested in determining whether the high IEQ performance group led to greater overall satisfaction than the mid-performance group, and whether the low IEQ performance group had lower satisfaction than the mid-performance group. The reference group had a dummy coding of (0, 0). A dummy variable (coded 1, 0) was assigned to the high-performance group, while another dummy variable (coded 0, 1) was assigned to the low-performance group. This procedure was repeated for nine IEQ factors.

This study tested both simple linear regression models with dummy variables and mixed effects regression models with dummy variables and compared their goodness-of-fit parameters. According to Field (2013), the responses obtained from a subject in a multilevel model can be understood as the combined influence of fixed and random effects. Fixed effects contribute to the overall population mean, while random effects alter the covariance structure of the data. The comparison of two models showed that the mixed effects model, which took into consideration the hierarchical structure of the data (Snijders & Bosker, 2012), produced a superior goodness-of-fit value compared to the simple regression model. Hence, a mixed effects model was chosen for the data analysis, and the results are presented in the following sections.

A mixed effects model was constructed using the dummy coding, wherein the dependent variable was the guest rating of the premise (also referred to as the overall satisfaction), and the independent variables consisted of nine IEQ items with dummy variables. According to the findings of Li et al. (2020), IEQ impacts on overall satisfaction was mediated by factors such as the star ratings of the premises, locations, travellers' origin (whether they were national or international travellers), and the year of travel. In our prior study utilising the identical dataset, it was discovered that guest ratings exhibited a statistically significant decline after the onset of the COVID pandemic (Apr 2020 in Australia) in comparison to pre-pandemic levels (Zhang et al., 2023). Hence, to accurately model the asymmetric effects of IEQ factors, the mixed effects model accounted for the differences between cities, nationality, and time of travel in relation to COVID-19 by adding three covariates in the model.

Table 2 presents the statistical summary of the hotels and apartments examined in the current study. The database comprised of IEQ-related reviews from a total of 543,213 visitors from 188 different nations. These visitors had stayed in a collective sum of 1,397 hotels and serviced apartments located in ten cities across Australia. The database consisted primarily of Australian visitors, comprising 90.4% of the reviewers, with international visitors representing only 9.6%. These visitors have evaluated their lodging experience on a numerical scale ranging from 1 to 10 through the platform provided by Bookings.com. The data presented in Table 2 implies a positive correlation between the star ratings of tourist lodgings and the average guest ratings. Given that the guest accommodations categorised as "2 star" and "3 star" facilities accounted for only 1.5% and 13.7% of the total entries in the database, respectively, these two categories were combined for the purpose of conducting statistical analysis. To develop mixed effects models, the dataset was partitioned into three subsets based on the three categories of star ratings, specifically, 3 stars and below, 4 stars, and 5 stars.

Table 2. Breakdown of hotels and apartments according to accommodation star ratings

Star Rating	No. of Hotels/ Apartments	Percentage (%)	Number of Reviews	Average Guest Rating
2 Star	21	1.5	3,660	6.9
3 Star	191	13.7	39,944	7.3
4 Star	829	59.3	308,181	7.9
5 Star	356	25.5	191,428	8.2
Total/Group Mean	1,397	100	543,213	7.9

Both a two-level and a three-level hierarchical structure (customer-hotel, and customer-hotel-city) were tested while developing mixed effects models. In this study, a two-level structure was used since the goodness-of-fit measures and covariance parameters showed that a three-level structure did not enhance the model's fit over a two-level structure. When developing mixed effects models for three categories of star ratings, random slopes for all independent variables were evaluated; if they did not enhance the models' goodness-of-fit, they were removed from the model. Equation (1) represents the mixed effects model being tested. In the subsequent analysis, we only report and interpret the fixed effect coefficients. Equation (1) yields two fixed-effect coefficients for each of the nine IEQ items: one coefficient b_x pertained to the high-performance group, examining the effect when the sentiment polarity of the IEQ item was satisfied, while the other coefficient $b_{x'}$ pertained to the low performance group, assessing the impact when the sentiment polarity of the IEQ item was dissatisfied.

$$Y_{ij} = (b_0 + u_{0j}) + (b_1 + u_{1j})HP_{thermalcomfort,ij} + (b_{1'} + u_{1'j})LP_{thermalcomfort,ij} + \cdots + (b_9 + u_{9j})HP_{layout,ij} + (b_{9'} + u_{9'j})LP_{layout,ij} + (b_{city} + u_{city,j})city_{ij} + (b_{nationality} + u_{nationality,j})nationality_{ij} + (b_{time} + u_{time,j})\ time\ of\ travel_{ij} + \cdots + \epsilon_{ij}$$
(1)

In Equation (1), Y_{ij} is the customer *i*'s rating of the lodging *j*; $(b_0 + u_{oj})$ denotes a random intercept where b_0 is the intercept of the overall model and u_{oj} is the variability of intercepts around the overall model; *HP* denotes the dummy set for high IEQ performance groups; *LP* denotes the dummy set for low IEQ performance groups; $(b_x + u_{xj})$ refers to a random slope for the HP dummy sets, where b_x is the slope of the overall model and u_{xj} is the variability of slopes; $(b_{x'} + u_{x'j})$ refers to a random slope for the LP dummy sets. *city* is a categorical variable for the ten Australian cities; *nationality* and *time of travel* are two binary variables indicating if the traveller was from Australia or overseas, and if the travel was before or after the pandemic (Apr 2020 in Australia), respectively; ε_{ij} is the error for the *i*th customer from the *j*th lodging. In the reference group, both dummy variables HP and LP were coded as 0, thus the model estimated the average guest ratings when IEQ performance was deemed as neutral across all nine IEQ factors. This estimation was conducted for a reference city, nationality, and time of travel. In the HP group, the dummy variable HP was coded as 1, and LP was coded as 0, and the regression coefficients b_x indicated the difference between the average ratings of the HP and the reference group for nine IEQ factors, respectively. Similarly, In the LP group, the dummy variable LP was coded as 1 and the HP as 0, then $b_{x'}$ indicated the differences between the average ratings of the LP and the reference group.

The coefficient of determination, denoted as R^2, provides a measure of the goodness-of-fit of a model, which cannot be derived from the Akaike Information Criterion (AIC) commonly employed in mixed-effects models. The incorporation of the statistical metric "variance explained" (R^2) as a relevant summary indicator in mixed-effects models has not been frequently observed in prior studies. In this project, the pseudo-R^2 measures were computed using the methodology proposed by Nakagawa and Schieizeth (2013) to illustrate the explanatory power of the developed model. The decision to utilise a mixed effects model instead of a simple regression model was also based on the comparatively higher pseudo-R^2 value of the former. All statistical analyses were conducted in SPSS Version 29.0. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Statistical Summary

Figure 2 illustrates the distribution of three sentiment polarities across nine IEQ factors. The primary sources of dissatisfaction among guests were the facilities of the accommodation, which accounted for 32.03% of the responses, followed by cleanliness and maintenance at 18.24%. Other factors that contributed to guest dissatisfaction included acoustics (7.75%), available space (6.42%), indoor air quality

(4.33%), exterior view (2.92%), lighting (2.22%), thermal environment (2.10%), and layout and design (0.17%).

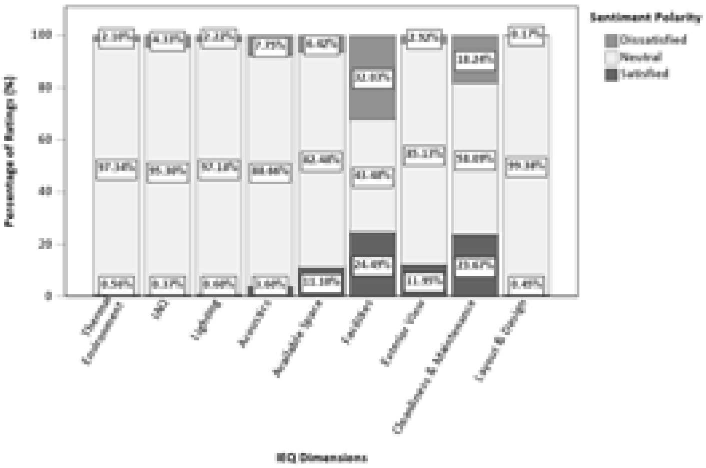

Figure 2 Proportion of three sentiment polarity scales in nine IEQ factors (Source: Zhang et al., 2023)

Upon examining the assumptions of the mixed effects model, it was discovered that the models' residuals exhibited a slight positive skewness across all three sub-samples of star ratings. Despite this, the homoscedasticity of residual variances and the independence between predictors have been confirmed. Mixed effects models are robust, according to Schielzeth et al. (2020), even if the distributional assumptions are violated. Therefore, we believe that the models are accurate, and the estimates are unbiased.

3.2. Asymmetric effects of IEQ factors

As depicted in Figure 1, IEQ factors can be classified as Basic, Performance, or Excitement Factors by comparing the satisfaction differences between the mid-performance and high-performance groups to those between the mid-performance and low-performance groups. The former is represented by the HP group regression coefficient b_x and the latter by the LP group regression coefficient $b_{x'}$ in the mixed effects model. An IEQ factor is categorised as an Excitement Factor if the magnitude of b_x is greater than that of $b_{x'}$, as a Basic Factor if otherwise, and as a Performance Factor if the magnitudes of b_x and $b_{x'}$ are comparable. The 150% difference criterion proposed by Kim and de Dear (2012) was utilised to determine if the two regression coefficients are comparable. If the magnitude of b_x exceeds 150% of the magnitude of $b_{x'}$ for an IEQ factor, that factor is considered an Excitement Factor. If, however, the magnitude of $b_{x'}$ exceeds 150% of the magnitude of b_x, then this IEQ factor is categorised as a Basic Factor. The IEQ factor is classified as a Performance Factor if neither of the conditions are met.

Table 3 presents the regression coefficients pertaining to nine dummy variables representing low and high IEQ performance. These coefficients were derived from three mixed effects models constructed to analyse accommodations with varying star ratings. The discrepancies between cities, tourist origins, and time of travel have been adjusted in these models. In Table 3, when the regression coefficient for the LP group achieved statistical significance but the regression coefficient for the HP group did not, the corresponding IEQ factor can be identified as a Basic Factor without applying the 150% difference criterion. This is because overall satisfaction in the low-performance group was significantly lower than in the mid-performance group, but there was no significant difference between the mid-performance and high-performance groups. This characteristic corresponds to the definition of a Basic Factor; failure to meet the needs induces dissatisfaction, whereas meeting the needs does not guarantee satisfaction. In other instances, ratios between the magnitude of regression coefficients for the LP and HP groups were computed to assess the classification of an IEQ factor using the 150% difference criterion. The findings indicated that, except for the exterior view, all other IEQ factors were classified as Basic Factors across tourist accommodations with different star ratings. The exterior view played a role as an Excitement Factor in lower-end hotels and serviced apartments, functioning as a Performance Factor in middle-level guest homes, and serving as a Basic Factor in higher-end tourist lodgings.

Table 3: Regression coefficients for nine IEQ dummy sets in the mixed effects model for tourist accommodations with various star ratings while controlling for cities, nationality, and time of travel

Star Rating	IEQ factors	Low IEQ Performance	High IEQ Performance	Ratio (magnitude of LP/HP)	Three Factor
3 Star and below	Thermal Environment	-0.314***	0.046n.s.	—	Basic
	Indoor Air Quality	-1.217***	0.297n.s.	—	Basic
	Lighting	-0.222***	0.120n.s.	—	Basic
	Acoustics	-0.637***	0.262***	2.43	Basic
	Available Space	-0.488***	0.248***	1.97	Basic
	Facilities	-0.715***	0.030n.s.	—	Basic
	Exterior View	-0.285***	0.513***	0.56	Excitement
	Cleanliness & Maintenance	-1.420***	0.473***	3.00	Basic
	Layout & Design	0.040n.s.	-0.054n.s.	—	—
4 Star	Thermal Environment	-0.423***	0.102**	4.15	Basic
	Indoor Air Quality	-0.987***	0.103n.s.	—	Basic
	Lighting	-0.328***	0.090*	3.64	Basic
	Acoustics	-0.715***	0.223***	3.21	Basic
	Available Space	-0.445***	0.256***	1.74	Basic
	Facilities	-0.619***	0.050***	12.38	Basic
	Exterior View	-0.543***	0.380***	1.43	Performance
	Cleanliness & Maintenance	-1.292***	0.356***	3.63	Basic
	Layout & Design	-0.422***	0.206***	2.05	Basic
5 Star	Thermal Environment	-0.423***	0.051n.s.	—	Basic
	Indoor Air Quality	-0.919***	0.107n.s.	—	Basic
	Lighting	-0.192***	0.057n.s.	—	Basic
	Acoustics	-0.687***	0.174***	3.95	Basic
	Available Space	-0.415***	0.173***	2.40	Basic
	Facilities	-0.589***	0.104***	5.66	Basic
	Exterior View	-0.647***	0.347***	1.86	Basic
	Cleanliness & Maintenance	-1.284***	0.338***	3.80	Basic
	Layout & Design	-0.328***	0.096n.s.	—	Basic

(***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; n.s.: not significant)

3.3. IEQ contribution to the overall satisfaction

According to Nakagawa and Schieizeth (2013), the variance explained by the fixed factors is considered by the marginal R^2, whereas the variance explained by both the fixed and random factors is considered by the conditional R^2. Table 4 listed the marginal R^2 and conditional R^2 measures for three mixed effects models. In the context of hotels and serviced apartments with 3 stars or lower, the combined fixed and random impacts of IEQ factors were found to account for 32.7% of the variations observed in guests' overall satisfaction with these establishments. It is noteworthy that the explained variance attributed to IEQ factors exhibited the highest proportion in lower-end accommodations but shown a gradual decline in middle-level (27.4%) and higher-end guest residences (23.8%).

Table 4: Pseudo-R^2 Measures for mixed effects models

Star Rating	Pseudo-R^2 Measures	Values
3 Star or Below	Marginal	0.215
	Conditional	0.327
4 Star	Marginal	0.201
	Conditional	0.274
5 Star	Marginal	0.188
	Conditional	0.238

4. Discussions

4.1. Comparison with previous studies

Table 3 supports the applicability of the Three-Factor Theory in explaining the IEQ impacts on guest ratings of tourist accommodations. All IEQ factors apart from the exterior view acted as Basic Factors. The absence of these factors has been found to result in dissatisfaction and lower ratings of the premises. The inclusion of a quality exterior view was considered a bonus feature in lower-tier accommodations, however, regarded as an essential feature in higher-end hotels and apartments. This is understandable as customers would have elevated expectations towards luxury hotels and apartments for which they are paying.

Based on the absolute value of the regression coefficients provided in Table 3, Table 5 displays the top four IEQ factors ranked by their impacts on guests' overall satisfaction. The ranking has been conducted separately for situations where the perceived IEQ was unsatisfactory and satisfactory. When guests perceived the IEQ factors to be unsatisfactory, the primary contributors across all star ratings were cleanliness and maintenance, indoor air quality, and acoustics. When IEQ performance was perceived to be satisfactory, the top contributors across all star ratings would be exterior view, cleanliness and maintenance, acoustics, and available space. To avoid receiving a low rating, hospitality managers must ensure satisfactory performance in all IEQ factors, with a particular focus on cleanliness and maintenance, indoor air quality, and acoustics as they are the top dissatisfiers. Based on their respective ranks in the LP and HP groups, exterior view and available space were more influential in eliciting satisfaction than dissatisfaction, although available space was a Basic Factor, as was exterior view in 5-star buildings.

Table 5: Top four IEQ factors that have contributed to the overall satisfaction / dissatisfaction in both low and high IEQ performance groups

Star Rating	Rank	Low IEQ Performance	High IEQ Performance
3 Star and below	1	Cleanliness & Maintenance	Exterior View
	2	Indoor Air Quality	Cleanliness & Maintenance
	3	Facilities	Acoustics
	4	Acoustics	Available Space
4 Star	1	Cleanliness & Maintenance	Exterior View
	2	Indoor Air Quality	Cleanliness & Maintenance
	3	Acoustics	Available Space
	4	Facilities	Acoustics
5 Star	1	Cleanliness & Maintenance	Exterior View
	2	Indoor Air Quality	Cleanliness & Maintenance
	3	Acoustics	Acoustics
	4	Exterior View	Available Space

The results of this study are generally consistent with the findings of prior research. In the study conducted by Li et al. (2020), an examination was carried out on five hotel attributes, namely *cleanliness*, *location*, *room*, *service*, and *value*. The findings revealed that these attributes were all Basic Factors for mid-range and high-end hotels. However, some attributes became Performance or Excitement Factors for budget hotels. While these five attributes encompass broader domains than indoor environment, it is evident that the attributes of *cleanliness*, *room*, and *service* exhibit some overlap with IEQ. Therefore, the results generally agreed with the current study.

4.2. Implications for building design and management

The present study provided strong empirical evidence that demonstrates the substantial influence of IEQ on the overall satisfaction of travelers in guest homes. Most IEQ factors have been recognized as crucial prerequisites by guests, thus they must be performing adequately to achieve satisfaction. The importance of IEQ is particularly pronounced in budget hotels and apartments rated three stars or lower, as it constitutes approximately one-third of guests' overall satisfaction with the establishment. When guests opt for more luxurious accommodations, such as those with 4 or 5-star ratings, their expectations regarding the quality of the buildings and rooms they occupy are elevated. Consequently, the importance of IEQ reduces in relation to their overall satisfaction. Nevertheless, even in luxury hotels and serviced apartments with 5 stars, IEQ remains a significant factor, contributing to approximately one-fourth (23.8% as shown in Table 4) of their overall satisfaction.

The individuals tasked with making resource allocation decisions in retrofitting the built environments, including building managers, architects, and service engineers, rely on their subjective assessment of the significance of different IEQ factors. According to a study conducted by Roumi et al. (2023), building professionals may possess divergent perspectives regarding the relative importance of different IEQ factors. To establish rational priorities, it is imperative for professionals to possess a comprehensive understanding of the effects that different IEQ factors have on occupant satisfaction. This holds particular significance in situations where there are constraints on the resources that are accessible. In this manner, the allocation of scarce resources can be directed towards the IEQ factors that hold the greatest significance in achieving overall satisfaction.

Managers of hotels and serviced apartments with different star ratings should also formulate tailored strategies to effectively cater to the diverse expectations of their customers. Optimising all IEQ factors may not be as advantageous for budget accommodations as achieving satisfactory performance across all IEQ factors while exceeding customer expectations in one Excitement Factor. The presence of Excitement Factor elicits a delight among customers and may result in higher levels of satisfaction and loyalty.

4.3. Limitations of the study

The present study employed web-mining and NLP methodology for data collection and processing. Consequently, it is important to acknowledge the inherent limitations associated with text-mining approaches. The primary constraint would be the classification accuracy of IEQ factors. Despite our efforts to eliminate sentences containing the appropriate keywords but incorrect contextual information, there remain extraneous phrases within the database that have compromised the precision of subsequent analyses. Future studies may adopt more advanced techniques to improve the classification accuracy and remove irrelevant phrases.

This study exclusively examined the impact of IEQ factors on guests' overall satisfaction. According to previous hospitality studies, there are non-IEQ attributes that will significantly affect overall satisfaction, such as location, price, staff attitude, quality of food, among others. Subsequent investigations may consider these significant attributes in the models to enhance the modelling precision of IEQ factors.

This study lacks the differentiation of hotel guests based on their demographic characteristics, such as gender, age, and education. Subsequent research endeavours may investigate the potential presence of moderating influences contingent upon the demographic composition of tourists.

5. Conclusion

To examine the asymmetric impacts of IEQ factors on guests' rating scores, we employed the Three-Factor Theory of customer satisfaction and utilised mixed effects models. Results showed that factors related to IEQ, except for exterior view, were found to be Basic Factors. This implies that customers would expect the performance of these factors should be satisfactory. Failure to meet these requirements would consequently lead to dissatisfaction. The exterior view of accommodations served as an Excitement Factor in establishments with a rating of 3 stars or lower, as a Performance Factor in those with a rating of 4 stars, and as a Basic Factor in 5-star guest homes. The relative importance of IEQ factors was contingent upon their respective levels of performance. When the IEQ performance was considered satisfactory, the most influential factors were exterior view, cleanliness and maintenance, and acoustics. Conversely, when the IEQ performance was deemed unsatisfactory, the most influential factors were cleanliness and maintenance, indoor air quality, and acoustics. The findings of this study highlight the importance of allocating resources towards improving IEQ in tourist accommodations to enhance customer satisfaction.

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Improving resilience of housing for low socio-economic older people: Let’s first look at the frailty level!

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Abstract: This research aims to gather information about existing house conditions of low socio-economic older people in South Australia including of those from culturally and linguistically diverse groups, in order to advance knowledge about resilient and affordable older people’s housing. The first stage includes focus group discussions, which so far have involved more than 40 older people and were conducted in English, Mandarin and Cantonese. The second stage involves collecting relevant data of 50 older occupants who participate in indoor environmental monitoring and occupant surveys, through interviews as well as frailty level assessments using validated tools. Environmental data loggers have been installed to record indoor and outdoor dry bulb temperatures, indoor globe temperatures, relative humidity, air velocity as well as indoor and outdoor CO2 concentration, every 15 minutes. Thermal image camera and blower door tests are used to detect sources of air leakage and calculate infiltration rates in selected homes. In the third stage, data collected will be analysed to develop improvement and new design strategies to improve wellbeing and reduce operational costs. This paper reports the preliminary results from the indoor environmental monitoring and occupant surveys. The results so far show significant differences between older participants identified to be frail and severely frail and those who are identified to be non-frail and vulnerable in terms of their thermal sensation, preference and satisfaction as well as the strategies they take to be comfortable. Lessons learned from these shall be considered in developing the relevant housing improvement strategies for the future.

Keywords: Older people, housing, thermal comfort, frailty.

1. Introduction

The last few decades have seen an increasing number of studies about the relationships between indoor environmental quality, particularly on thermal comfort, and older people’s health and wellbeing. It has now been well understood that, as people age, they face increased vulnerability to a range of physical and health related issues that can be exacerbated by poor indoor environmental quality (IEQ) and extreme weather conditions (van Hoof et al., 2017, Watts et al., 2020).

There are however very few studies conducted specifically to gather information about the IEQ of housing of older people in Australia and to investigate its impacts on older people’s health and wellbeing. This is despite the fact that the proportion of older people (those aged 65 years old or over) in Australia is expected to increase significantly in the next 40 years to be around 25% of the total population (ABS 2015). There can be no doubt that ensuring quality living environments for older people has become a critical issue, now more than ever.

In 2012, Loughnan, Carroll and Tapper (2012) conducted a study in a rural Victorian town to investigate the relationship between housing quality and thermal comfort of older people during a hot period. Later Bills conducted a thermal comfort study of 17 older people in South Australia who lived at home (Bills, 2016) and found that the participants preferred to be in the cooler side of the temperature range deemed by ASHRAE Standard 55 to be thermally acceptable. Her study also found a significant relationship between indoor temperatures and number of votes with reported health symptoms, with indoor temperatures lower than 21°C and higher than 24°C showing an increase in health symptoms (Bills, 2018). In New South Wales, Tartarini et al. (2017a) conducted a thermal comfort study of more than 300 older people in dementia care facilities. The results showed that the residents preferred warmer temperatures than what they experienced in their rooms. The study also found an increase in agitated behaviours when the older residents were exposed to indoor temperatures higher than 22.6°C and lower than 20°C (Tartarini et al., 2017b).

Funded by the Australian Research Council, between 2018 and 2021, we conducted the first Australian state-wide thermal comfort study, monitoring the homes of 71 community-dwelling older people living in three climate zones in South Australia (*BSk, Csa* and *Csb* climate zones according to the Köppen-Geiger climate classification system). Similar to the findings by Bills (2017) and Tartarini et al. (2017), we found a significant relationship between indoor operative temperature and self-assessed health and wellbeing, with indoor temperatures below 15°C and above 28°C associated with poorer health and wellbeing (Williamson et al., 2022; Hansen et al., 2022). Another important finding to highlight is, unlike most other thermal comfort studies of older people that considered the participants and reported the results as one group or at least analysed them based on sex, further analysis of the data from our study using a clustering analysis methodology shows that the older participants can actually be grouped into six clusters or “thermal personalities”. These thermal personalities were based on 18 features, which included age group, sex, annual income, health-related wellbeing dimensions, number of reported weather-related health symptoms, as well as preferred actions to maintain thermal comfort (Bennetts et al., 2020). The acceptable operative temperatures of these six clusters were also different, with four clusters being rather similar (where their acceptable temperatures were within the acceptable operative temperatures according to the adaptive model in ASHRAE 55), a cluster that preferred to be always warm, and a cluster that preferred much cooler temperatures in winter and accepted much higher temperatures in summer than that suggested by ASHRAE 55 (Arakawa Martins et al., 2022). Findings from this study have led to the development of ‘Thermal Comfort at Homes: A Guide for Older South Australians’ (Soebarto et al., 2022) that has been widely circulated and presented to older people’s groups as well as many organisations in South Australia.

Notwithstanding the significant findings and impact from our study above, a very small number of the participants were those with low socioeconomic backgrounds or those who lived in areas identified to be disadvantaged as indicated by the SEIFA (Socio-Economic Indexes for Areas) index (ABS, 2006). This is despite recent data highlighting that 1 out of 4 people in South Australia live in these areas (Ellard-Gray et al., 2015) and are most likely to have the lowest wellbeing index (Tanton et al., 2018). All participants spoke English with the vast majority having an Anglo-Saxon background, and we did not have any participant who recently migrated to Australia despite the fact that there were more than 100,000 migrant arrivals in South Australia, aged 65 years and over, between 2018 and 2021 (ABS, 2021). This was a shortcoming of the study that needed to be addressed, as it is older people of low socio-economic status who will potentially benefit most from evidence-based knowledge on affordable modifications that improve housing resilience to adverse circumstances. Increased housing resilience would help improve their well-being of the occupants and reduce the likelihood of them requiring costly institutional care.

Another limitation of our previous study was that only 6 (8%) of participants who had their homes monitored were frail, as measured using the Edmonton Symptom Assessment Scale (Bruera et al., 1991). Frailty refers to a state of increased vulnerability to stressors resulting in adverse health outcomes such as hospitalisations, falls and fracture and loss of independence (Clegg et al., 2013). Consequently, no relationship between participants' frailty levels and their thermal comfort were observed. This is similar to the finding of another study by Soebarto et al. (2019) who investigated the thermal comfort of 22 older and 20 younger people in an environmental chamber in 2017-2018, where only 3 out of the 22 older participants (14%) were assessed to be frail and no correlation was found between frailty and thermal comfort. However, before a relationship between frailty and thermal comfort can be discounted, it is important that a study involving a larger proportion of participants with frailty be conducted. Frailty is increasingly common in Australia, with a 2019 study by Taylor et al. identifying that more than half of community dwelling older Australians aged 65 years and older were frail in 2016 and over a third of older people in South Australia were classified as frail and over half as pre-frail (Dent et al. 2017). As lower socio-economic status is associated with increasing frailty, especially when measured using a frailty index (Thompson et al., 2018), it is likely that research focusing on lower socio-economic older people will include a larger proportion of frail individuals.

2. Objectives

Whilst the overall objectives of the research project are to: (1) understand the living environment of this cohort of older people in South Australia, including those from CALD (culturally and linguistically diverse) background, (2) to examine the relationships between the older people, their living environment, frailty level, thermal comfort and wellbeing, (3) examine the relationships between house design, household energy use and cost, and (4) explore strategies to achieve resilient and affordable housing for low socio-economic older people, this paper capitalises on the monitoring and survey data from the first six months and focuses on the first two objectives. To address the knowledge gap as discussed earlier, we aim to explore the relationships between IEQ, thermal comfort and behaviours, and frailty.

3. The context

The study focuses on older people living in Local Government Areas (LGAs) in South Australia with higher proportions of socio-economically disadvantaged households, as indicated by relatively low SEIFA rankings, based the Index of Relative Socio-Economic Disadvantage (IRSD) and the Index of Relative Socio-Economic Advantage and Disadvantage (IRSAD). They are Playford (855/853), Salisbury (917/908), Port Adelaide Enfield (936/940), Charles Sturt (1000/993) and Murray Bridge (894/878). In comparison, the SEIFA scores of the City of Adelaide are 1014/1058. The first four LGAs are within the same climate zone, i.e., *Csa*, while Murray Bridge is has a *BSk* climate according to Köppen-Geiger climate classification system. The first four LGAs are also chosen because they were not captured in the previous study while Murray Bridge was selected to represent a regional town with a relatively high proportion of older people (more than 20%). Further, we made efforts to recruit older people who do not speak English and those with non-Anglo-Saxon backgrounds.

Participants were recruited with the assistance of the above local Councils, Migration Resources Centre, social housing and retirement village providers, as well as other community organisations. Information sessions were held from July to November 2022 with some employing a translator in the participants' language – Mandarin, Cantonese, Spanish, Persian, Uygur, Nepalese, and Burmese. These resulted in 42 older people willing to participate in focus group discussions and 50 people from 39 households in the indoor environmental monitoring and occupant survey. Two of the focus group discussions were conducted in Mandarin and Cantonese, while out of the 39 householders in the house monitoring and occupant survey, 6 householders (10 people) are non-English speaking. Human Research Ethics approval was obtained from The University of Adelaide Human Research Ethics Committee with approval number H-2022-134.

4. Methods

4.1. Focus group discussions

The objective of the focus group discussions was to collect qualitative data to gain understanding about the relationships between housing conditions, house design, indoor conditions and the occupants' attitudes, perception and satisfaction in relation to achieving comfort in the participants' dwellings. Based on our previous experience (van Hoof et al., 2019), focus groups are particularly useful to encourage participations by those who would be reluctant to be interviewed on their own or feel that they have nothing to say. Each focus group was led by one of the researchers who simply prompted a question or scenario, and each participant was encouraged to respond. There was no right or wrong answer as the objective for all participants to share their views of the issues. Each focus group had 6-10 participants to ensure that everyone had the same opportunity to express their views during the discussion, which lasted around 1.5 hours. In the focus groups with non-English speaking participants, the discussion leader asked the question in English, and an interpreter translated the question or statement into the relevant language. The interpreter then translated each response into English to the discussion leader. All discussions were audio recorded and transcribed (and translated into English) for the data to be analysed qualitatively. Results from the focus group discussions are reported elsewhere.

4.2. Indoor environmental survey and occupant survey

While the focus group discussions provide some understanding about the housing conditions of the older participants, we require more information on, for example the actual conditions inside the dwellings and the actions the occupants take to achieve comfort. To do this, we are conducting indoor environmental monitoring and occupant survey for at least 9 months from end of January 2023 to cover summer, winter and in-between periods. Data loggers used in our previous study (Soebarto et al. 2019b) have been modified to record, every 15 minutes: indoor and outdoor dry-bulb temperatures, relative humidity, and CO2 concentrations; indoor globe temperatures (used to calculate operative temperatures based on the method given in ISO 7726:1998 (ISO 1998)) and indoor air velocity. The main sensors and loggers monitored the conditions in the living room connected while two nodes measuring and recording dry-bulb temperature, relative humidity and CO2 concentration, are connected to the main logger, one placed in the main bedroom and another is placed outside of the living room. iButtons (DS1925 Thermochron) are also placed on the air-conditioning unit outlets and/or any heating equipment used in the monitored rooms, measuring temperatures which will indicate the AC or heater on/off status.

As in the previous study, the indoor environmental survey questions are uploaded onto digital tablets to be used by the participants to reflect their perception, satisfaction, and response to the IEQ, at least 3 times a week. Participants are also asked to reflect on their perception of health and wellbeing and any health-related symptoms at the time they respond to the survey and whether they feel that these are affected by the IEQ. The questions have also been translated into simplified Chinese and Nepalese to be used by Chinese and Bhutanese participants, respectively. Figure 1 shows the data acquisition system used in this study: main logger, node, tablet and iButton, while Table 1 summarises the survey questionnaires.

Each logger transmits the data to an FTP site every day as a text file that contains time-stamped measurements and survey responses. The file is stored in a directory linked to the logger's unique telephone number. Researchers are able to access the files on the FTP site which are named based on the date when they were created by the logger. A system has also been set up to identify the activity of each logger and tablet so that if any of them has stopped working, the researchers can remedy the problem immediately. Downloaded data are then analysed using various statistical methods, as will be presented next.

Before the monitoring and occupant survey took place, we conducted an interview with each participant to collect demographic data and other information such as their weather preference, actions taken to be comfortable, perception of or self-assessed health/wellbeing, and their personal capacity using SEARCH (Self-Assessed Report of Personal Capacity & Healthy Ageing) questionnaires developed by Thompson et al. (2021) that assess all the domains that indicate frailty, such as nutritional status, fatigue, pain, physical activity, strength, walking speed, balance, memory, mental health, medications, health conditions, and sensory. If architectural drawings of the house were not available, a researcher measured the room dimensions, took a note on the building materials, drew the floor plan of the house, as well as took photographs of the inside and outside of the building.

Figure 1: Data logger and survey tablet (left); the node (centre); iButton (right)

Table 1: Summary of occupant survey questionnaire

Type	Questions	Answers
Identification	Person No:	Person 1, Person 2
	Which room are you in?	Living room, Bedroom
Thermal comfort related questions	How are you currently dressed?	Very light, Light, Moderate, Heavy, Very heavy
	Describe your activity in the last 15 minutes in this space:	Very relaxed, relaxed, light, moderate, active
	What actions have you done to be warmer or cooler in the last 30 minutes?	Adjust clothing, Adjust activity, Open/close windows/doors, Turn on/off cooler or heater, Turn on fan, Nothing, Other
	How do you feel right now?	Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm, Hot
	Would you prefer to be…	Cooler, No change, Warmer
	How satisfied are you with the temperature in this room?	Very satisfied, Satisfied, Partially satisfied, Dissatisfied, Very dissatisfied
Heating, cooling, ventilation related questions	The air conditioner in the room is…	On, Off
	A heater in this room is …	On, Off
	A fan in this room is …	On, Off
	Curtains / blinds in this room are…	All open, Some open/close, All close
	In this room, windows and door(s) to outside are:	All open, Some open/close, All close
	In this room, door(s) to other room(s) are:	All open, Some open/close, All close
Air quality questions	Do you think the air in this room is…	Stuffy, OK, Draughty
	Do you feel that the air quality in this room is:	Very good, Good, OK, Poor, Very poor
Health/well-being related questions	How would you describe your health and well-being at the moment?	Very good, Good, Reasonable, Poor, Very poor
	Have you experienced in the last 30 minutes any of these?	Headache, dizziness, Racing heart, Coughing, Shortness of breath, Joint pain, Loss of balance, Fever, Unexplained tiredness, Dehydration, Excessive sweating, Sleeplessness, Depression, Agitation
	The conditions in this room influence my health and well-being:	Definitely yes, Probably yes, Yes, Unsure, Probably not, Definitely not

5. Results

5.1. Socio-demographic information of participants

Although not equal, there is an adequate distribution of participants in relation to where they live, although the Salisbury area has the highest number of participants. There are more female than male participants. About half of the participants are from the middle-older group (70-79 years) and there is almost the same proportion of the younger (< 70 years) and older -older group (>79 years). Ten out of 50 participants did not speak English and were assisted by a interpreter when their homes were visited. There is quite a spread of education levels among the participants, from those who do not have any formal education at all (who were also born overseas), to those who completed primary education only, secondary, and vocational education as well as those who completed a university degree. Almost half of the participants live alone, while the rest live either with their spouse or other family member(s). While most of them are either pensioners or self-funded retirees, some still work on a part-time basis. Those who receive pensions or government support have annual household income of up to $40,000, those who are self-funded retirees receive $40,000-60,000 and still receives up to $80,000. Table 2 summarises the socio-demographic information of the participants.

Using the SEARCH (Self-Assessed Report of Personal Capacity & Healthy Ageing) Frailty assessment scale (Schultz and Beilby 2020; Searle et al., 2008), we were able to calculate each participant's frailty score (ranging from 1 to 25). SEARCH frailty scores of 0-3.5 indicate 'non frail', 4-8 as 'vulnerable, 8.5-17.5 as 'frail' and 18+ as 'severely frail' (Thompson et al., 2021). The results show that 64% are considered 'frail' (this includes 'severely frail') and 36% 'non frail' (including 'vulnerable'). During the interview we also asked each participant to state their perception of their health/wellbeing status by giving a score out of 100 (< 60 poor, 61 < 80 ok, > 80 good). Interestingly, 9 out of 23 participants (39%) believing to have a 'good' health were considered to be 'frail' and 'severely frail' by the SEARCH assessment. Nonetheless, Chi-Square test indicates a significant association between Frailty level and self-assessed health ($p < 0.001$) as those who felt to have 'OK' and 'poor' health were indeed those who were considered to be either 'frail' or 'severely frail'.

Table 2: Socio-demographic information, frailty level and self-assessed health of the participants (n = 50)

	Number	**Percentage**		**Number**	**Percentage**
Location:			Education:		
Playford	6	12	No education	4	8
Salisbury	15	30	Primary (incomplete)	1	2
Port Adelaide Enfield	10	20	Primary (completed)	8	16
Charles Sturt and West	8	16	Secondary (completed)	10	20
Torrens	11	22	Vocational (completed)	11	22
Murray Bridge			University (incomplete)	1	2
			University (completed)	15	30
Sex:			Income source (multiple		
Male	17	34	answers)	7	
Female	33	66	Work part-time	43	
			On pension	4	
			Self-funded retirement		
Age group:			Household annual income:		
< 70	12	24	$12,001 - $20,000	8	16
70 – 79	27	54	$20,001 - $40,000	24	48
80 - 89	11	22	$40,001 - $60,00	17	34
			$60,001 - $80,000	1	2
Language spoken at			SEARCH Frailty:		
home:	40	80	Non frail	7	14
English	10	20	Vulnerable	11	22
Non English			Frail	25	50
			Severely frail	7	14
Living arrangement:			Self-assessed health:		
Live alone	21	42	Good	23	46
With partner	24	48	OK	22	44
With other(s)	5	10	Poor	5	10

5.2. House constructions and air-conditioning systems

Twenty participants live in detached homes, 13 in semi-detached house, 5 in a unit of an apartment building, and 1 in the so-called “granny flat” (in this case, a 2-rooms small dwelling behind the main house). A vast majority of the buildings have brick veneer walls (69%), mostly uninsulated, while the rest have double brick walls (29%), and one house is lightweight with steel-cladding on metal frames. More than half have tile roofing while the rest have steel roofing. Two of the dwellings are on the first floor of an apartment building of concrete structures, but the majority of the houses are single story built on concrete slab floor (72%) or have timber flooring (18%). More than 80% of the participants stated that their dwellings had ceiling insulation but no insulation under the roofing material. Most have sliding sash windows, nine dwellings have awning windows, and the rest have either double hung or casement windows, all with single glazing. All windows have internal covers, either curtains or blinds but almost half of the dwellings have no external blinds or covers. It is worth noting that a vast majority of those who have external blinds stated that they never open them. Likewise, around half of the participants stated that they never opened the windows though some would open the doors (behind security doors with fly screens).

Twenty-four dwellings have reverse cycle (split) system(s) for cooling and heating in their living rooms, while the rest have ducted reverse cycle (6), wall-mounted reverse cycle (5) and ducted evaporative cooler (3). One dwelling has no cooler and only has a portable heater in the living room. Some houses have gas heaters, either wall mounted or a ducted system. Thirteen houses have no fan installed, while nine have ceiling fans and seven have portable fans. Interestingly, despite having air-conditioning systems, during the time the participants responded to the thermal comfort survey until the end of July 2023, they only used them around 21-22% of the time, with those who are considered ‘frail’ using the coolers and heaters more often than the ‘non frail’ participants ($p < 0.001$), as shown later in Figures 2 and 3.

5.3. Indoor environmental quality

During summer (January to March) 2023, the indoor dry bulb temperatures in the living rooms of the dwellings altogether ranged from 17.2 to 39.3°C and between 16 and 38.9°C in the bedroom. The highest temperatures were recorded in a one-bedroom semi-detached dwelling of a social housing, and occurred when the outdoor temperature was 36.2°C. During part of winter (June to July) 2023, the lowest indoor temperature recorded was 11.2°C in the living room and 10.8°C in the bedroom when it was 9.6°C and 8.9°C outside, respectively. The average indoor temperatures in summer were 24.3°C in the living rooms and 24.0°C in the bedroom, while in winter they were 18.2°C and 17°C respectively. The relative humidity ranged from 25 to 80% and 34 to 80% in the living rooms and bedrooms, respectively.

The air velocity in the living room ranged from 0.1 to 0.37 m/s with an average of 0.15 m/s in summer and between 0.1 and 0.93 m/s with an average of 0.11 m/s during winter months, indicating that indeed many of the participants rarely opened the windows. Throughout the monitoring period, CO2 concentrations in the living rooms ranged from 291 to 1589 ppm and between 177 and 1390 ppm in the bedrooms. CO2 levels above 1000 ppm are often associated with complaints of poor air quality (Bonino, 2016). To date blower door tests have been conducted in 6 houses. Air change rates at 50 Pa were recorded at 6.5 ACH in one of the relatively new dwellings, 29.4 ACH in one of the older homes and from 14 to 20 ACH in the other four houses, indicating that most of these houses were very leaky according to international standards of energy efficient homes (0.6 ACH). Further analysis of the indoor environmental quality of these homes will be reported elsewhere.

5.4. Thermal comfort-related actions and perceptions

During the interviews we asked the participants to indicate their first action to be cooler during a hot day. Their answers varied from turning on the air-conditioner, turning on fan, closing the blinds and doors, and so on. Chi-Square Tests show a significant association between these first actions and frailty levels ($p < 0.001$). In other words, the first action taken to be cooler between the 'frail' and 'non frail' group was significantly different. As shown in Figure 2, while there were a range of answers, for the 'frail' group, the largest percentage of the response was to "turn on cooling", whereas for the 'non frail' group, the largest percentage was to "close inside curtains or outside blinds". For the 'non frail' group, turning on the cooler as the first action during a hot day was only mentioned by few people, together with "drinking water or cold drinks". Interestingly, to be warmer in a cold day, the majority in both groups indicated that increasing clothing layers was the first thing they would do; however, a number of people in the 'frail' group also mentioned a variety of other actions to be warmer whereas in the 'non frail' group only 2 people mentioned other actions: using electric blanket and taking a warm shower without mentioning the need to turn on the heater (Figure 3).

We also asked the participants about their concerns over cooling and heating costs. The results (Figure 4), indicate concerns over these costs increase with frailty level ($r^2 = 0.75$ for cooling, $r^2 = 0.87$ for heating, $p < 0.001$) even though the concerns slightly decreased between the 'vulnerable' and 'frail' groups. Nonetheless, we found no significant correlation between income level and the concern over cooling and heating costs nor between income and frailty levels. This indicate that concerns over cooling and heating costs were not associated with low-income levels and those identified as 'frail' did not necessarily have lower incomes either. It is possible that the 'frail' group felt that they required to use air-conditioning frequently, hence were worried about the cost implications, more so than the 'non frail' were.

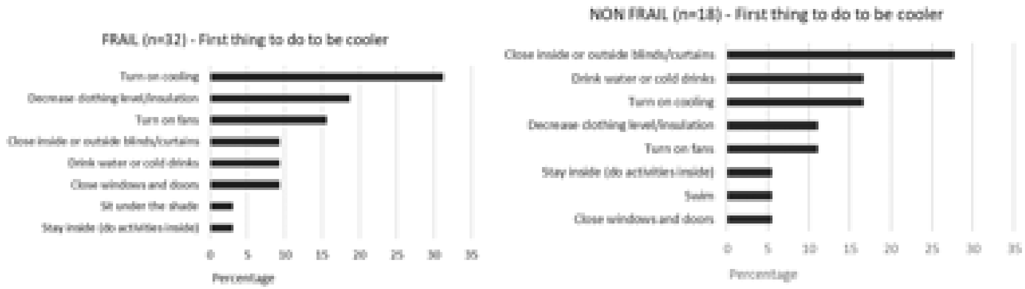

Figure 2: First action to be cooler in a hot day by the 'frail' (left) and 'non frail' (right) groups

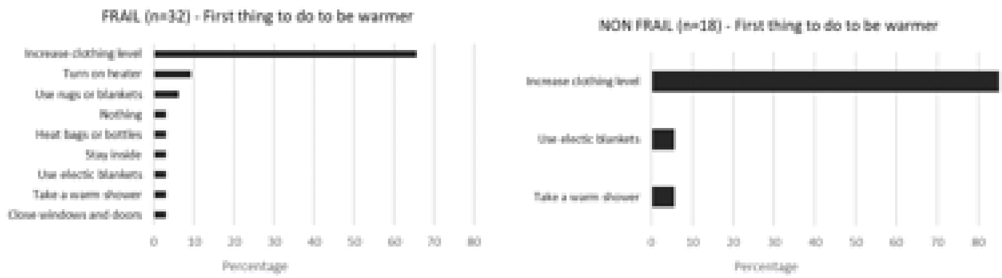

Figure 3: First action to be warmer in a cold day by the 'frail' (left) and 'non frail' (right) groups

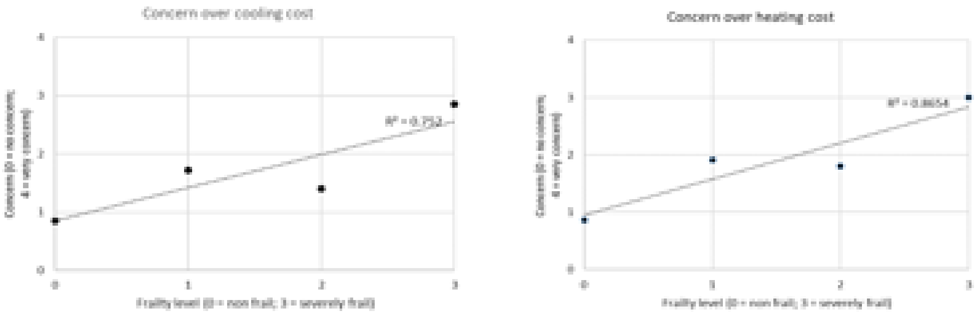

Figure 4: Concerns over cooling (left) and heating (right) costs (showing mean value in each frailty group)

5.5. Thermal neutrality and preference

The occupant survey responses until July 2023 have been compiled with the IAQ parameters that were recorded around the same time of the responses. The mean thermal sensation votes (TSV) and thermal preferences (TP) of the 'non frail' and 'frail group' have been calculated for every 0.5°K of operative temperature with a regression line fitted using the weight according to the number of votes in each 0.5°K bin.

The results show the thermal sensation and preference between the 'non frail' and 'frail' groups are significantly different. For thermal sensation, the slope for the 'frail' group appears to be slightly steeper (F_{frail} = 101.2, p < 0.000, $F_{non\text{-}frail}$ = 32.1, p < 0.000). The fitted models indicate temperature neutrality (when TSV = 0) of 24.3°C for the 'non frail' group compared to 21.1°C for the 'frail' group. On the other hand, the slope of the thermal preference of the 'non frail' group is steeper than that of the 'frail group" ($F_{non\text{-}frail}$ = 114.5, p < 0.000, F_{frail} = 52.1, p < 0.000), with the preference of "no change" (Pref = 0) of the 'non frail' group occurred at 23.2°C and at 24.7°C for the 'frail group'. It appears that while the 'non frail' group felt neutral at 24.3°C they actually preferred to be in a slightly cooler condition (23.2°C). On the contrary, while the 'frail' group would start to feel slightly warm when temperature went above 21.1°C, they indeed preferred to be warmer as they preferred temperature was 24.7° C. See Figures 5 and 6.

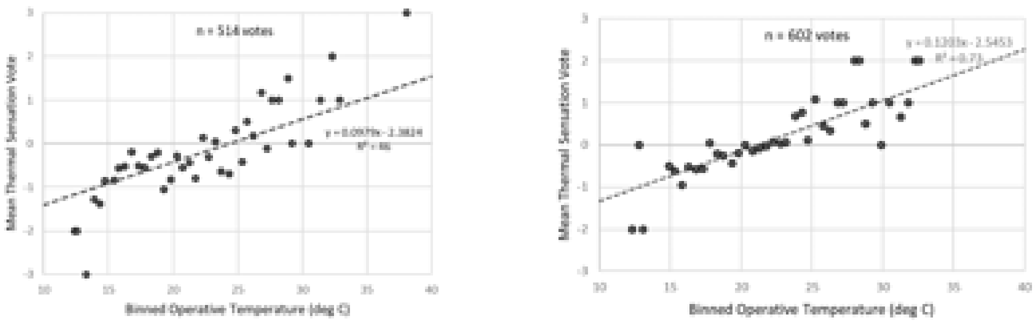

Figure 5: Mean Thermal Sensation Vote vs Binned Operative Temperature – Non frail (left) and Frail (right)

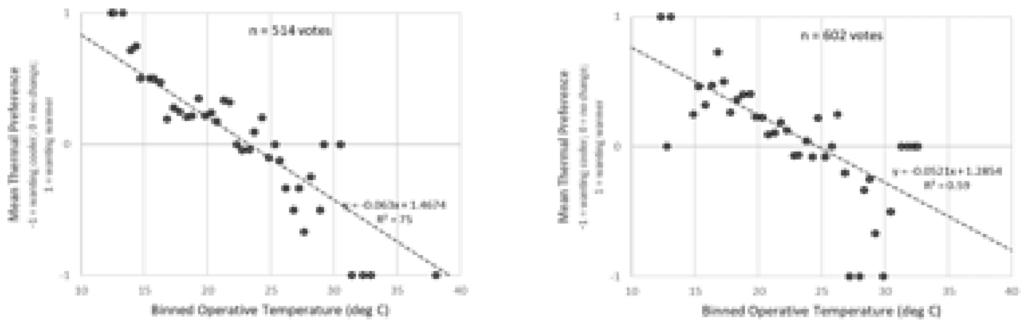

Figure 6: Mean Thermal Preference vs Binned Operative Temperature – Non frail (left) and Frail (right)

The association between indoor operative temperature and perception of health/wellbeing is found to be more prevalent with the 'non frail' group with temperatures between 18.5°C and 26.5°C associated with 'good' health ($F_{non\text{-}frail}$ = 7.50, p < 0.005), as shown in Figure 7. Their perception of health would decrease as the temperature goes beyond these points. On the contrary, the association is found to be weak in the 'frail' group (F_{frail} = 0.15, p > 0.005), with the participants indicating that health and wellbeing to be more or less the same regardless of the indoor temperature. Similarly, the association between indoor operative temperature and thermal satisfaction is found to be stronger with the 'non frail' group with the occupants feeling the most satisfied with indoor temperatures between 17.2 and 27.6 ($F_{non\text{-}frail}$ = 25.53, *p* < 0.000). On the other hand, there is no strong association between indoor operative temperature and thermal satisfaction among the 'frail' group (F_{frail} = 0.23, *p* > 0.005).

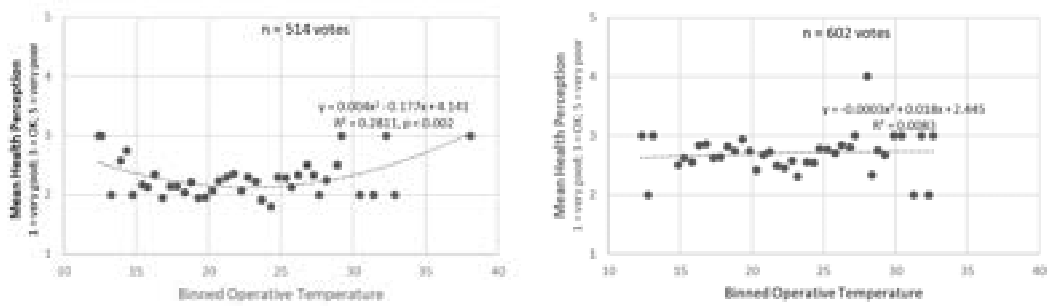

Figure 7: Mean Health Perception vs Binned Operative Temperature – Non frail (left) and Frail (right)

As shown earlier, increasing or decreasing the clothing insulation was one of the main strategies almost all participants employed to be more comfortable. Further analysis, as shown in Figure 8, however, indicates that there is a difference in the clothing layers between the 'frail' and 'non frail' groups. During warmer temperatures, the 'non frail' group seemed to wear fewer clothing layers than the 'frail' as shown in a steeper slope of the fitted regression line ($F_{non\text{-}frail}$ = 89.11, p < 0.000; F_{frail} = 40.82, p < 0.000). It is possible that the reason the 'frail' group wore more clothing layers during warmer temperature was because they always preferred to feel warm, as discussed above.

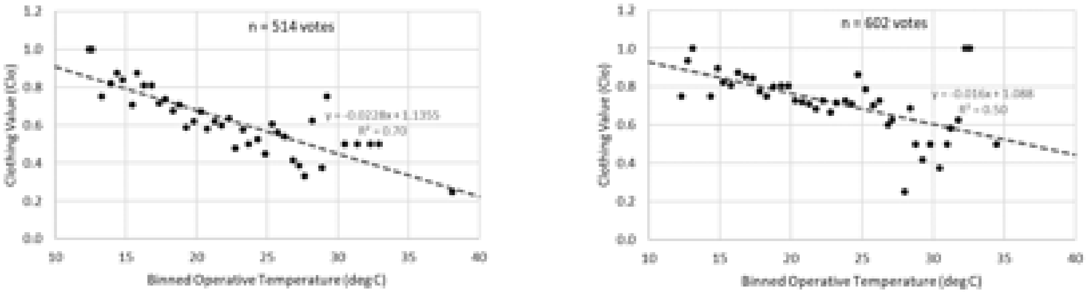

Figure 8: Mean Clothing Value vs Binned Operative Temperature – Non frail (left) and Frail (right)

6. Discussion

The study participants' demographics show that 64% have low income (up to $40,000 p.a.) and around 20% of them come from a CALD background. This is in contrast with our previous study (Soebarto et al., 2019a) where less than 40% had low income and none had a CALD background. The indoor environmental monitoring data showed that many of the participants were living in dwellings that were quite cold in winter unless heating was used and quite warm in summer without cooling, indicating poor housing quality, whereas in the previous study we found less frequent usage of heating and cooling (Hansen et al., 2021).

In the current study, we also identified that 64% of the participants were frail and severely frail, whereas in the previous study only less than 10% were considered frail. While in the current study we found no significant correlations between frailty level, background (country of birth or language spoken at home), income level, education level, home ownership, and house construction types, we found significant correlations between frailty, thermal comfort (sensation, preference), behaviour and in the relationship between indoor temperatures and perception of health/wellbeing. This, to the best of our knowledge, is the first thermal comfort study of older people that identify these associations.

The analyses show that there is an association between frailty level and first actions taken by the participants in order to feel cool in hot weather. The first actions taken by the 'frail' group were significantly different from that by the 'non frail' group; the majority of them would turn on the cooler when feeling warm while the majority of the 'non frail' group would close the blinds first. We also found that thermal sensation, preference, as well as neutral and preferred temperatures to be significantly different between the two groups. As shown in Figure 5, the mean TSV of the 'frail' group was almost 0.5 higher than that of the 'non frail' group, yet they still preferred to be in a warmer temperature than the preferred temperature of the 'non frail' group. The 'frail' group also wore more clothing layers than the 'non frail' group did, depicting their preference to be in a warmer indoor environment. Further, a significant association between indoor operative temperatures and occupants' perception of their health/wellbeing as well as satisfaction with the indoor environment was only found in the 'non frail' group. In the 'frail' group, satisfaction with the indoor environment as well as perception of health/wellbeing of the 'frail' group did not seem to be associated with indoor temperatures. It is possible that their frailty has more profound effects on them that their satisfaction with the indoor environment or perception of health/wellbeing did not significantly change with indoor temperature changes.

This is not to say that improvements of the living environment for older people are only necessary to those who are not frail. The results indeed show that the 'frail' group preferred to be in a warm condition, but when they felt hot, many had to resort to the air-conditioner to feel cooler. This indicates that the living environment particularly for those who are frail needs to be designed to ensure a satisfactorily warm environment but also not too hot to avoid their concern of the cost associated with having to use an air-conditioner.

7. Conclusions

This paper has reported the initial findings of the study aimed to understand the living environment of older people living in relatively disadvantaged areas in South Australia in order to develop strategies for resilient and affordable housing for older people. Based on the data collected so far, we have identified that there are significant differences in thermal comfort (sensation and preference), behaviour, neutral and preferred temperatures, perception of health/wellbeing as well as satisfaction with the indoor environment between older people who are frail and less or not frail. To the best of our knowledge, no existing thermal comfort studies of older people have explored the associations between indoor environment quality particularly the thermal environment, and frailty. While data collection is still ongoing, these preliminary findings indicate that future explorations to develop resilient housing for older people must consider the frailty issue. An understanding of this can help anticipate what will be needed to ensure future housing design will be resilient and affordable not only when the occupants are not frail but also as they become frailer.

8. Acknowledgements

This study is funded by the Australian Research Council through the Discovery Project grant, ARC DP2203213. We wish to acknowledge the assistance from the Cities of Salisbury, Playford, Port Adelaide Enfield, Charles Sturt, and Murray Bridge; Salisbury Jack Young Centre, Australian Migration Resource Centre, Multicultural Commission SA, Chinese Welfare Centre, Greek Welfare Centre, Cottage Homes, Westside Housing Company, Murray Bridge Lutheran Homes, Believe Housing Australia (Anglicare), University of the Third Age Port Adelaide, and Killburn Community Centre. We are grateful for all older people participating in this study, and we acknowledge the assistance of Ying Le, Anugra Kc and Chiara Ha Thanh Le during the house visits to the non-English speaking participants. The blower door tests were conducted by Darren Harris of SUHO, assisted by Dr Artur Miszczuk.

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Indoor environmental quality and occupants’ satisfaction in high-rise mixed-use buildings: Preliminary results from a case study

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Abstract: Indoor environmental quality (IEQ) can impact occupant’s health, productivity, and wellbeing, as evidenced in various building performance studies with an occupant-centric approach. Quantifying the impact of each of the IEQ parameters – thermal comfort, visual comfort, acoustic comfort and air quality – on occupants’ satisfaction with the indoor environment (IE) is a key step to move towards a human-centric building performance evaluation, and consequently, to improve building design and their performance in fostering IE satisfaction, enhancing occupants’ wellbeing. This study conducted a post-occupancy evaluation (POE) at U City, a high-rise mixed-use building in Adelaide, South Australia. The POE investigated the correlation between IEQ and occupants’ satisfaction with the indoor environment, collecting data from apartment residents and office workers. The data collection included surveys, monitoring of indoor environmental parameters with data loggers, observations of public space use in the building and focus groups. This paper presents the preliminary results on how each of the IEQ parameters affected the overall satisfaction with the IE as part of a broader framework to evaluate building performance in fostering wellbeing. The preliminary statistical analysis showed significant correlations between IEQ parameters and IE satisfaction for both residents and workers. Indoor temperatures, noise issues or sound quality and air quality were found to be the most significant factors that affected IE satisfaction. The outcome of this investigation will inform the elaboration of a metric that will be embedded in a building design evaluation tool based on computational 3D model analysis.

Keywords: Indoor Environment Quality, Human-Centric Performance, Building Design, Wellbeing

1. Introduction

The indoor environment quality (IEQ), which encompasses thermal comfort, visual comfort, acoustic comfort and air quality, integrates an important part of occupant’s satisfaction with the indoor environment and wellbeing. Numerous studies have extensively demonstrated the influence of IEQ parameters on occupants' health and productivity, and therefore, on their wellbeing (Al horr et al. 2016; Bourikas et al. 2021; Vladoiu, Isopescu, and Maxineasa 2021). An extensive body of literature has established the importance of thermal comfort for health and wellbeing, linking extreme temperatures, both cold and heat, may augment mortality rates (Diaz et al. 2005; Nicholls et al. 2008; Hansen and Soebarto 2019). Visual comfort also plays a vital role in wellbeing. It impacts office workers by affecting their performance and stress levels (Boyce, Hunter, and Howlett

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2003; Heschong and Mahone 2003), sleep patterns (Chang and Chen 2005), and overall health and mood (Denissen et al. 2008; Borisuit et al. 2015).

Numerous studies have shown that acoustic discomfort can impact the health and wellbeing of building occupants, influencing aspects such as mental health (Laird 1933), mood (Thompson, Schellenberg, and Husain 2001), and life satisfaction (Urban and Máca 2013). Some research indicates a direct link between acoustic comfort and worker productivity in commercial buildings (Sundstrom et al. 1994; Martellotta 2011). Excessive environmental noise can lead to stress, decreased concentration, job dissatisfaction, and increased workplace conflicts (Leather, Beale, and Sullivan 2003; Mak and Lui 2012).

Indoor air quality is another critical factor for occupant wellbeing. Inadequate ventilation rates resulting in high CO2 levels can lead to sick-building syndrome (SBS) (Carrer et al. 2015; Maddalena et al. 2015) and increased exposure to microbial pollutants, often linked to respiratory diseases, allergies, asthma, and immunological reactions (Myatt et al. 2004; Heseltine, Rosen, and World Health Organization 2009). Additional studies highlight the impact of indoor air quality on performance and learning (Federspiel et al. 2004; Bakó-Biró et al. 2012).

This study is a component of a broader research project that aims to investigate how aspects of building design influence IEQ, occupants' IE satisfaction and overall wellbeing. The research introduces a framework for assessing the IE performance in fostering wellbeing. The proposed framework is divided into three distinct dimensions: comfort, delight, and social (Croffi et al. 2023). This paper focuses on the comfort dimension only (Figure 1), investigating its impact on occupants' IE satisfaction and presents the initial findings.

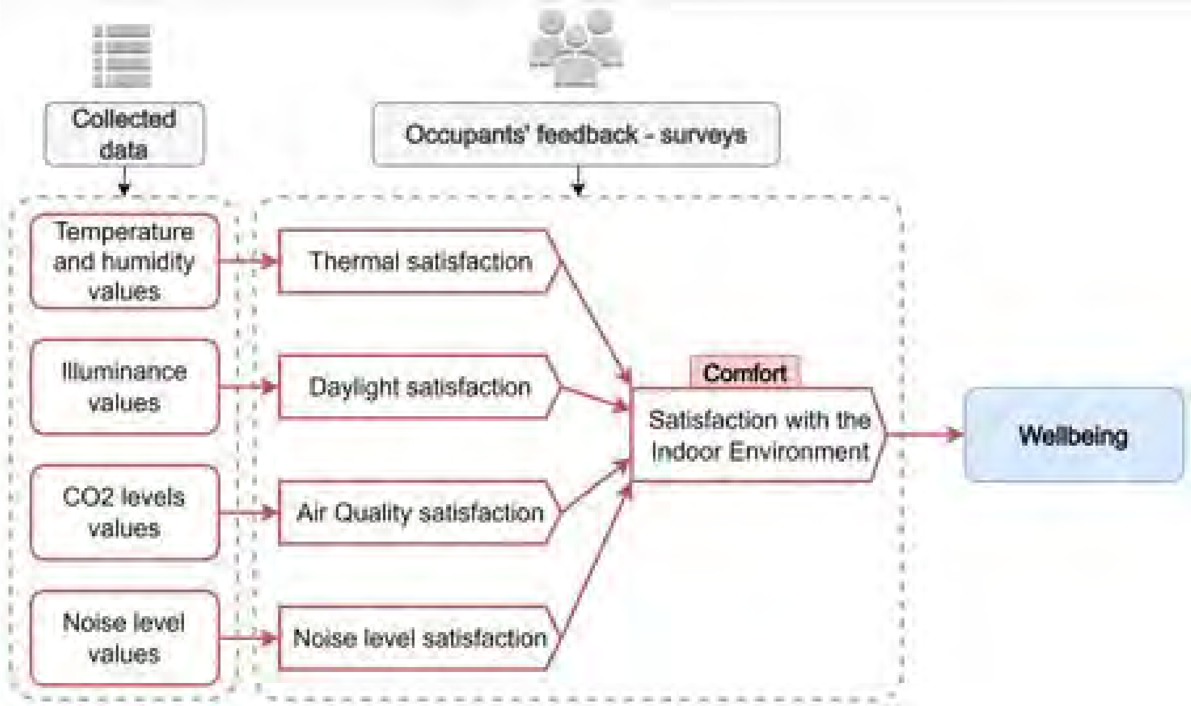

Figure 1: Proposed framework – Comfort dimension (Croffi et al. 2023)

2. Methodology

This research collected data through a post-occupancy evaluation (POE) conducted in a case study high-rise mixed-use urban development in Adelaide Central Business District, South Australia. Throughout the study period from July 2022 to December 2023, the building occupants participating in the study regularly responded to surveys conducted via smart devices. These surveys included a series of questions on indoor environmental quality, covering thermal, visual, and acoustic comfort, as well as indoor air quality and overall wellbeing at the given time (Table 1). Additionally, participants provided valuable insights into their adaptive behaviours in response to the prevailing indoor environmental conditions. This included information about their clothing choices, types of activities, window operations, and indoor lighting usage. Throughout the research period, each participant was expected to respond to the survey at least twice a week, at different times of the day, for a duration of 12 to 18 months. This extended timeframe allows for capturing their experiences across various seasons throughout the year.

In the surveyed spaces, the IE conditions were tracked and recorded at 30-minute intervals through data loggers or measured periodically with handheld devices. These conditions consisted of indoor dry bulb temperature, globe temperature (a measure of radiant temperature), relative humidity, lighting levels, noise levels, air movement, and CO2 levels. Collecting data of IE parameters allow us to identify the specific conditions, such as temperature and lighting, at which occupants' express satisfaction or dissatisfaction with the indoor environment.

The collected data were processed, and statistical analyses were conducted using Python 3.11 with the libraries Pandas, Sci-kit learn and SciPy. To establish the correlations between the independent variables (thermal sensation, thermal satisfaction, daylight perception, daylight preference, sound perception, sound preference, air quality and air movement) and the dependent variable (IE satisfaction), Pearson correlation factors and p-values were calculated for each variable.

Subsequently, the data were binned, and statistical regression analyses were conducted. For every independent variable, the data were binned according to the variable category, and the mean value of the dependent variable 'IE satisfaction' in each bin was computed. The data were also binned based on indoor temperature (in increments of 0.25° C) to assess thermal comfort, and on relative humidity (in 3% increments) to explore its influence on air quality. In other words, for each bin, the average temperature or relative humidity (from the times the votes were entered) as well as the average value representing the votes given within that bin was calculated (for example TSV of cool, slightly cool, neutral, slightly warm, and warm were transformed into 1, 2, 3, 4, and 5 in order to calculate the average TSV). Linear regression and polynomial regression were then fitted to the data to demonstrate the correlation between those variables.

Table 1. IEQ monitoring survey.

Questions	Possible answers
Which room are you in?	Living, Bedroom 1, Bedroom 2/Other room
How are you currently dressed?	Very light, Light, Moderate, Heavy, Very Heavy
In the last 15 minutes, your activity in this room is:	Very relaxed, Relaxed, Moderate, Active, Very active.
Air-conditioning (for cooling) in this room is:	On, Off
Air-conditioning (for heating) in this room is:	On, Off
Fan in this room is:	On, Off
Blinds or curtains in this room are:	All opened, All closed, Some open / some closed
Windows or doors to the outside are:	All opened, All closed, Some open / some closed
What do you think about the indoor temperature right now?	Cool, Slightly cool, Neutral, Slightly warm, Warm
Would you prefer to be:	Cooler, Warmer, No change
How satisfied are you with the temperature in this room?	Very satisfied, Satisfied, Neutral, Dissatisfied, Very dissatisfied
Without turning on the artificial light, do you think this room is:	Bright, A bit bright, Ok, A bit dark, Dark
In this room, would you prefer to have:	Have more natural light, No change, Have less natural light
At the moment, this room feels:	Quiet, A bit quiet, Ok, A bit noisy, Noisy
In this room, would you prefer to:	Have more sound or noise, No change, Have less sound or noise
At the moment, the air in this room feels:	Stuffy, ok, Draughty
At the moment, the air quality in this room feels:	Very good, Good, Ok, Poor, Very poor
How would you describe your health/wellbeing at the moment?	Very good, Good, Reasonable, Poor, Very poor
Overall, how satisfied are you with this room at the moment?	Very satisfied, Satisfied, Neutral, Dissatisfied, Very dissatisfied
At this moment, which factor affects the level of your satisfaction in this room? You may answer more than one factor:	"The temperature", "The lighting or natural light", "The sound or noise level", "The air quality", "The air movement"

2.1. Case Study

The case study building is *U City* (Figure 2), a 19-story mixed-use urban development in Adelaide's CBD, completed in 2019 and owned by Uniting Communities, a not-for-profit entity providing social services. Unlike typical CBD mixed-use structures, *U City* uniquely combines elements such as apartments for seniors on upper floors, disability accommodations on middle levels, various social services for marginalized groups, and commercial spaces, including art studios and retail areas accessible to the public. Four floors are designated for community gathering, serving elderly residents, disability accommodations, office workers, and the public.

U City operates as a carbon-neutral, 6-Star-rated building (according to the Green Star environmental rating assessment by the Australian Green Building Council) and was awarded the 2020 Good Design Australia Award for Social Impact. It aspires to be a socially sustainable building, fostering wellbeing through a design that facilitates a vertical living community. Notably, its design emphasizes indoor environmental quality, featuring apartments with accessible balconies for personal green spaces, optimizing natural light and thermal comfort, and mitigating noise disruption through specific materials and construction techniques for the building envelope and partitions. The building design thus presents an ideal case study for investigating the social value of architecture.

Figure 2: U City building in Adelaide, South Australia.

3. Results to date

Until August 2023, apartment residents had responded to the survey a total of 588 times, while the office workers responded 337 times. The initial findings indicated a high level of satisfaction with the IE among both residents and workers, with over 80% expressing satisfaction or strong satisfaction (Figure 3). Less than 20% felt neutral, and around 5% reported dissatisfaction. These outcomes aligned with expectations, given the building's 6 Green Star rating and its well-designed indoor environment, resulting in a IEQ good performance.

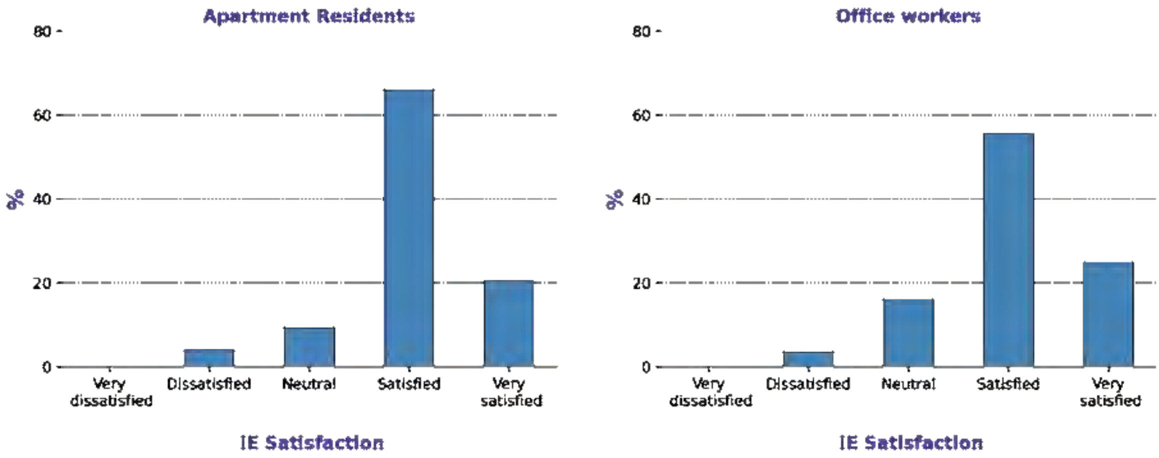

Figure 3: Apartment residents and office workers IE satisfaction.

Preliminary statistical analysis showed that there was a significant correlation between overall satisfaction with the indoor environment and IEQ ($p < 0.05$) for both apartment residents and office workers (Figure 4). Significant factors that predicted overall satisfaction in apartments were thermal sensation, thermal satisfaction, daylight perception, daylight preference, sound preference, and air quality, with a higher correlation with thermal satisfaction, followed by air quality and daylight perception. Among the office workers, the significant factors were thermal sensation, thermal satisfaction, sound perception, sound preference and air quality, with a higher correlation with thermal satisfaction, followed by air quality, sound perception and sound preference.

Apartment Residents

	p-value	corr coef
Thermal Sensation:	0.040	0.085
Thermal Satisfaction:	0.000	0.685
Daylight Perception:	0.000	0.247
Daylight Preference:	0.001	-0.133
Sound Perception:	0.434	0.032
Sound Preference:	0.010	0.106
Air Quality:	0.000	0.253
Air Movement:	0.093	-0.069

Office Workers

	p-value	corr coef
Thermal Sensation:	0.003	0.162
Thermal Satisfaction:	0.000	0.711
Light Perception:	0.721	-0.019
Light Preference:	0.046	-0.109
Sound Perception:	0.000	0.359
Sound Preference:	0.000	0.225
Air Quality:	0.000	0.386
Air Movement:	0.366	0.049

Figure 4: Levels of significance (p-value) and correlation coefficients of various IEQ parameters.

3.1. Thermal Comfort

Regarding thermal comfort, preliminary analysis from the occupant indoor environmental survey and monitoring covering a period of a spring season to early summer indicated that the majority of the apartment residents found their dwellings to be 'neutral' to 'slightly cool' while 10% found it to be 'cool' (Figure 5).

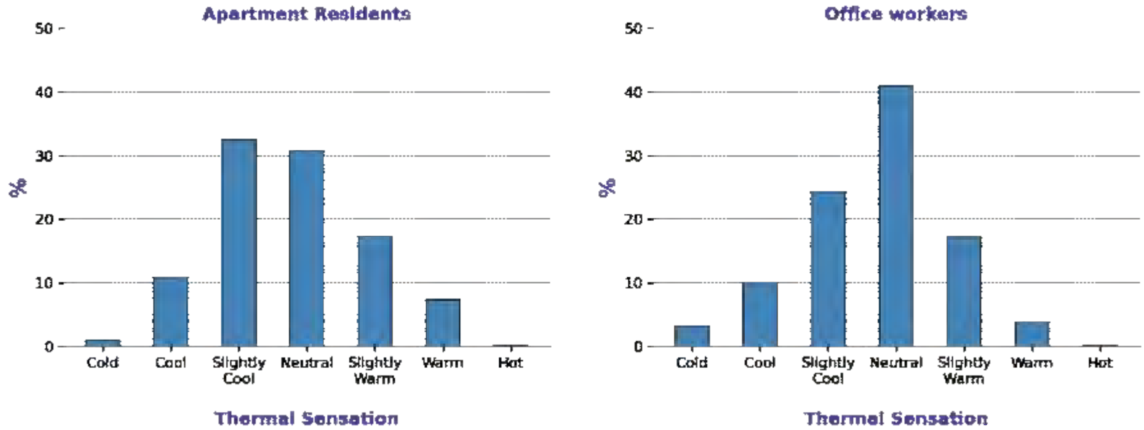

Figure 5: Thermal sensation perception.

By binning the data into temperature intervals of 0.25 °C and computing average values for the variables, a regression analysis was fitted to establish a clearer relationship between thermal satisfaction and satisfaction with the IE. The apartment exhibited a wider temperature range (16 to 30° C) but their residents displayed less variability in their thermal satisfaction, ranging between neutral and very satisfied responses. Conversely, the office setting featured a narrower temperature range (20 to 27 °C), yet showed greater fluctuations in thermal satisfaction, ranging from dissatisfied to very satisfied (Figure 7). The office workers results presented a weaker correlation between temperature and IE satisfaction in comparison with residents (Figure 6). Resident IE satisfaction occurred within a temperature range of approximately 16 to 27 °C , but their level of satisfaction notably declined when temperatures exceeded 27 °C, whereas office workers reported IE satisfaction between 21 and 25 °C (Figure 6).

When the data were analysed based on the thermal sensation categories, it was identified that when feeling slightly cool, neutral or slightly warm, the residents and workers felt satisfied with the IE, but their IE satisfaction dropped when feeling cool and warm, and significantly dropped when feeling cold or hot (Figure 8).

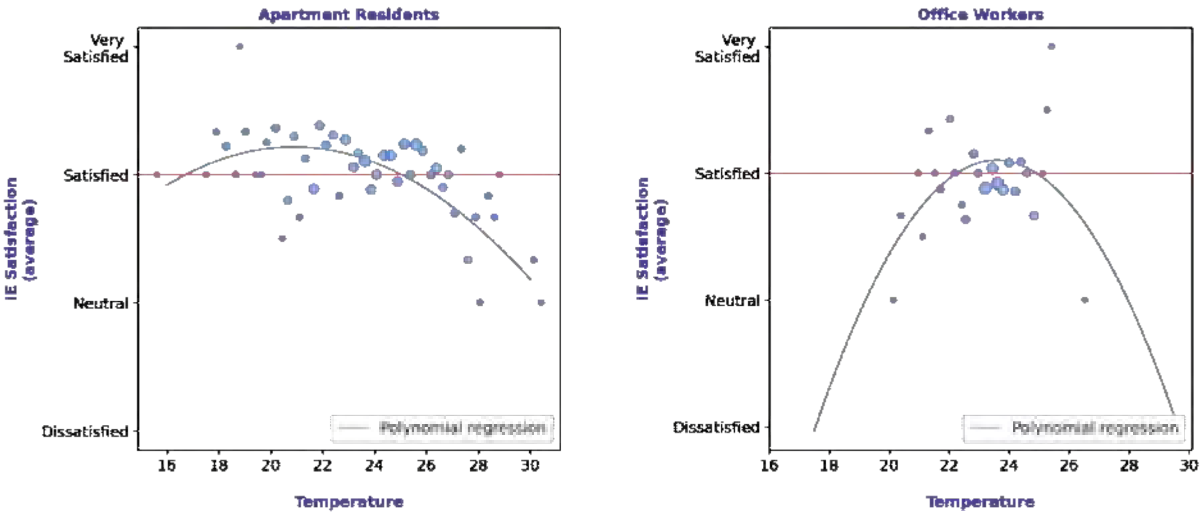

Figure 6: Temperature vs IE Satisfaction - binned by temperature.

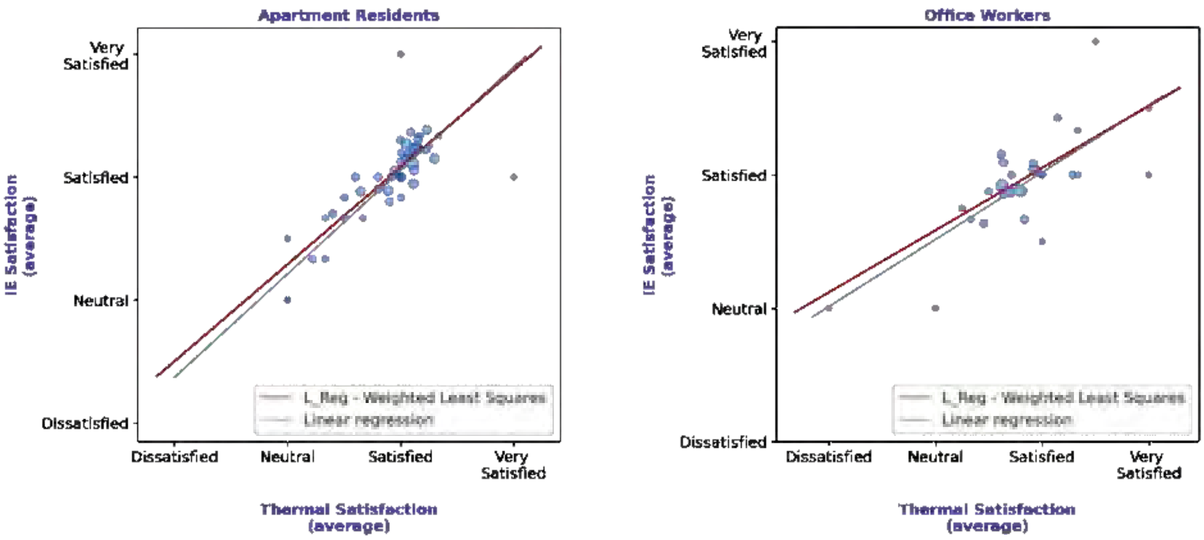

Figure 7: Thermal Satisfaction vs IE Satisfaction - binned by temperature.

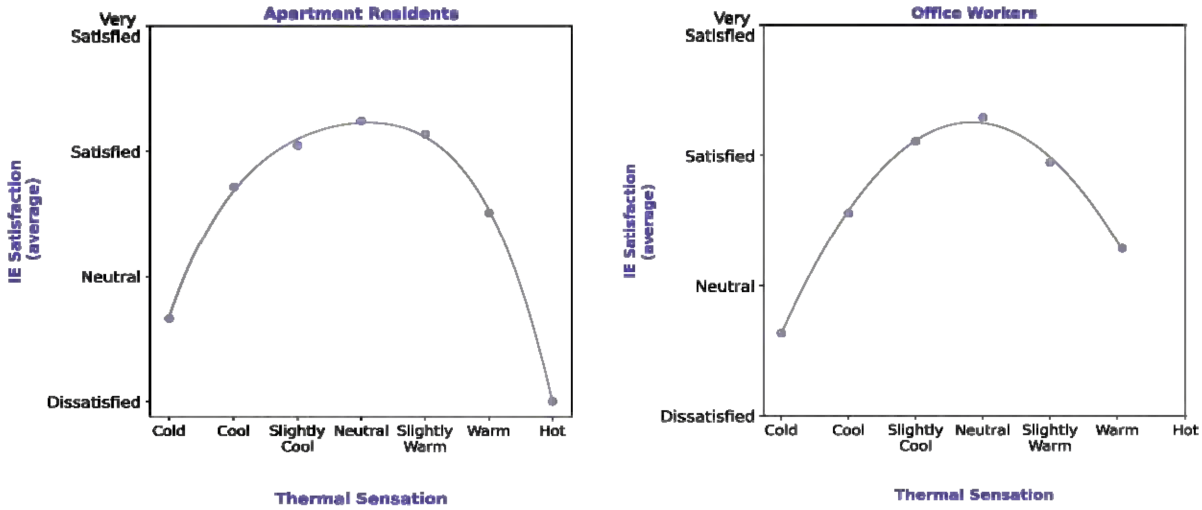

Figure 8: Thermal Satisfaction vs IE Satisfaction - binned by Thermal sensation categories.

3.2. Acoustic Comfort

Regarding sound levels, approximately 75% of the residents rated their apartments as either 'quiet' or 'OK,' with only 15% expressing a preference for reduced noise. A substantial majority of residents (85%) indicated contentment with the existing sound levels and desired no change. Among office workers, satisfaction levels stood at around 65%, in contrast to a 35% dissatisfaction rate (Figure 9). When analysing the sound perception by its categories (noisy, a bit noisy, ok, a bi quiet, and quiet) and averaging the IE satisfaction variable, it made possible to identify a trend: increased noise was associated with diminished IE satisfaction for both residents and workers. Notably, residents tended to experience higher IE satisfaction when perceiving a neutral sound level, while workers reported higher IE satisfaction levels in quieter settings (Figure 10).

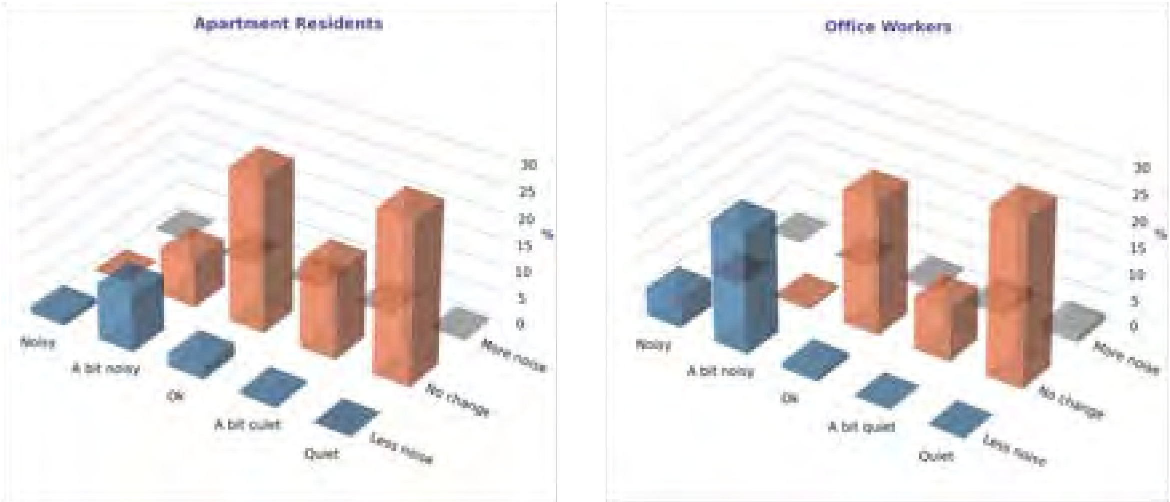

Figure 9: Sound perception vs Sound preference.

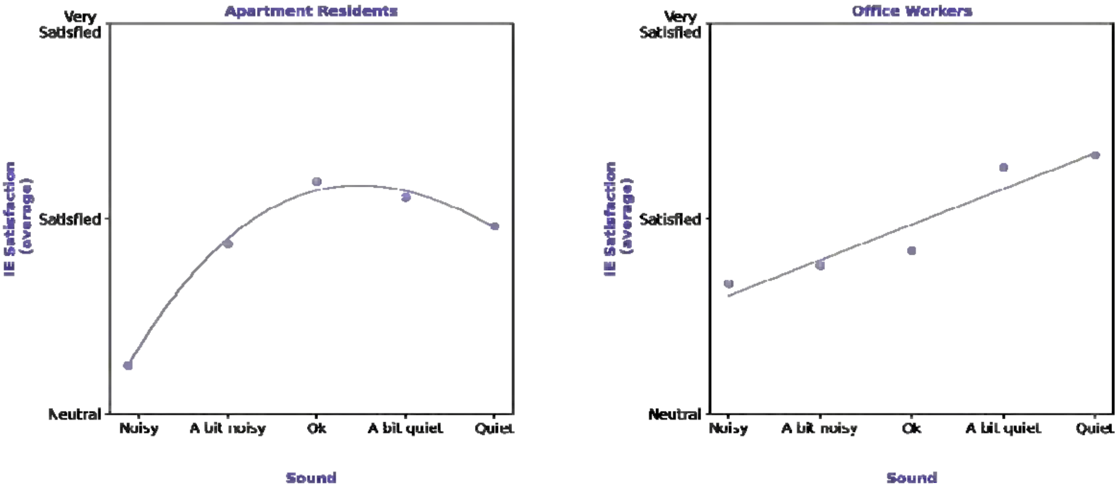

Figure 10: Apartments: Sound perception vs IE Satisfaction - binned by Sound perception categories.

3.3. Visual Comfort

In relation to natural light, a significant proportion of participants - approximately 90% of residents and around 85% of office workers - perceived both apartments and workspaces to have an adequate amount of natural illumination. Interestingly, when analysing the data into the daylight perception categories, it was possible to recognise a pattern of increased IE satisfaction at higher levels of light perception among the residents. However, this correlation did not manifest among office workers (Figure 11), possibly because they did not necessarily have access to natural light and the predominant light source in the office spaces was electric lighting.

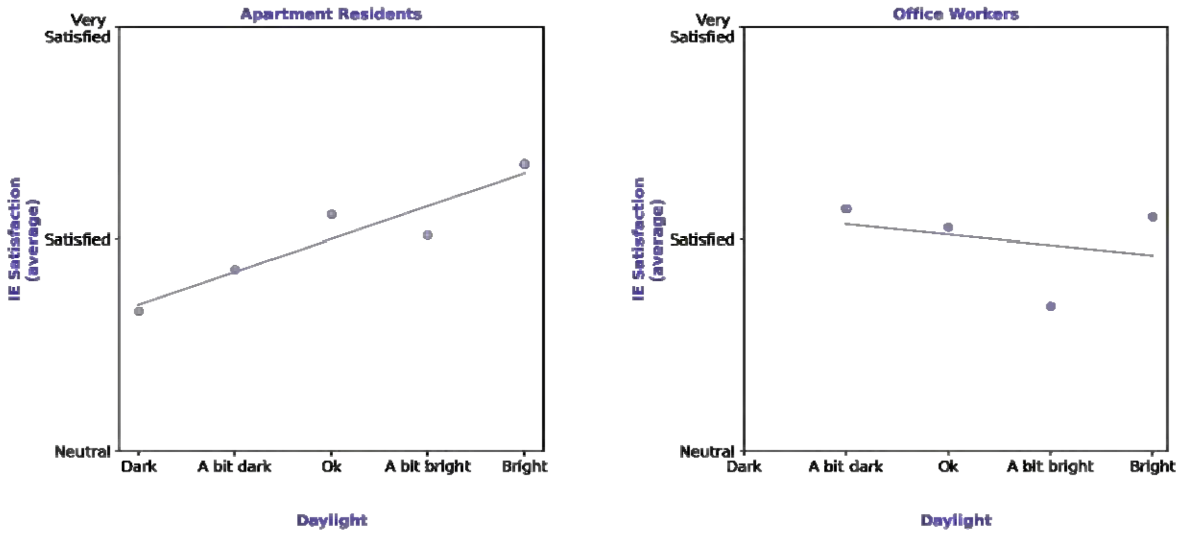

Figure 11: Daylight perception vs IE Satisfaction - binned by Daylight perception categories.

3.4. Air Quality

Air quality was perceived as either good or very good by nearly 75% of both residents and workers, with around 20% perceiving it as neutral and approximately 5% categorizing it as poor. Air quality was predominantly favourable for both groups, having a similar influence on occupants' IE satisfaction when binning the air quality categories (Figure 12). Upon binning the relative humidity (RH), the analysis revealed that office workers tended to perceive air quality between good and very good when relative RH levels fell within the range of 30% to 50%. Conversely, air quality perception diminished when RH values deviated from this specified range (Figure 13). Nonetheless, among the residents, the RH variance did not show any impact on their air quality perception (Figure 13).

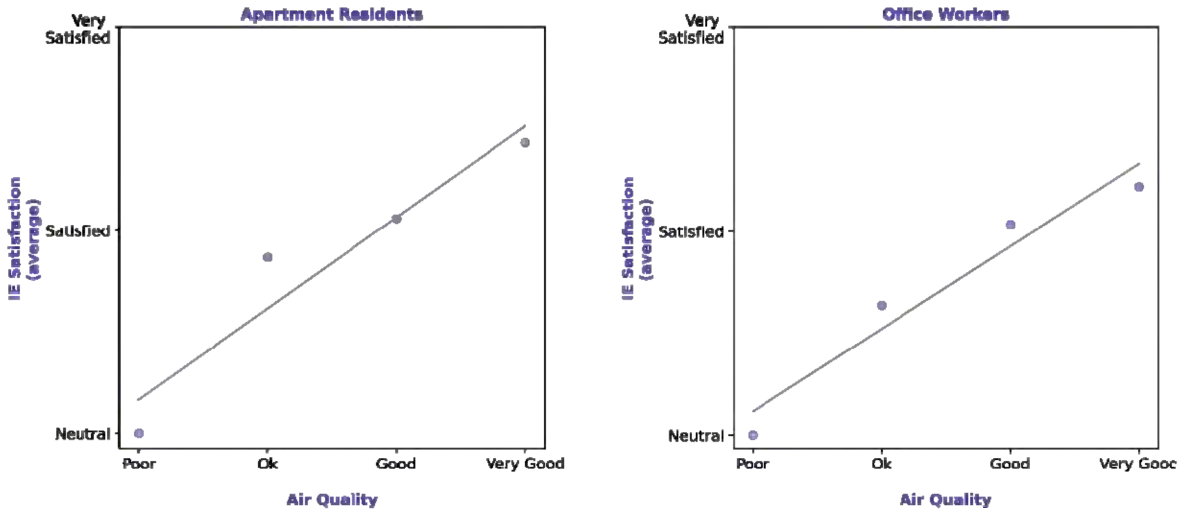

Figure 12: Air Quality perception vs IE Satisfaction - binned by Air Quality perception categories.

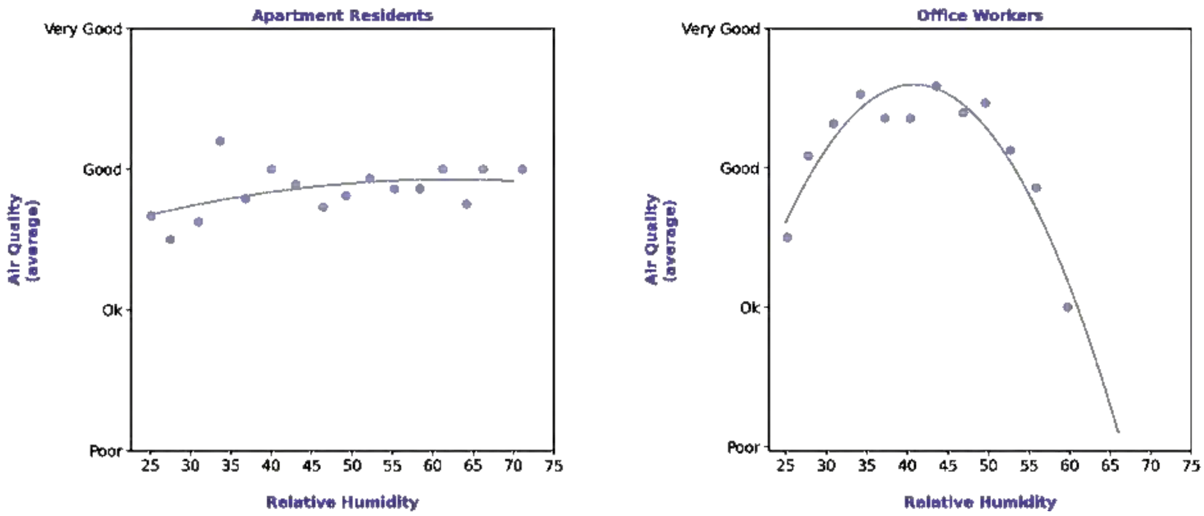

Figure 13: Relative Humidity vs Air Quality perception - binned by Relative Humidity

4. Discussion

This research has delved into examining the relationships between IEQ parameters and occupants' IE satisfaction. Understanding and quantifying how much each parameter influences IE satisfaction contributes to a holistic understanding of how building design can affect the wellbeing of building occupants within a broader context.

The mixed-use case study has allowed us to unpack the differences on IE satisfaction between residents and workers, which made the study somehow comparable since both groups inhabit the same building, built with same material and very similar design features. As observed in the Results section, there were disparities between resident and worker IEQ perception and satisfaction. The divergences could be attributed to different opportunities and levels of adaptability. Furthermore, variances arose from the distinct activities undertaken by these two groups, which were differentially affected by IE parameters.

When analysing the thermal comfort impact on IE satisfaction, for example, for the office workers the temperatures seemed to have less impact on their levels of satisfaction with the IE in comparison to residents (Figure 6). This might arise due to the smaller temperature variance in the office, which was regulated by the air conditioning system. Consequently, the indoor temperature consistently fell within a more comfortable range, therefore how office workers perceived thermal sensation and thermal satisfaction was more significant for IE satisfaction than the temperature values per se. Despite presenting a smaller temperature variance, however, the office workers' thermal satisfactions varied a lot more than that of the residents (Figure 7). This can be due to the fact that office workers have less options for adapting, such as changing their clothes, opening windows, or using fans, for example.

Another interesting divergence between the groups can be observed when analysing the impact of sound perception on IE satisfaction. Office workers reported higher IE satisfaction levels in quieter settings, while residents seemed to prefer a neutral sound level (Figure 10). This difference was likely due to the need or preference for office workers to be in a quieter environment to concentrate on tasks, given that any degree of noise can disrupt their focus.

In terms of visual comfort, the lighting levels perception seemed to have a lower impact on office workers in comparison to the residents (Figure 11). This divergence could be attributed to the significant use of electric lighting in the workspace, ensuring consistent illumination throughout the day, while the apartment residents used less electric lighting. Also, the apartments have deep balconies that can impact on illuminance levels.

Air quality had similar impact on IE satisfaction for residents and workers (Figure 12). However, the RH variation had higher impact on air quality perception among office workers (Figure 13). This was probably related to the fact that in the office the windows were not operable, and there was no ceiling fan installed in the offices, while apartment residents had more control on their ventilation rates through opening and closing the windows and doors as well as turning on or off the ceiling fans.

In an upcoming study, this research will undertake a comprehensive comparison between the findings and the established Australian standards and guidelines to assess various aspects of the indoor environment.

5. Limitations

As discussed in previous publication (Croffi et al. 2023) this study was based in a POE within a single case study, concentrating on occupants with specific age, financial, and educational characteristics. Such a narrow focus might introduce biases and constrain the generalizability of the results. Nevertheless, it is essential to underscore that this research can provide a basis for future inquiries across diverse case studies. Broadening the study's scope to include various environments and occupant demographics would enhance the applicability of the results to a wider context and yield a more comprehensive understanding of the link between indoor environments, occupant satisfaction, and wellbeing.

6. Conclusion

The preliminary results presented in this study explore the correlation between the IEQ parameters and occupants' satisfaction with the IE. As a component of a broader framework aimed at elucidating how building design can contribute to fostering wellbeing, this study serves to facilitate the understanding of how each specific IEQ parameter influences occupants' satisfaction with the IE, thereby directly impacting their overall wellbeing.

Following the identification and establishment of these correlations and significances, the gathered data will be utilized to train a machine learning model. This model will classify occupants' levels of IE satisfaction. Subsequently, this model will be incorporated into a computational design tool. This tool will utilize inputs derived from simulation results, combined with parameters encompassing other dimensions such as delight and social factors (Croffi et al. 2023). By integrating these inputs, the computational tool will assign a score, evaluating the building's efficacy in promoting holistic well-being. This will be addressed in future work.

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Integrated planning as a 'smart' solution for improved sustainability of construction logistics: A transport perspective

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Abstract: The trans-disciplinary nature and extent of the construction supply chain make it prone to inefficiencies at its component domain/segment boundaries. Project-centric delivery accentuates these. Logistics, a significant element of the construction supply chain, forms part of complex systems with multiple stakeholders and a wide range of concurrent on-/off-site in-action activities, processes, and systems. Transport is the largest logistics component, with most other processes (except warehousing) being business processes and not 'real' ones. The low-value/high-volume nature of construction materials leads to substantial transport requirement, even for small projects, with costs up to half the logistics costs or a fifth of construction costs. Transport is naturally fragmented, with a component intrinsic to every business, and asset ownership and deployment typically external to it. Incremental inefficiencies, driven by siloed planning between involved stakeholders, aggregate into visibility at the macro level. Adverse sustainability impacts are the obvious consequence. Transport optimisation results from re-configuring activities, re-combining resources, and re-positioning actors, which demand integrated strategic and/or operational planning. This paper undertakes data-driven analysis of an integrated business model as a 'smart' solution for improved transport efficiency in a specific New Zealand construction supply chain segment. Quantification and validation of sustainability benefits is undertaken using domestic/international parameters.

Keywords: Construction transport; Integrated Planning; Sustainable logistics; Vertical integration

1. Introduction

The construction industry typically contributes approximately 13% to the global Gross Domestic Product (GDP) (Barbosa et al., 2017). This sector plays a significant role in generating employment, enhancing infrastructure, and supporting businesses. Its activities are crucial for socio-economic progress but also lead to significant consumption of resources. As of 2019, the construction domain accounted for 35% of the world's energy usage and contributed 38% to global emissions (UNEP, 2020). These figures are the result of various factors, including upstream issues leading to embodiment of resources, and downstream (operation and maintenance related) factors. The construction sector is highly fragmented (Guerlain et al., 2019; Jones et al., 2022; Riazi et al., 2020; Shakantu & Emuze, 2012). This manifests at two levels *viz* from an industry perspective due to the presence of numerous small firms, and from a construction project perspective due to disaggregation of the construction process and entities (Alashwal & Hamzah, 2014; Alashwal & Fong, 2015). Logistics, which encompasses aspects

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like transportation, warehousing, and inventory management, is a critical interdisciplinary aspect of the complex Construction Supply Chain (CSC). It significantly impacts project management and costs (Ying and Tookey, 2014). Fragmentation leads to challenges in coordination and integration, resulting in inefficiencies and wasteful resource dissipation (Alashwal & Fong, 2015), typically at the boundaries of the comprising organisational or process elements. These ultimately lead to concerns about the sector's sustainability. The diverse elements within logistics offer substantial opportunities for optimisation within the construction sector, both in terms of strategic planning and operational execution.

Transportation constitutes the largest component within the realm of logistics, as highlighted by various sources (Bowersox et al., 2002; Madadi et al., 2010), mainly due to the fact that most logistics processes, excluding warehousing, are conceptual rather than physical operations (Szymonik, 2012). Given that construction materials possess a high volume but relatively low value when compared to other industries (Balm & Ploos van Amstel, 2018; Lovell et al., 2005), transportation assumes a significant role within the domain of construction logistics. Consequently, transportation needs, even for relatively small projects, can be considerable. Apart from considerations related to energy consumption, emissions, and financial costs (Smith et al., 2002; Szymonik, 2012; Ying et al., 2014), there are additional externalities associated with transportation that affect various dimensions of sustainability. These externalities can be immediate and direct, such as pollution, noise, and traffic congestion, or more indirect, including the disruption of ecosystems, health consequences, and a diminished quality of life (Chatziioannou et al., 2020). Therefore, optimisation of the transportation function of construction logistics has the potential to result in improved sustainability.

This paper studies the impact of vertical integration of business processes and integration of the planning function between the service provider and the consumer as 'smart' solutions to optimise transportation operations and, therefore, improve sustainability. It studies a narrow New Zealand CSC segment of plasterboard distribution in Auckland, providing indicators for the manufactured construction products market.

2. Establishing the baseline

The baseline for this paper will be established along four dimensions *viz* the construction logistics problem, the construction supply chain for material delivery, parameters for assessing efficiency of freight transport, and a description of the problem whose analysis was undertaken. The idea of smart solutions is embedded in the problem description.

2.1. Construction logistics

Construction logistics are concerned with preparing, coordinating, controlling, and managing the flow of products from processing of raw materials processing to final application of the finished product in a project, and the reverse logistics of removing waste and finally disposing it off (Agapiou et al., 1998; Ying & Tookey, 2014). Complex systems with diverse stakeholders comprise construction logistics. These are concurrently engaged on- and off-site in wide-ranging activities, processes, and systems. These can be conveniently grouped into the three domains of organising and planning, transportation, and activities taking place on-site (Janné, 2020; Janné et al., 2018).

The logistics process provides a framework for integrated decision-making regarding inventory, warehousing, transport, materials handling, and industrial packaging. Efficient construction logistics require planning, management of loading and unloading zones, warehousing (internal and external to the construction site), on- and off-site handling of materials, and transportation for linking actors and channels of a logistics system (Ekeskär & Rudberg, 2016; Janné & Fredriksson, 2019; Janné et al., 2018).

Construction logistics costs are invariably embodied in the material cost without distinction (Ying & Tookey, 2014). Transport in construction logistics does not get the attention it merits, even though a substantial proportion of urban goods-vehicle movements related to construction. Hence, construction deliveries are referred to as 'hidden' logistics in literature (Balm & Ploos van Amstel, 2018; Verlinde, 2015; Ying & Tookey, 2014), their costs being referred to as 'hidden' costs.

The construction logistics problem is typically viewed from the contractor's perspective, who needs to manage all suppliers and deliveries at the project level (site). The issue has its genesis primarily in the limited storage space on any construction site. On-site logistics coordination addresses a project's horizontal (disaggregation of skill sets/expertise) and vertical (straitjacketing of a construction project into well-defined phases) fragmentation issues. It is, however, incapable of addressing longitudinal fragmentation (between projects); the supplier, the construction site, and the transporter are independent entities with minimal co-ordination, coming together only for site-centric deliveries.

The perspective, however, reverses when viewed from the supplier's end. When managed by the supplier, deliveries effectively get consolidated, therefore demonstrating higher efficiencies as compared to business-as-usual (Dhawan, 2023).

2.2. The materials delivery supply chain

Between the manufacturers (or major or bulk suppliers) at one end of the construction supply chain (CSC), and the consumer (the site) at the other, sit the Builders' Merchants (BMs). BMs represent a storage and consolidation point as the primary intermediary between the manufacturer (major or bulk supplier) and the contractor. Manufacturers of construction materials and components sell goods through three typical models, i.e., direct to the customer, sale of a limited range of goods through a specialist stockist, and a BM.

The first model (direct to the customer) is invariably applied for large consignments such as steel framing etc. that need not go through intermediaries. The second model (sale through specialist stockists) is typically employed when manufacturers market their inventories through their own subsidiaries. The third model (supplies by the BM, referred to as the Freight-into-Store model) is what works for most situations, where the retail quantities are usually too small to be managed by bulk suppliers or manufacturers.

The proliferation of the Freight-into-Store model is also due to the unstated but critical economic function of the BM providing the working capital for construction by extending a line of credit to contractors. A fluctuating market demand compels the retention of high safety stocks, whose carrying costs are borne by BMs, anywhere upto 20% of the inventory cost itself annually, including invested capital (Agapiou et al., 1998; Bowersox et al., 2002; Dhawan, 2023; Vidalakis & Tookey, 2005; Vidalakis et al., 2011). BMs supply a variety of essential construction materials to the sector, with significant over-the-counter deliveries to the buyer. These deliveries are for both 'heavy' (sand, bricks, blocks, and aggregate) and 'light' (fixtures, fittings, tools, plumbing, and heating supplies) materials.

Typically, BMs may operate at the national, regional, and local merchant level. Those operating at a national scale may have national and/or regional distribution centres (RDCs), with local depots/warehouses (WHs) serving specific geographical areas for interfacing with customers. The transport function of these depots is not an entity in itself; rather, it is a derived demand existing to serve the purpose of materials delivery to the customer. The fleet of depot is typically small and serves a local customer network which may include the residents, construction sites, and bigger construction businesses or organisations. Planning of delivery trips is based on the staff's knowledge about the local routes and locations. While regional and national merchants maintain centralised control over their fleet, which is managed professionally by a nominated manager, at the BM's depot level the depot manager, who is not a transport professional, manages the transport fleet and its operations. The focus of depots is customer service and not efficiency of transport utilisation. Orders are typically accepted a day in advance for the ensuing day's work (Dhawan, 2023).

2.3. Transport efficiency assessment

The important factors impacting the efficiency of physical goods handling are Filling rate, Vehicle/Resource Efficiency, Freight Transport Efficiency, and System Efficiency/Effectiveness (Pahlén & Börjesson, 2012). The first and second are operational/tactical, while the third and fourth are strategic. To understand vehicle utilisation, 'Filling Rate' is introduced here as, *"the ratio of the actual goods moved to the maximum achievable if the vehicles, whenever loaded, are loaded to their maximum loading capacity"* (McKinnon, 1999). In the case of a truck, vehicle utilisation (the ratio of the vehicle capacity utilised to the available vehicle capacity) narrows down to five measures (McKinnon, 2010; Pahlén & Börjesson, 2012): -

- **Level of empty running:** The proportion of the distance travelled empty.
- **Weight-based loading factor:** Ratio of the actual weight carried by the truck to the maximum weight it can carry (the rated payload capacity).
- **Tonne-km loading factor:** Ratio of the actual tonne-km transported to the maximum tonne-km (based on the rated payload capacity) possible. Unlike the weight-based loading factor, which assumes a constant loading factor on a trip, tonne-km is dynamic as they vary with delivery or collection of consignments.
- **Volumetric loading factor:** A three-dimensional perspective of vehicle fill that considers proportion of the total cubic capacity of the vehicle occupied by the load.
- **Deck-area coverage (or 'load area length')** A two-dimensional view of vehicle loading that considers proportion of the vehicle floor (or deck) area covered by a load. In case of loading height limitations or constraints, deck area limits loading and not the cubic capacity.

The efficiency of the construction industry's transport function depends upon the utilisation of vehicle capacities across onward and return trip segments. A major logistical challenge is finding backloads for returning vehicles. Empty running of vehicles, earlier considered only a wasted resource, is now viewed through the lens of environmental liabilities. Consequently, from a policy and business model perspective, reduction of empty running is a key focus of most sustainable distribution strategies (McKinnon & Ge, 2006).

2.4. Problem description and research questions

Fragmentation is an identified challenge in the construction sector, with transport being a major contributor. Evidence-based decision-making in the construction freight/logistics domain is constrained by a general dearth of pertinent data. Data relates to individual freight journeys with a general lack of an SC perspective, amongst others (McKinnon, 2015). These present barriers to quantifying optimisation as a result of implemented SC models and assessing further improvement potential of implemented SC and/or logistics models. The problem under investigation pertains to the supply of plasterboard by New Zealand's largest supplier in Auckland.

In the business-as-usual scenario, distribution is through a disaggregated SC in the form of the Freight-into-Store model, with three nodes of interest, i.e., the manufacturer (warehouse), the BM network, and the consumers or construction sites. The model has two links (Manufacturer – BM and BM – Construction Site) linking three nodes for both information and material movement. Each one of the nodes has storage as one of its primary functions. This model has substantial time and space associated with the intermediate node (the BM), where material arrives in bulk from the manufacturer and departs in bulk or retail to consumers (construction sites). The Freight-into-Store model represents the ‘Distributor storage with carrier delivery’ logistics model (Chopra et al., 2013). A transformation to a more efficient logistics model involved (forward) vertical integration of plasterboard distribution as an extension of manufacture, followed by outsourcing of the transport function on a Second Party Logistics (2PL) basis.

The modified model presents three nodes with three links, as opposed to the Freight-into-Store model. Two of these links handle the exchange of information for invoicing and delivery (Contractor – BM, BM – Manufacturer). The third link is the physical transportation of material between the Manufacturer and the Construction site. In the context of this research, this model is referred to as the 'Direct-to-Site' model and can be viewed as an instance of the 'Manufacturer storage with direct shipping' approach to logistics. (Chopra et al., 2013).

The dataset indicated employment of approximately 26 trucks of different payload capacities and 42 truck trips daily. The pricing of transportation was uniform on a ‘per-tonne’ basis across Auckland irrespective of the destination. The trucks employed are all flat-bed trucks which consume diesel fuel.

Ostensibly, the Direct-to-Site solution is ‘smart’ as it uses hardware (transport), intelligent elements (internal organisational intelligence and analysis), data elements (truck movement data, consumer demand, BM invoicing), and intangible service elements (consumer satisfaction and personnel competencies) (Huikkola et al., 2022) to deliver a service with a higher efficiency. The improvement in transport efficiency was, however, not quantified. This presented the following research questions: -

- **RQ1.** What is the quantum of efficiency improvement achieved by implementation of the Direct-to-Site model over the Freight-into-Store model?
- **RQ2.** What is the potential for further improvement in transport efficiency and the means to achieve it?

3. Transport efficiency analysis

3.1. Transport efficiency measures

The two measures (from section 2.3) selected for analysing the transport efficiency in this paper are the weight-based loading factor (termed ‘loading efficiency’ - at dispatch) and tonne-km-based loading factor (termed ‘capacity utilisation’). The former is static, as it is a measure at a point in time and does not consider distances, while the latter is dynamic as it includes loads and distances across the complete trip.

The dataset for analysis included the dispatch load, delivery destinations, and loads consigned to each destination. It did not, however, include the sequence of delivery and distances between various nodes along the route. Sampling of the dataset needed to be undertaken for introducing distances into the analysis (due to the dataset size). A sample size of about 370 was found to be statistically significant for the available dataset (Krejcie & Morgan, 1970). Simple random sampling (probability sampling) was undertaken. Data reflecting more than three drops was deleted as this formed less than 1% of the dataset, hence, not considered significant.

3.2. Quantification of efficiency improvement from the Direct-to-Site over Freight-into-Store model

As a result of VI, and therefore, the distribution function's inclusion into the manufacturer's operations, the Direct-to-Site model modifies the transportation network by eliminating one node and one linkage in the transportation network. Figure 1 illustrates the transportation network in the Freight-into-Store and Direct-to-Site configurations. Considering that the three linkages joining the three nodes form a triangle, the length of any one link will always be less than the sum of the other two unless all three nodes lie on the same line, in which case they will be equal. However, actual manifestations of road and destination networks are rarely composed of straight lines. Therefore, an evaluation of the reduction in distances travelled in the Direct-to-Site model compared to those that would have been travelled under the Freight-into-Store model for each set of BM-destination combination facilitated quantification of benefits vertical integration creates for transportation operations in the CSC.

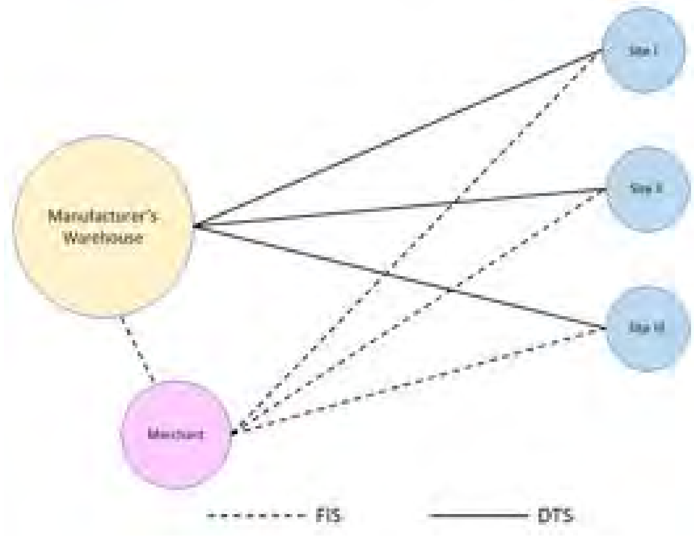

Figure 1: Transport network configurations for the Freight-into-Store and Direct-to-Site distribution models.

Even though these would be indicative for this segment of the CSC (plasterboard distribution) and contextual to Auckland, they provide a benchmark for improved efficiencies. A comparison of the distances involved in the Direct-to-Site and Freight-into-Store models for every trip provided a straightforward assessment of the improved transport efficiency in terms of reduction in travel distances. The aggregated results are presented in Table 1.

Table 1: Quantification of reduction in distances travelled by trucks in the Direct-to-Site model on the Freight-into-Store baseline.

Parameter	Direct-to-Site (km)	Ratio of Direct-to-Site to Freight-into-Store
Average	27.04	0.7086
Maximum	119.1	2.19
Minimum	3.8	0.1047

Individual BM-destination distances were considered for the analysis since circa 75% of the truck trips in the dataset involved a single drop. Instead of presenting the distances travelled individually in the Direct-to-Site and Freight-into-Store models, a ratio of the distances presents a stronger indication of improved efficiency through reduction of distances travelled. On an average, the distances travelled in the Direct-to-Site model are 70% of the Freight-into-Store model. A 30% reduction in distances travelled translates to approximately 11.11 km per trip.

3.3. Potential for further transport efficiency improvement

To investigate further potential for efficiency enhancement within the Direct-to-Site model, the problem was formulated as, *"Assessing the potential for improved efficiency of 'Direct-to-Site' transport operations for plasterboard supply in Auckland, New Zealand, proposed to be addressed through operational data analysis."* The sequence of drops was introduced in the sampled dataset from the 'Eroad' (a private IT services company in New Zealand providing GPS enabled tracking for transport) database. Based on distances between nodes, and the sequence of drops, the loading efficiency at dispatch (static) and the capacity utilisation (tonne-km based - dynamic) were calculated. Table 2 presents these analyses.

Table 2: Loading efficiency and capacity utilisation of trucks (Direct-to-Site model).

Drops	Trips	Loading Efficiency			Capacity Utilisation		
		Maximum	Minimum	Average	Maximum	Minimum	Average
1	261	99.21	4.31	55.89	49.61	2.16	27.99
2	81	99.77	6.45	57.08	55.79	3.33	27.84
3	28	90.33	14.99	60.53	42.11	4.93	24.82
Weighted (fleetwide)		Average		56.36			27.61

The following were inferred from the above analysis: -

- Underutilised truck (payload) capacity (nearly 252 tonnes daily on average), resulting in 72% of tonne-km going unutilised.
- The potential for optimisation of daily truck operations through reduction in the number of trips by better loading, indicating the requirement of better planning.

3.4. Operations Research as a further 'smart' solution

Application of Linear Programming (LP) (the Transportation Model) from operations research was explored as an optimisation tool. The basic design of a transportation problem is represented by a network with nodes representing sources and destinations and arcs linking the nodes representing routes, quantities of material moving, and the per unit shipping cost on that route (Taha, 2008). It aims to minimise the cost of satisfying the requirements of the destinations within the existing production capacity (Uzorh & Innocent, 2014). The problem under consideration presented certain peculiarities that differentiated it from a standard transportation problem. Hence, it was reformulated as follows: -

- The sampled dataset was disaggregated into one day's operations at a time.
- Instead of the warehouse, each truck trip was considered a source with a capacity equal to the truck payload capacity (supply).
- Each delivery undertaken during the day was taken to be a consumer (demand).
- The channel cost (per unit transportation cost) was assumed to be unity (being fixed), in the absence of specific figures (being commercially sensitive). Any other positive number would do equally well.

The 'Solver' add-in to MS Excel was used for solving the transportation problem using LP, with a restriction of not more than 200 objective co-efficients in the problem matrix. Since the exercise was a proof-of-concept, the dataset was truncated in a manner to include as many truck trips as possible from a day, while maintaining trip integrity (i.e., no trips were split). The specific parameters applied were: -

- Total load to be delivered equal to the summation of the node demands ('equal to').
- Total load to be delivered less than or equal to the trip capacities ('less than equal to').
- The objective co-efficients (per unit channel transportation costs) taken as unity.
- The objective function is taken to be minimisation of the cost (in this case it transforms to minimisation of transportation resources - trucks, since channel costs were constant - unity).

The matrix was then solved for decision variables (allocation of loads to trucks). The resulting optimisation of transport across the sampled dataset is shown in Table 3.

Table 3: Transport optimisation (improved efficiency) using LP.

Parameter	Manual allocation	LP-based allocation	Improvement (over manual baseline)
Average loading efficiency	56.36%	89.85%	59.42%
Daily truck trips	11	7	36.36%
Capacity utilisation (tonne-km)	27.61%	49.38%	78.84%

The figures in Table 3 pertain to truncated (sampled) dataset presented to the transportation model. The number of trips for the complete sample works out to about 26 (pro-rata), which is a reduction of 16 truck trips daily. This quantification will be used for evaluating sustainability benefits. Application of LP presents a manifestation of the need for integrated planning. In the status quo, the manufacturer's aim was transportation of certain quantities of plasterboard daily. The employment of resources was left entirely to the discretion of the 2PL service provider, as a consequence of the payments model which considered the daily tonnages transported, rather than the distances covered. There is no imperative for resource-use analysis, as long as the daily tonnages are delivered. Maximising transport utilisation becomes an imperative under two conditions. Either the payments model is per-km, or the sustainability perspective is introduced, which brings in the requirement for minimising distances travelled by trucks for the required deliveries. Integration of the manufacturer in the planning process, even if to the extent of monitoring transport utilisation, is an outcome. This integration is considered a 'smart' solution as it meets the criteria of hardware (transport), intelligent elements (internal organisational intelligence and analysis), data elements (truck movement data, consumer demand), and intangible service elements (consumer satisfaction and personnel competencies) to optimise the distribution process. In this case the involvement of the manufacturer is as a consumer of 2PL services.

4. Sustainability benefits

From the analysis so far, sustainability benefits accrue from the following individual contributors: -

- Adoption of the Direct-to-Site model over the Freight-into-Store model for plasterboard distribution (status quo).

- Improved loading of trucks as a result of optimisation through LP (analysis), and therefore, improved capacity utilisation.
- Reduction in the number of trucks as a consequence of improved loading (analysis).

4.1. Reduction in fuel consumption from adopting Direct-to-Site over the Freight-into-Store model

As a result of adopting the Direct-to-Site model, there is a reduction of 11.1 km in distance travelled per truck trip. An analysis of the sampled dataset showed the average payload capacity of trucks as being 21,170 kg. This was benchmarked against a longitudinal study (2015-2018) in New Zealand (Wang et al., 2019), where truck fleet in New Zealand has been categorised based on Gross Vehicle Mass (GVM), and the fuel consumption of each GVM category assessed, irrespective of the payload. The average payload of 21,170 kg fits neatly into the GVM category of 20,000 kg to 24,999 kg, with an average fuel consumption of 46.7 litres of diesel per 100 km. A reduction of 11.1 km translates to 5.18 litres of diesel per trip. Considering 42 trips a day, the overall daily diesel consumption reduction is 217.56 litres. @ 247 working days annually, ***reduction in diesel consumption works out to nearly 53,700 litres per annum***. ***In terms of distance, the reduction is 126,100 km annually.***

4.2. Reduction in fuel consumption from improved capacity utilisation of trucks

The reduction in diesel consumption due to improved capacity utilisation is reckoned from the work of Henningsen (2000), which presents a plot of the approximate fuel consumption in tonnes per kilo-tonne of load (y-axis) for various capacity utilisation factors (x-axis) when transported over a distance of 3,218 km by various transportation modes (experimental results). The improvement in fuel efficiency is converted to actual reduction in fuel consumption by superimposing capacity utilisation data from Table 3 on the plot (Figure 2).

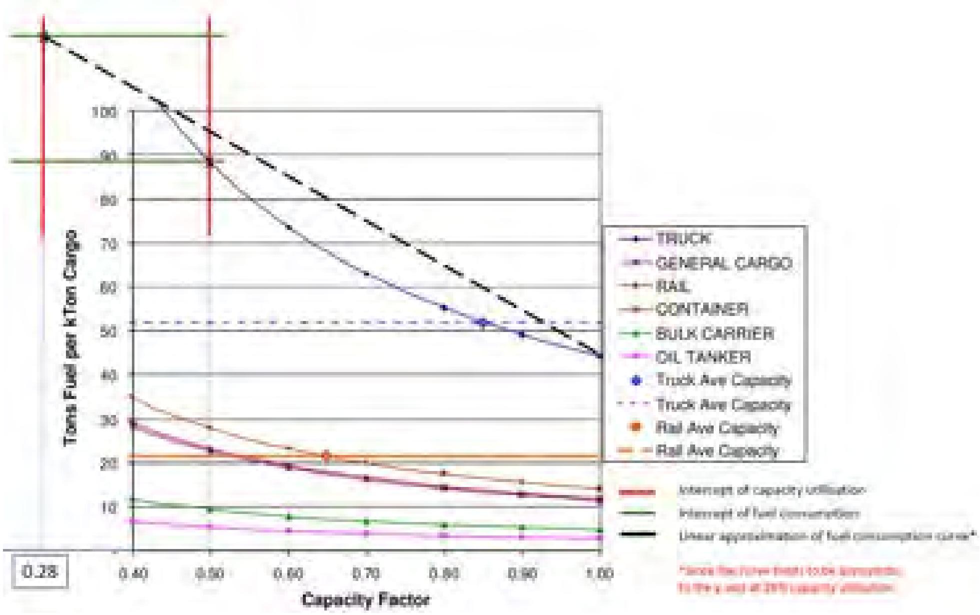

Figure 2. Estimation of reduction in fuel consumption due to improved capacity utilisation of trucks based on Henningson, 2000

The intercept between the green lines is converts to a figure of about 0.0074 kg/tonne-km (0.0082 litres/tonne-km) of reduction in diesel consumption [(113,000 – 88,000)/(3218 x 1000) kg/tonne-km]. In the scenario of improved capacity utilisation, 330 tonnes of plasterboard are transported across 26 trips, each trip transporting approximately 12.69 tons. For a vehicle carrying 12,690 kg of load, it converts to 0.1057 litres of diesel reduction per km. The trip length is found from the average distances between destinations in a three-drop trip obtained from the sampled dataset. These are presented at Table 4. The generalised trip length works out to approximately 52.3 km.

Table 4. Distance parameters for a generalised trip.

Drops	Trips	Distances			
		WH – Drop 1	Drop 1 –Drop 2	Drop 2 – Drop 3	Drop 3 – WH
1	261	22.76	0	0	22.76
2	81	24.92	10.55	0	28.22
3	28	23.67	11.84	16.16	32.6
Weighted Average		23.29	3.21	1.22	24.62

The reduction in diesel consumption per trip, therefore, is 52.3 x 0.1057 = 5.53 litres of diesel. 26 trips daily, over 247 working days annually translate to approximately ***35,500 litres of diesel annually***.

4.3. Reduction in fuel consumption due to reduction in the number of truck trips

The number of truck trips reduce by 16 (from 42 down to 26) on application of the transportation model. Considering the generalised trip length of 52.3 km, 16 trips convert into approximately 836 km per day, and 206,700.00 km annually. Considering the average GVM of trucks as being employed (status quo) of the 20,000 – 24,999 kg category, 206,700.00 km annually translate to a reduction of 46.7 x 206,700.00 / 100 = ***96,524 litres of diesel per year. This is in addition to 16 trucks effectively going off the road, and the associated reduction in distances travelled.***

4.4. Aggregating sustainability benefits

4.4.1. Emissions reduction

From the emissions guide issued by the Ministry for the Environment (MfE, 2022a), the CO2-e per litre of diesel is approximately 2.69 kg. An annual reduction of approximately 185,700 litres of diesel from adoption of the Direct-to-Site model, improved loading of trucks, and reduction in the number of trips converts to ***513,585.00 kg CO2-e, or 513.58 tonnes CO2-e annually.***

4.4.2. Monetised benefits

Monetisation of benefits is quantified per km based on statistics obtained from various documents in the public domain on a per km basis in Table 5.

Table 5: Monetisation of benefits on a per km basis (Briggs et al., 2016; Climate Change Commission, 2021; Ernst & Young, 2021; Ministry for the Environment, 2021; New Zealand Transport Agency, 2021; Stroombergen, 2023).

On account of	Impact or value	Based on	Per km impact
Emissions contribution	21% 24.8%	Emissions contribution from the transport sector Contribution of freight transport to transport emissions	Multiplication factors
Social cost of damage by freight transport	NZ$520mn per annum	Transport sector share is NZ$2.1bn annually Freight transport share is 24.8% 3bn annual freight km	NZ$0.173
Cost of deaths due to freight transport	NZ$693mn per annum	51.5 deaths per bn freight km 3bn annual freight km NZ$4.47mn monetised cost of death	NZ$0.231
Annual Air Quality and GHG costs from HGVs	NZ$673.9mn per annum	NZ$465mn and NZ$208.9 air quality and GHG costs per annum, respectively, from HGVs	NZ$0.225
Shadow carbon price		NZ$108.9 average central estimate of shadow per tonne carbon price (2022-2035) 3bn annual freight km 82681 kilotonnes GHG emissions in 2021 24.8% of transport sector (21%) contribution by freight transport	NZ$0.157
Congestion costs per vehicle km removed from the road		Simple average of congestion costs per vehicle-km in various regions of NZ	NZ$0.95
Total impact			NZ$1.736

Based on the above table, a total reduction of 332,800 km annually (from a summation of reduced km due to adoption of the Direct-to-Site model and those due to reduction in vehicle trips due to improved loading) translates to nearly ***NZ$577,700.00 annually*** in monetised benefits.

5. Conclusion

The analysis undertaken in the paper pertains to application of 'smart' solutions based on hardware (transport), intelligent elements (internal organizational intelligence and analysis), data elements (truck movement data, consumer demand), and intangible service elements (consumer satisfaction and personnel competencies) (Huikkola et al., 2022) to deliver a service with a higher efficiency. The specific transportation function addressed is the distribution of plasterboard from the manufacturer's warehouse. In the first stage, the 'smart' solution of vertically integrating the distribution function as an extension of manufacturing was undertaken. The business model was integrated; however, the planning was still disaggregated, with no participation of the manufacturer in transport planning. In the second stage, further integration in the form of manufacturer participation in transport planning, along with the use of ICT tools (computer-based algorithm for applying LP to transport planning) was undertaken. The first stage though has been implemented, and the second stage of integration is still a recommendation. The aggregated impact of both the 'smart' solutions is an annual reduction of nearly 513 tonnes of CO2-e in emissions, and a monetised benefit of almost NZ$577,700.00 annually due to the reduced movement of trucks. Integrated reverse logistics can potentially provide further opportunities for achieving even higher levels of emissions reduction, and therefore, sustainability in transport operations.

Though the analysis pertains to a very narrow segment of the New Zealand CSC (plasterboard delivery), it provides benchmarks and pointers towards the potential for transport optimisation, and therefore, improved sustainability existing in the manufactured construction products sector.

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Integration of Multiple Intelligence Skills in Architectural Design Process in Sri Lanka

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Abstract: Architecture is a subject that requires multiple skills thus necessitating architecture students to be competent as a multi-skilled person. Skills related to technology, spatial visualization, creativity, analytical and logical thinking, verbal and communication are among the vital skills needed. Design studio is the core of architecture learning process where the students put these skills into practice. Use of Multiple Intelligence Theory (MIT) for architectural education has been discussed in international context. However, research on the relationship between multiple intelligence and architectural design process has not been researched in Sri Lankan context. The aim of this research is to identify the level of multiple intelligence integration in architectural design studios in architectural education institutes of Sri Lanka. Separate questionnaires were developed for the architecture students, academic staff and design instructors based on the MIT and the Multiple Intelligence Development Assessment Scale (MIDAS). Application of the eight factors of MIT in different stages of design process by the architecture students was questioned through the survey. Through the analysis of collected data analysis, it was identified that the MIT is not familiar in local context and direct application of multiple intelligence in design process is not utilized by both the students and the academia. However, unknowingly, identified factors of MIT is applied in different levels. Further, when introduced, probable applications were well acknowledged by a majority of respondents highlighting the relevance of integrating MIT to improve overall design skills in architecture students.

Keywords: Multiple intelligence theory, Design studio, Design skills, Architectural education.

1. Introduction

Architecture is a combination of art and science or combination of aesthetics and technics that lead for the designing of buildings, landscapes, and spaces. Architecture is generated with a set of multiple skills, basically creative skills, techniques and technical skills. Outcome of architecture is a space, with powerful combination of creativity and science. Architecture is a subject which fulfills the expressive and the practical requirements at the end of aesthetic and utilitarian.

When considering architecture as a subject, architecture is considered as a time-consuming and challenging degree in the world education level. Architecture education is mainly based on the designing and the creativity, as the core of architecture education. An architect must be good at multi skills of thinking, dimensions and volumes, quantities with the areas of the building, unique quality of each space, geometry, history, urban studies, landscape etc. Aesthetics makes an important link and combination between architecture, design and technological development. So, architecture can be considered as a subject that relate with the aesthetic. There is no measuring unit for creativity. Creativity has numerous definitions. Creativity makes new imaginative ideas into reality as various types of creative outputs. According to Cropley, D., & Cropley, A. (2008), Creativity is in the

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 420 - 434.

eye of the beholder, that is, it involves an aesthetic judgment. Therefore, aesthetics has a powerful combination with the creativity. Architecture needs creativity and the multi-skills to convert imaginative ideas into reality.

Design studio can be considered as the core of the architecture education and the role of design studio is very crucial. The architectural design studio can be identified as a potentially valuable model and most functional space in architecture educational reform (Schön, 1984). Therefore, architectural design studio is the space where architecture students engage in their designs according to the curriculum and the course modules while understanding the design problems and solving them along with the tutoring sessions, with the lecturers and peers. So, a design studio can be considered as a place that not only a lecture is given but also a social interaction between the lecturers and the student and also between students. Communication is more important when exchanging design ideas among the students and between the students and lecturers, in architecture education.

At present the complexity of design activities need individuals to acquire a wide array of skill sets such as problem solving, spatial visualization, communication and verbal skills etc. Further, Architecture is an amalgamation of multi-skilled and multi-talented subjects that need to be learnt through hands on experience and practical applications. In identifying the value of nurturing multiple skills D'Souza (2007) proposes a multiple intelligence approach for architectural design studios to emphasize the value of various individual cognitive strengths and to evaluate different aspects of design thinking by implementing diverse tools. However, in present it is observed that due to the high use of technology and software applications architectural learning process is somewhat limited to manipulation of forms and graphical skills. It is perceived that even though this graphical skill is essential for design process, it represents only a partial skill set required for an architect to work in real world context. Therefore, nurturing diverse skills become vital.

1.1. Multiple intelligence theory

To define the multiple intelligence and the multi-skills in architecture education, multiple intelligence theory introduced by Howard Gardner is identified as one of the prominent educational theories applied in the educational field throughout the world. Multiple intelligence theory implies that traditional psychoanalytic ideas about intelligence are very limited. Today, design tasks and design education require a wide range of skills like communication skills, space visualization, interpersonal skills, problem solving and verbal skills etc. and also more skills on the handling and developing graphics (D'Souza, 2007). These latter skills, while essential to design, predict only part of a designer's application in the real-world context. It is important for architects and researchers to recognize and identify multiple intelligences for architects and researchers to appreciate and nurture the diversity of architecture, to empathize with variations in each cognitive power, and to implement different tools to evaluate different aspects of design thinking.

While evaluating each "candidate" intelligence, Gardner devised a set of eight inclusion criteria based on a range of scientific fields. Rather than describing intelligence as a single, generic capacity, MI theory suggests that it be divided into various "modalities of intelligence." According to this definition multiple intelligence theory defines the many methods in which pupils learn and absorb knowledge (Gardner,1983). Gardner states that true intelligence will have a separate faculty linked to the brain and defines eight forms of intelligences: Verbal/ linguistic, Logical/mathematical, Musical, Spatial, Bodily-kinesthetic, Intrapersonal, Interpersonal and Naturalistic intelligences. The multiple intelligence theory today is accepted in educational settings, for which the appeal of varied abilities has become immediate.

1.2. Multiple Theory in Architectural education

The idea of a multi-talented architect is not new. Architects in the vitruvian era were multi-skilled and adapted to the role of master builders (Newton. 2007). Although the word "architect" is derived from the Greek word meaning "master builder", in practice "architecture" has gradually taken on the meaning of "the art of building". An experienced architect is recognized not only for his ability to pursue a masterpiece design, but also for his ability to comprehend those designs and to skillfully weave the raw material from which they are made. Not all architects today accept architecture an art. Some of them insist that it is an application of technology while others say that it is a science " (Social Sciences, 1968). Art and science are totally different subject areas and that is why an architect must be a master builder or a multi-skilled person within the construction industry. Barrow (2000) says, a re-emergence of the key building concept in the current practice is observed, and architects are challenged to integrate project leadership when dealing with a dynamic network of consulting teams in the design process. Thus, the architect must be a person with a vast knowledge regarding all the aspects in architecture subject. This means that architects sometimes fall into the role of masterminds as a 'integrator' of various skills and knowledge (Newton.2007).

Architecture is often referred to as a friendly discipline. A collection of principles in fields on mathematics, design, sociology, psychology, anatomy, economics, environmental studies and etc. The built environment is made up with variety of living and non-living factors, where all of them that play a unique role, in space in which they are built and constructed. These characteristics that set architecture apart from other fields imply that architectural education has a particular set of obligations. Further, architecture is frequently referred to as a related field. A synthesis of design, structures, mathematics, psychology, economics, sociology and environmental studies concepts. Building or rebuilding in nature is plainly formed of a range of animate and inanimate variables, all of which play a unique role in creating not just constructed and unbuilt space, but also a person's perception and the experiences of it, just as nature is composed of both living and nonliving components. Aside from technical and professional talents and skills, an architect must have creativity and imagination on various levels, as well as aesthetic and intellectual ability. Therefor architect must be with the abilities and the responsibilities of making or designing the perfect space for the occupant. That is the skill and the intelligence of the architect as a professional. With the aforementioned ideas in mind, architects engage in a multi-step and iterative process of changing spatial configurations, moving between perspectives, sizes, or modes of representation, and considering both aesthetic and the functional needs while designing a structure (Rowe, 1987; Akin, 2001; Cross, 2011). While architectural design requires a wide range of skills and abilities, mentally picturing spatial changes is considered essential. Spatial thinking has been demonstrated to be a predictor of success in a variety of fields, including science, engineering, technology, and mathematics (Wai et al., 2009; Uttal et al., 2013b).

Architecture education is with a long training period, due to the wide range of skills to be practiced. Architect must understand the technical aspect of a building. And also, the building must be designed as an aesthetical place for those who use it and live. Therefore, an architect plays a dual profession of a scientist and an artist. Whether there may be the need of the multiple intelligence for the architecture education, the intelligence of the overarching skill that is needed in the designing process of architecture education. Architects and the architecture education also need the skills of a more generic modern employee; such as paying attention to detail, accepting and acting on feedback, and being a useful member of a team. Architecture and the architecture education need a mix of 'hard' and 'soft' skills. A hard skill is something practical and measurable; for an architect, one example might be the ability to create a drawing or plan using CAD software. This ability can be tested by asking someone to sit down in front of a computer and create the required drawing or plan. On the other hand, a soft skill is one that cannot be easily demonstrated such as; negotiation and critical thinking, which tend to be learnt naturally. Usually, it takes time to find out whether a person possesses a particular soft skill.

The study of the "Design intelligences: a case for multiple intelligences in architectural design" by D'Souza (2007) is a study that has investigated the multiple intelligence theory, design skills, design ability and architecture design studio teaching. The study says that the complexity of design tasks requires individuals with a wide array of skillsets: for example, spatial visualization, problem-solving, verbal skills, communication skills and interpersonal skills, etc. The study identified that the design education today seems to limit skills to form manipulation and graphical skills. In essence, this study proposes a multiple intelligence approach to architecture design in the studio environment using Howard Gardner's multiple intelligence theory. The study has shown the architect must be a multi-skilled person with an overview of architectural design inquiry relating to design intelligence.

Only a few research studies are there to study regarding the architecture education and the multiple intelligence theory. The studies have concluded that it is possible to develop the architecture education with the support of the multiple intelligence theory. In present context, where technology is conquering many professional fields, architecture too is seemingly facing the same scenario. It is observed that many architecture students focus on developing technical skills associated with software rather than creative skills. Further, the need to create a sustainable built environment to overcome the environmental challenges, calls for professional with an empathy towards society and environment. Thus, influencing architects to become sensible and creative professionals is vital. With the need to identify possible aspects to uplift the architecture education in Sri Lankan context, a research was initiated to investigate the Multiple Intelligence Theory in Sri Lankan architectural education context. The basic idea of this study is to develop the architecture education within Sri Lankan context with the involvement of the multiple intelligence theory.

2. Methodology

As per the literature, an architect needs to be a multi-skilled person and architecture is a subject that needs the multi-skills for the design studio activities. A qualitative approach of data collection was utilized to collect data. With Multiple Intelligence Development Assessment Scale (MIDAS) and eight factors of multiple intelligences theory as the basis, the questionnaire was developed to identify up to which extent architecture students apply the eight factors of multiple intelligence theory for their design studio activities.

The questionnaire was focused at the architecture students of four architecture schools in Sri Lanka where the students were asked to rate up to which extent they apply each subskill of multiple intelligence theory for their design studio activities. Further, a questionnaire was developed focusing the lecturers, tutors and supervisors (Academic staff, Design instructors) of four architecture schools to obtain their perception on up to which extent students apply the eight factors of multiple intelligence theory in their design studio activities according to their experience.

The analysis was conducted using the "perception probability analysis". Analysis was conducted to identify how the eight factors of MIT is related to design studio activities and how far the students apply them for their academic studies, design studio activities and for their skill developments and to enhance creativity and communication. Accordingly, a hierarchy of the eight intelligences was established based on how students relate and apply them to the design studio activities. Based on the results analysis, conclusions were derived. As per the results of the questionnaire analysis, several new solutions, developments, changes and new recommendations for the present issues were identified to improve the design studio working environment based on the Gardner's multiple intelligence theory.

2.1. Sample Population

University students in all four architecture schools in Sri Lanka, lecturers of each architecture school and tutors that works with the students taken as the sample population of this study. It was assumed that students of third year, fourth year and final year, would have a better idea on the skills and the intelligence with the architecture education. Thus, a convenient sample of 100 architecture students was taken from third year, fourth year and final year from each architecture school. The internal tutors and the external tutors are directly involved with the design subject in architecture education. Thus, perceptions of the tutors were the best way of getting the idea on how students relate the factors of multiple intelligence with the design studio. A sample population of the 30 lecturers and design instructors was taken from all four-architecture school.

3. Analysis and Discussion

Perception Probability Analysis is the main method used for the data analysis. It is done under three steps.

3.1. First step of the analysis

The ranks used for perception probability analysis is as shown below in table 01. Here it gives 5 points for 5 rates of the questionnaire as below.

Table 1: Rank for each statement

Very Poor Perception	+2
Poor Perception	+1
Neutral Perception	0
Good Perception	-1
Very Good Perception	-2

Each response count was multiplied from each point and divide it from the total responses as per the equations 01 and 02. Then to identify the gap, the different between two total values were considered. + and – was taken to symbolize the statement as poor or good. Figure 01 shows the responses and the table 02 shows the results of the calculations.

$$\text{Perception Probability value} = \frac{\text{Rank (a) x Response count (b)}}{\text{Total Responses(c)}} \quad (1)$$

$$\text{Perception Probability gap} = \text{Height value} - \text{Lower value} \quad (2)$$

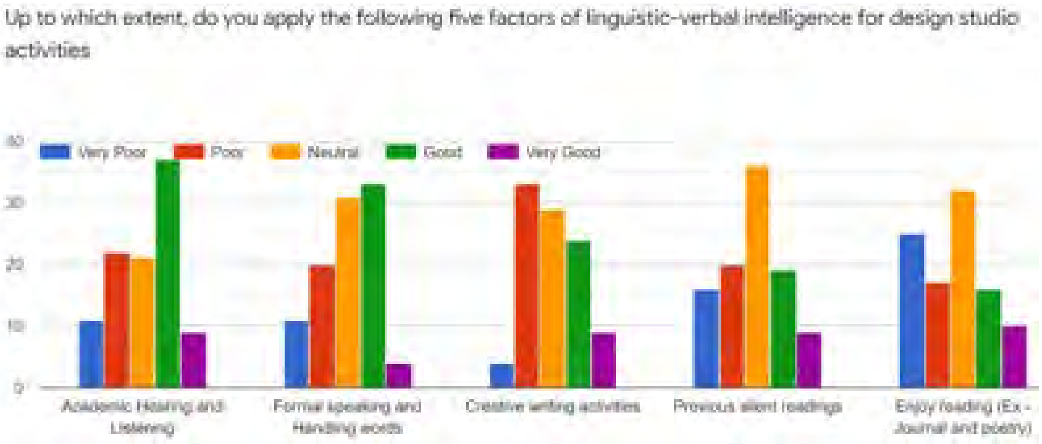

Figure 1: Example of Data analysis of linguistic- verbal intelligence

Table 2: Example for calculation of Perception Probability Analysis- Academic hearing and listening

State	Rank (a)	Response count (b)	Results	Divide by total Responses(c)	Value	Total value	Gap
Very Poor	(+2)	11	+2 x 11 = +22	+22 / 100	+0.22	+0.44	-0.11 Good
Poor	(+1)	22	+1 x 22 = +22	+22 / 100	+0.22		
Neutral	(0)	21	0 x 21 = 0	0	0		
Good	(-1)	37	-1 x 37 = -37	-37 / 100	-0.37	-0.55	
Very Good	(-2)	09	-2 x 9 = -18	-18 / 100	-0.18		

3.2. Second step of the analysis

From the step one, the gap between the total value was identified. Then a range for the gap is given to identify the state of each sub-skill of each intelligence as shown in table 03, which is taken as the final result of each individual sub-skill.

Table 3: State and the range of gap

Range of the gap	State
More than -51	Very Good
Between -50 to -1	Good
0	Neutral
Between +1 to +50	Poor
More than +50	Very Poor

After the state of each sub-skill is identified, it is utilized to obtain a point for each perception range for the hierarchy analysis as shown in table 04.

Table 4: Perception range and points for each perception

Perception on Very Poor	-2
Perception on Poor	-1
Perception on Neutral	0
Perception on Good	+1
Perception on Very Good	+2

3.3. Third step of the analysis

Subsequently, the given points for each sub-skill are added together to get the “total point” of the main intelligence. Each eight intelligence get a total point individually as indicated in table 05.

Table 5: Example calculation of total points of Verbal/Linguistic intelligence

Sub-skills of Verbal/Linguistic intelligence	Perception	Point
Academic Hearing and Listening	Good	+1
Formal speaking and Handling words	Neutral	0
Creative writing activities	Good	+1
Previous silent readings	Poor	-1
Enjoy reading (Ex - Journal and poetry)	Very Poor	-2
Total points		-1

Finally, the calculated total points for each intelligence is used to obtain the hierarchy of the eight intelligences which helps to identify which intelligence is mostly applied and which intelligence is least applied by the students for their design studio activities. Following the above steps, collected data for each intelligence category were analyzed individually in terms of student perception as well as lecturers and design tutors perception.

3.4 Hierarchy of students’ perception on eight intelligences

According to data analysis, it is identified how the eight intelligence of multiple intelligence theory are applied by the students for their design studio activities in the existing context. According to the architecture students’ perception, intrapersonal intelligence (“Self-smart”) is the intelligence that is mostly used by the students. Next, they use and apply Visual-Spatial intelligence (“Picture Smart”) and Interpersonal intelligence (“People smart”) at same level for their design studio activities. Logical-mathematical intelligence (“Number/Reasoning Smart”) is placed at sixth and Bodily-kinesthetic intelligence (“Body Smart”) is placed at seventh place in the order of application in their academic studies within the design studio. According to their perception students seldomly apply Verbal/Linguistic intelligence (“word smart”) and Naturalistic Intelligence (“Nature smart”). And Musical intelligence (“Music smart”) is the intelligence that they apply least for their design studio activities. The findings are shown in table 6 and figure 2.

Table 6: Calculation of total point of eight multiple intelligences – students’ perception

Intelligence	Total Points
(1) Verbal/Linguistic intelligence (“Word smart”)	0
(2) Logical-mathematical intelligence (“Number/Reasoning smart”)	+5
(3) Musical intelligence (“Music smart”)	-3
(4) Visual - Spatial intelligence (“Picture smart”)	+8
(5) Bodily-kinesthetic intelligence (“Body smart”)	+2
(6) Intrapersonal intelligence (“Self-smart”)	+10
(7) Interpersonal intelligence (“People smart”)	+8
(8) Naturalistic intelligence (“Nature smart”)	-1

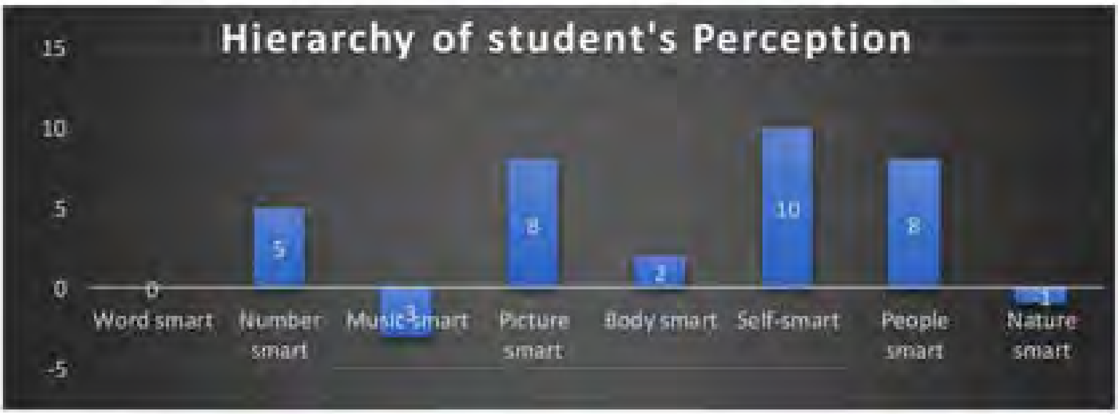

Figure 2: Hierarchy of student's Perception

3.5 Hierarchy of academic staff perception on eight intelligences

According to the perception of the academic staff, clearly, it can identify the perception on eight multiple intelligences, how students use and apply for their design studio activities. According to the academic staff's perception, Interpersonal intelligence ("People smart") is the intelligence that mostly use by the students. Next, they use and apply Visual-Spatial intelligence ("Picture Smart") for their design studio activities. The academic staff says that Intrapersonal intelligence ("Self-smart") using at the next level and after that student use and apply Logical-mathematical intelligence ("Number/Reasoning Smart") for their academic studies within the design studio. Verbal/Linguistic intelligence ("word smart") will use and apply by the students at the next. According to the academic staff idea and the perception, students are less at using and applying Musical intelligence ("Music smart") and Bodily-kinesthetic intelligence ("Body Smart") at design studio activities. Same as the student's perception, academic staff also says that Naturalistic intelligence ("Nature smart") is the lowers intelligence that students use for design studio activities.

Table 7: Calculation of total point of eight multiple intelligences – academic staff's perception

Intelligence	Total Points
(1) Verbal/Linguistic intelligence ("Word smart")	-3
(2) Logical-mathematical intelligence ("Number/Reasoning smart")	+7
(3) Musical intelligence ("Music smart")	-4
(4) Visual - Spatial intelligence ("Picture smart")	+9
(5) Bodily-kinesthetic intelligence ("Body smart")	-5
(6) Intrapersonal intelligence ("Self-smart")	+8
(7) Interpersonal intelligence ("People smart")	+10
(8) Naturalistic intelligence ("Nature smart")	-6

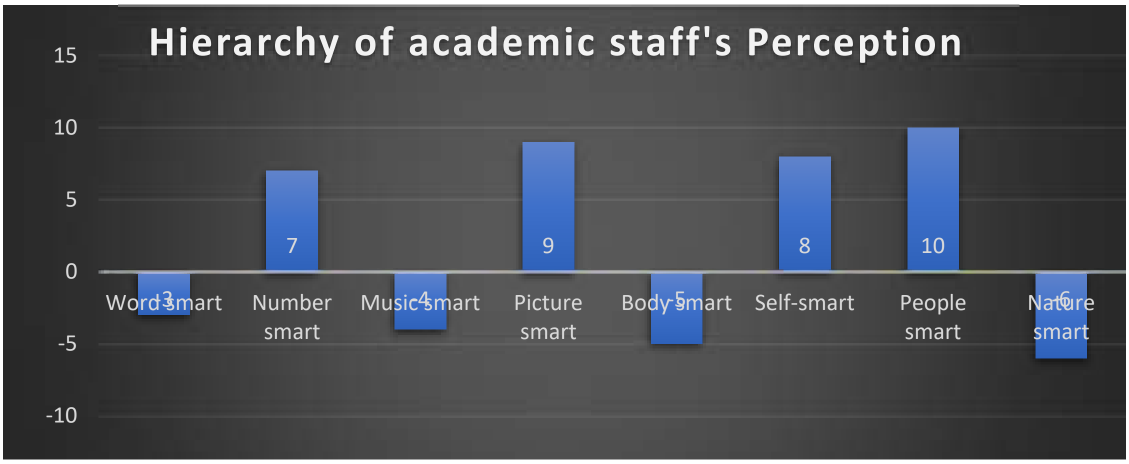

Figure 3: Hierarchy of academic staff's Perception

According to the analysis of the eight multiple intelligences, clearly it can see a hierarchy of the perception of the students and the academic staff on using and applying the eight intelligences by the students in their design studio activities. In some cases, there are differences between the student's hierarchy and the academic staff's hierarchy on each intelligence.

3.5.1. Verbal/Linguistic intelligence ("Word smart")

According to student's perception and the academic staff perception, students lack the use of verbal/linguistic intelligence in the design studio. Students always try to move with the technology and they don't get any time to work with the reading materials and all. Without reading subject-related materials and knowledge, students get lost their skills to develop their creativity. Literature has proved, when a person is getting more knowledgeable, that person becomes a creative person. Students read the books, but only for academic purposes. They don't read for enjoyment and something other than the subject. If students are good at writing, speaking and all, they get creative ideas that need for the design purpose. To develop verbal/linguistic intelligence and to be word smart in architecture, students must be a focus on creative reading materials. And Students can apply the things that they read and work with linguistic intelligence for their creative skills on design. Students should be intelligent at how to read, write, think creatively and what was read and written, and how to apply all those things for design studio activities.

3.5.2. Logical-mathematical intelligence ("Number/Reasoning smart")

According to responses of academia and students, Logical-mathematical intelligence is in the mid of the hierarchy of analysis. It says that the students use and apply maths, logic, and numbers including various patterns like number patterns, color patterns, and visual patterns for their creative works. In Logical-mathematical intelligence, patterns will be one of main thing in creativity that can apply to the design works. Mathematical and logical thinking also will help for the student's creativity and abstract ideas will generate a new way of thinking on creativity. To increase the combination between critical thinking and mathematical thinking, students should focus on more logical problem-solving activities. And also, the design with abstract ideas also will make students mind into new ways of thinking while doing the design activities. For the logical development of the students, the technology base also must be applied to the education process. But for architecture students, specially technology must be limited at a certain level, whether they study logical thinking for creativity. The student should not let to think and work mechanically in architecture and students should be free at thinking

3.5.3. Musical intelligence ("Music smart")

According to the student's hierarchy, students are weak at using musical intelligence. With the perception of the academic staff, musical intelligence is in the 6^{th} place of the hierarchy. Music can separate as another main subject area, with considering with another seven intelligences. Students think that music is an almost totally different subject and no way of apply to architecture. But the student didn't get the idea, how music can apply to their design studio developments activities. Music is a good inspiration for creativity and also a kind of meditation that can make people much more creative. The inspiration for the creativity in music works with whole music and vibrational patterns, sounds, beats, and tones. If students may not good at music in architecture, students can try to work, Enjoy, listening, sensitiveness to music, and get inspiration for design activities. As an activity and a suggestion that can give to students, the student can listen to music and can go for the architecture design according to the feeling of the music. They can get the patterns of the pitch, melody, rhythm, tone and do the design task. Likewise, music intelligence can get up to a considerable level within architecture education.

3.5.4. Visual - Spatial intelligence ("Picture smart")

Student's and academic staff's perception of visual-spatial intelligence is at the same level of hierarchy and students are very good at visual-spatial intelligence for their design studio activities. Visual-spatial intelligence can be considered as one of the main needs of the designing process. Seen of the patterns, shapes, textures, images, and designs for the external are the representation of visual-spatial intelligence. If students are enjoying patterns, shapes, textures, images, designs, drawing, painting, and visual arts, students will more talented with creativity in the architecture design process. According to architecture, spatial orientation is the main thing in visual-spatial intelligence. To increase more and more visual-spatial intelligence, activities related to spatial orientation can be developed with more practical and more experience. And also, patterns, shapes, textures, images, designs, drawing, painting, and visual arts can convert into creative thinking, creative ideas, and a new corner of looking with new ideas. As another activity that can develop the student on spatial intelligence is the let students to working with sculptures and make, build, fix or assemble things related to design activities. This activity is more important to 1st-year students. Then the student could be able to work with space arrangements and how to works with the space in architecture creatively, practically, and aesthetically.

3.5.5. Bodily-kinesthetic intelligence ("Body smart")

Students' perception of bodily-kinesthetic intelligence is in mid-level and academic staff says that students are poor at bodily-kinesthetic intelligence in design studio activities. With the discussion, it got an idea of why students don't use bodily-kinesthetic intelligence for their design studio activities. Most students think that bodily-kinesthetic intelligence is for hard works like model making and all. But it is not so. When we work, there is rhythm on the way of working. Actually, from those rhythms students can get inspiration for their design process. In some cases, without knowing students use bodily-kinesthetic language for the designing activities and it depends on each other. This process can explain as learning by doing and kind of experiencing learning like physical movement of body and way of movements happens. By looking at that movements, inspiration for the design process can happen with the physical body activities. Students can get inspiration from looking at practice of drama, dancing, sports, and also students can mimic other people's rhythms, gestures or mannerisms for their design activities. As an example, if a student is doing dancing, that student can inspire by the rhythm, ways of the body moving and how steps work, for their design activities. The thing is students may use them up to a certain level, but academic staff says that students are not up to the level that bodily-kinesthetic intelligence needs for architecture.

3.5.6. Intrapersonal intelligence ("Self-smart")

Intrapersonal intelligence is the intelligence that is most used and applied by the students for their design studio activities and academic staff says students are good at applying the intrapersonal intelligence. An architect must be good at self-awareness and emotions. Then the architect could be able to give something more than today, for the future. When the students are good at intrapersonal intelligence it is really valuable for architecture. Students say that they have the ability to recognizing personal feelings and emotions and students can convert those emotions into creativity. The students should be aware of personal knowledge, own ideas and personal goals that help to achieve their goals. The student should be able to identify their own strengths for design tasks with more creative and abstract ideas. Not only that, students must be good at theoretical analyzing ideas and could be able to work with spatial problem-solving with self-awareness. Students should experience architecture. Without experience in architecture, students don't get problems to solve. At this point, theoretical analysis of the student should apply on spatial problem-solving. To be an intrapersonal intelligence in architecture, the student should identify themselves. So, students should be excellent in activities such as silent reflection, concentration skills and higher-order reasoning.

3.5.7. Interpersonal intelligence ("People smart")

Students and the academic staff both say that the students are very good at Interpersonal intelligence within their desi studio activities. That means the student has the ability to recognize other's feelings, beliefs, intentions, emotions, moods, expressions and understand people and relationships. Therefore, students get the chance to get the other person's ideas while recognizing the other's feelings, beliefs and intentions. And also, students get inspiration for the design activities by looking at them. The communication and the relationship are the one of main valuable thing for the Interpersonal intelligence. Specially architecture students work as groups within the design studio. Therefore, the student gets the chance to identify the other's feedback, motivations and counseling from the others for them. And also, with communication and relationship, students understand the different perspectives of others. That perspective will generate and can get inspiration for the students' academic works. But that communication must be closer to get the real ideas and the perception on the other persons. With the developments of technology face to face discussions have been gone back and close relationship makes more interpersonal intelligence. With the present pandemic situation of Covid 19 also the gathering of the students, physical communication and relationships has been gone down within the design studio.

3.5.8. Naturalistic intelligence ("Nature smart")

Naturalistic intelligence is one of the best intelligences that can be marge with architecture. But according to the students and the academic staff perception, students are very poor at using and applying naturalistic intelligence for their design studio activities. For an architecture student, naturalistic intelligence is one of the most important things for creativity and for the relaxation of the mind. Not only for relaxations, but that nature is also a place where that can create more ideas and get inspiration for the design task. But the thing is why students don't use naturalistic intelligence for their design activities. The present students don't move with nature that much and always they try to work with the technology. The feel and knowledge of nature get by the technology, without experiencing nature. With the experiencing the nature, textures, colors, patterns, sound, rhythm, movements and many elements relate with the natures to get inspiration for the design activities. Watching the wildlife, understanding the animal behavior, needs and characteristics will make the students minds into a creative world while looking at them. And also, the mind gets to relax and the thinking process can be developed with nature. Students must focus on nature and get inspiration for their design task. A subject like ecology will be good for the architecture student at the problem of that lack of using the Naturalistic intelligence for their design studio activities.

4. Conclusion

This study was conducted in order to find out how the present architecture student use and up to which extent the architecture students apply the multiple intelligence theory for their design studio activities. With the help of the questionnaire, it was able to identify, up to which extent architecture students apply the eight factors of multiple intelligence theory for their Design Studio activities, how multiple intelligence theory could be useful for the architecture students in design studio periods for their academic activities and to know the perception of the architecture students and academic staff regarding the multiple intelligence theory. When comparing analysis results of academia and students, clearly can identify a hierarchy of applying the eight intelligences by the students. But the hierarchy of the student's perception and the academic staff's perception get some difference. Same perceptions and ideas of the students and the academic staff on applying of multiple intelligence theory on design studio were observed. And also, there are some different perceptions on each intelligence by students and the academic staff where students state they are rich with few sub-skills of multiple intelligences, but lecturers state that students are poor.

Students and lecturers both state that students are rich with few sub-skills of multiple intelligences. While Lecturers state students are rich with few sub-skills of multiple intelligences, students state that they are poor. However, students and lecturers both state that students are poor with few sub-skills of multiple intelligences. Further, it was observed that as architecture students they are good at using and applying Visual-Spatial Intelligence ("Picture Smart"), Intrapersonal intelligence ("Self-smart") and Interpersonal intelligence ("People smart") as three intelligences that need for architecture students. Naturalistic intelligence is an intelligence that can be more applicable for the design studio and for the student's inspiration, creativity and mind relaxation. But the students and the academic staff state that the students are very poor at using and applying naturalistic intelligence to their design studio. Moreover, within a mid-range of the hierarchy, verbal/linguistic intelligence ("Word smart") and the logical-mathematical intelligence ("Number/Reasoning smart") are applied and used by the students for their design activities. Thus, there are possibilities to improve intelligence which are used less by students with the several kinds of design activities and design projects.

The learning style of the student can change by using and involving the multiple intelligence theory. According to the analysis, there is a probability for improving the less using intelligence for the design studio activities. There are some intelligences that use by the students, without any idea of using them. That means the students say that they are poor at that intelligence and academic staff says that the students are good at that intelligence. Sometimes the student think that they are good at that intelligence and they work with their ideas and perception. But the academic staff's perception is, there are more to develop in that intelligence in the students for design studio activities. There can identify some gaps and differences between each sub-skills in the same intelligence when the students are using them for their design studio activities. The present architecture education process is not that much involved with the multiple intelligence theory and students also don't have that much idea on multiple intelligence theory and how to use it for their design activities.

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Investigating strategies to be future-climate ready: A case of dwelling for low-income older people

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Abstract: Recent studies have discovered that many people in Australia live in cold homes but also in homes that become extremely hot in summer. The dwellings can only become comfortable with heating and cooling; however, not all occupants use air-conditioning due to cost implications, worsened in recent years due to increasing energy prices. Extremely cold or hot indoor environment and a total reliance on air-conditioning indicate poor design that should be urgently addressed not just in new but also existing homes as poor thermal environment is linked with poor health/wellbeing outcomes. Addressing this problem becomes more critical in older people's housing, because as people age, they become more vulnerable to poor indoor environment. The warming climates further highlight the need to address this issue now. This paper presents a preliminary study of investigating the current thermal performance of an existing dwelling of an older occupant using building monitoring and simulation where the model was calibrated to measured data. The calibrated model was then used to predict the dwelling's performance in 2030 and 2050. To improve resilience of this dwelling in future climates, strategies were investigated, including those of low cost as well as more substantial changes such as installing double glazing and changing the floor construction. The results indicate that passive design strategies already known for years, such as thermal mass, shading and reducing leakage, will increase the chance of the dwellings to be comfortable without heavy reliance on heating/cooling even in future climates, but these are often absent in current housing developments.

Keywords: Older people, housing, thermal performance, future climates.

1. Introduction

A recent study conducted in Australia using data from the HILDA (Household, Income and Labour Dynamics in Australia) survey conducted by Daniel et al. (2021) show that out of more than 190,000 people surveyed, around 50% lived in cold homes and were unable to heat their homes. This may be a contrary to the general view that Australia is a hot country where extreme heat waves have been shown to result in the highest number of fatalities compared to the total number of deaths from all other natural hazards (Coates et al., 2014). In another study of 100 homes in temperate climates in Australia (Barlow, Daniel, Baker 2023), 81 homes were found to have indoor temperatures below 18°C, which is the minimum threshold of indoor temperature recommended by the World Health Organisation (2018). A field study conducted in the Adelaide metropolitan area in 2019 involving 19

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households also indicated that the internal temperatures of these houses were 18°C during winter (Daniel, Baker, Williamson, 2019).

Turning to the summer period, a study of 10 low to middle income housing in Adelaide conducted earlier in summer 2012 found that in each of the dwellings, the indoor temperature reached above 29°C and above, which occurred in 4 consecutive days in February that year (Soebarto and Bennetts, 2014). This was despite the fact the design of each of these dwellings was rated at 7.5 Stars (out of 10 Stars) in the Nationwide House Energy Rating Scheme (NatHERS). A 7.5-stars rated design is supposed to indicate a relatively energy-efficient design (at the time the minimum requirement was 6 Stars). Even though all dwellings were equipped with an air-conditioning system, the occupants of five of them did not use it throughout summer even though the outdoor temperature reached around 40°C. The maximum indoor temperatures in those five homes were found to range from 32.2°C to 37.1°C. The occupants stated that the main reason for not using the air-conditioning was the running cost. In the other five homes, even though air-conditioning was used, the indoor temperature ranged between 24.6 to 30.6°C, indicating a relatively high thermostat setting or sparse usage of the air-conditioning, again due to cost concerns by the occupants.

In 2022 Williamson et al. reported a study conducted in 2019-2020 to investigate the indoor environment and occupant thermal comfort and behaviours in 59 homes of older people in the three climate zones in South Australia (*BSk* or Climate Zone 4 of the Iron Triangle region (Port Pirie, Port Augusta and Whyalla), *Csa* or Climate Zone 5 of the Greater Adelaide Metropolitan area, and *Csb* or Climate Zone 6 of the Fleurieu Peninsula area and Adelaide Hills) (Williamson et al., 2022). The term "older people" refers to those aged 65 years and over. In this study, a vast majority of the participants lived in dwellings that are more than 20 years old and only a small portion lived in homes built after the introduction of the Energy Efficiency provision in the Building Code of Australia (Soebarto et al., 2019; Bennetts et al., 2020). Indoor temperatures were found to range from 12.6 to 28.9°C, 11.8 to 38.1°C, and 6.8 to 33.4°C, respectively in Iron Triangle, Greater Adelaide Metropolitan and Fleurieu and Adelaide Hills areas (Hansen et al., 2022). The occupants only used heating for around 16% (Fleurieu and Adelaide Hills) to 22% (Iron Triangle) of the time during winter, and used cooling for no more than 10% of the time during summer. The lower usage of heating in the Fleurieu and Adelaide Hills homes. as also indicated by the very low measured indoor temperature during winter, was due to the concerns over the heating cost. On the contrary, the older occupants of the Iron Triangle homes had no concerns over the heating and cooling cost, as indicated by the relatively higher indoor minimum temperature in winter (although 12.6°C is still quite a low temperature) and lower indoor maximum temperature in summer. The occupants of the Adelaide homes used cooling most sparingly due to both cost and environmental concerns, and as the result, the average maximum indoor temperature in the summer was around 32°C with one house reaching 38°C.

On average the occupants in the above study felt satisfied with indoor temperatures between 15.3 and 28.5°C (Williamson et al., 2022), and stated that their perception of health and wellbeing started to decline at indoor temperature below 15°C and above 28°C. This shows that very low or high temperatures do have impact on the occupants' health and wellbeing and should be avoided. It has been shown by others that mortality due to hypothermia increases during period of cold and morbidity to increase during hot periods, and many fatalities and hospitalised are older people (Rodrigues et al., 2021; Huynen, et al., 2001). The risk of low and high temperatures on health/wellbeing of older people will only increase with increasing occurrences of extreme cold and hot weather.

Data from the Australian Bureau of Meteorology (BOM) shows the lowest temperature in Adelaide during winter 2022 was 2.7°C (BOM 2022) while 2.9°C was recorded as the lowest temperature in July 2023 (BOM 2023a). Using Equations 1 and 2a in the work by Hansen et al., 2022:

$$T_{op} = A + B * (1 - exp(-K * T_{db}^{n})) \qquad (1)$$

where for Adelaide A = 15.621, B = 11.181, K = 0.00044 and n = 2.48,

and:

$$T_{op}Min = A - 1.33 * SD_{Top} \qquad (2)$$

where SD_{Top} is 3.27°C,

the mean operative temperature inside a dwelling of older people in Adelaide with outdoor temperature of 2.7 to 2.9°C would be 15.7°C, but the minimum would be 13°C, which is well below the minimum threshold recommended by the World Health Organisation of 18°C and shown in the previous study to result in reduced satisfaction to the indoor temperature and decline in the occupants' health and wellbeing (Williamson et al., 2022).

Turning to summer, BOM data also shows that the highest outdoor temperature in Adelaide in 2022 and 2023 was 41°C (BOM 2023b). Without using air-conditioning, this would result in an indoor operative temperature reaching around 31°C, based on equation (1) above and equation 2b in Hansen et al., 2022 (*TopMax = A + B + 1.33 * SDTop*). Likewise, such indoor temperature is beyond the temperature range considered to be satisfactory and conducive to the health and wellbeing of the occupants as found in the study by Williamson et al. (2022).

The maximum temperatures in South Australia have been projected to continue to rise in the coming years with more extremely hot days (EPA, 2018). Analysis of using data from the Australian Climate Observations Reference Network — Surface Air Temperature (ACORN-SAT) data for Kent Town (2.4 km from Adelaide CBD) shows that the number of days when the outdoor maximum daily temperature was above 42°C increased from less than 10 in 1980's to almost 50 days in 2010s (BOM, 2023c). With outdoor temperatures expected to continue to rise and the occurrences of both extreme hot are expected to be more frequent in the coming decades (extremely cold days will still occur but less often), efforts to improve the existing housing stock as well as to design and build new housing (particularly for the more vulnerable population such as older people) to be more resilient to the impacts of climate change are urgently needed.

2. Objectives

The main objective of this study is to explore affordable strategies that can be implemented to improve the thermal performance of an older persons' dwelling as much as possible before relying on air-conditioning (heating or cooling) in order to be future-climate ready. Note that this dwelling is used as only an example and not intended to represent all homes of older people. Lessons learned from looking into improving the thermal performance of existing dwellings will indicate the design parameters that should be implemented in new housing development now and in the future.

3. Methodology

The study was conducted by using building performance simulation to: (1) assess the existing performance of an existing dwelling occupied by an older person in Adelaide, South Australia, (2) predict the performance of the dwelling in future climates and (3) explore strategies to improve indoor thermal comfort and reduce energy use in future climates, using DesignBuilder Version 7.02.006 with EnergyPlus simulation engine. The indoor environment parameters of the living room and main bedroom, particularly dry bulb and globe temperatures, relative humidity, air velocity, CO2 concentration, as well as the outdoor dry bulb temperature, relative humidity and CO2 concentration, are being monitored (since February 2023 until January 2024), as part of an on-going larger study on "Developing resilient housing for low socio-economic older people" (ARC Discovery Project 220103213). Data are being recorded every 15 minutes and during this monitoring period, the occupants respond to indoor environmental quality (IEQ) surveys at least 3 times per week. Thermal comfort related questions in this IEQ survey ask the participants to reflect on their thermal sensation, preference and satisfaction. Details of this monitoring are reported in another paper for this conference.

Building geometry and construction material data were collected through on-site measurements (for the geometrical data) and observation, confirmed by the occupants (for the construction materials). Air infiltration rate and sources of air leakages were estimated from blower door tests and thermal photography of the building envelope. Window/door operations, heating/cooling usage as well as other occupancy patterns were noted based on the information from the occupants confirmed through the occupant IEQ surveys (some of the questions asked the occupant to indicate which room they were in, whether or not the windows, doors, and blinds were opened, or whether or not the heating/cooling/fan was turned on.

Monitored indoor temperatures were used to calibrate the simulation model by comparing simulated indoor temperatures to these measured data. Relevant adjustments were then applied to the simulation model to minimize the discrepancies between simulation results and measured data. We considered a CV(RMSE) of the difference between the two of up to 10% would indicate an acceptable simulation model.

To model the existing building, we used actual weather data file for 2023 (until July) in EPW file format, produced by Exemplary Energy (2014) that obtained hourly weather data from the Bureau of Meteorology. Using the calibrated model, we then examine the indoor temperatures without air-conditioning during the hottest summer week and coldest winter week. The same model was then used to predict future performance; in this case, we used the climate data files for 2030 and 2050 under 2 future climate scenarios – RCP 2.6 and RCP 4.5 obtained from CSIRO (Ren et al., 2022). We did not use RCP (Representative. Concentration Pathway) 8.5, which reflects a scenario of continuing to rely on coal as the main energy source, because since 2020, South Australia has already generated 70% of its electricity from renewable sources (Government of South Australia, 2020) and expected by 2030 to generate electricity from 100% renewable sources. RCP 4.5 represents a scenario where 100% of electricity is generated by renewable sources but there is still a mix of using conventional and electric cars, which is a likely scenario for South Australia in 2030. RCP 2.6 is the best-case scenario, where not only does the State generate electricity from 100% renewable sources, it also captures the carbon emission. Within this scenario, only electric vehicles are used (in addition to bicycles), which is a possible scenario if the State of South Australia continues to commit to reducing its carbon emission.

4. Case study dwelling

The case study is a 2-bedroom 55m2 unit in the middle of an east-west elongated one-storey block with the living room and main bedroom facing south (Figures 1 and 2). This small dwelling was chosen as it is a typical home of low- income older people. The building has uninsulated cavity (double-brick) walls, uninsulated timber flooring (about 400 mm above ground), brick internal walls, insulated plasterboard ceiling, uninsulated tiled roofing and single glazed sashed windows with timber frames. There is a small yard on the south (and north) of the building, fenced with a 2-m tall concrete wall from the neighbouring property. Only one person lived in this dwelling, aged 79 years. Throughout the monitoring period, the occupant very rarely turned on the split system air-conditioning unit both during summer and winter, and very rarely opened the windows. The monitored data showed almost constant air velocity of around 0.15 m/s and only occasionally the air velocity in the living room went up to around 1.3 to 1.5 m/s, indicating that the windows were being opened at the time (the dwelling has no fans). Minimum temperature in the living room during winter and maximum in summer were recorded at 16.2°C and 25.6°C, respectively, as shown in Figure 3. The blower door test result showed an air infiltration rate of 29.42 ACH @at 50 Pa, which indicates a 'very leaky' house compared to other houses (Ambrose and Syme, 2017). Using a thermal camera, we identified that air was leaking mostly through the cracks around the window and door frames.

Figure 1: Dwelling A: actual (left), modelled (right)

Figure 2: Floor plan of the case study dwelling (Unit)

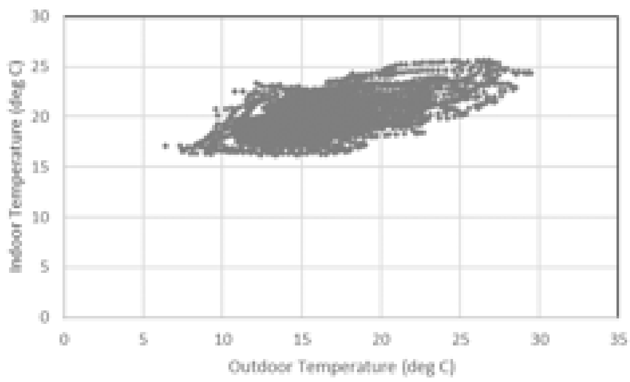

Figure 3: Monitored indoor vs outdoor temperatures in the living room

Based on measurements of wall thicknesses as well as observation of the building, the thermal properties of the building envelope were estimated and modelled as follows:

Table 1: Thermal properties of the building envelope

Construction	Conductivity (W/m.K)	Sp. Heat (J/kg.K)	Density (kg/m3)	Total R-Value (K.m2/W)	U Value (W/m2.K)
Roof: 25mm concrete tiles	0.850	840	1900	0.169	
Ceiling: 150 mm batt insulation, 13mm plasterboard	0.036 0.250	840 896	160 2800	4.359	
External wall: 110 mm bricks x 2, 40 mm air gap 13mm plasterboard	0.620 0.250	800 896	1700 2800	0.732	
Internal wall: 110 mm brick, plasterboard	As above	As above	As above	0.517	
Floor: 19 mm Timber floorboard	0.140	1200	650	0.406	
Windows: Single glazing					5.894

5. Results

5.1. Existing performance

Relevant data, including the building geometry and surrounding structures, the building envelope's thermal properties and measured infiltration rate, were entered as inputs to the simulation model of this dwelling. As the floor of this dwelling was a suspended timber construction approximately 400mm above the ground supported by the external walls, we modelled the building with an unconditioned space under the floor. Further adjustments made in the simulation model to ensure that the simulation model was well calibrated to the actual building were mostly on the use profiles. Figure 3 shows the comparison between the simulated and measured indoor operative temperatures (calculated by the method given by ISO 7726:1998 (ISO 1998)) during a period when no heating/cooling was used during April-May 2023. The calculated CV(RMSE) was 2.2%, indicating that the simulation model is quite accurate in representing the actual dwelling. See Figure 4.

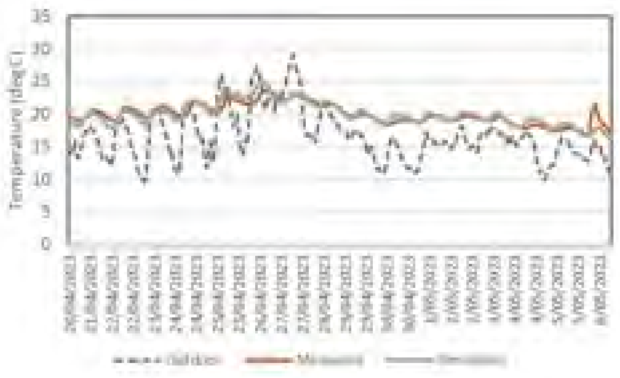

Figure 4: Simulated vs measured indoor temperatures of living room operative temperature

5.2. Predicting Future Performance

Using the calibrated model, the future performance of this dwelling was predicted for 2030 and 2050, using the RCP 4.5 as well as RCP 2.6 climate files. Figure 5 (left) shows the predicted indoor operative temperatures in the living room during the hottest week of 2030 and 2050 based on the RCP 4.5, compared to that in 2023. As can be seen, the living room temperature in this dwelling can be up to 6.3°K higher in 2030 and 5.7°K higher in 2050 than the maximum during the hottest week in 2023 without air-conditioning (Figure 5, right). It is worth noting that while the focus of this investigation is the temperature in the living room, the temperature in bedroom 2, which faces north, was predicted to reach 35°C during the same hot period.

With RCP 2.6 the maximum increase would be 5.8°K (Figure 6). Note that there would be little difference between 2030 and 2050 hence the data seem to be overlapping.

Please also note that we compared the indoor temperatures of the current performance during the hottest or coldest week in 2023 to its future performance in 2030 and 2050 during the hottest or coldest week of that year, which does not necessarily fall on the same calendar week of the other years. For example, the hottest week in 2023 was during the second week of January, whereas in the RCP 4.5 the hottest week in 2030 was predicted to occur in mid-February while in 2050 it would be in second week of December. Also, to avoid confusion, the outdoor temperatures have been omitted from figures 5 to 8.

As expected, higher outdoor temperature could also result in an increase in the indoor temperatures in winter although only by a small amount (Figures 7 and 8), and this increase might actually be beneficial to the occupant as some older people prefer higher temperatures than the younger cohort's preference (Schellen et al., 2010). Regardless of this benefit in winter from the warming temperatures, the expected increase in the indoor summer temperatures could affect the health and wellbeing of the occupant as well as increase their energy use as the occupant might need to use the air-conditioner more frequently than they currently do, to cope with much warmer conditions.

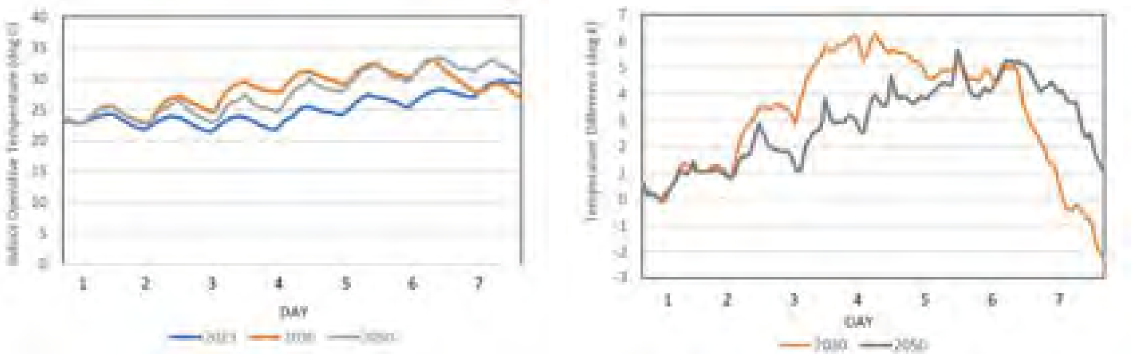

Figure 5: Predicted future indoor temperatures in the living room (left) and the predicted differences with 2023 data (right) during the hottest week based on RCP 4.5

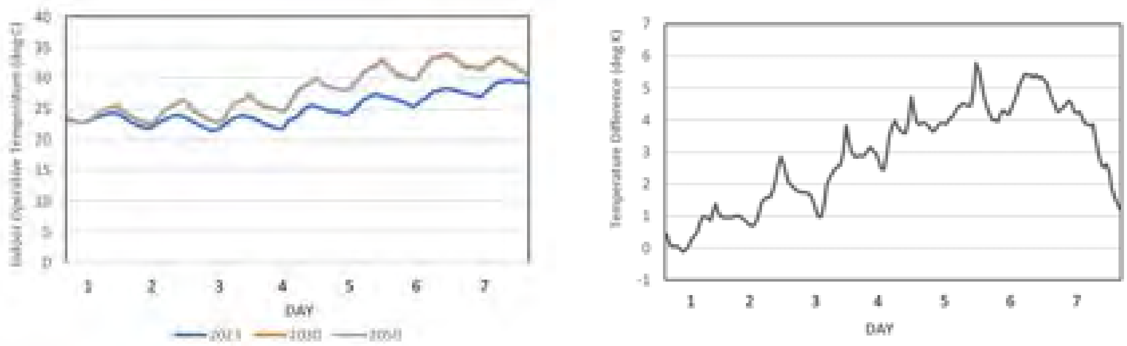

Figure 6: Predicted future indoor temperatures in the living room (left) and the predicted differences with 2023 data (right) during the hottest week based on RCP 2.6

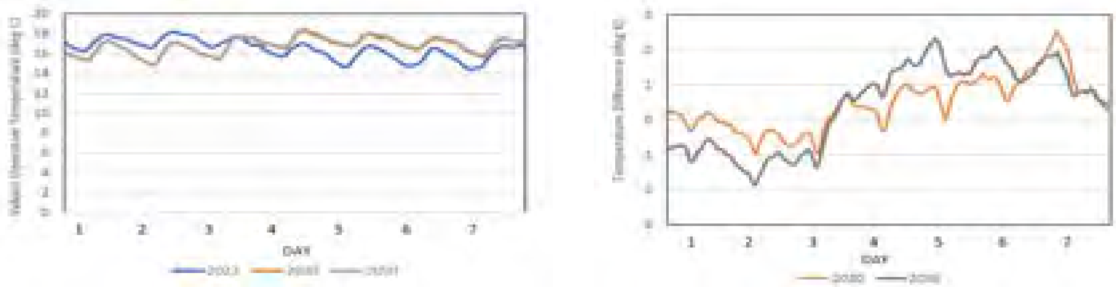

Figure 7: Predicted future indoor temperatures in the living room (left) and the predicted differences with 2023 data (right) during the coldest week based on RCP 4.5

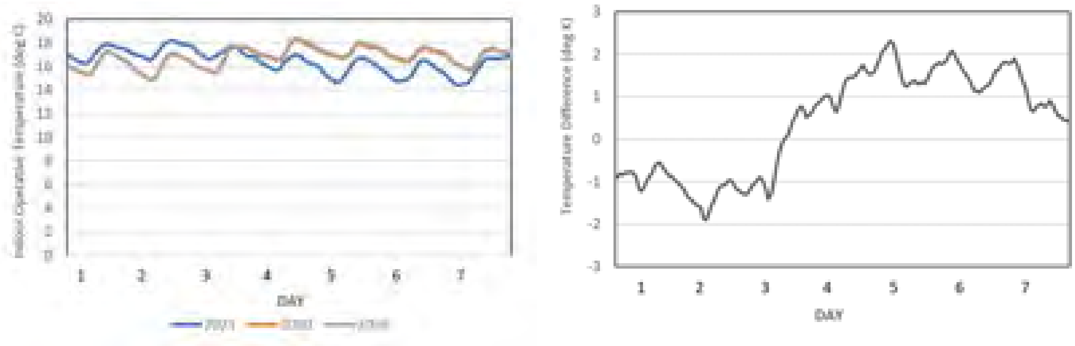

Figure 8: Predicted future indoor temperatures in the living room (left) and the predicted differences with 2023 data (right) during the coldest week based on RCP 2.6

5.3. Exploring improvement strategies

Data from the IEQ survey responses particularly on the thermal preference as well as the recorded indoor dry bulb and globe temperatures (to calculate operative temperatures) were used to calculate the preferred temperature of the occupant. Thermal preference refers to the preference to be either cooler (-1), no change (0) or warmer (+1). Recorded indoor operative temperatures were binned every 0.5°C and the mean thermal preference as well as mean operative temperature in each bin were calculated. A regression line was then fitted to analyse the association between indoor operative temperature and thermal preference, using the weights reflecting the number of votes in each 0.5°K bin. This process resulted in a regression equation of Pref = 4.127 – 0.171 Top ($p < 0.05$). Using this regression equation, the preferred temperature (or the temperature when the occupant preferred no change or Pref = 0) was calculated, resulting in the preferred temperature of 24.1°C. Using a 5°C band, the preferred temperature was assumed to range from 21.6 to 26.6°C.

The percentage of time the existing dwelling's temperature was within the preferred temperature range was found to be 23%. As the indoor temperature never went above 26.6°C, the remaining of the time was when the temperatures were below the lower limit of preferred temperature (i.e., 21.6°C), indicating that this was a rather cool house as opposed to a warm house. Nonetheless, the indoor temperatures never went below 15.6°C, which is the lower limit of indoor temperature for the occupant to feel satisfied and have good wellbeing based on a previous study (Hansen et al., 2022). In other words, at the present time the house can be considered as quite adequate in providing thermal comfort; however, this would change in future climates, with indoor operative temperature predicted to rise to almost 35°C in the hottest week in the summer mentioned earlier. Improvements that need to be tested will therefore focus on those that will reduce indoor temperatures during hot days.

To explore these improvements, we only used the RCP 4.5 climate file based on the assumption that by 2030, even though all electricity in South Australia is expected to be generated from 100% renewable sources, there will still be a mix of electric and conventional vehicles, which is the scenario reflected by RCP 4.5. The predicted performance of the current dwelling in 2030 as shown in Figures 5 and 7 was considered as the base case to which the impact of the changes will be compared. The main goal of the improvements was to reduce the predicted peak temperature of 33.1°C (Figure 5) without having to rely solely on air-conditioning, even though air-conditioning is routinely proposed by health authorities as a measure to offset the effects of extreme heat

(PwC, 2011). This was because the cost of electricity was predicted to continue to rise, which was a great concern of the occupant who had a limited income.

Two types of improvements were investigated: (1) low-cost strategies that could easily be implemented by the homeowner, and (2) high-cost strategies that could be implemented by the homeowner should they had the means to do so, or by the housing provider. Note however that, as the ceiling in this dwelling was already well insulated and the windows were already shaded by overhangs, the proposed improvements did not include adding insulation nor adding overhangs. Also, due to space limitation, we only focused the study for 2030.

5.4 Low-cost improvements

The first improvement that could be done by the occupant is to reduce air leakiness/infiltration by adding sealants or weather-stripping around the window and door frames and on any other cracks found in the house. While such improvement will have more impact on winter by reducing the amount of heat loss, this strategy could also reduce warm air from penetrating into the house during hot days. In practice, this could be done in a relatively low budget. For example, a 2.5m long weather seal tape costs around $5.00 and a self-adhesive door seal costs only $10.00. It was estimated that to seal all the external window and door frames in this dwelling would cost no more than $100.00. Rugs could also be added to the floor to reduce heat loss through the timber flooring. A study of pre- and post-draught sealing that we conducted in another dwelling and reported elsewhere shows that this simple retrofit could reduce air infiltration rate to 10-11 ACH. Assuming this could also be implemented in this dwelling, the infiltration rate at 50 Pa in the simulation model was reduced from 29 ACH to 10 ACH. This resulted in predicted peak temperature in summer to be reduced slightly to 32.8°C while the impact in winter would be more significant as the minimum temperature would increase by 1.2°C. Assuming a split system with COP = 3 was used for space heating and the thermostat was set to 21.6°C with a setback temperature of 15.6°C, this air infiltration reduction through draught sealing could reduce heating from 183 kWh in the base case to only 65 kWh, reducing heating cost by 76%.

Further improvement could be achieved by adding external blinds. While the dwelling already had internal blinds, installing external blinds would further minimize external heat gain as the heat would be reduced before being transmitted by the glass windows to the inside. In this dwelling, even though the living room faced south, the fence wall 1.7m from the south-facing wall of the living room and one of the bedrooms would reflect as well as radiate the heat to the glass windows. Adding external blinds with highly reflective slats and modelling the blinds to close between 11am and 5pm would significantly reduce the peak summer temperature by 2°C. The windows were also modelled to be opened slightly at night to allow the warmed air to escape and replaced with cooler air. Figures 9 and 10 show the temperature changes from implementing the above improvement(s) during the hottest and coldest weeks, respectively.

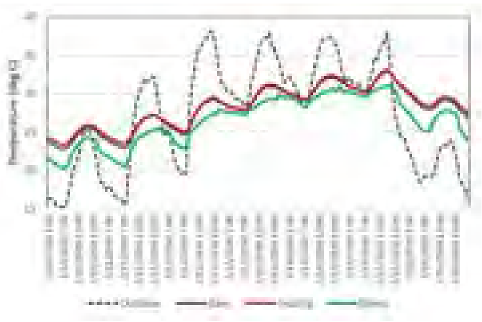

Figure 9: Predicted operative temperatures during the hottest week with low-cost strategies

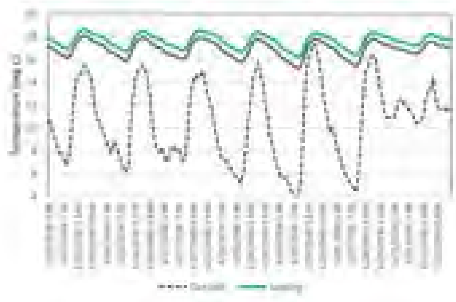

Figure 10: Predicted operative temperatures during the coldest week with a low-cost strategy

Despite the fact that these simple improvements could reduce indoor temperatures during the predicted hottest week in 2030, the temperatures would still be higher than the preferred temperature of 24.1°C. In this case, the split air-conditioning system may need to be used during summer as well. Modelling the set point for cooling at 24.1°C with a setback temperature of 26.6°C, it was predicted that with the changes above (however, with closed windows when the air-conditioner was on), the cooling energy for the entire summer months would be reduced to 277.5 kWh, showing a 23% reduction from the predicted cooling energy of the base case of 360 kWh.

5.5 High-cost improvements

The existing dwelling, as most houses in South Australia, had single glazed windows. If the homeowner had the capacity to retrofit the windows to use double glazing and change the window frames, or if the housing provider was willing to do so, a further improvement could be achieved. Modelling the building with clear double glazing of 3mm with 6mm air gap (U-Value = 3.159 W/m2.K), the peak indoor summer temperature would be further reduced by 0.4°C. Using double glazing would also result in increasing the lowest temperature in winter from 15.2°C in the base case to 16.5°C. With double glazing and the other improvements, if space heating was used, the heating energy would be further reduced to 24 kWh, demonstrating a significant reduction in the heating cost. Please note that during winter, the windows were assumed to be closed all the time while the blinds were assumed to be opened during the day.

This dwelling also had a floor construction commonly found in many older homes in South Australia, i.e. uninsulated suspended timber flooring, about 400 mm above the ground. If this floor construction could be replaced with concrete slab on ground, further improvement could be achieved. To model this, the existing uninsulated floorspace was removed (or deleted from the model) and the existing timber floor was replaced with 100mm concrete slab coupled to the ground (adjancy = adjacent to the ground). This change was predicted to signigicantly reduce the indoor operative temperatures in summer that even during the hottest week, the living room's peak temperature was only 26.6°C without using any cooling as long as the improvements explored above were implemented (i.e. draught sealing, external blinds). Please note also that this improvement could be achieved even without using double glazing.

Futher, if the double brick external walls could be insulated by pumping-in loose-fill insulation (40mm), and all other strategies were implemented, the indoor temperatures during the hottest week in summer could be further reduced (Figure 11). The impacts of these strategies during the coldest week are presented in Figure 12, showing that the lowest indoor operative temperature could be increased to 16.6°C from 15.2°C.

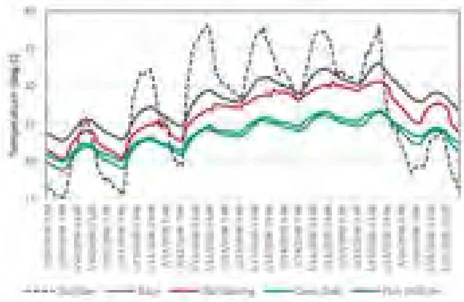

Figure 11: Predicted reduced operative temperatures during the hottest week with high-cost strategies

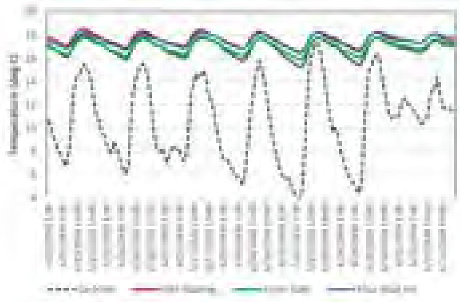

Figure 12: Predicted operative temperatures during the coldest week with high-cost strategies

6. Discussion

Passive design principles, such as proper building orientation, thermal mass, insulation, increasing airtightness, using operable windows preferably double glazing to minimize heat loss, and having proper external shading, are nothing new. Unfortunately, a large proportion of the current housing stock in South Australia does not necessarily employ these design principles. The case study building presented here is one of the many examples of the old housing stock in the State; it is leaky, lacking thermal mass, using single glazing, and having minimal amount of external shading. While this particular case study did not perform too badly in today's weather condition, it was predicted that as global temperatures continue to increase, as reflected in the future climate files for 2030 and 2050, this dwelling could warm up significantly during summer (while the increase during winter would only be slightly higher and could actually be beneficial to the occupants as the increase would reduce the need to heat the building).

To reduce indoor temperatures during hot days to be closer to the preferred condition by the occupant, a number of low-cost strategies were explored. Applying external blinds was shown to reduce external heat gain quite effectively, coupled with opening the windows at night. Draught-sealing could further lower the peak temperature, though its effectiveness, as expected, would be more noticeable during winter. If this dwelling was heated in winter, reducing air leakiness (from 29 ACH to 10 ACH) through draught-sealing could significantly reduce heating energy, by more than 70%.

Further reduction in summer indoor temperatures and some increase in winter indoor temperatures could be achieved by replacing the existing window glass with double glazing. Such improvement, however, would be much more costly compared to the other improvements, and unless the occupant or housing provided would be willing or able to do this, this might not be a realistic option. Occasionally running the air-conditioning that the occupant already installed would be cheaper and more practical. Likewise, replacing the existing timber flooring with concrete slab on ground and inserting loose-fill insulation in the double brick walls would reduce the indoor operative temperatures quite significantly during the hottest week in the summer but these, particularly changing the floor construction to concrete slab on ground, could be difficult and expensive to implement in an existing and currently occupied building.

What these explorations show, however, is that if new dwellings are built to follow the already-known passive design principles mentioned above, it is likely that they can be much more resilient to future climates compared to most residential buildings in South Australia built in the past 50 years and even those built today. Many new homes built nowadays still have single glazed windows that are not always openable, with no or minimal external shading. Even house designs that are rated at 6 to 8 Stars may not be heat resistant and have increased reliance on air-conditioning (Hatvani-Kovacs et al., 2018). The average homes built recently are also leaky, with infiltration rate of 20 ACH still found in relatively new homes in Adelaide (Ambrose and Syme 2017). With the proportion of older people from the general population continues to increase and many of which have low income, building more heat resistance homes as well as homes that can withstand extreme cold weather is at the critical point now more than ever.

7. Conclusions

This study has investigated the indoor thermal performance of an existing dwelling occupied by an older person with relatively low income. The majority of the time the indoor temperatures in the living room in both summer and winter (up to July 2023) were in within an acceptable range of 16.2°C and 25.6°C although the occupant's preferred temperature was calculated to be at 24.1°C. The living room was however predicted to be quite warm in 2030 with indoor temperature in the south-facing living room the north-facing bedroom reaching 33°C and 35°C, respectively, without the use of air-conditioning. These rooms were predicted to be even warmer in 2050 if no improvements were implemented.

Though using air-conditioning is often recommended by health authorities to maintain a healthy indoor environment, this study focused on implementing simple and affordable improvements that can be done by the occupant. These include draught-sealing, adding external blinds and opening windows at the right time. Implementing these strategies altogether could reduce the peak temperature during the hot week in 2030 by 3 degrees, thus reducing the use of air-conditioning should the occupant need to do so. Likewise, draught-sealing could reduce heating cost quite significantly.

The other strategies tested – replacing the single glazed windows to double glazing, inserting wall insulation and changing the floor construction to concrete slab to increase thermal mass would result in much further improvements both during the hot period and coldest times of the year. Such improvements are however costly and may never be realized in an existing building. Nonetheless, the improvements that could be achieved from implementing these strategies indicate that should every new dwelling built today be designed and built to follow passive design principles relevant to the local context, it is likely that they would perform well not only now but also in the future. This study has also demonstrated that in order to achieve a future-climate resilient building of a new building, its performance must be analysed not only for today's climatic conditions but also be predicted for future climates.

8. Acknowledgements

This paper presents a preliminary investigation of the impact of future climates on an existing home. It is part of a larger research project funded by the Australian Research Council through the Discovery Project grant, ARC DP2203213. We would like to thank the owner of the case study dwelling. The blower door test, funded by the FAME Healthy Societies Grant from The University of Adelaide, was conducted by Darren Harris of SUHO and assisted by Dr Larissa Arakawa Martins.

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Investigating the effect of the building envelope and weather conditions on the transport and distribution of pollutants within residential buildings

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Abstract: Air pollution is an acute problem for numerous prominent cities in the global south. This paper explores the case of India's capital - Delhi. The temporal variations in ambient air pollution levels are studied for the city based on data from the years 2018-2022. The ambient pollution levels are within acceptable levels for less than 20% of days in the year. The pollution levels peak in winter, where ambient concentrations of the most prominent pollutant, PM_{10}, exceed 600 μg/m^3 for continuous stretches of a few hours regularly. A typical residence is modelled in this context to understand the impact of outdoor pollution on indoor Air Quality. Infiltration is estimated based on a 2021 study of residential apartments in Ahmedabad (India), where blower door tests were conducted in 20 apartments. The infiltration data in air changes per hour (ACH) was translated into the effective leakage area of the envelopes. The derived leakage area estimates are used for modelling with CONTAM, a multizone airflow network simulation software. Modelling the transportation of PM_{10} particles reveals that higher wind speeds and higher envelope leakage rates lead to faster transmission of pollutants indoors. It took 15 hours for the indoor pollutant level to match the outdoors in the room to the windward side in the modelled residence when the leakage area was 4 cm^2/m^2 under steady-state environmental conditions. It can be concluded that active removal of indoor pollutants is essential for maintaining acceptable indoor air quality levels.

Keywords: Indoor air quality; Multizone airflow network simulation; Particulate matter pollution.

1. Introduction

The Global South is urbanising rapidly, but the growth in urban population is matched with a lack of adequate infrastructure, leading to environmental degradation. The various lists of the most polluted cities often feature prominent cities from this part of the world. The cities in the Northern Plains of India house some of the fastest-growing urban populations while simultaneously having some of the worst air quality in the world. This study takes the case of Delhi and investigates the temporality of ambient air pollution in the city and its impact on indoor air quality.

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 448 - 462.

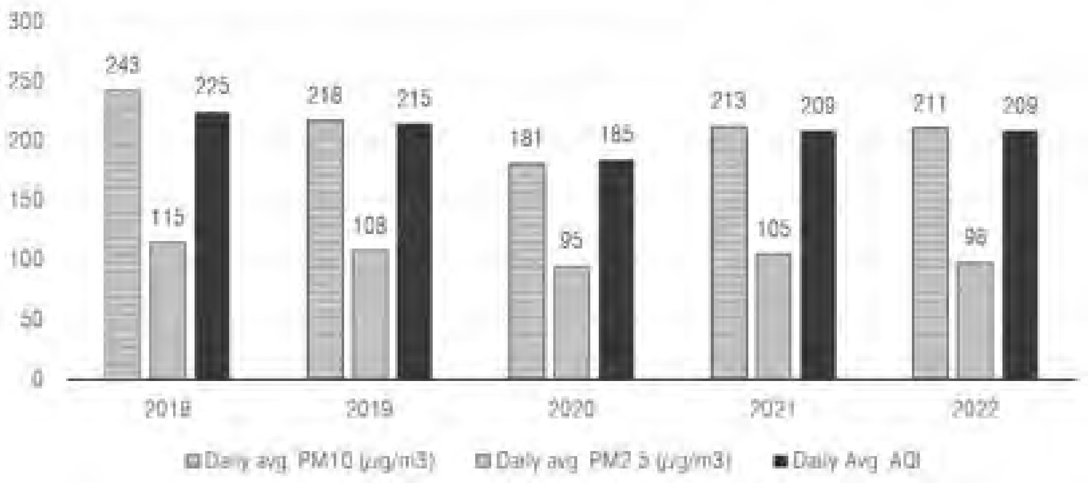

Figure 1: Daily Average AQI for Delhi for the last five years (Source: MoEFCC, 2023)

1.1. The air quality in Delhi

Only the COVID-19 hit year of 2020 had a Daily Average Air Quality Index (AQI) <200 in the last five years (Figure 1) in Delhi. The data shows that Particulate Matter (in particular PM_{10}) has been the dominant pollutant throughout the study period. AQI >200 is considered 'Poor' per the national classification (MoEFCC, 2014). These classifications far exceed the safety guidelines by the World Health Organization (WHO, 2021), which suggests a maximum limit of 15 µg/m^3 for average annual PM_{10} concentration. The WHO recommendations are based on a systematic review of literature connecting air pollution and mortality, and the standards were revised to be lower in 2021, considering the new evidence collected in this regard. The health risks associated with prolonged exposure to PM have been widely covered in the literature (Achilleos, et al., 2017).

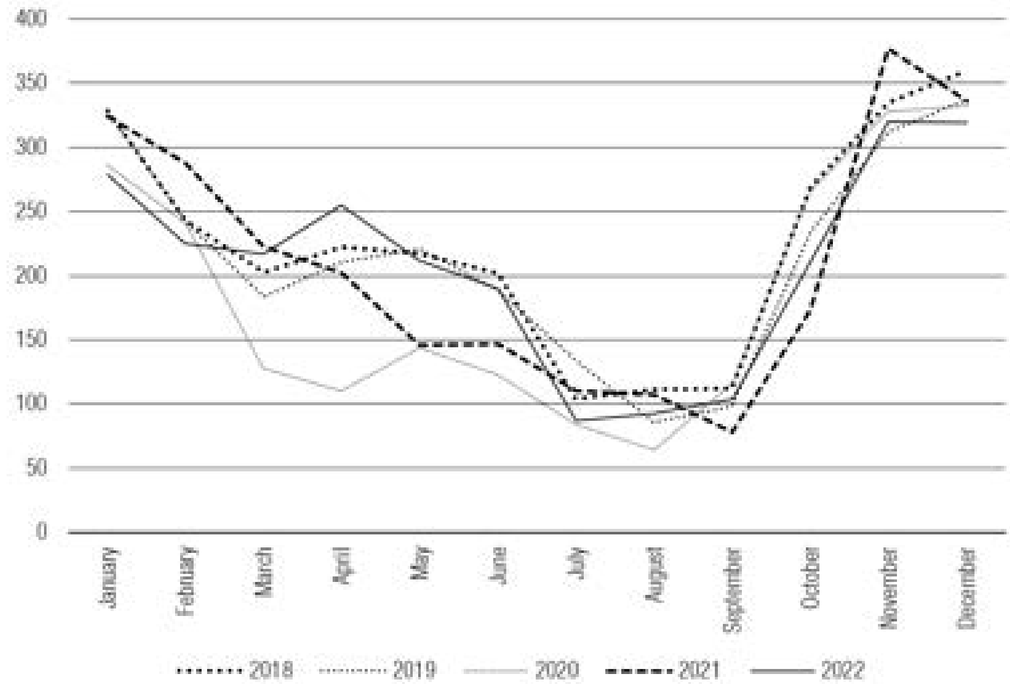

Figure 2: Monthly Average AQI in Delhi 2018-2022 (Source: MoEFCC, 2023)

Table 1: Classification of days per AQI category status in Delhi for the last five years; both the absolute number of days and percentage of days are mentioned in the Table (Source: MoEFCC, 2023)

AQI Category		2018		2019		2020		2021		2022	
Good	(0-50)	0	0%	2	1%	5	1%	1	0%	3	1%
Satisfactory	(51-100)	53	15%	59	16%	95	26%	72	20%	65	18%
Moderate	(101-200)	106	29%	121	33%	127	35%	124	34%	95	26%
Poor	(201-300)	114	31%	103	28%	75	21%	80	22%	130	36%
Very Poor	(301-400)	72	20%	56	15%	49	13%	64	18%	66	18%
Severe	(401-450)	20	5%	19	5%	13	4%	20	5%	6	2%
Severe +	>450	0	0%	5	1%	2	1%	4	1%	0	0%

Figure 2 illustrates the seasonal variation in air quality. The pollutant concentrations are highest in winter, from November to January, where the air quality remains dominantly in the 'Poor' to 'Severe' range. These months are marked by a relatively low Average Daily Temperature of ~15℃. Low temperature and still air decrease the mixing height of air and prolong the suspension time for pollutants in the ambient (Murthy et al., 2020). The summer months, from March to June, and the post-monsoon month of October, are characterised by AQI in the "Moderately Polluted" to "Poor" zone. Higher ambient temperatures and windy conditions increase the mixing height of air, which aids pollutant dispersion in the summers and improves air quality. The best months for AQI are the monsoon months from July to September, where rains aid in settling pollutants (wet deposition), and AQI comes down to 'Satisfactory 'levels. However, even during the monsoon, the pollutant concentrations are substantially more than the safe limits prescribed by WHO.

When the classification of days as per the AQI category is looked into (Table 1), ~60% of the year, the air is moderate to poorly polluted, with ~20% falling into the severe pollution category. When the ambient air is consistently so polluted, the pollutants are bound to find their way indoors.

1.2 Aims and Scope of the Study

This study investigates the transport of ambient pollutants indoors. Indoor emissions will not be covered within this study's scope, nor will the study consider particle deposition, indoor sinks and resuspension factors, as there are not enough studies in this context to support reasonable assumptions concerning these aspects. The investigation will be limited to modelling only one pollutant, i.e. PM_{10}. The choice of the pollutant is justified by its significance in determining the AQI. Wind speed and envelope leakage impact will be studied using a multizone airflow network simulation software CONTAM.

2. Methods

Winters and Monsoons represent the two extremes of Air Quality for Delhi. A small residence will be modelled for representative instances to study the transport of pollutants through infiltration. Bhanware et al. (2019) developed a layout plan for a typical apartment in India with a floor area of 80 m^2 after a survey of 40 projects. This layout will be used for the modelling exercise. CONTAM can model airflows across multiple connected zones (NIST, 2023) and is used for indoor air quality analysis in this study. The following sections cover the most significant modelling parameters.

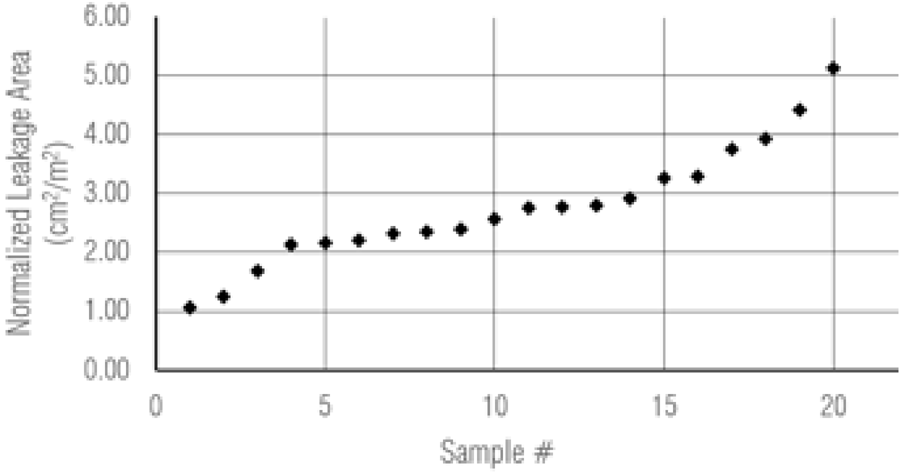

Figure 3: Building envelope leakage areas in Mathur & Damle (2021)

2.1 Envelope Leakage

Residential buildings rarely have dedicated air handling units. They rely on openings in the envelope to meet their ventilation needs. The openings in the envelope could be intentional, like doors and windows, or they could be adventitious openings formed near the joinery of floors, walls, and windows. The outside air and contaminants reach the interiors through natural ventilation and infiltration.

There is a dearth of data regarding envelope characteristics in the Indian context, making detailed infiltration modelling difficult. However, Mathur and Damle (2021) have conducted blower door tests on residential apartments in Ahmedabad (India). The multistorey apartments examined showed an infiltration range of 0.53 – 1.63 ACH at atmospheric pressure. These infiltration values can be used to derive the Effective Leakage Area (ELA). ELA is the area of a hypothetical orifice that would produce the same amount of air leakage as the entire envelope at the reference pressure, and its relation with airflow and reference pressure is given per equation 1 (Chan et al., 2003). The leakage area is affected by factors like Wall Window Ratio, window types and usage schedule and varies for different pressure conditions.

$$Q_f = ELA.\ \sqrt{(2P_f/\rho)} \quad (1)$$

Where

Q_f = Air Flow; ELA = Effective Leakage Area; P_f = Reference Pressure; ρ = Air Density.

In their study, Mathur and Damle (2021) also reported the exposed surface area and interior height. These values can estimate the normalised ELA for exterior wall surfaces, assuming most of the air leaks outside in the test with minimal leakage into the upper and lower floors. Figure 3 shows the distribution of Normalised ELA across the samples at a pressure difference of 4 Pa. Most residences had a Normalised ELA between 2-4 cm^2 per 1 m^2 of exposed wall surface area.

2.2 CONTAM model

The envelope leakage was modelled in CONTAM as a single flow path assigned to all exposed wall faces. The internal wall leakage was assumed to be ten times the exterior wall leakage. Figure 4 shows the wind pressure at different flow paths adjacent to the ambient for different wind directions (the pink lines indicate the direction of air movement). When the bedrooms are on the windward side in the first image, the pressure difference drives the air outwards through every other surface except the windward one, which is the expected behaviour. Changing the wind direction changes the pressurisation across flow paths in an expected manner, validating the model behaviour.

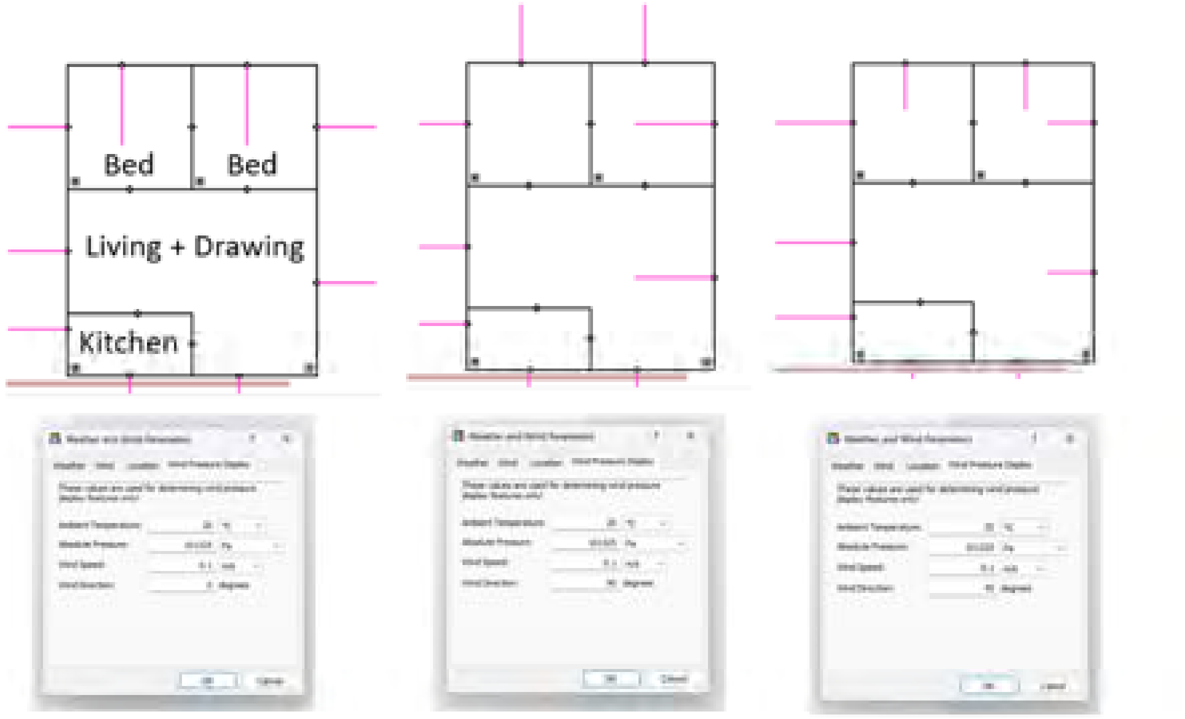

Figure 4: Wind pressure at flow paths adjacent to ambient zone for different ambient wind directions

2.3 Representative weather data

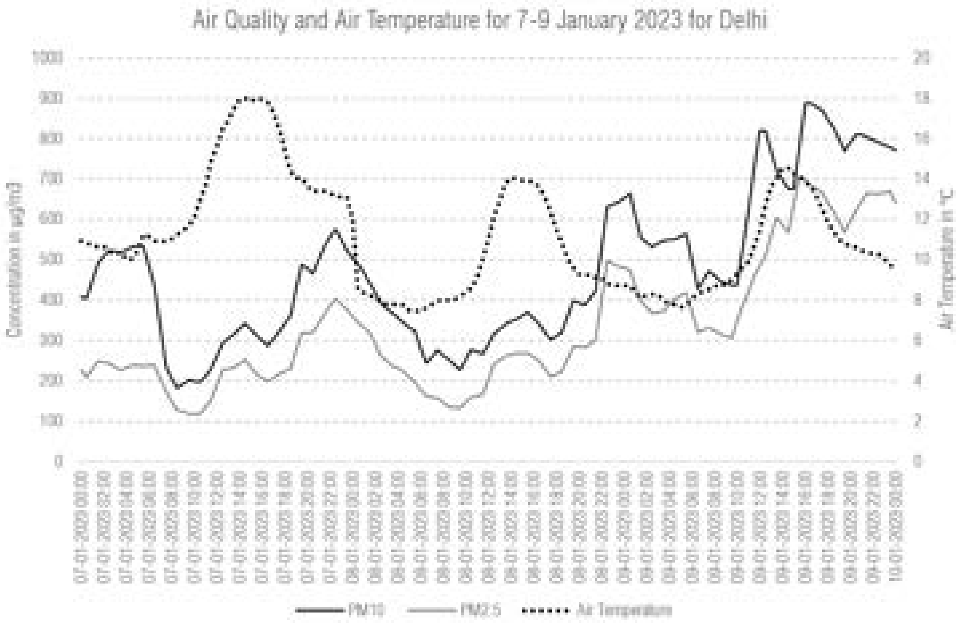

Figure 5: Ambient pollutant concentrations and air temperature for a representative period during winter (Source: CCRAQM, 2023)

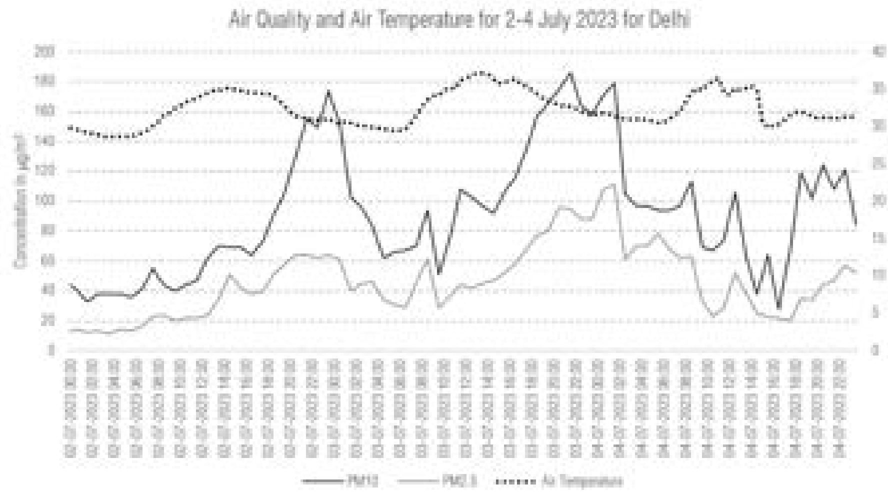

Figure 6: Ambient pollutant concentrations and air temperature for a representative period during the rainy season (Source: CCRAQM, 2023)

Figures 5 and 6 show the hourly variations in ambient PM concentrations for 7-9 January 2023 and 2-4 July 2023 for the monitoring station at Karni Singh Shooting Stadium in Delhi. These two periods are representative of the two extremes of ambient air pollution levels. The winter case shows a decrease in ambient concentrations as the temperature increases during the day for the first two days, but the third day shows no such relation. The 24-hour Average PM_{10} concentration for 7 January was 388.69, which would hide that hourly concentrations were >600 μg/m^3 for significant periods of the day. The corresponding average for 9 January was >650 μg/m^3 because the pollutant concentration consistently stayed over 600 μg/m^3, reaching a peak concentration close to 900 μg/m^3 during the study period. Guttikunda et al. (2012) have investigated the role of meteorology in explaining the temporality of air pollution in Delhi and found that summer wind speeds vary between 3-6 m/s, while it is 1-3 m/s for winters. Lower wind speeds in winter also partly explain the decreased mixing height and higher pollutant concentrations near the surface. The representative monsoon period had stretches where the ambient concentration dropped below 50 μg/m^3, but that did not last for any considerable period, and the daily averages hovered around 100 μg/m^3.

3. Results

A constant ambient PM10 concentration of 200 μg/m^3 and a constant wind velocity of 2 m/s from the South direction (the kitchen was on the windward side) were taken for the first simulation runs. 2 m/s represents an average wind speed for winter conditions and 200 μg/m^3 is approximately the annual average PM_{10} concentration.

Figure 7 shows the results from two simulation runs under steady ambient conditions, modelling the impact of leakage area on pollutant transport. The simulations assume zero initial indoor concentration of pollutants. Under these conditions, the outdoor wind would enter through the kitchen and living room, and the bedrooms would be the last to be exposed. It took 12 hours for the kitchen's indoor pollutant level to match the ambient pollutant level when the ELA was 4 cm^2/m^2. The difference in the volume can explain the difference between pollutant concentrations in the kitchen and Living rooms. The concentration does not cross 70 μg/m^3 in the bedrooms on the leeward side when the ELA is 2 cm^2/m^2 over 24 hours. The pollutant concentration is the same in either bedroom. The impact of envelope leakage is quite pronounced in these results. The indoor pollutant concentration takes double the time to match the outdoors for the kitchen when ELA is 4 cm^2/m^2 as opposed to 2 cm^2/m^2 (~12 hours as opposed to ~24 hours).

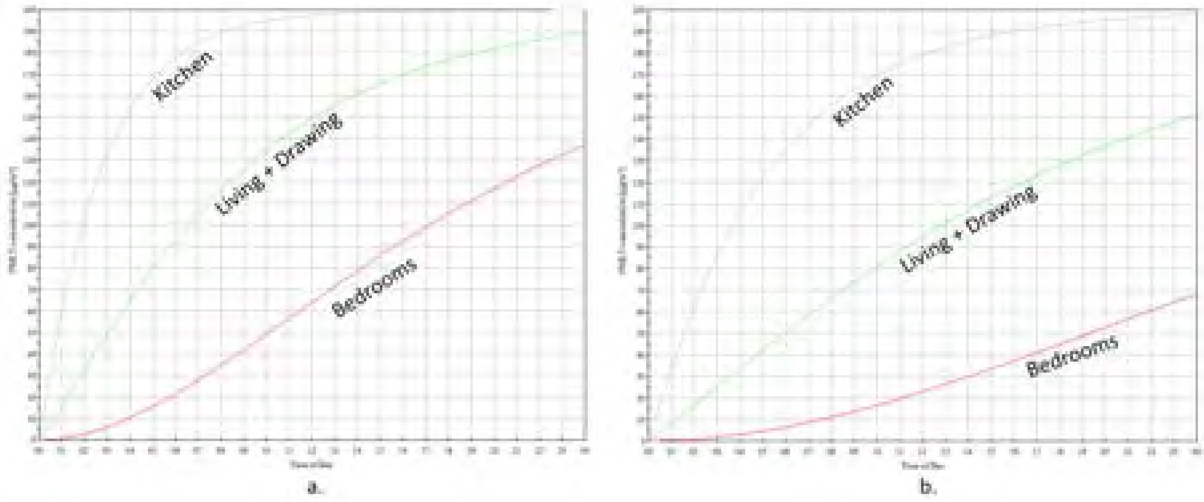

Figure 7: Indoor PM_{10} concentrations over 24 hours under a constant ambient pollution level and wind speed. Case (a) is for ELA = 4 cm^2/m^2, while (b) is for ELA = 2 cm^2/m^2

Figures 8 and 9 show the simulation results when considering the temporal variations in ambient pollutant concentration. The initial indoor concentration was also considered zero for these simulation runs. The ambient PM_{10} concentrations for 7-9 January 2023 have been used for the simulation while assuming a constant wind velocity of 2 m/s (with the living room and kitchen falling on the windward side). When the tests were run with the wind direction reversed, such that the bedrooms were windward, they showed a similarly steep rise in their pollutant concentrations.

These results only estimate the pollutant transport through infiltration. Opening a door, opening windows, broken glasses or other punctures in the envelope are all factors that would lead to a greater than modelled air exchange.

Figure 8: Modelled indoor PM_{10} concentration for 7-9 January 2023 when ELA = 4 cm^2/m^2

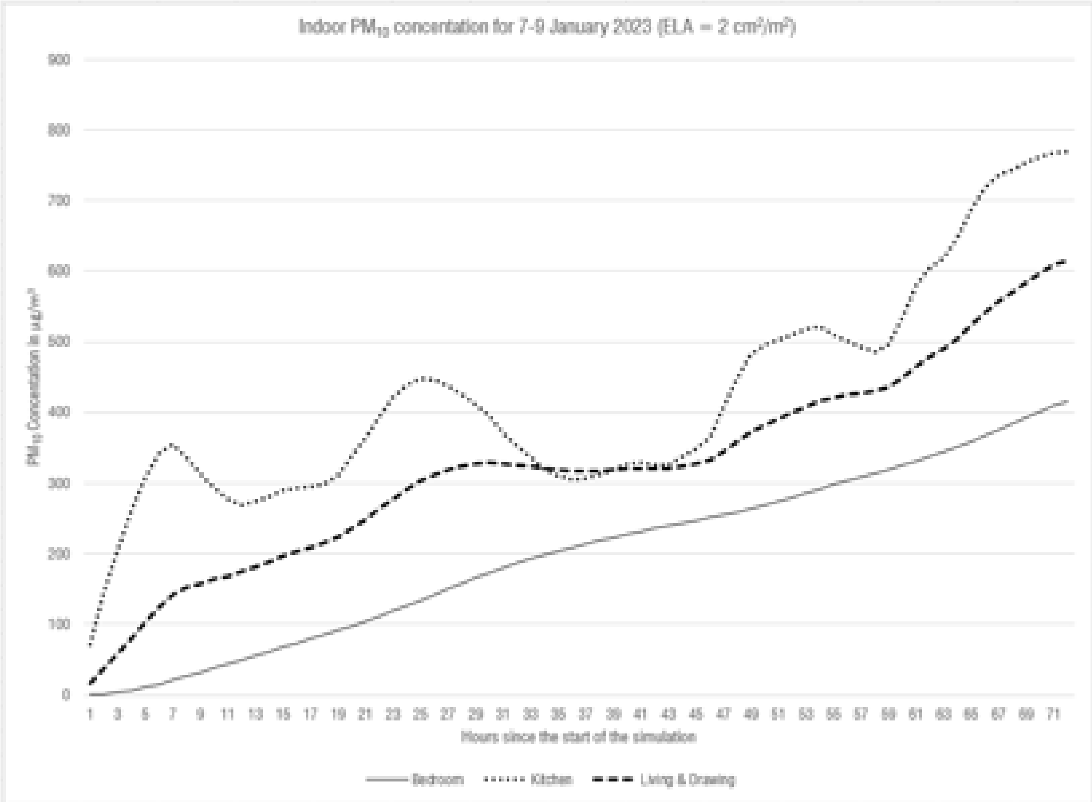

Figure 9: Modelled indoor PM_{10} concentration for 7-9 January 2023 when ELA = 2 cm^2/m^2

Emissions from indoor sources such as cooking, incense stick burning and smoking would also add to the pollutant load. The ambient PM concentration never stays in the safe levels for too long. Unless there is an active mechanism to clean the air, the indoor air quality will tend towards the same levels as outside.

4. Discussion

Building envelope infiltration is generally a concern for the energy efficiency of buildings, as increased infiltration leads to additional cooling and heating load (Choi et al., 2023). One of the drawbacks of reducing infiltration, as identified in the literature, is increased exposure to indoor PM emissions and reduced Indoor Air Quality (IAQ) in buildings which lack an air handling system (Shrubsole, 2012). However, this study's narrative is quite contrary; a prominent conclusion of this research is how higher leakage through the envelope leads to faster accumulation of pollutants indoors in the study area and reduces IAQ.

Since the pollutant load stays consistently high in the ambient, the indoor pollutant concentration is unlikely to ever fall to zero throughout the year. Resuspension and residence time of indoor PM are important parameters in this discussion, and many studies (Thatcher & Layton, 1995; Qian et al., 2012; Wang et al., 2021) have investigated them. Due to resuspension, the pollutant concentrations might be higher indoors than outdoors during the monsoon. Human activities and movement in the household have been found to cause resuspension of deposited particles and further deteriorate the IAQ. The presence of fans and ventilators would also impact the resuspension and spatial distribution of pollutants. The larger particles have been found to have much less residence time than smaller particles. However, no studies have investigated the residence time with such severely polluted ambient conditions.

Ambient wind speeds are positively correlated with air exchange through the envelope. Also, residential apartments in Delhi operate under natural or mixed-mode ventilation, which implies that windows would be kept open during the summer. A combination of these factors would suggest that the transfer of pollutants indoors would occur at a more incredible speed in the summer. Even though the ambient pollutant concentrations are less severe during the summer, the seasonal variations in IAQ warrant further investigation.

A multizone model works under a significant assumption of perfect mixing within a zone. Constant conditions across a zone are assumed, and spatial variations in pressure within a zone are not considered. These assumptions are the great strength of multizone models as they lead to practical computation times for these simulations, but this advantage does compromise the accuracy. There are pressure variations across the surface of the building envelope, owing to the interaction between wind and the envelope, which affects the transmission through the envelope. The assumption of constant conditions within a zone implies that spatial variations in pollutant concentrations within a zone would not be considered in a multizone model. CONTAM does have Computational Fluid Dynamics (CFD) ability, but such calculations are resource-intensive. Future research could take a CFD-based approach to further study the spatial distribution of pollutants and also model the air movement through the envelope at a higher resolution and greater accuracy.

The pollutant concentration is not constant across the city, and microclimatic and other factors lead to significant variations (Shukla et al., 2020). Trees and water bodies are parameters that would affect the ambient pollution levels (Vailshery et al., 2013). These variations could also be accounted for in future research.

5. Conclusion

The research investigated the temporal variations in ambient air pollution levels in Delhi. Ambient pollution levels peak in the winter, where ambient PM_{10} concentration exceeds 600 $\mu g/m^3$ for significant periods. The extremes of observed AQI levels are explained by decreased mixing height during winters and wet deposition during monsoon. Even though AQI levels in the monsoon season are significantly lower than in summer and winter, they still exceed the WHO standards. A household was modelled in CONTAM to understand the role of building envelope infiltration and weather conditions on IAQ with such ambient pollution levels. Indoor pollutant levels in leakier envelopes under slightly windy conditions could match the outdoors in less than 8 hours for some parts of the residence. The model considered an ELA of 4 $cm^2/m^{2,}$ which only corresponds to 1.6 ACH, but various standards suggest a minimum of 3-4 air changes in an hour for habitable spaces. Even at such a low ventilation rate, the indoor air gets polluted too quickly. The results of this modelling exercise have significant implications for the well-being of the residents of the many cities on the Northern Plains of India.

Air filters are becoming more popular in cities struggling with ambient air pollution, but their efficacy needs to be examined in this context. The filtration mechanism needs to not only clean the air but also do it at such speeds that a healthy indoor ambience can be maintained. For ensuring healthy IAQ, it would be imperative that untreated air be kept from leaking indoors, which would require maintaining a positive indoor pressure through the supply of treated air at favourable speeds. The results highlight the need to explore ways to reduce the leakiness of residential envelopes while developing air-handling systems targeted for residences that also integrate filtration mechanisms.

A lack of empirical data regarding the infiltration of building envelopes in India limited the degree to which the simulation model could be detailed. Such empirical investigations must be further taken up to understand better the behaviour of building envelopes, as it would have implications for IAQ and energy performance. Fans, other mechanical means, and household sources of PM pollution are other factors that should be included in future research.

6. Acknowledgements

Air pollution data for Delhi at a temporal resolution of 30 minutes was sourced from the website of Central Control Room for Air Quality Management <https://app.cpcbccr.com/ccr/#/caaqm-dashboard/caaqm-landing>, which sources data from multiple agencies. The authors thank the concerned agencies for facilitating the data acquisition. The first author of this paper is supported by the PhD scholarship provided by the Ministry of Human Development of the government of India, for which he is grateful.

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Keeping it simple: Public messaging and climatic design guidance for the built environment

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Abstract: A variety of resources, toolkits, guides, and frameworks have recently emerged to manage built environment outcomes in response to climate change however methodologies for assessing the social and economic value of design guidelines have not been established. This is because the procurement of guidelines by local and state governments has, to date, been relatively reactive, reflective of rapid social change and climate events. Assessing the impact and successful implementation of guidelines is challenging because of a lack of data and benchmarks. This paper emerges from a larger research project that aims to firstly collate various design guidance documents published by local and state governments in Australia and then to establish a method to analyse the social, environmental and economic value of design-led policy for the built environment. Utilising a content analysis method, this paper focuses on climatic and climate resilience design guidelines produced by local government authorities in Southeast Queensland and the Queensland State Government to establish a preliminary framework for assessing different communication methods employed.

Keywords: Design guidelines; community engagement, design governance.

1. Introduction and background to design guidelines for buildings

Design guidelines serve as tools that can shape the built environment in meeting functional, technical, aesthetic, and socio-cultural needs. While design guidelines are mostly non-statutory for building and planning legislation in Australia, they are primarily utilised as tools to educate the public, built environment professionals and internal government stakeholders on best practice design approaches. Early guidelines often focused on aesthetics, while more recent documents encompass more complex concerns to educate building users and owners as well as built environment professionals on specific issues. The topics that design guidelines cover are as diverse and varied as the organisations that employ them as part of their procurement or approval processes. Design guidelines for buildings are published by all levels of government in Australia, institutions such as universities, large private organisations with significant investment in real estate, Not-for-Profit and NGO advocacy groups, and commercial organisations. There are design guidelines relating to architecture that address topics including access and inclusion, energy efficiency, regionally specific climatic design responses, designing for Country and first nations' perspectives, climate resilience, retrofitting and renovating character and heritage design guidance and many other topics.

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 462 - 476.

Design guidelines for built heritage are produced by various organisations, including not for profits such as International Council on Monuments and Sites (ICOMOS), local and state government and religious organisations that own heritage stock (Sánchez, et al 2020). These documents provide guidance on integrating local aesthetics, historical context, and community values. As such, guidelines that can contribute to the creation of unique, identity-rich places that resonate with residents and visitors alike. One of the reasons that design guidelines for heritage have sustained continual publication and development is that they are often community driven, resulting from grass roots action to conserve or save buildings, shaped by public sentiment, in addition to the governing legislation (Sánchez, et al 2020). More recently, design guidelines which articulate Indigenous Frameworks for Designing with Country disseminate crucial knowledge around place-based, climatically appropriate and sustainable outcomes and processes. Examples of private organisations publishing design guidelines include documents that embed First Nations' perspectives into campus design for universities, through guidelines such as Queensland University of Technology's Campus to Country guidelines (BVN & QUT, 2021) and University of Queensland's Campuses on Countries Design Framework (UQ, 2021)

There are also guidelines for inclusive design, which seek to prioritise accessibility for all individuals, irrespective of physical and cognitive abilities. Creating barrier-free environments ensures equal participation and enhances the quality of life for individuals with disabilities, the elderly, and families with young children (Ward et al, 2013). An example of guidelines for inclusivity are the Liveable Housing Association (LHA) Guidelines, which were adopted into Volume One and Two of the National Construction Code in 2022. The effectiveness of the LHA guidelines is an important case study on the potential impact of design guidelines and how they might be being translated from non-statutory to statutory design governance. The translation of guidelines from non-statutory to statutory is one method to evidence the success of a guideline. Success can also be measured by their ability to engage and connect with community stakeholders, and the receptiveness of communities in adopting their advice.

Design guidelines are arguably more impactful when developed through a participatory process that engages stakeholders, including residents, businesses, and local organizations. In theory, involving the community ensures that guidelines align with their needs and aspirations and foster a sense of ownership. While there is international evidence to support strategic engagement in the development of more effective built environment legislation around sustainability and broader acceptance of stakeholder engagement as a measure of the success of guidelines (Tufte & Mefalopulos, 2009). There is currently no adequate methodology or framework to support the need for consultation in developing design guidelines. Academic literature from public health disciplines on the success and uptake on guidelines and public messaging provides some clues. Advice for guidelines from public health is straightforward, keep it simple. Similar to built environment policies, public health requires multi-level approaches, from organisational, local, state and federal governments. However, this approach will always risk "losing specificity and practical applicability" of guidance in certain contexts. (Aro & Absetz 2009). Simplicity presents the same challenges, where it might bring success in messaging that "cuts through" to the general public, what are the compromises in information quality and rigour required to distil a singular, simple message? (Aro & Absetz 2009)

2. Contextual Review: Design Guidelines and Public Messaging

While design guidelines can support better environment outcomes, challenges persist. Striking a balance between prescriptive guidance and flexibility remains an obstacle. Flexibility allows for timely responses to emerging trends, technological advancements, and unforeseen challenges, ensuring their longevity and relevance. This highlights the importance of utilising online publishing formats for design guidelines, which allow more agility in implementing and disseminating iterations and updates. However, clarity and technical rigour are of equal importance. The following contextual review provides some background on building design guidelines in Australia.

As modern guidelines have evolved from their initial format to encompass a wide range of considerations beyond aesthetics they have become more complex. Design guidelines for the built environment now serve as important tools for creating sustainable, diverse and inclusive towns and cities. Design guidelines require a nuanced and specific skillset to execute effectively. The expansion of design governance through local and state government architects' offices and their shifting roles from practitioners to advisors within government has spurred the production of design guidelines, especially for climate resilience (Holden & Volz, 2023). Peak industry bodies have engaged with expert researchers and specialist practitioners to communicate technical knowledge and emerging best practice to the industry at a local and regional scale. National and international guidelines have generally taken a process-based approach to design guidance for the architectural profession (Holden & Volz, 2023). These key documents are broadly applicable in a variety of socio-cultural and climatic contexts but don't generally provide the essential place-based information required to encourage and streamline uptake of recommendations.

At a local scale design guidelines are a tool for regional councils to educate and engage the public around specific place-based outcomes to build community resilience. In these contexts, guidelines have been useful for disseminating architectural science to stakeholders who may not otherwise have the resources to access specialist consultants (Brogden & Volz, 2023). The procurement of high-quality design guidelines by local authorities can be a costly exercise and the full impact of these documents is yet to be measured. Qualifying the social and economic value of guidelines could illustrate their capacity to improve connections to place and foster community responsiveness to climatic challenges as well as uncovering the challenges and obstacles to their effective implementation. One example included in this study of design guidelines for climate resilience in the built environment is the Flood Resilient Building Guidance for Queensland Homes authored by James Davidson Architect (JDAco.) and jointly developed by the Queensland State Government, SEQ water. JDAco. also designed and consulted on the Brisbane City Council's Flood Resilient Homes Program procured by Brisbane City Council after the 2011 Brisbane floods.

As the architectural profession adapts to rapidly changing environmental, social, and legislative contexts, effective guidance from government and peak bodies will be paramount. Utilising tools for effective communication and cooperation between sectors is critical for the architectural profession to maintain relevance and effectively serve communities impacted by climate change. Design guidelines have the potential to bridge the gap between practitioners, researchers, educators, governments, and communities seeking to respond collaboratively to complex emergent challenges. In an attempt to address this, there are guidelines developed by industry peak bodies aimed specifically at built environment professionals. One example is the Australian Institute of Architects' Environmental Design Guide (EDG) which has now been incorporated into the Acumen digital resource made available to their membership (RAIA, 1999-2023). A 2020 survey celebrating the 25 year evolution of the document indicated a relatively high level of support for the guide and its impact on sustainability knowledge within the profession (RAIA, 1999-2023). The survey also captured the areas where respondents were seeking further guidance – amongst these and in addition to more recent phenomenon such as life-cycle assessments and designing for net-zero carbon was climate responsive design guidance. As well as illuminating a knowledge gap amongst expert professionals that could be met by more effective climatic design guidance it also indicates the importance of reflective and constant iteration of design guides.

Climatic design guidelines play an important role in educating the public on passive design strategies (Hyde, 2012). Design Guidelines for climate resilience and climatically responsive design often work to complement construction and planning legislation, such as the National Construction Code and State Government Planning Acts. The Australian Government's 'Your Home' website as a guideline tool is a notable example of this, providing domestic house designs tailored to suit the eight climatic zones defined by the National Construction Code. Now in its sixth iteration it provides a variety of information becoming more climatically specific and is constantly updated to address emerging climate science and construction technology. Your Home works to provide supplementary and explanatory content for homeowners that aids in the implementation of the NCC's energy efficiency legislation (McGee & Clarke 2021). Guidelines work across levels of government, often generated from Local Government Authorities to provide further detail, providing context specific information that supports application of broader built environment legislation without deviating from requirements.

Legislation for energy efficiency in buildings is often founded on incorrect assumptions and fails to incorporate models for accounting human behaviour in buildings and their use (Enker & Morrison, 2020). This is where person-centred design guidelines, can bridge the gap between economic rationalisation of building energy use and how people live in and use buildings in specific settings and places. Design Guidelines diligently address the 'information asymmetry' associated with built environment legislation, where consumers and building owners often lack basic knowledge on energy efficient, climate resilient or designing for climate responsiveness (Enker & Morrison, 2020). Public debates about integrating Passive House (Passivhaus) principles into the National Construction Code and the recognition of Passive House Standard as a pathway to meeting the legislated thermal performance requirements in NSW are a good example of information asymmetry (Nunn et al, 2021). The arguments against primarily revolve around initial outlay and contextual nuance. Despite supportive technical data and case studies as evidence, Australian Passive House Association has not been able to effectively communicate it's potential to built environment practitioners in warmer climate zones (Nunn et al, 2021).

The success of any legislation or compliance with regulation is heavily dependent on peoples' knowledge and buy-in for compliance (Enker & Morrison, 2020). The primary purpose of guidelines is to provide education to the general public about issues relating to the built environment, provide strategic advocacy for desirable outcomes (such as circular or decarbonising economy, climate resilience, etc), technical information to support the work of built environment professionals. Additionally, guidelines can be required to the extra heavy lifting associated with cultural capital of place based, regional or city marketing.

Community and engagement should be the starting point in the development of successful guidelines. example of how consultation can be incorporated and used to inform the development of Guidelines is The Queensland Government's Social Housing Design Guideline (SHDG) (2021), authored by the Office of the Queensland Government Architect and informed by consultation firm, Surroundings. It is informed by tenant stories gathered via consultation with social housing residents. The Social Housing Design Guidelines are explicitly 'person-centred' and state the objective of integrating post-occupancy evaluations into subsequent revisions of the guidelines. Another strategy that these guidelines have incorporated is the inclusion of results from an architectural competition, The Density and Diversity Done Well competition. Employing these two methods for design guidelines means that information was drawn both users and built environment professionals and both are reflected in the document, empowering ownership to designers and users. Folding in awards, competitions and other programs alongside guidelines works to both promote and enhance engagement with the content. Brisbane City Council sponsor a 'Buildings that Breathe' category is the Australian Institute of Architects Regional Brisbane awards to support and promote their design guidelines for passive ventilation. These guidelines are discussed in this paper and clearly the target audience of these guidelines in architects and built environment professionals.

There is limited research that assesses the effectiveness or uptake of climatic design guidelines. Raymond Cole (1998 & 2013) has published some research that assesses the uptake of global green building standards and rating systems, such as LEED (Leadership in Energy and Environmental Design) and BREEAM

(Building Research Establishment Environmental Assessment Method). However, in order for climatic design guidelines to be most effective, local and not global information is required (Brogden & Volz, 2022). As climate change poses new challenges, climatic design guidelines are evolving to address shifting weather patterns (Santamouris 2014). In the case of climate resilience for extreme climate events, these guidelines have to take into consideration the availability of specific materials and access to qualified tradespeople and built environment professions for each region. For this reason, an analysis of the effectiveness of climatic design guidelines, requires a fine grain approach that analyses documents available for specific regions against the prevalent climate challenges and socio-economic conditions in that locale. It also means that the role of the researcher is to synthesise guidelines produced across different government bodies, and operating at different tiers (state and local) of government.

3. Research Method: Content analysis framework for climatic and climate resilience building design guidelines

Content analysis is an especially useful approach in the study of urban design governance (Carmona, 2016). This method begins with the collection of textual or visual data relevant to design governance. This data can include documents such as urban plans, zoning regulations, architectural guidelines, public policy documents, meeting minutes, and visual materials like photographs, maps, or architectural drawings. Content analysis allows researchers to systematically extract meaning from a large volume of textual and visual data, helping to uncover trends, policies, and issues that influence urban development and design decisions. This study focused on collating climatic and climate resilient design guidelines for southeast Queensland local and state government authorities. From this, a coding scheme, detailed in Table 1, was produced to categorise the content into meaningful and manageable categories. This coding scheme was based around different communication techniques that were identified in each document. Examples of the graphic and photographic communication strategies adopted in the majority of the guidelines can be seen in Figure 1 & 2, drawn from the Toowoomba Regional Council Warm Temperate Climate Building Design Guidelines (Volz et al, 2022). The guidelines were then systematically read through and the established codes were applied to segments of the text or visual elements.

Future research would benefit from a thorough, formalised linguistic analysis, drawing from communication theory to address further subjectivities and biases. Regardless, this process revealed several recurring themes and patterns in the data as well as a few notable anomalies. Based on the analysis of the content, conclusions and insights were drawn about the effectiveness of different design guideline communication strategies, which are discussed in this paper. These interpretations and hypotheses can be used to inform further research into effective communication strategies for climatic design guidelines.

Table 1: Framework for analysing design guidelines communication approach

Framework category	Category descriptors
Audience	**Expert:** Guidelines written for built environment professionals such as architects, building designers, planners, builders, and engineers
	General Public: Guidelines written for building owners, building users and renters, leaseholders, and landlords. Written in a way that assumes no training in built environment professions.
Graphic Style	**Architectural:** Either hand sketched or computer-generated presentation drawings, with people and trees for context, including plans, sections, perspectives and axonometric or isometric drawings. Often with annotations.
	Technical drawings: Technical architectural drawings such as wall sections and plan details as well as detailed plans, sections and elevations to describe a specific construction method and materials application.
	Colourful diagrams: Either hand sketched or computer generated colourful diagrams that explain a concept relating to a built environment outcome (planning or building) which includes a climatic response. Often with text integrated or annotations.
	Annotated photographs: Photos with text integrated or with annotations. The photos might be used to communicate a specific outcome or used as aspirational imagery to promote lifestyle or other factors related to place-based climatic principles.
	Tabulated data and dimensions: Data relating to construction methods or materials to describe a specific technical solution. Especially for flood, cyclone or fire resilience.
	Videography: Short videos presented online with supported text to explain concepts. Videos are accommodated on Council/Government websites and are shareable via social media platforms.
Structure	**Discussion/Consultation paper:** A higher level document that contains research behind guidelines or a document that doesn't prescribe any specific outcome. Mostly identifies challenges and/or issues that could be addressed by built environment professionals and/or the construction industry.
	Report: A text driven report with technical information, often informed by research, supported by either photographs, diagrams, architectural or technical drawings as well as information presented in charts and tables.
	Drawing Set: A set of technical drawings which prescribe technical outcomes.
	Graphically driven booklet: A short document populated with mostly drawings, diagrams and photographs and minimal text to support or explain content that is communicated graphically.
	Interactive Online: Interactive presentation of guidelines with click through links, explanatory videos and interactive graphics
Purpose	**Educational:** The document aims to educate built environment professionals and clients on specific technical approaches for climate resilient design.
	City/Regional marketing: Where climate relates to lifestyle factors, the document is used to promote aspirational elements of living in a region due to specific climatic attributes.
	Strategic/Advocacy: When a document is aimed at a specific audience or context in an attempt to affect change.
	Technical information: Prescribed technical data to inform a specific technical response such as material application or construction method communicated through tabulated data and technical drawings.

Intent	**Inspire:** An aspirational document that may not contain all of the information required to execute an outcome but will inspire people to investigate further or pique interest on a topic. The information is not prescriptive. **Advise:** Provide technical or descriptive advice on best-practice outcomes. The advice might direct readers to information for a prescribed outcome but the document itself only provides general information. **Direct/suggest:** Prescriptive outcomes that might be qualitative or technical in nature. Described through text, images and often in reference to a demonstration project.

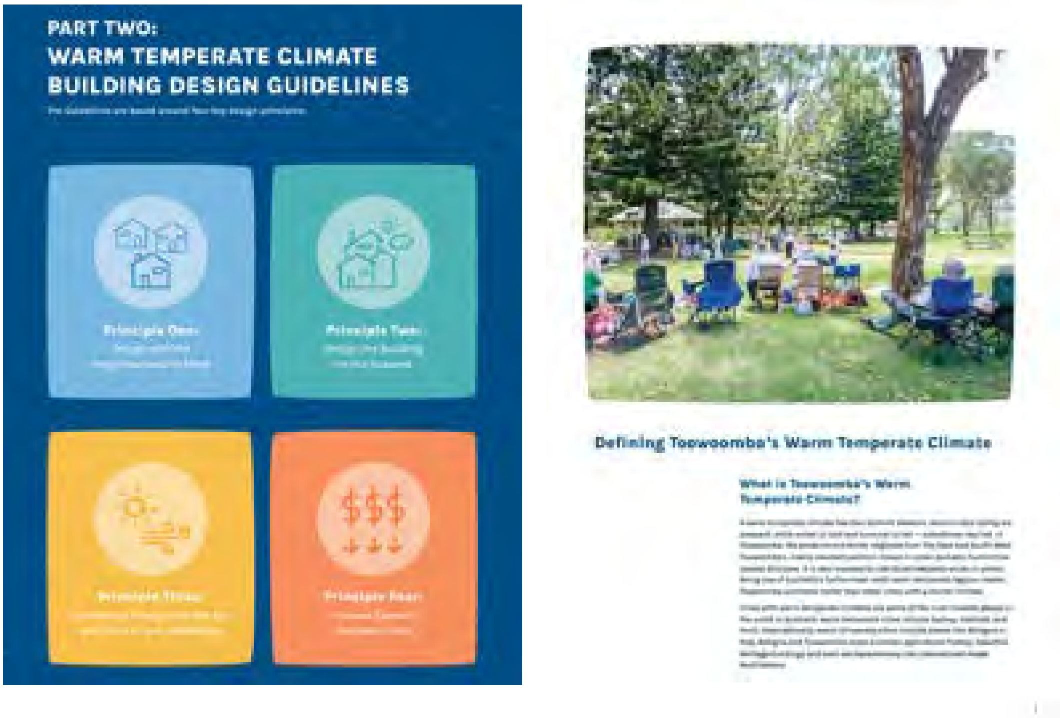

Figure 1: Example pages from the Toowoomba Regional Council's Warm Temperate Climate Building Design Guidelines. The page to the left shows an infographic method for communicating design principles. The Page on the right shows an annotated photograph. This type of photography is aspirational in nature to show the relationship between region specific climate and lifestyle. (Source: Building Design Guide: Warm Temperate Climate Building Design Guidelines)

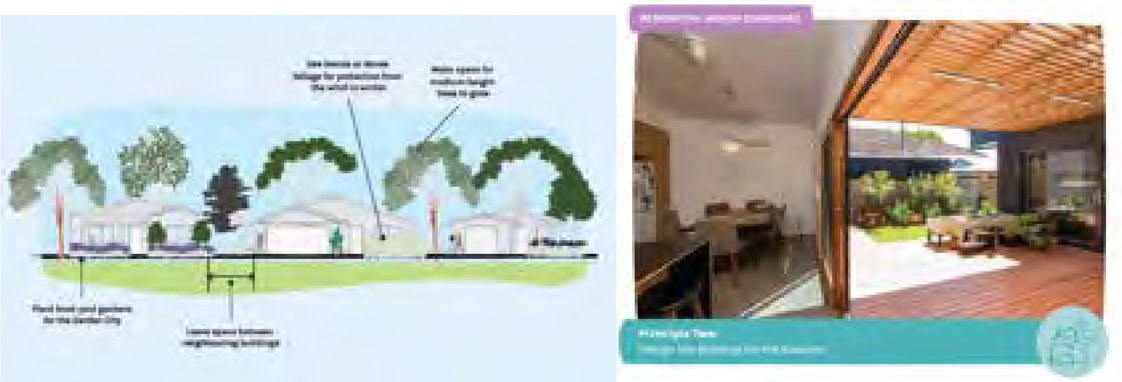

Figure 2: Two images selected from Toowoomba Regional Council's Warm Temperate Climate Building Design Guidelines. The image on the left shows an example of an architectural sketch explaining climatic design principles. The image to the right shows an annotated photograph of an exemplar project showcasing climatic responsive design. (Source: Building Design Guide: Warm Temperate Climate Building Design Guidelines)

4. Findings from an analysis of Southeast Queensland climatic and climate resilience building design guidelines

Nineteen design guidelines from five local government authorities in southeast Queensland and the Queensland Government were analysed. There are seven local government authorities in southeast Queensland but design guidelines were only found to be published by the five included in the results tables to follow. These guidelines were sorted into two separate tables representing two types of guidelines – those communicating climatic design information (climate responsive design principles) and those disseminating climatic resilience information (designing for extreme climate events). The tonal gradation in the table below has been used to graphically illustrate the findings. Lighter colours represent a smaller authority (regional councils), shorter length and less intensity of information with darker colours representing higher authority (state government), longer lengths, greater intensity and/or complexity of information requiring a higher level of expertise to understand/interpret.

Table 2: Content analysis of climatic design guidelines published by Southeast Queensland Local Government Authorities and Queensland State Government

Guideline Name	Published By	Document length	Audience	Graphic Style	Structure	Purpose	Strategy
Buildings that Breathe	Brisbane City Council	60 pages	Expert	Architectural and Annotated Photographs	Graphically Driven Booklet	Educational	Inspire and Advise
Your Climate Smart Living Guideline	Moreton Bay Regional Council	16 pages	General Public	Architectural and Annotated Photographs	Graphically Driven Booklet	Educational	Advise
Next Generation Home Guideline	Moreton Bay Regional Council	11 pages	General Public	Architectural and Annotated Photographs	Graphically Driven Booklet	Educational	Advise
Naturehoods | Your Backyard and Outdoor Spaces Guideline	Moreton Bay Regional Council	15 pages	General Public	Architectural and Annotated Photographs	Graphically Driven Booklet	Educational	Advise
Q Design Manual	Queensland Government	40 pages	Expert and General Public	Annotated Photographs	Graphically Driven Booklet	Strategic / Marketing	Inspire
Warm Temperate Climate Building Design Guidelines	Toowoomba Regional Council	32 pages	Expert and General Public	Architectural and Annotated Photographs	Graphically Driven Booklet	Educational	Advise
Key Design Principles	Gold Coast City Council	9 pages	Expert and General Public	Annotated Photographs	Graphically Driven Booklet	Strategic	Inspire
Sunshine Coast Design	Sunshine Coast City Council	238 pages	General Public	Annotated Photographs	Graphically Driven Booklet and Interactive Online	Strategic / Marketing	Inspire
Cool Homes for the Sunshine Coast	Sunshine Coast City Council	20 pages	General Public	Architectural and Annotated Photographs	Graphically Driven Booklet	Educational	Advise
Sunshine Coast Design Principles	Sunshine Coast City Council	Online	General Public	Videography	Interactive Online	Educational	Advise and Inspire

Table 3: Content analysis of **climate resilient** design guidelines published by Southeast Queensland Local Government Authorities and Queensland State Government

Guideline Name	Published By	Document length	Audience	Graphic Style	Structure	Purpose	Strategy
Flood Smart Buildings Guidelines	Moreton Bay Regional Council	11 pages	General Public	Architectural and Annotated Photographs	Graphically Driven Booklet	Educational	Advise
Design Guidance for Flood Resilience Homes	Queensland Government	17 pages	General Public and Expert	Architectural	Graphically Driven Booklet	Educational	Advise
QRA Bushfire Building Design Guideline	Queensland Government	71 pages	Expert	Architectural and Technical Drawings	Graphically Driven Booklet and Drawing Set	Educational and Technical Information	Advise and Direct
Cyclone Resilience Building Guideline	Queensland Government	48 pages	Expert	Annotated Photographs and Technical Drawings	Report	Technical Information	Direct
How to improve flood resilience for homeowners	Brisbane Sustainability Agency for Brisbane City Council	Online	General Public	Videography	Interactive Online	Educational	Advise
Bushfire resilient Design Guidelines	Gold Coast City Council	36 pages	Expert and General Public	Architectural and Annotated Photographs	Graphically Driven Booklet and Technical Drawings	Educational and Technical Drawings	Advise and Direct
Flood resilient design Guidelines	Gold Coast City Council	36 pages	Expert and General Public	Architectural and Annotated Photographs	Graphically Driven Booklet and Technical Drawings	Educational and Technical Drawings	Advise and Direct
Guideline for improving flood resilience for new development: a selection of case studies.	Sunshine Coast City Council	34 pages	Expert	Annotated Photographs and Technical Drawings	Report	Technical Information	Direct

Guideline for improving flood resilience for existing development.	Sunshine Coast City Council	82 pages	Expert	Annotated Photographs and Technical Drawings	Report	Technical Information	Direct

5. Discussion: Developing methods for measuring impacts of design guidelines in Australia

There are some general observations that can be drawn from the findings presented in Tables 2 and 3. Most guidelines fulfil the purpose of providing education to building owners and users. The educational nature of design guidelines for climate responsive design can be understood as an attempt by local and state governments to address the information asymmetry of building legislation, such as the NCC, especially in relation to energy efficiency and climate resilience (Enker & Morrison, 2020). To ensure compliance with this legislation, community buy in is essential and the benefit of regulation must be abundantly clear to users and owners. Guidelines for health campaigns have historically achieved this through complementary awareness and advertising campaigns (Aro & Absetz 2009). Most Australians would be familiar with campaigns such as "Slip Slop Slap" and "Life Be It". These campaigns successfully translated guidelines, informed by scientific research, to a general audience. While these messages might be reductive, their cur through is evident of their success. Keeping it simple. Herein lies the fine line to walk between engaging and accessible messaging and getting the right information out there (Aro & Absetz 2009).

Applying a method of simple messaging is demonstrated via City of Moreton Bay's suite of guidelines; Your Climate Smart Living Guideline, Next Generation Home Guideline, Naturehoods - Your Backyard and Outdoor Spaces Guideline, and Flood Smart Buildings Guidelines. What distinguishes these guidelines from the others is that they are by far the shortest documents. Each document has a specific focus for a building type which is targeted at a general audience. Interestingly, these documents have avoided detailed information about local microclimate and have directly presented climatic design principles without any detailed context. The success of these guidelines can be measured via their external recognition. They have won several awards, including commendations from the Planning Institute of Australia, the Australian Institute of Architects and the Department of Energy and Public Works Minister's Urban Design Awards. The next phase of this research will be to quantify their impact by collating data on engagement through download metrics and social media engagement.

In contrast to the Moreton Bay approach, documents such as QDesign published by the Queensland Government, Sunshine Coast Design and Key Design Principles published by Gold Coast City Council go into great detail about the local climate. These documents tie in culture, lifestyle and other qualitative elements of the climate to communicate a narrative about place and city making designed in response to a specific climate. In particular, Sunshine Coast Design is published as a bright yellow book, ready to be used as a marketing tool for the region's undoubtedly enjoyable climate and natural environment. However, the efficacy of this strategy and how it translates the public's attention to designing for climate and climate resilience is yet to be determined by the same methods outlined above.

Guidelines focused on climate resilience strategies, which respond to a specific climate event—flood, bushfire, and cyclone—tend to be published by the State Government. This is potentially because of the more technical nature of these guidelines and the risk of contravening with state or federal based building legislation (such as the NCC, AS1684, or the Queensland Development Code). There is the exception of flood design guidelines which were published by Sunshine, Gold Coast and Brisbane City Council. One reason for this might be that flood impact is varied from each location, catchment and river or waterway system. In saying that, the technical information contained in these documents is similar in nature, only the preamble and contextual information around flood impacts on each region or city were place specific. In general, climate resilience design guidelines were aimed at a professional audience and consisted of technical information and drawings that would require oversight from a builder or built environment professional to effectively execute. This suggests that if stakeholders were to be surveyed or interviewed as part of subsequent research, it would be pertinent to direct questions about the success of climate resilience guidelines to built environment professionals while climatic design guidelines could be assessed by a broader general audience.

One strategy for flood resilient design guidelines stood out from the others and this was produced by Brisbane City Council. The "How to improve flood resilience for homeowners" published by the Brisbane Sustainability Agency for Brisbane City Council is an example of council creating an external agency to engage with the community. This is a common strategy in Australia (Aulich, 2009). Where public or industry trust in government produced guidelines is low, rebranding as an independent agency can assist in building community trust. This approach also relinquishes organisations from onerous governmental communications oversight and control. In addition to publishing through an external agency, these guidelines are one of only two in the region studied that are published through an online interface with short explainer videos and interactive online content. The other interactive online guideline is the Sunshine Coast Design Principles. The "How to improve flood resilience for homeowners" online guidelines provides all of the technical information of the other flood resilient design guidelines but this is presented alongside videos that explain technical information to the general public. Probably the most beneficial outcome from this approach is that live data on the number of people and how they engage with content on this website can be collated. For the next stages of this research, this data will be very useful, in comparison to static guidelines that are published as PDFs and posted online, where only data on the number of downloads can be ascertained.

6. Conclusion

This conference paper has presented a snapshot of a larger research project focused on creating more effective design guidelines. The purpose of this paper was to test a framework for content analysis of climatic design and climate resilience guidelines. One of the findings from this content analysis framework was the benefit of keeping communications simple. Short, targeted information for specific building types that communicates how to design for climate and climate events, without excessive context or microclimate data resonates with the public and industry. There is a fine art to distilling complex science, ensuring technical rigour and addressing contextual nuance while creating a streamlined, accessible document. It is also important that design guidelines specifically address their target audience. Future research will investigate data on engagement by collecting information from local authorities on how people have accessed these tools and utilised them. It will also look at demonstration projects that directly relate to these guidelines as examples of engagement with these tools.

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Key factors affecting the implementation of integrated project delivery for sustainable construction

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Abstract: Integrated Project Delivery (IPD) is an approach that integrates people, systems, business structures, and practices into a process that collaboratively utilises the skills and opinions of all project participants to enhance sustainability through waste reduction. IPD aims to minimise waste in construction projects, improving sustainability, health and safety, cost, schedule, and quality and address the trust issues in the construction industry by attempting to promote a positive collaboration based on mutual respect. Though numerous literatures are available on IPD, an in-depth analysis of the barriers to IPD has never been conducted. This study addresses this research gap and aims to present the barriers to IPD in detail. A systematic literature review (SLR) was conducted using four databases and key publishers- Scopus, Emerald, ScienceDirect and International Group for Lean Construction using the keywords "integrated project delivery" and "challenges". Additional searches using synonyms such as "barriers" and "obstacles" were conducted; the keywords yielding the highest results were selected, and every paper was examined to identify either explicit or implicit mention of IPD barriers. The SLR identified 222 barriers to IPD globally. The barriers were grouped into themes and separated as primary codes. The themes include Legal, Financial, Technological, Cultural/Organisational, Collaboration and Communication, and Governmental/Political. The barriers are displayed using VOSViewer to visualise the co-occurrence of factors. The implications of this research will aid researchers and industry practitioners in understanding existing barriers comprehensively and identifying the most frequent barriers to IPD for sustainable construction in the global context.

Keywords: Integrated project delivery; challenges; barriers; obstacles

1. Introduction

Integrated Project Delivery (IPD) is slowly gaining recognition as a choice of project delivery. The American Institute of Architects (AIA) describes IPD as a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively utilises the skills and opinions of all project participants to enhance project results, increase value to the owner, reduce waste, and maximise efficiency through all stages of design, fabrication, and construction (AIA, 2007). IPD leverages early contributions of expertise and knowledge through the application of new technology, enabling all project participants to reach their highest potential while expanding the value they provide throughout the project lifecycle. However, IPD presents challenges for the project team, and its implementation is not easy (Naismith et al., 2016).

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 476 - 489.

2. Methodology

A systematic literature view was conducted to identify all existing barriers to IPD in the literature using four databases and key publishers, such as Scopus, Emerald, ScienceDirect and International Group for Lean Construction (IGLC). The step-by-step procedure is detailed below:

1. A broad search for “Integrated Project Delivery” was conducted.
2. The search results were narrowed down using the keywords “Integrated Project Delivery” AND “Barriers” OR “Challenges” OR “Obstacles”.
3. Relating to the research question, another search was carried out using the keywords "Integrated Project Delivery" AND "Stakeholders".
4. Inclusion criteria: (A) Articles with keywords “Integrated Project Delivery” or related synonyms such as “Relational Contracting” or “Collaborative Contracting”. (B) Articles with keywords “Barriers” OR “Challenges” OR “Obstacles” AND “Integrated Project Delivery”. (C) Articles with keywords "Stakeholders" AND "Integrated Project Delivery".
5. Exclusion criteria: (A) Articles without keywords “Integrated Project Delivery” or related synonyms such as “Relational Contracting” or “Collaborative Contracting”. (B) Articles without keywords “Barriers” OR “Challenges” OR “Obstacles” AND “Integrated Project Delivery”. (C) Articles without keywords "Stakeholders" AND "Integrated Project Delivery".
6. The search results of "Integrated Project Delivery" AND "Barriers" OR "Challenges" OR "Obstacles"; and "Integrated Project Delivery" AND "Stakeholders" had many shared articles.
7. A total number of articles selected was 128, of which 66 had either explicitly or implicitly mentioned barriers.
8. All identified barriers were grouped into themes such as Collaboration and Communication (CC), Cultural/Organisational (CO), Financial (F), Governmental/Political (GP), Legal (L) and Technological (T).
9. A PRISMA chart for the systematic literature review is shown below.

Search engine	Keywords	Results
Scopus	"Integrated Project Delivery"	613
	"Integrated Project Delivery" AND "Barriers" OR "Challenges" OR "Obstacles"	154
	"Integrated Project Delivery" AND "Stakeholders"	114
Emerald	"Integrated Project Delivery"	435
	"Integrated Project Delivery" AND "Challenges"	392
	"Integrated Project Delivery" AND "Stakeholders"	347
ScienceDirect	"Integrated Project Delivery"	373
	"Integrated Project Delivery" AND "Challenges"	289
	"Integrated Project Delivery" AND "Stakeholders"	277
IGLC	Integrated Project Delivery	64
	Integrated Project Delivery Barriers	0

Figure 1: SLR search results.

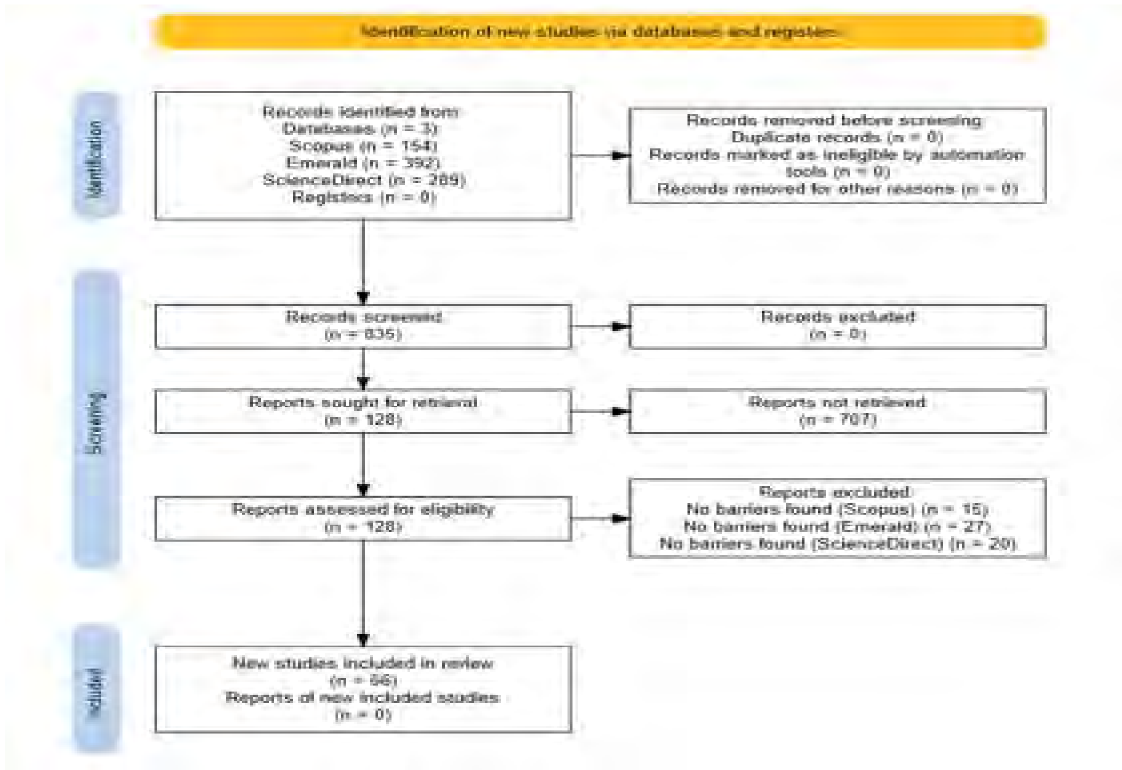

Figure 2: PRISMA chart for the SLR process.

3. Results

Two hundred twenty-two barriers were found from the 66 articles selected. Ninety-five of the 222 barriers were related to others; hence, those barriers were combined, and 127 were identified through this review. Table 1 details all 127 barriers, themes, sample author references, and total authors who identified the barriers.

Table 1: Barriers to IPD.

Barriers	Barrier theme	Sample Author(s) references	Identified by
Lack of CC among construction stakeholders	CC	Durdyev et al. (2019), Ma et al. (2022)	27
Lack of integration of key stakeholders	CC	Kahvandi et al. (2019), Osman et al. (2017)	17
Lack of transparency	CC	Charlesraj and Gupta (2019), Hettiaarachchige et al. (2022)	6
Self-protective approach	CC	Sherif et al. (2022), Sherif and Abotaleb (2023)	5
Poor transmission through all phases of the project	CC	Hettiaarachchige et al. (2022)	4
Mutual respect & trust	CC	Roy et al. (2018)	3

Achieving actual joint project control	CC	Rodrigues and Lindhard (2021)	2
Challenging cultural paradigms	CO	Naismith et al. (2016), Dalui et al. (2021)	50
Lack of IPD awareness/knowledge among stakeholders	CO	Forero et al. (2015), Alqahtani et al. (2022)	45
Resistance to change	CO	Li and Ma (2017), Karasu et al. (2022)	28
Inherent difficulties in changing organisational culture	CO	Zhang et al. (2018), Zuber et al. (2019)	15
Client's / owner's resistance to change	CO	Naismith et al. (2016), Govender et al. (2018)	13
Awareness and willingness about IPD among owners	CO	Khanna et al. (2021), Jadidoleslami et al. (2022)	11
Early contractor involvement	CO	Sherif et al. (2022), Ma et al. (2022)	9
Interoperability	CO	Azhar et al. (2015), Ghassemi and Becerik-Gerber (2011)	9
Participation	CO	Chalesraj and Gupta (2019), Sherif and Abotaleb (2023)	8
Lack of partnering as a tool for achieving lean construction performance	CO	Sari et al. (2023)	7
Owner not identifying advantages	CO	Govender et al. (2018), Karasu et al. (2022)	7
Lack of effective information sharing	CO	Elghaish et al. (2020)	6
Lack of responsive decision-making regimes	CO	Elghaish et al. (2020)	6
Lack of coordination in managing the project	CO	Kahvandi et al. (2018), Psomas and Alzraiee (2020)	6
Future orientation	CO	Sherif and Abotaleb (2023), Sherif et al. (2022)	5
Integration of information and knowledge management systems	CO	Charlesraj and Gupta (2019), Roy et al. (2018)	5
Inculcating the values of IPD	CO	Korb et al. (2016)	5
Lack of promotion of IPD	CO	Forero et al. (2015), McDonnell (2015)	5
Assigning project leadership	CO	Naismith et al. (2016)	4
Attitude-related barriers	CO	Evans et al. (2021)	4
Business risk	CO	Naismith et al. (2016)	4
Difficulties in converting strategic decisions to operational levels	CO	Zhang et al. (2020)	4
Inefficiency in resource planning	CO	Hettiaarachchige et al. (2022)	4
Industry participants lack chances to receive IPD-related training	CO	Ma et al. (2022)	4
Lack of leadership and uncertainty of risk involved	CO	Naismith et al. (2016)	4
Lack of trained professionals	CO	Naismith et al. (2016)	4
Lack of existing training material	CO	Hettiaarachchige et al. (2022)	4
Lack of organisational communication	CO	Hettiaarachchige et al. (2022)	4
Lack of owner involvement	CO	Gomez et al. (2018)	4
Lack of constraint analysis and planning process	CO	Gomez et al. (2018)	4
Lack of proficiency and strong management of the employer	CO	Kahvandi et al. (2018)	4
Lack of familiarity of contractors with IPD approach	CO	Kahvandi et al. (2018)	4

Lack of a standard way to measure the degree of design integration	CO	Ma et al. (2022)	4
Lack of a standard way to measure the whole life cycle project quality	CO	Ma et al. (2022)	4
Lack of proper definition of responsibilities of each party to the contract	CO	Kahvandi et al. (2018)	4
Lack of proper definition of the culture of teamwork among project key stakeholders	CO	Kahvandi et al. (2018)	4
Lack of sufficient knowledge about design and construction and maintenance among representatives of the employer	CO	Kahvandi et al. (2018)	4
Lack of experience and skills	CO	Khanna et al. (2021)	4
Lack of interest to upgrade	CO	Khanna et al. (2021)	4
Lack of lean knowledge	CO	Tillmann et al. (2012)	4
Logistical challenges	CO	Dossick et al. (2013)	4
Mindset of individuals	CO	Khanna et al. (2021)	4
Partner selection	CO	Su et al. (2021)	4
Poor data transfer among different phases of a project	CO	Kahvandi et al. (2018)	4
Project objectives-related barriers	CO	Evans et al. (2021)	4
Signing of participants' task scope	CO	Su et al. (2021)	4
Setting of incentive plans	CO	Su et al. (2021)	4
Structure for facilitation	CO	Bilbo et al. (2014)	4
The effect of a weak matrix structure	CO	Kahvandi et al. (2018)	4
Unclear responsibilities of the parties	CO	Hettiaarachchige et al. (2022)	4
Different criteria for services procurement	CO	Azhar et al. (2015)	3
Early definition of target goals without a fully developed design	CO	Roy et al. (2018)	3
Project management	CO	Azhar et al. (2015)	3
Risk allocation mechanism	CO	Azhar et al. (2015)	3
Subjectivity in measuring quality	CO	Roy et al. (2018)	3
Work processes	CO	Azhar et al. (2013)	3
Developing high quality design	CO	Ebrahimi and Dowlatabadi (2019)	2
Lack of industry-wide standardisation	CO	Kent and Gerber (2010)	2
Lack of experience in new roles	CO	Abdirad and Dossick (2019)	2
Making sound and timely decisions	CO	Ebrahimi and Dowlatabadi (2019)	2
New approach takes time	CO	Charlesraj and Gupta (2019)	2
Selecting the right team	CO	Ebrahimi and Dowlatabadi (2019)	2
Understanding the cross-functional organisational approach	CO	Laurent and Leicht (2019)	2
Institutional inertia	CO	Rowlinson (2017)	1
High initial investment	F	Evans et al. (2021), Hettiaarachchige et al. (2022)	8
Profit pooling – paying profits after all project works are completed	F	Elghaish et al. (2020)	7
Insurance products designed for IPD are not widely available	F	Ma et al. (2022), Kent and Gerber (2010)	6

Lack of fair IPD compensation models	F	Elghaish et al. (2020)	6
Compensation structure	F	Hettiaarachchige et al. (2022)	4
Hard pricing	F	Elghaish et al. (2020)	4
Seeking for the lowest cost	F	Zhang et al. (2018)	4
Inventory cost	F	Hettiaarachchige et al. (2022)	4
Lack of an accurate cost estimation methodology	F	Elghaish et al. (2020)	4
Lack of coordination for the compensator for F losses	F	Kahvandi et al. (2019)	4
Lack of a standard way to ascertain the credit rating/worthiness of a company	F	Ma et al. (2022)	4
Misunderstandings in risk contingency accounting	F	Elghaish et al. (2020)	4
The high F cost of new software and equipment	F	Hettiaarachchige et al. (2022)	4
The client needs to pay for the additional cost of drafting a new agreement for IPD	F	Ma et al. (2022)	4
The client needs to pay additional design fees due to time and material-based compensation	F	Ma et al. (2022)	4
Cost estimation challenges	F	Elghaish and Abrishami (2020), Seed (2014)	3
Reward not tailored to reflect the stochastic nature of the risks involved	F	Ma et al. (2023)	3
Difficulties in achieving F transparency	F	Rodrigues and Lindhard (2021)	2
Relative capital investment	F	Sherif and Abotaleb (2023)	2
Lack of transparency in spending done by the contractor	F	Charlesraj and Gupta (2019)	2
Lack of governmental support	GP	McDonnell (2015), Evans et al. (2021)	15
Lack of professional bodies	GP	Li and Ma (2017)	2
Contractual L aspects	L	Ibidapo et al. (2017), Alinezhad et al. (2020)	36
Lack of insurance policies and bonding arrangements	L	Ahmed et al. (2021), Bilbo et al. (2014)	22
Lack of existence of similar IPD contracts	L	Hettiaarachchige et al. (2022), Bilbo et al. (2014)	8
Lack of legislative regulations	L	Zhang et al. (2018), Ma et al. (2022)	8
A requirement of the new L framework	L	Hettiaarachchige et al. (2022), Roy et al. (2018)	7
Data sharing (contractual)	L	Ahmed et al. (2021)	7
Dispute resolution (contractual)	L	Ahmed et al. (2021)	7
Liabilities and indemnification (contractual)	L	Ahmed et al. (2021)	7
Risks and incentives (contractual)	L	Ahmed et al. (2021)	7
Selection of compensation and incentive structure	L	Sherif et al. (2022), Ghassemi and Becerik-Gerber (2011)	7
Suspension and termination (contractual)	L	Ahmed et al. (2021)	7
Application of IPD principles with no standard contract agreement	L	Gomez et al. (2018)	6
Lack of suitable liability waivers between stakeholders	L	Elghaish et al. (2020)	6

Expert contract administrators	L	Sherif et al. (2022), Sherif and Abotaleb (2023)	5
Implementation of strict rules, policies and regulations	L	Sherif and Abotaleb (2023), Sherif et al. (2022)	5
Contract signing	L	Su et al. (2021)	4
Deciding framework for contractual renegotiations	L	Naismith et al. (2016)	4
Inappropriate contractual strategies	L	Hettiaarachchige et al. (2022)	4
Non-availability of suitable IPD contracts	L	Khanna et al. (2021)	4
The tendency to use conventional contractual methods and resistance against new ideas	L	Kahvandi et al. (2018)	4
Unclear contract terms and objectives	L	Zhang et al. (2018)	4
Uncertainty of risk involved in multi-party contracts	L	Naismith et al. (2016)	4
Current construction rules and regulations	L	Li and Ma (2017)	2
Differences in contracting methodology	L	Mulholland and Clevenger (2018)	2
IPD contract types are not tested or understood	L	Charlesraj and Gupta (2019)	2
Lack of governmental incentives, policies, regulations or L frameworks	L	Evans and Farrell (2022)	2
No dispute resolution clause	L	Charlesraj and Gupta (2019)	2
Signing a contract with no hierarchical structure (IPD's organisational structure)	L	Buk'hail and Al-Sabah (2022)	2
Lack of usage of T advancements (ex. BIM)	T	Ebekozien et al. (2022), Rosayuru et al. (2022)	70
Availability of adequate Information Technology (IT) infrastructure	T	Naismith et al. (2016), Osman et al. (2017)	15
Governmental payment procedure, which entails T advancement	T	Alqahtani et al. (2022)	5
Industry participants' IT skills are insufficient	T	Ma et al. (2022)	4
Lack of Information and Communication Technology usage	T	Azhar et al. (2015)	3
BIM and IPD integration challenges	T	Elghaish and Abrishami (2020)	2

CC contains seven factors, with the most repetitive being lack of CC among construction stakeholders (27 author references) and lack of integration of key stakeholders (17 author references). CO contains sixty-four factors, with the most repetitive being challenging cultural paradigms (50 author references), lack of IPD awareness/knowledge among stakeholders (45 author references) and resistance to change (28 author references). F contains twenty factors, with the most repetitive being high initial investment (8 author references), profit pooling – paying profits after all project works are completed (7 author references), insurance products designed for IPD are not widely available (6 author references) and lack of fair IPD compensation models (6 author references). GP contains two factors, lack of governmental support (15 author references) and lack of professional bodies (2 author references). L contains twenty-eight factors, the most repetitive being contractual L aspects (36 author references) and lack of insurance policies and bonding arrangements (22 author references). T contains six factors, with the most repetitive being lack of usage of T advancements (ex. BIM) (70 author references) and availability of adequate IT infrastructure (15 author references). Using the text mining functionality of VOSViewer, all barriers were uploaded to the software in a text document to visualise the co-occurrence of factors. The result from VOSViewer is shown below:

Figure 3: Key barriers to IPD implementation shown in VOSViewer.

4. Discussion

This SLR aimed to detail the barriers to IPD and display the connectivity between factors. The results of SLR are shown in Table 1, and the connectivity of factors is offered through the VOSViewer visualisation diagram. The VOSViewer identifies and connects the most common barriers to IPD from the total 222 barriers found in the SLR. The results from VOSViewer group the barriers into five colour categories indicating the connections between the factors. Additionally, the link between barriers reveals the strength of the relationship- the thicker the connection, the stronger the relationship between those barriers. The barriers in red are contractor involvement, incentive structure, contractual, contractual L aspect, arrangement, compensation, uncertainty, policy, L, cultural paradigm, resistance, BIM, and usage. The barriers in yellow are lack, project, key stakeholder, advantage, contract, existence, coordination, and contractor. The barriers in green are IPD awareness/knowledge, stakeholder, mistrust, collaboration, communication, owner, IPD method, integration and willingness. The barriers in blue are risk, liability, time, law, client effect, sufficient practical experience, industry participant, and individual company's interest. The barriers in purple are governmental support, industry, knowledge, and promotion. It is also pertinent to know that the larger the font of a barrier, the more significance it has. The barriers in the red colour category can be categorised into cultural paradigms, resistance- either because of contractual L aspects, F matters such as compensation or incentive structure, or BIM usage required. The barriers in yellow can be categorised into a lack of several essential requirements- it is clear that lack is the largest font out of all the barriers displayed. In particular, the lack of coordination between key stakeholders and the lack of an existing IPD contract seem to be significant barriers. The barriers in blue can be categorised into a lack of sufficient practical experience regarding IPD, individual interests of project stakeholders, and risk and liability being major barriers to capturing a client's interest in implementing IPD. The barriers in green can be categorised into a lack of IPD awareness and collaboration issues- specifically, a lack of communication and mistrust between project parties. Finally, the barriers in purple can be categorised into a lack of governmental support and a lack of promotion of IPD. In all literature related to barriers to IPD, almost always barriers have always been divided into themes such as L, F, CO, CC, T and GP. In the CC theme, lack of CC among construction stakeholders and lack of integration of key stakeholders are the most significant barriers- it is clear that for IPD to be implemented, key construction stakeholders must improve on CC. In the CO theme, the key barriers are challenging cultural paradigms, lack of IPD awareness/knowledge among stakeholders, and resistance to change. These three key barriers in CO have interconnectivity in the sense that because of a lack of IPD knowledge, key construction stakeholders are resistant to change from their traditional practices, and this causes challenging cultural paradigms in the bigger picture.

In the F theme, high initial investment, profit pooling – paying profits after all project works are completed, insurance products designed for IPD are not widely available, and lack of fair IPD compensation models are the notable barriers. This indicates that key project stakeholders must be prepared for the costs required in implementing IPD and develop mutual trust among themselves through fair compensation models and paying profits. The GP theme has short and clear barriers- lack of governmental support and lack of professional bodies. The limitation is obvious in the sense that governments have to step in to increase the implementation of IPD- creating professional bodies that overlook the IPD process would be a good start. The L theme has contractual L aspects and lack of insurance policies and bonding arrangements as the noteworthy barriers. It is pertinent to note that different countries have different L requirements. As such, countries should make an effort to accommodate IPD in contracts and encourage its implementation through insurance policies and bonding arrangements. Finally, the T theme has a lack of usage of T advancements (ex. BIM) and availability of adequate IT infrastructure as the significant barriers. For IPD to be successfully implemented, organisations must upgrade their IT infrastructure and use the latest technology.

5. Conclusion

In summary, the barriers to IPD can be grouped into 6 themes- CC, CO, F, GP, L and T. CO contains the largest number of barriers, followed by L, F, CC, T and GP. The top 7 barriers to IPD (more than 20 author references) are: (1) lack of usage of T advancements (ex BIM), (2) challenging cultural paradigms, (3) lack of IPD awareness/knowledge among stakeholders, (4) contractual L aspects, (5) resistance to change, (6) lack of CC among construction stakeholders, and (7) lack of insurance policies and bonding arrangements. The results from VOSViewer have displayed the key barriers affecting the implementation of IPD among the 222 barriers found in the SLR. Thus, industry practitioners and academics could focus on these key barriers and develop solutions to overcome them. The practical implications of this study include individual attention and careful consideration of each barrier, along with a solution-focused framework to aid in eliminating these key barriers one by one. The theoretical implications of this study will be to come up with solutions to all key barriers to increasing the implementation of IPD. A major research gap is the interlinks between barriers to IPD that impacts its implementation.

5.1 Limitations

The limitations of SLR include risks of bias, such as selection bias, publication bias, attrition bias and selective outcome reporting. Articles published in less-known databases and those not in English may have been excluded. However, the SLR process overcomes these limitations.

5.2 Future studies

This study is a building block for researchers to focus on solving critical barriers to IPD implementation. As the barriers have been narrowed down to the most significant ones, this study should motivate researchers to focus solely on the solutions that will have a greater impact on the practical implementation of IPD in the global construction industry. Additionally, future research can study the interconnectivity and interlinks of barriers to IPD and their impact on its implementation in the global construction industry.

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This abstract was double blind peer reviewed within the conference practitioner stream. No conference paper was reviewed in this presentation

Let's Play Together
The Role of Positive, Creative & Collective Practices towards Building Adaptation.

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We would like to share a short film clip at the conference that documents our initiatives over the past year (c.6 minutes), that you can view here:
https://vimeo.com/manage/videos/855289738

Abstract: Throughout 2022-23 Watershed (cultural cinema & creative technology centre) have been working with George Lovesmith, an architect & socially-engaged artist on plans to adapt their building for the Climate Emergency. Watershed leads within its communities with a proud activist agenda and has set ambitious Zero Carbon 2030 commitments. Housed in a heritage structure where building operations form the majority of it's carbon emissions, the challenge is immense.
Integral to this endeavour are creative methods for coming together as an alliance of building users, staff, creatives, activists & visitors, demonstrating the value of creative practices (e.g. events, games, storytelling, play, metaphor, gratification, imagination, collective learning, reciprocating, entertaining…)
This is bringing people into partnership to address the challenge, establishing shared understandings of building retrofit principles. This isn't a purely technical challenge – Indeed the endeavour is intentionally re-framed as transdisciplinary, and inherently creative, because the way things are currently getting done internationally isn't working and has insufficient urgency. & because as an arts organization, addressing the climate emergency isn't only about technical solutions, it's about collective expression and welcoming people on board.
The practice and research have hinged around: -a recognition that design proposals are more successful if clients/users/others are invited to invest expertise, understandings, creativities and desires in the processes - testing the educational value of commoning – mutually engaging those same clients/users/others in design processes & - a belief in the net gain to society of increased critical design appreciation and a wider-spread ability to contribute to improvements of our built environment.

Keywords: Climate Emergency Retrofit, Creative Building Reuse, Green Public Heritage, Socially Engaged Creative Practice

Leveraging digital technologies for façade renovations

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Abstract: Digital tools have significantly influenced the design and construction of new objects and buildings, offering a broad range of specialties, including computational modelling for analysis, design, and optimization, as well as advanced manufacturing processes. These emerging digital technologies are gradually transforming the field and revolutionizing the way we approach design and construction. While their benefits for new building designs are well-documented, their application for retrofitting existing buildings remains relatively unexplored. This research aims to investigate the potential benefits of employing digital workflows for the analysis, reconfiguration, and optimization of existing facades. Building upon the case study of the 'F10 – New Law Building' at the University of Sydney, the design team, in collaboration with the Sydney Law School and Sydney Infrastructure leveraged multiple digital technologies to analyse the existing facade, evaluate various design options, and identify the most effective solutions. The process involved a quantitative and qualitative analysis and leveraged the use of shoebox analysis utilizing parametric models, multivariable optimization considering factors such as daylight, radiation, glare, and view factor, an online questionnaire to gather valuable feedback from building users and establish performance priorities, a user-centric design approach employing virtual reality to assess the visual impact of potential design solutions and their potential impact on occupants' well-being. This paper presents the proposed research methodology and implementation of the holistic data-driven design approach and meaningful engagement with simulation data and its communication to a wide range of key stakeholders using VR technologies.

Keywords: Virtual Reality, project assessment, performance simulation, data-driven design.

1. Introduction

Nowadays, the use of novel digital technologies and digital workflows has been successfully integrated across numerous industrial sectors. However, the systematic uptake of these technologies in the industry of Architecture, Engineering, and Construction (AEC) has been notably slow and fragmented in comparison. It is widely acknowledged that digital tools and workflows allow us to improve design, optimisation, and production stages, enabling better management of resources and ultimately leading to more sustainable outcomes. The case studies illustrating the implementation of the new tools predominantly focus on the use of novel digital technologies for the design and construction of new buildings, while their application for the retrofit of existing buildings is significantly underexplored. There is a growing interest in addressing this gap to support the effective use of resources and create a better understanding of how to improve the management and retrofit of the existing building stock to

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 492 - 507.

achieve the Sustainable Development Goals (SDGs) (SDG Goals, 2023) and reach ambitious sustainability targets set for 2050 (Taylor, 2021).

The overarching aim of this research project is to develop a methodology that uses a wide range of digital technologies (Caetano et al., 2020; Krstić-Furundžić et al., 2019; Khajavi et al., 2019), commonly adopted for the design of new buildings, that can be employed for retrofit interventions. These digital technologies include digital simulations and optimisation, digital fabrication, and implementation of interactive Virtual Reality (VR) applications. In this paper, we present the implementation of digital technologies for the retrofit of an existing façade of the 'F10 – New Law Building' at the University of Sydney where the industry partner collaborated with the Sydney Infrastructure and Sydney Law School to evaluate various design options and identify the most effective solutions. The digital workflow integration process involves both quantitative and qualitative analysis as a holistic iterative approach (Ali et. Al., 2021). It leveraged the use of parametric models, multivariable optimization, and an online post-occupancy questionnaire gathering valuable feedback from building users and establishing key performance priorities. The adopted user-centric design approach employed for Virtual Reality (VR) applications aimed to communicate the results of quantitative analysis to the key stakeholders and broader audiences as well as assess the visual impact of potential design solutions and their potential impact on occupants' well-being (Zhong et. al., 2022).

This paper presents the implementation of the digital data-driven design approach and meaningful engagement with simulation data and using VR technologies to engage with different stakeholders to allow for engaging co-design and collaborative decision-making. The methodology discussed in this paper was developed through literature reviews, the study of precedents from the construction industry, and industry and academy collaboration. This study primarily focused on examining workflows and employed an innovative approach to assess and expand design decision-making. Consequently, due to its specific scope and objectives, there was a deliberate limitation on investigating various aspects of background, built environment relevance, and economic/resource analysis, which fell outside the study's defined parameters. The digital workflow, methodology and tools implemented in this research present an effective design-to-implementation pipeline that could be successfully deployed in future façade retrofit projects and beyond.

2. Research Methodology and Approach

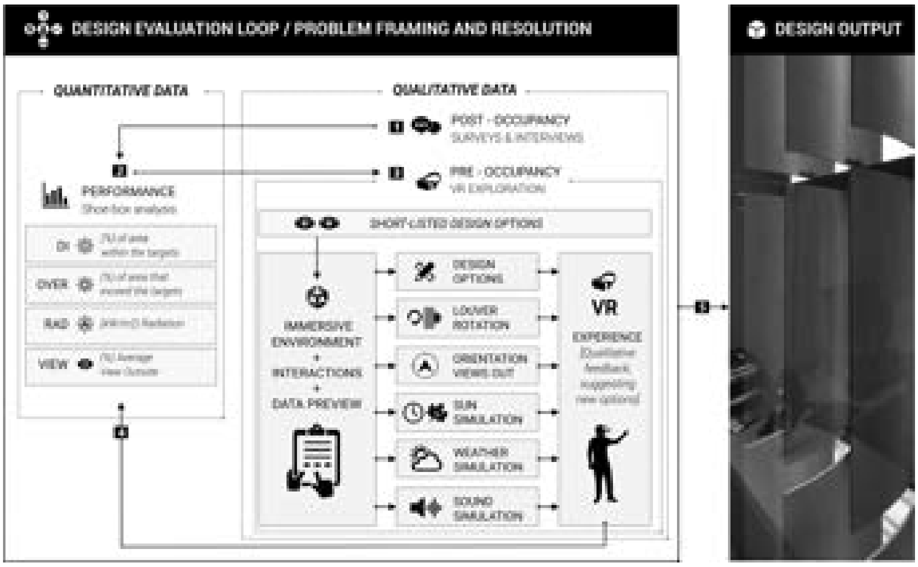

Figure 6: Design evaluation loop: Qualitative and Quantitative Data

The proposed design and implementation methodology followed a holistic approach aimed at equally balancing and optimizing both the quantitative performance and the qualitative aspects (Moloney et.al., 2020), as illustrated in Figure 1. The design evaluation loop developed for this project involved several iterative investigations. These included:

[1] Post-occupancy surveys and interviews/ that aimed to engage with the existing building occupants. This user perception analysis allowed us to gain a better understanding of the use of the space and identify key design indicators that clearly described occupants' preferences and priorities.

[2] Performance simulation included parametric modelling and shoebox analysis of different facade design options and configurations. The multi-variable optimization was carried out to help identify a set of best-performing design solutions.

[3] Virtual reality application was developed to not only allow stakeholders to experience alternative design options to assess the visual impacts of the possible design solutions but also to visualise and communicate the quantitative metrics associated with each design configuration.

[4] Additional analysis was carried out for the design options suggested via VR user engagement.

[5] The design pre-production studies also engaged with early-stage prototyping through 3D printing, where façade components were digitally fabricated to test different fixings mechanisms.

2.1. Post-Occupancy Survey

The Post-Occupancy Evaluation (POE) survey was carried out to better understand the key qualities and parameters of the existing indoor spaces. The data obtained from 37 respondents allowed us to identify the hierarchy of the design criteria, based on what the occupants perceived to be of high importance in their workplace. The results of the survey also helped to validate the design assumptions in relation to the shading systems and the use of space patterns. The survey engaged with such criteria as level of visual and thermal comfort; frequency and reason for the use of operable external louvres and internal roller blinds; and priority between such design factors as access to view, daylight quantity, protection from glare, level of privacy and thermal comfort.

Results of the study indicated that the average user valued access to view and daylight the most. Interestingly the level of privacy in the working space was not perceived as a high priority. Different façade configurations proved to affect the scores for 'access to view' and 'thermal comfort'. The findings suggested that the West-facing offices were more subjected to poor visual comfort conditions. On the other hand, the East-facing offices were prone to overheating. This meant that the design assessments for different orientations should focus on different priorities and parameters. POE allowed us to establish the ranking of the design factors based on the user's perceptions. This data also informed the multivariable optimization, which was undertaken at the back of the shoebox parametric modelling.

2.2. Performance Analysis

2.2.1. Design Parameters

The findings of the POE survey helped to establish design parameters for the multivariable optimization (Castillo et. Al. 2019) and helped to balance the priorities for competing design criteria (Vazquez & Walker, 2021; Mishra, 2022). As a result, the parametric design models (Caetano et al., 2020) and design variables aimed to maximize daylight and outside visual connection (sky view factor) and minimize glare and solar heat gains to reduce overheating (East façade in particular) (Figure 2). The design parameters were then further prioritized to reflect design goals, favouring criteria that only depended on the design of the façade shading system over those that could be mitigated with other strategies, such as the use of internal roller blinds.

2.2.2. Shoebox Analysis

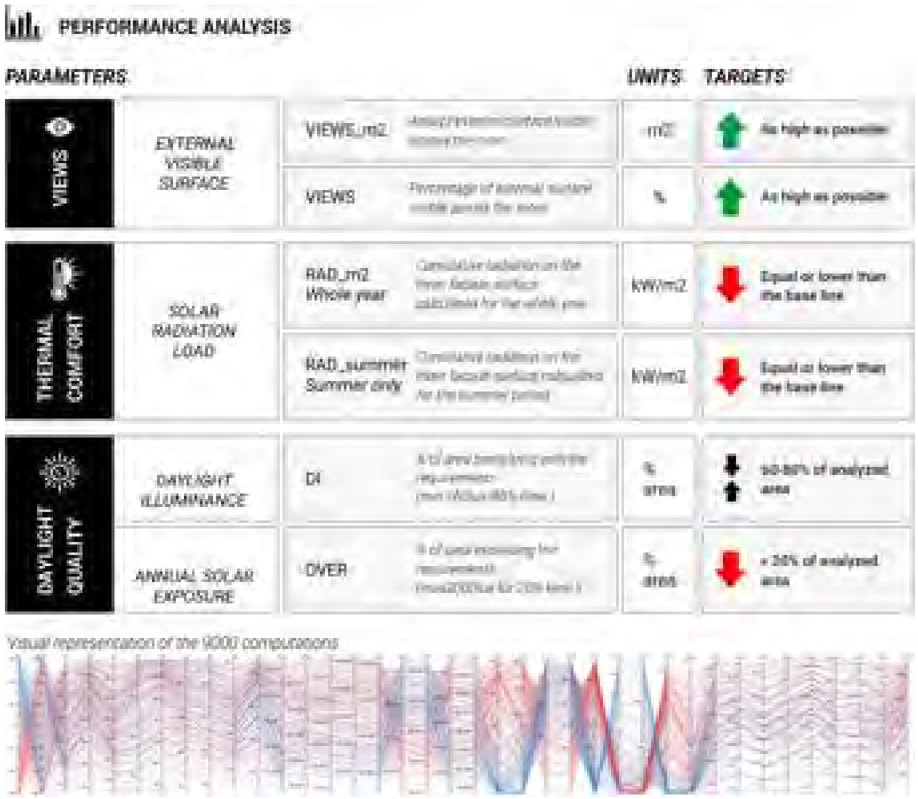

Figure 2: Performance Analysis / Computation Results

To avoid repetitive calculations and make simulations more time-effective, the analysis focused on a set of typical rooms (9 options), representative of the main offices and collaboration spaces in the building. The selection of the rooms considered such factors as orientation (W/E/SE); overshadowing from both the building itself and nearby buildings; and the size of the room (single offices and collaborative spaces). Figure 2 illustrates the key quantitative parameters, units and targets established for this project. These included the 'Views' category, which was calculated for the area (ViEWS_m2) and percentage (VIEWS) of the external surface visible across the room. This parameter was aimed to be as high as possible. 'Thermal Comfort' was calculated for cumulative solar radiation on the inner façade surface for the whole year (RAD_m2) and for the summer period (RAD_summer), with resulting values aimed to be equal to or lower than the baseline. The baseline was calculated by undertaking a survey of the existing façade. Lastly the 'Daylight Quality' was evaluated using Daylight Illuminance (DI) and Annual Solar Exposure (OVER) parameters. The former metric was aimed to be between 60-80% of the area complying with the min16olux/80%time requirement and the latter was aimed to be <20% of the area exceeding the max2000lux/20%time requirement.

3. Design and Implementation of VR Application

The VR application was developed to meaningfully integrate both quantitative and qualitative evaluation metrics into the process and allow stakeholders to explore different façade options in an immersive and engaging way. It should be noted that while numerous existing studies previously used VR for pre-occupancy evaluation and decision-making, there has been limited integration of performance simulation results within a combined VR solution (Schiavi et. al., 2021, Tseng, 2022; Globa et al., 2022).

3.1. VR Development

Several alternative ways to produce an immersive 3D environment were explored for this project. As this was a retrofit project, it was possible to capture and modify the existing built environment, including both interior and exterior spaces, which is not an option when dealing with new buildings. The following alternative VR scene development approaches could be considered for creating VR applications for retrofit projects: creating scenes using 3D modelling software; 3D scanning with photogrammetry (Polycam, 2023), 3D scanning with laser scanning (LiDAR) (Leica BLK360 Imaging Laser Scanner, 2023); and using 360 photography (360-degree camera RICOH THETA, 2023). Table 1 details the pros and cons of using each approach. For our project, we have adopted the 3D modelling approach using Rhino (2023), mainly due to the design requirement of being able to easily modify the lighting and texturing of the VR scene. However, as noted in the table, different projects might benefit from alternative 3D VR scene development approaches. The VR scene integration was implemented with Unity (2023). The development workflow consisted of two stages: scene content creation and programming behaviours and functionality. The soundtracks for the VR environment were recorded in the actual building and were added to the environment based on the simulated time of day and weather conditions.

The 3D modelled geometry from Rhino was arranged in a structured hierarchy to allow effective behaviour programming and then imported into the Unity software as mesh objects. The 3D geometry was optimized for the best performance and appearance. The follow-up application of materials and visual effects was done directly in Unity. Various scene objects such as books, pictures, monitors, and furniture were imported from Unity assets (Unity Asset Store, 2023) and other online repositories. Façade elements/prefabs were configured and tested for accurate louvre rotation to enable realistic interactive façade system simulation in VR (Figure 3).

Table 9: Comparison between alternative VR scene development approaches.

Approach	Pros	Cons
3D modelling	Ability to freely create/modify 3D geometry Ability to better control texturing and detailing	Time and resource-heavy approach
Photogrammetry	Outputs textured 3D mesh. Easy-to-use and affordable	Low accuracy for certain geometries and scales. Difficulty processing reflective surfaces. All mesh surfaces will be connected. Not separate objects. Hard to edit textures and geometry. Hard to change lighting conditions, materials, etc.
LiDAR	Outputs textured 3D mesh High-accuracy equipment available in the market Most of the latest mobile devices support this technology	High-end long-range scanning might require expensive equipment Difficulty processing reflective surfaces. All mesh surfaces will be connected. Not separate objects. Hard to edit textures and geometry. Hard to change lighting conditions, materials, etc.
360 Photography	Easy-to-use and affordable Fast VR development pipeline available.	Navigation only through teleportation. Hard/impossible to map design interventions Hard/impossible to change the lighting conditions, materials, etc.

The Unity scene used mixed lighting settings. The static 'backed' lighting was implemented to allow better performance and visual quality. The dynamic 'real-time' lighting and shadows were implemented to generate sun movement, simulating different times of the day. The sun simulation was developed with the SunLight tool (2022). The 'post-processing' behaviours and effects were applied to the main camera in the VR scene to portray different times of day, seasons, and weather conditions more realistically. The 'views' parameter was identified as of high importance during the POE survey, therefore the accurate simulation of views outside of the office window was an important part of the VR scene development, aiming to create a feasible and believable representation of dynamically changing views without. A 360-panoramic view image map with the alpha channel enabled was used, allowing a dynamic change in the sky and the ground colours while retaining the realistic representation of surrounding buildings and green spaces. (Figure 3).

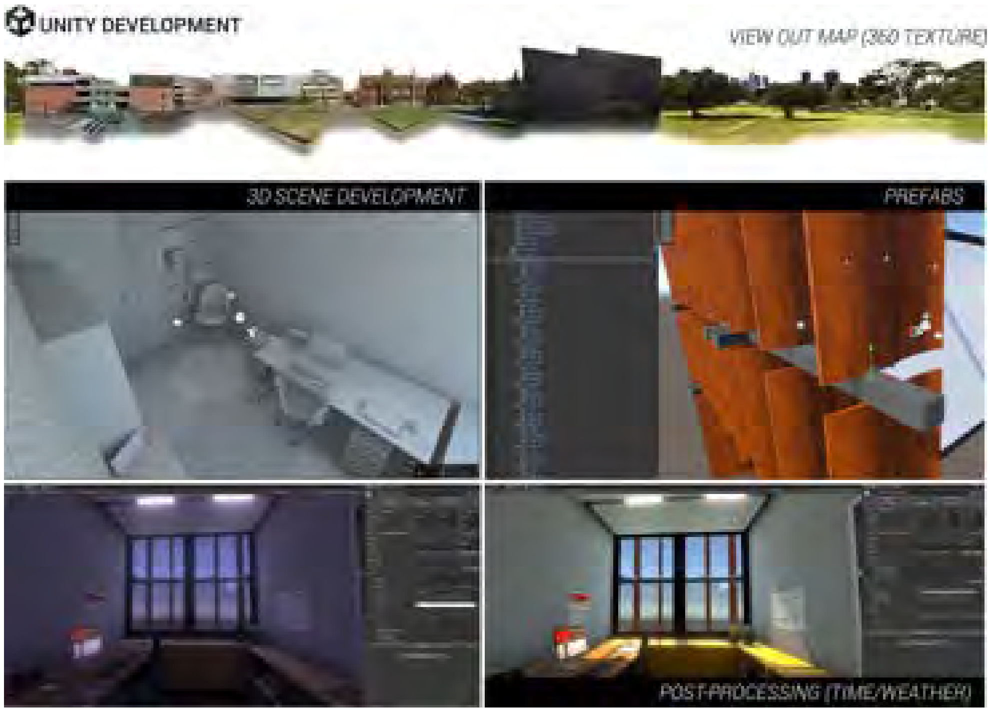

Figure 3: Unity Development Pipeline

3.2. Integration of Quantitative Data into VR

The VR environment was introduced to the digital workflow to allow the experience of both tangible and intangible aspects of the simulated office space and façade elements visible through the office windows. VR allows users to explore the interior space of the office the space through a range of dynamically changing external and internal conditions, engaging with visual, audio, and kinaesthetic human senses (Globa et al., 2022). The results of the performance analysis for views, solar radiation, daylight, and over parameters (Figure 3) were integrated into the VR User Interface (UI). The values for each short-listed design option were visualised and dynamically changed when the user switched between design options. In the current VR application, the numbers for the quantitative parameters were input directly into Unity as pre-defined values. Future research might explore an opportunity to allow certain values to be calculated on the fly.

3.3. VR Functionality

UI was implemented as a hand-held panel with values and buttons, attached to the left-hand controller. The right-hand controller was used as a laser pointer via the index finger trigger (Figure 4). Different UI versions were developed for the night-time and day-time conditions to better suit different visibility settings in the scene. The functionality of the VR environment allowed users to switch between ten shortlisted design options, to assess best-performing louvre rotation configurations that were suggested by the performance analysis. In addition to pre-defined façade configurations, the user could also rotate the louvres freely (from -90 to +90 angles) to explore custom configurations that were outside of the shortlisted design range.

Figure 4: Mapping Performance Metrics into VR Environment and Interface

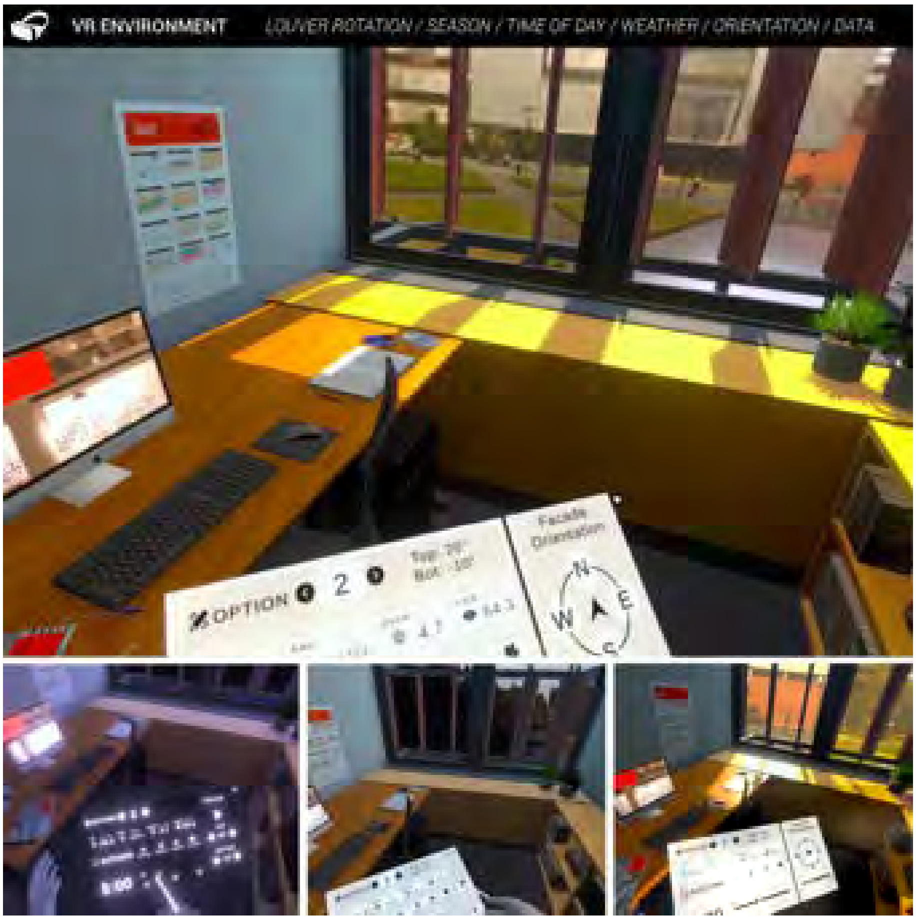

Figure 5: Simulation of weather and sunlight in VR

It was possible to switch façade orientation to West-facing, East-facing, North-facing, and South-facing; or to rotate the office at any custom angle. The rotation of the office happened relative to the 'world center' of Unity, which meant that the sun's position and sunlight direction, as well as the views-out, were adjusted accordingly. The system allowed users to explore light and shadows in real-time (SunLight, 2023), switching between the four seasons: summer, autumn, winter, and spring; and navigating between different times of day using sliders. The weather conditions simulation enabled us to test the sunny, cloudy, and rainy conditions, which affected the views, colour temperature and amount of incoming sunlight. Figure 5 illustrates the sunny conditions during different times of day, indicating where the shadows and glare would occur (top and bottom right images). The figure also shows the example of a nighttime view and cloudy weather conditions during the day (bottom left and center respectively).

4. Integration of the Collaborative Decision-Making Approach

The VR prototype was implemented in practice as a part of the real-world decision-making process for the façade retrofit development. Two Meta Quest (2023) headsets and large screens, on which the VR camera view was projected were used for both collaborative decision-making sessions (Figure 6). The screen projections allowed all participants to see what the person in VR was doing and seeing, making the process more inclusive and engaging. The VR implementation allowed different stakeholders including, designers, architects, building occupants and management to experience a wide range of design options, weather, and light conditions. This building is currently occupied by the Sydney Law School academics, professional staff and students, and it is expected to continue its current use in the future. It made it possible for both experts and non-expert participants to compare performance analysis data by combining the quantitative and qualitative aspects of design evaluation. The VR environment integration enabled the design team to employ a user-centric collaborative decision-making approach.

Two collaborative sessions were conducted for this project, each targeting different stakeholder groups. The first VR session involved academics, project managers, designers, and consultants. The second collaborative VR session involved building management and senior members of the Sydney Law School. It also included a wider range of academic and administrative staff that currently occupied the building. All involved stakeholders had an integral role in the decision-making for the façade re-design project. Each session took about 2 hours – that included iterative VR experiences and follow-up discussions and consultations. In this project, the use of VR had many direct and indirect benefits for all parties involved.

Firstly, it allowed a connection between the design process, which is often driven by the designers' and architects' views on performance and aesthetics, to the end user and final stakeholders. The design process became more ‘democratic’ and allowed the designers and consultants to provide the end client with the information necessary to contribute to the decision-making process.

A fundamental aspect of this collaboration lies in the real-time feedback loop established by VR-driven decision-making. Stakeholders could actively participate and offer immediate input during the early design stages, resulting in refined and tailored solutions that resonate more effectively with the stakeholders' needs and expectations.

Secondly, a broad inclusivity that ranges from architects to client senior leadership, ensures a diverse range of perspectives are considered, enriching the collaborative process, leading to more well-rounded and comprehensive design outcomes, and de-risking the project delivery process for the design team and end client.

In general, the use of the interactive data-driven VR application allowed a reduction of time, cost and resources spent to generate visual and performance mock-ups. At scale, this approach can contribute to the transition towards a more optimised and less carbon-intensive AEC sector.

Lastly, this collaborative approach allowed the University of Sydney Infrastructure Department, which manages the University building assets, to engage with the research/academic section of the University and test first-hand the active research streams, while directly benefiting from it. The feedback from the department strongly indicates that all involved stakeholders found significant value in engaging with immersive VR and performance simulation technologies, with the implemented methodology being a cost-effective approach, that is worth to be implemented for future projects.

Figure 6: Consultations with key stakeholders of the design project using VR application.

5. Discussion and Future Work

5.1 Multi-Sensory Simulations in VR

Digital VR technology and workflow provide unique opportunities for the architecture and built environment sectors by enabling fully immersive life-like experiences. It opens doors for virtual pre-occupancy and collaborative decision-making. Yet, its current uptake in the field remains relatively limited predominantly focusing on new development or research applications. Current VR applications also mainly focus on visual experiences, which is extremely limiting. To further enhance the sensory immersive experiences in VR we enabled the soundscape (spatial sound) of the VR scene to dynamically change with the associated weather and time of day variables. In the scene, the sound of the rain was activated when the user chose rainy weather conditions using UI. Different daytime and night-time soundtracks were switched during and after working hours.

There is a growing interest in incorporating soundscapes, touch, and thermal experiences for VR in various fields. Latest advancements in wearable scent technology could provide unique potential to extend the sensory palette of VR experiences further to include a sense of smell. This could be particularly useful when testing different biophilic design options and vegetation alternatives. The next stage of this project will explore the incorporation of digital smell simulation using the OVR technology (2023). Figure 7 shows the Ion smell simulation device and spatial smell simulation in the Unity scene. The ethics application was updated and approved to include the incorporation of the sense of smell in VR to be tested for two scenarios. One revolves around façade retrofit design and pre-occupancy evaluation, and another includes an interactive change of furniture and materials of the office room, as well as the integration of various biophilic design features, such as indoor plants, green facade, and nature-inspired soundscapes.

Another future offshoot of this project is planned to investigate the value of using brain activity analysis (Emotiv, 2023), motion, and behaviour tracking, as well as the eye-tracking and facial expression interpretation capabilities of VR systems (Pico 4 pro, 2023). This would allow us to gather more comprehensive data on user responses and interactions with spaces. As a result, it could potentially lead to a deeper understanding of user preferences for design options and architectural spaces and allow to engage with new ways to inform the decision-making process using various digitally recorded metrics.

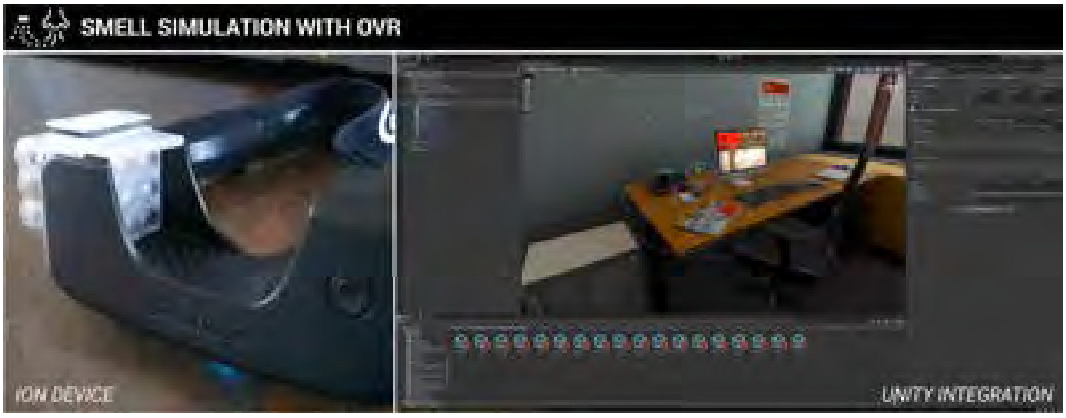

Figure 7: Simulation of Smell in VR (implemented with the OVR technology)

5.2 Future industry/academia collaboration

This study demonstrates how the dynamic partnership between academia and industry holds immense potential to redefine how we understand, analyse, and optimize architectural designs before they become tangible spaces. The lessons learned from this project have laid the foundation for collaborations between Campus Infrastructure, research and industry partners that have the potential to shape the way the University of Sydney campus is designed, built, and operated.

Benefits of VR-drive collaborative decision-making include early detection of potential design flaws, and optimization of spatial configurations and user experiences, ultimately reducing costly post-occupancy revisions and rectifications. On the other side, future studies will aim at establishing standardized evaluation metrics and frameworks for assessing the effectiveness of immersive VR experiences in pre-occupancy studies.

As this partnership evolves, the architecture field will be at the forefront of a paradigm shift that redefines how we conceptualize and create spaces, ultimately leading to more functional, aesthetically pleasing, and user-centric built environments. The next steps of this research will investigate integrating acoustic and thermal comfort, combining the use of VR with a climatic chamber, and optimising/automating the workflow that now is scattered across multiple platforms with limited compatibility.

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Live data-driven digital twin approach for assessing social and environmental building performances in high-rise mixed-use developments: a conceptual framework and evaluation of the operational platforms for its implementation.

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Abstract: As the demand for socially responsible practices in the built environment industry increases, incorporating social considerations within building performance evaluation becomes essential. Current building performance evaluation approaches predominantly emphasise environmental performance, lacking a comprehensive understanding of the interplay between social and environmental performances. This paper proposes and explores a conceptual framework for developing a digital twin-enabled approach that facilitates a holistic assessment of building performance, focusing on the interplay between social and environmental performances. The presented framework provides a foundation for developing a digital twin-enabled tool that captures various building performances through live data collection. The paper discusses the underlying technology, data availability, and methods for data collection and incorporation. To demonstrate the applicability of the conceptual framework, an assessment of digital twin operational platforms was conducted. This research addresses challenges in modern building performance evaluation, such as limited scope and focus, insufficient data collection and analysis, and lack of longitudinal studies. This approach integrates performance metrics from various social and environmental assessment methods to contribute towards a more holistic and dynamic understanding of building performance, emphasising the importance of integrating social performance in building performance evaluation and fostering more sustainable, occupant-centric built environments.

Keywords: Digital Twin; Digital Twin Operational Platform; Building Performance Evaluation; Post-Occupancy Evaluation.

1. Introduction

Recent international effort in adopting more socially considered practices has resulted in an apparent shift across various sectors, including Architecture, Engineering, Construction, and Operation (AECO) (Samuel et al., 2020; Raiden and King, 2022). This transformation has been particularly noticeable in

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Building Performance Evaluation (BPE) systems such as LEED, BREEAM, and GREEN STAR, which were previously centred mainly on environmental and economic performances but are now expanding to incorporate a social occupant-centric dimension (Atanda and Öztürk, 2020).

This expansion in scope has facilitated the integration of tools like Social Return on Investment (SROI), Post-Occupancy Evaluation (POE), Life Cycle Assessment (LCA), and Cost-Benefit Analysis (CBA) into BPE systems (Clark, 2019). These tools are becoming indispensable in assessing a building's comprehensive performance; however, incorporating social and occupant-centric metrics into BPEs has particular challenges that slow the wide adoption of these new tools as an integral part of BPE (Fujiwara and Dass, 2020).

Most of these challenges are data-related, specifically regarding the collection of real-time data, data processing, analysis, and visualisation; with each introducing additional layers of complexity (Watson et al., 2016). If these challenges are left unaddressed, they will suppress the effective integration of social considerations into BPE systems, limiting the overall progress towards more holistic building assessments (Goldstein, Glueck and Khan, 2011).

Digital Twin (DT) technology, which incorporates technologies like the Internet of Things (IoT), Machine Learning (ML), Cloud Computing (CC) and other data analytical tools, presents a possible solution to these data-related problems (Wang et al., 2022). However, the practical application of DT technology for assessing building performance is still in its early stages. The industry currently lacks theoretical and practical implementations (Shahzad et al., 2022). This paper presents a conceptual framework for developing a DT-enabled tool for assessing social and environmental building performances of high-rise mixed-use urban development in the Australian built environment context and evaluating the operational platforms for its implementation.

Six DT operational platforms were evaluated based on user scenarios, specifically testing available commercial products for suitability based on end-user needs. This study showcases how different user scenarios can benefit from the adoption of various platforms, each requiring different levels of complexity, development and preparational work to perform DT-enabled building performance assessment.

As part of a bigger Australian Research Council (ARC) linkage project, this paper presents a framework as a first step towards developing the DT-enabled tool for assessing social and environmental building performances in high-rise mixed-use urban housing.

2. Background

This section summarises relevant background information for applying DT technology for social occupant-centric and environmental building performance assessment; briefly outlining the current state of building performance assessment tools, current challenges, and the application of DT technology for such assessment.

2.1. Evolution and challenges of building performance systems: shifting towards social considerations.

In recent years, BPE has experienced notable changes with various sustainability assessment systems now embracing the social aspects of sustainability in their evaluation criteria (Clark, 2019). Frameworks such as BREEAM, Green Star, LEED, CASBEE, and SBAT have started considering the social impacts on the community alongside economic and environmental performance (Atanda and Öztürk, 2020). Such changes highlight a noticeable shift in the building performance evaluation paradigm, putting occupants' experience at the forefront; however, these frameworks lack a holistic analytical and data processing approach to measure the social aspects, which delays the adoption of a comprehensive assessment of the social performance of buildings (Oberfrancová and Wollensak, 2021).

Among long-existing assessment systems, new tools like the WELL Building Standard have emerged, which are predominantly focused on the social dimension, considering factors like the health and well-being of building occupants (GBCA, 2017). The WELL Building Standard encompasses diverse categories known as 'concepts' such as Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind, and Community (WELL V2, 2022), while Green Star Performance focuses on Management, Indoor Environment Quality, Energy, Transport, Innovation, Water, Materials, Land Use and Ecology, and Emissions (Green Star Performance, 2022). This emphasis on social aspects, particularly in the WELL Standard and Green Star, underscores the importance of occupant-centric considerations. Despite the similarities of some categories between these two assessment tools, the WELL Standard predominantly focuses on the social aspects, whereas Green Star focuses on the environmental aspects of building performance (Atanda and Öztürk, 2020).

Integrating both environmental and occupant-centric assessment metrics like thermal comfort and indoor environment satisfaction linked to corresponding environmental building performances offers a comprehensive view of a building's social performance (Hosamo *et al.*, 2023b). Although all categories covered in WELL Building Standard are crucial for a comprehensive understanding of a building's social performance, the satisfaction and experiences of occupants, especially in areas like thermal comfort, air quality, and visual and acoustic comfort, remain central to the social performance within buildings (Seminara *et al.*, 2022). These factors are influenced by environmental conditions like temperature, CO2 levels, and noise and play a critical role in determining the quality of life and well-being of those using the spaces (Altomonte *et al.*, 2020).

Assessing the social performance of the built environment presents several challenges and practical limitations, mainly related to data collection and analysis, data availability, and stakeholder collaboration (Li, Wang and Hong, 2021). The assessment of social building performance requires quantifiable metrics and the qualitative experiences of occupants, closely linked to the indoor environment. Current approaches to assessing the social performance of a building include qualitative and quantitative surveys, for example, qualitative surveys like POE are used to understand occupants' experiences and satisfaction with building design and operation (Artan, Ergen and Dönmez, 2018). The dynamics of social performance can be highlighted by live data on elements such as thermal and acoustic comfort, indoor air quality, and visual amenities; enhancing the assessment process. This provides a deeper understanding and analysis of the social value present within the built environment (Raiden and King, 2022).

2.3. The digital twin-enabled performance evaluation tools

Digital Twin (DT) is an emerging technology that demonstrates the ability to address some applicational and technology-related challenges that BPE systems currently face (Tao *et al.*, 2018). DTs have been widely used for similar purposes in closely related design industries and recently received widespread attention in the AECO sector (Davila Delgado and Oyedele, 2021; Tagliabue *et al.*, 2021). Currently, there is a lack of a universally accepted definition of DT (Tomczyk and Van Der Valk, 2022), however within the context of this study, DT is proposed to be defined as the next generation of a digital representation of physical building assets, distinguished by its ability to communicate, analyse, visualise, and influence its physical counterpart performance in real-time, thus facilitating data-driven decision-making.

Since 2018, research on applying DT technology in the AECO sector has started to increase (Boje *et al.*, 2020). As the next technological stage in digitalising physical assets, DT is taking place along with its preceding technologies, such as BIM (Shahzad *et al.*, 2022). DT's supporting technologies like IoT, ML, CC, and Big Data offer solutions for data collection and integration, allowing monitoring devices to collect real-time building environmental performance data and position this data in relation to the building's geometry, enabling more effective data collection and processing (Khajavi *et al.*, 2019). The use of IoT technology in DT allows the creation of a robust sensor-based network that can collect real-time data about the building, which is essential for management and maintenance as well as for creating historical datasets to use in future simulations (Rodriguez Larrad *et al.*, 2018). To effectively store, process and optimise this data, DT is required to employ various data analytical technologies such as CC, ML, Deep Learning and Neural Networking. Integrating these applications into the current practice can potentially bring a user-oriented design approach to a qualitatively and quantitatively advanced level. That will help the AECO sector be more impact-aware of the final product and make better decisions based on more accurate predictions using end user's data (Al-Sehrawy and Kumar, 2021).

While the DT approach has demonstrated great potential in analysing, optimising, and predicting the future state of the physical assets across other industries, application in the AECO sector is in its earlier stages and requires further theoretical and practical research (Shahzad *et al.*, 2022). For example, the use of DTs in evaluating the social performance of buildings remains largely unexplored – the dynamic nature of DTs operation, combined with its supporting technologies, can enhance our understanding and perception of the real-time environmental and social building performances, which underlines the need for more comprehensive research and adoption of DTs for these purposes.

3. Methods

This research adopts two main approaches to address the challenges of developing a DT-enabled tool for evaluating social and environmental performances in high-rise mixed-use urban developments. First, a literature search was undertaken on research papers discussing the development of digital twins in the AECO sector. This assisted further understanding of the current state of the field and in the selection of suitable research for the project's framework development. Second, various operational platforms for DTs were evaluated based on specific user scenarios outlined in the framework. This ensured the appropriate design and level of development (LoD) of the tool to accommodate anticipated functions, aligning with the objectives set for the tool and based on the user scenarios of the case study.

3.1. Case study: U City building

As a part of a bigger ARC linkage project, this study examines the U City building in inner-city Adelaide - a 19-story 'extreme' mixed-use urban development in the CBD of Adelaide with a Six-Star Green Star energy rating. The building consists of 60 retirement residences, assisted short and long-term disability accommodation, social services hubs and commercial units for both profit and non-profit businesses as a case study (Earl, 2020; Barrie *et al.*, 2023). This case study provides various occupant data and vast environmental performance data. The building's design minimises the use of heating and cooling appliances to maintain thermal comfort, maximise natural light, and reduction of noise disturbances through strategic material choices. Residents and occupants of the U City building are an active part of the research data collection and provide this project with a vast amount of social occupant-centric data for further application in this study.

3.2 Framework for developing a Digital Twin-enabled tool for building performance evaluation

To develop a framework, a literature search and desk analysis were conducted to identify applications of the DT technology within the AECO industry and to extract detailed applications with objectives suitable for this study (Chen *et al.*, 2021; Eramo *et al.*, 2022). Subsequently, the framework was designed to integrate specific data sets derived from the WELL Building Standard version 2 and the Green Star Performance v2 metrics.

3.3. Evaluation of the operational platforms

Based on Stage One of the framework 'Conceptual Design, Planning, and Preparation', determining the right operational environment for DT is an integral step for the tool's development. This study evaluates available DT platforms based on their ability to process specific environmental data from loggers and handheld devices and occupant-centric data gathered from surveys, questionnaires, and focus groups.

This research employs the metrics from the WELL Building Standard version 2, which includes categories like Air, Light, Thermal Comfort, and Sound, and the Green Star Performance v2, with a focus on criteria from the 'Positive' and 'Healthy' categories such as Energy Use, Air Quality, and Light Quality. The environmental data comprises indoor dry bulb temperature, indoor and outdoor temperature, relative humidity, air movement, CO_2 levels, lighting levels, noise levels, and electricity consumption. For the occupant-centric aspect, we focus on thermal comfort, indoor air quality, visual comfort, acoustic comfort, and overall indoor environment satisfaction. In addition to data compatibility, the platforms were assessed based on their alignment with user scenarios, user interface design, and accessibility to ensure a comprehensive and user-friendly experience.

4. Conceptual framework

To start the development of a DT-enabled tool for evaluating building performances, a conceptual framework is presented as a first step to guide the further development of the tool. The proposed framework comprises four stages: Conceptual Design, Planning and Preparation; Data Collection & Integration; Real-Time Data Analysis & Visualisation; and Feedback & Maintenance.

4.1. Conceptual design, planning and preparation

This first stage starts with identifying Potential User Scenarios. It is crucial to determine the different user groups, such as building occupants, facility managers, and industry practitioners or researchers, with consideration to their unique objectives and tasks (Casado-Mansilla *et al.*, 2018). This stage involves defining the objectives and functionality of the DT based on the target user group, where the complexity and classification of the DT vary from a simple descriptive to a complex prescriptive model and are determined by the user group and objectives (Weber *et al.*, 2017; Fuller *et al.*, 2020; Olsen and Tomlin, 2020). For instance, in an occupant scenario, a DT-enabled tool is used primarily for visualising individuals' data about their resource consumption and various social indicators such as comfort and well-being. In this case, the model and supporting technology would require a lower maturity and LoD of the DT, focusing primarily on descriptive functionalities to visualise current performances and potentially simulate specific future performances, such as energy use or carbon footprint, based on the current trends supported by the historic data.

For scenarios tailored to research and industry practitioners, the DT-enabled tool would require a higher level of complexity, facilitating the evaluation of combined performance and analysing the correlations between different performance types. This leverages both the descriptive and predictive functionalities of the DT (Eramo *et al.*, 2022).

For the operational and facility management (FM) scenarios, the DT-enabled tool necessitates a comprehensive and detailed virtual representation of the building, encompassing all its systems. A higher maturity and LoD are required to enable predictive and descriptive functionalities, as well as prescriptive measures, fine-tuning the building's performance to align with anticipated Key Performance Indicators (KPIs) and influence the physical twin performance (Niavis, Laskari and Fergadiotou, 2022).

Once the scenario and anticipated functionalities are defined, the digital representation of the physical building using 3D modelling tools or BIM can be created. The complexity of the model needs to be based on the set objectives as defined in the user scenario stage. Besides the future DT's maturity and LoD, the data's geometrical location also needs to be considered – the model has to recognise the input and output data equipment to be appropriately linked to the building geometry. At this stage, it is advisable to identify the data collection equipment and methods to adequately prepare the model and its supporting environment to be suitable for the further integration of the data (Gourisetti *et al.*, 2023).

4.2. Data collection and integration

In the Data Collection & Integration stage, the method of collecting data from the physical object and transferring it to the DT is defined. This involves integrating environmental building performance metrics by utilising various data-capturing tools, such as loggers, meters, and sensors. These devices monitor temperature, humidity, CO2 levels, air quality, lighting, and noise levels, allowing for the primary collection of real-time data. Concurrently, social data are routinely gathered through multiple focus groups, online surveys, questionnaires, and activity reports. These social insights are timestamped to align with corresponding environmental performance metrics at specific moments. Once this data is assimilated into the DT environment, it is further processed in the subsequent stage to extract anticipated performance insights. The level of integration of the DT is also determined at this stage, which could range from lower to higher, starting with a less integrated Digital Model to a Digital Shadow and, ultimately, a fully integrated DT (Tao *et al.*, 2019). The DT's hierarchy is defined by its scale, influencing the complexity of the necessary technical infrastructure (Singh *et al.*, 2021).

4.3. Real-time data analysis and visualisation

The Real-Time Data Analysis & Visualisation stage equips the DT with relevant data. The methodology for data transfer is determined at this stage, which could involve both historical and real-time data (Sepasgozar, 2021; El Mokhtari, Panushev and McArthur, 2022). After the data is transferred, it is processed and analysed to meet specific objectives. At this stage, attention is also given to how the DT visualises data and the user interface for interaction (Hu *et al.*, 2021).

For instance, if assessing the building’s thermal performance, various environmental data such as indoor/outdoor temperature, humidity, air quality, wind speed, air flow as well as occupants’ thermal comfort reports will be collected, correlated, and presented by the digital model. This phase involves determining what type of DT is to be implemented. This could be a Descriptive type of DT, which displays the current state of the building's performance, and a Predictive Twin, which, based on the acquired data, simulates potential scenarios and forecasts the future state of the building using historical data to ensure it will perform as anticipated. Furthermore, ultimately, it could be a Prescriptive type where the DT can impact its physical counterpart to operate in accordance with previously established KPIs (Casado-Mansilla *et al.*, 2018; El Mokhtari, Panushev and McArthur, 2022). At this stage, it is crucial to deliberate on how the Digital Twin will visualise the data and its applicational user interface through which it will interact with the end users (Hu *et al.*, 2021).

In a case when the purpose of the DT is to forecast the future state of its physical counterpart; for example, for facility management, it should possess capabilities for Predictions and Simulations (Fuller *et al.*, 2020). By using both historical and real-time data gathered from the physical twin, the digital model can be trained to predict and simulate multiple scenarios. This data is then processed and analysed to detect patterns and correlations, which assists in the creation of a dynamic model capable of imitating the object's response to different conditions and predicting its future state (Schluse and Rossmann, 2016; Sepasgozar, 2021). Depending on the technical capabilities of the operational platform it's developed on, it can utilise diverse data analysis techniques, including ML and AI-based analysis.

Upon achieving full data analysis, simulation, and prediction capabilities, DT can evolve into an automated virtual system, facilitating bi-directional communication with its physical twin—applying the concept of the Prescriptive Twin (Olsen and Tomlin, 2020). At this stage, DT should be capable of operating autonomously, where it receives, displays and predicts data and influences the physical counterpart. It can prescribe actions to optimise the performance of the building based on the processed and analysed data and initially set KPIs (El Mokhtari, Panushev and McArthur, 2022).

4.4. Feedback & Maintenance

The feedback and maintenance stage is integral for the smooth functioning of DT, addressing potential challenges that may arise. The main concern at this stage is the secure storage, transfer, and management of data, ensuring that gathered information aligns with strict privacy norms without compromising the safety, security and confidentiality of the occupants. Robust security measures are vital in protecting the integrity and confidentiality of data throughout its collection, transfer, and storage phases (Niavis, Laskari and Fergadiotou, 2022). Efficient data management practices ensure data is clean, organised, and readily accessible, making regular checks and maintenance of data collection devices indispensable for precise data collection (Sepasgozar, 2021). Regular compliance assessments verify that DT operates in line with the predefined objectives and KPIs, with updates incorporated in the event of discrepancies (El Mokhtari, Panushev and McArthur, 2022). All these measures underscore the importance of privacy and safety in maintaining the operational environment where the DT functions (Olsen and Tomlin, 2020; Rafsanjani and Nabizadeh, 2023).

The proposed framework follows a four-stage approach for creating and maintaining a DT-enabled tool for BPE, presented below in Figure 1. By integrating different user scenarios, it can serve diverse user groups and enhance the understanding and application of DT technology in assessing building performances.

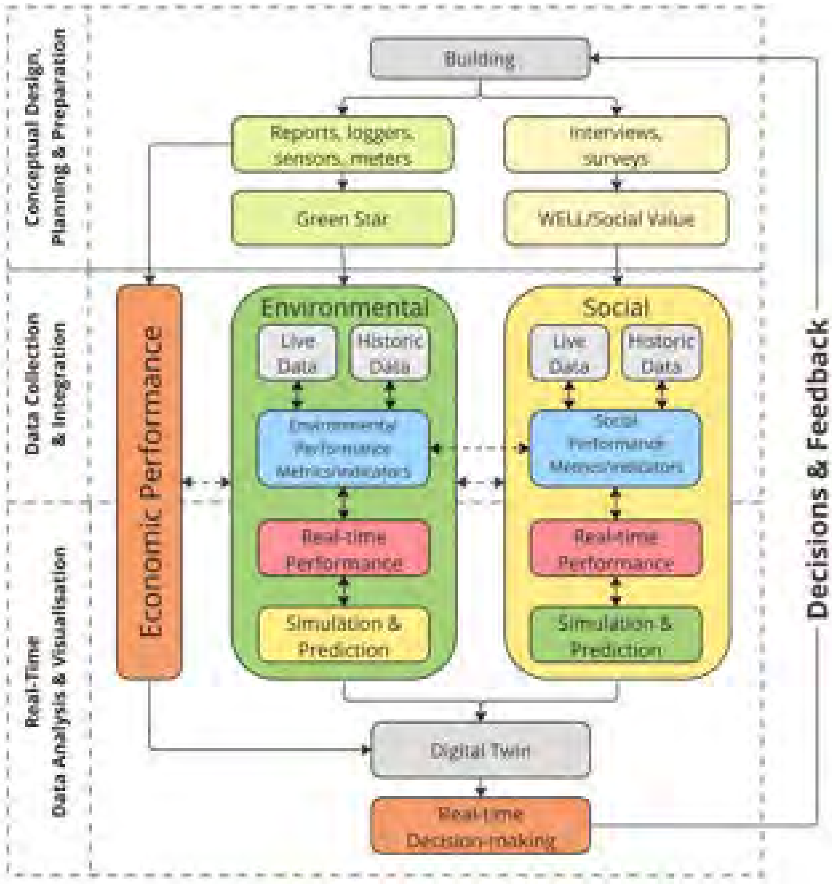

Figure 7: A conceptual framework for assessing social and environmental performances in mixed-use development through a live data-driven digital twin approach.

5. Implementation of the framework

As elaborated earlier, multiple factors have to be considered to enable efficient and feasible development of the DT-enabled tool for assessing building performance. At the beginning stage, the primary aim is to identify a suitable operational platform as the base for the DT operation. This research examined various existing platforms on their ability to work with specific environmental and social data, classifying them based on the foundational principles of the operational environment into centralised and distributed operating approaches.

Centralised systems predominantly adopt either a one-to-one or a many-to-one approach. In the context of this study, the base geometry storage under consideration is BIM. In a one-to-one centralised system, a single BIM encompasses all the spatial information about building geometry, materials and their properties, and the building operating systems and equipment and is directly linked to the DT platform. This system is represented in commercial DT platforms such as Autodesk Tandem, where DT is built upon an initial single BIM integrated from Autodesk Revit. In this context, the DT platform undertakes all data manipulations based on the information contained within the BIM, encompassing aspects like energy analysis or air ventilation performance. Such platforms are designed explicitly for designated tasks, allowing more significant interaction and integration within the designated scope. However, integrating custom datasets that are not part of the default platform design, such as data on occupant satisfaction, necessitates the incorporation of custom scripts through the Application Programming Interface (API) within original BIM software such as Revit (Hosamo *et al.*, 2023a).

Conversely, a many-to-one system hosts multiple BIMs or 3D models of the physical entity, with each model holding distinct datasets curated for specific tasks, for example, ventilation or energy models. These are unified under a single virtual environment; examples of such platforms are NVIDIA Omniverse, Unity Reflect or Unreal Engine. As single cloud platforms, they present extensive capabilities in data monitoring, software cooperation, and real-time simulation. They can connect and control multiple models, each with different functions, under one platform, providing flexibility and extended functionality within a single controlled environment. Regarding diverse data integration, these platforms demonstrate more flexibility and freedom of incorporating custom data sets, which are not limited by the default functionalities of the platforms.

In contrast, distributed systems are represented by a many-to-many approach, where the DT is built upon numerous BIM or 3D models, each situated in distinct virtual environments and dedicated to a particular function. Such platforms are Rhino 3D, with its visual programming plugging Grasshopper or Revit and Dinamo. Demonstrating the distributed approach, multiple simulations, or analysis algorithms for individual functions can be developed via these platforms, offering versatility. These platforms can operate independently or integrate into one platform depending on specific needs. Rhino and Grasshopper further distinguish themselves by having the ability to integrate with multiple single-based platforms such as Unity Reflect or Unreal Engine, showcasing adaptability in a distributive environment, therefore facilitating the accommodation of diverse environmental and social data sets.

The selection between these approaches heavily relies on user scenarios. Different scenarios necessitate variations in DT complexity and the scalability of the system. For instance, the distributed or many-to-many approach appears more suitable in an occupant scenario. This requires a lower maturity and LoD of the DT, focusing primarily on descriptive types to visualise and simulate specific performance metrics such as thermal comfort, acoustic balance, visual comfort, air quality, and occupant satisfaction. These distributed DTs can be depicted as real-time, flesh-based web pages, translating current performances online. This translation facilitates the appropriate delivery of functionality tailored to this particular user group to meet the specific objectives.

For scenarios tailored to both research and industry practitioners, it is optimal to position the DT within a centralised environment, employing a many-to-one approach. In this context, several single-function DTs can be consolidated within a singular environment, enabling the assessment of combined performance. Furthermore, this setup allows for the analysis of interdependencies between diverse performance types, which can be examined as distinct, isolated performance evaluations or as a combination. This approach effectively enables both the simulative and predictive capabilities of the DT. The comparison between different platforms is presented in Table 1.

Table 10: The comparison of the DT operational platforms.

Performance Indicator/metric	**Centralised Approach**				**Distributive Approach**	
	One-to-one	Many-to-one			Many-to-many	
	Tandem Autodesk	NVIDIA Omniverse	Unity Reflect	Unreal Engine	Revit + Dynamo	Rhino3D + Grasshopper
Environmental Green Star Performance	**Functional** Relies on initial BIM complexity	**Functional** Relies on integrating external modules	**Functional** As an operational and computational environment	**Functional** As an operational and computational environment	**Functional** Customisable modelling environment + Data integration	**Functional** Customisable modelling environment + Data integration
Social WELL Building Standard	**Limited** Will require a custom integration via API	**Functional** Relies on integrating external modules	**Functional** As an operational and computational environment	**Functional** As an operational and computational environment	**Functional** Customisable modelling environment + Data integration	**Functional** Customisable modelling environment + Data integration

Lastly, a centralised one-to-one system is suitable for operational and FM scenarios. Such scenarios necessitate a comprehensive representation of the building, encompassing all its systems. A higher maturity level and LoD are integral to enable predictive and descriptive functionalities and prescriptive measures, fine-tuning the building's performance to align seamlessly with anticipated KPIs, and enabling complex bi-directional communication between virtual and physical entities.

In addition, the User Interface (UI) requires significant consideration, given that varying user groups possess diverse technical knowledge and competencies. Accordingly, an appropriate UI is essential to ensure an optimal user experience with the tool. For instance, the tool's UI for occupants is designed mainly for visualisation, accommodating a diverse audience without necessitating advanced software knowledge. This UI should be straightforward and easy to navigate, catering to all users regardless of their technical abilities. On the other hand, the FM scenario would necessitate a deeper understanding of the DT operational platform to offer thorough analytical and operational capabilities, allowing the DT to fulfil its intended functions.

This examination underscores the importance of DT operational platform selection in harnessing the full potential of DT technology. The choice of centralised or distributed approaches should be in accordance with the user's requirements, data types and the expected objectives for the DT tool.

6. Discussion

This paper introduces a conceptual framework for developing a DT-enabled tool to evaluate building performances, along with an examination of the operational platforms for its implementation. The first part of this section delves into the application and significance of this study, while the second part addresses its limitations and directions for future research.

6.1 Application and significance

The proposed framework offers a structured approach for developing a DT-enabled tool that facilitates building performance evaluation. This framework emphasises the importance of considering user scenarios at the preliminary stage, setting the direction for the subsequent development of the DT tool. This early consideration helps determine the necessary complexity of the DT, which guides adequate resource allocation for its creation—this includes the LoD of the initial 3D geometry or BIM, the necessary data types, required equipment for data collection and storage, as well as user interface and the optimal operational platform software. The alignment of the framework with industry-building certification metrics from systems like WELL and Green Star provides practical application within the Australian built environment industry.

Exploring the operational platforms, particularly the distinction between different types of systems, clarifies further development steps. The platform choice can directly affect the DT-enabled tool's efficacy and adaptability. By allocating platforms according to user scenarios, the framework provides insights into which platform might be best suited for specific applications, aiding stakeholders in making more informed choices when leveraging DT technology in building performance assessments.

6.2 Limitation and future research

The presented research offers valuable insights into the development of a DT-enabled tool for building performance evaluations. However, it is important to outline some inherent limitations of this study. The primary limitation of this study is regarding the collection of occupant-centric social data. Gathering this type of data presents difficulties outside of a research setting, especially when considering the ethical concerns and feasibility of the data collection methods. Consequently, our study is based on a specific set of data collected through surveys and focus groups, all under the umbrella of the ARC linkage research project and adhering to ethical and privacy standards. Additionally, the study does not cover certain qualitative aspects of interior design, such as colours, textures, ergonomics, aesthetics, furniture, and artwork. While these components significantly influence a building's visual appearance and the occupant’s aesthetical satisfaction, they fall outside the scope of this research. Moreover, the framework incorporates only specific categories from WELL and Green Star, determined by available data and the project's practicality.

However, while this specific selection of assessed criteria is a limitation, the proposed framework holds potential as a foundational model for more expanded studies in the future. Including diverse settings and a broader range of occupant profiles in subsequent studies would advance the wide adoption and offer new insight into the dynamic correlation between environmental and social building performance.

From a technical standpoint, the study faces constraints related to commercial or corporate version availability of certain functionalities on specific platforms, preventing a complete examination of their capabilities. Some platforms, which were in early development or beta stages at the time of evaluation, still lack comprehensive technical guidance, creating constraints for objective evaluation. Additionally, challenges with the compatibility of data collection equipment and diverse and complex data types further add challenges to the process of integrating building performance data into DT.

Considering these limitations, future research should aim for a more comprehensive exploration of the rapidly advancing DT sector, including operational platforms and software. The wider integration of diverse environmental and social datasets should be the main focus of upcoming studies. Future investigations on addressing data collection equipment challenges and ensuring compatibility with BIM and DT operational platforms and software are desirable; for example, incorporating existing Building Management Systems via APIs to channel current performance data into the DT landscape in real-time.

In the future, applying this framework in diverse real-world situations will further validate its broader relevance.

7. Conclusion

This research addresses challenges in modern BPE and POE such as limited scope and focus, insufficient data collection and analysis tools, and lack of longitudinal studies, by introducing a framework for developing DT-enabled tools for building performance evaluation. While the application of DT technology in BPE is still in its early stages, this paper has proposed a framework for future exploration and implementation. The proposed approach integrates performance metrics from various social and environmental assessment methods to comprehensively understand building performance with incorporated end-user experience.

The current lack of standardisation in the application of DT technology and complexities in adoption presents considerable challenges. However, the preliminary findings from this research indicate substantial potential for DT technology in advancing building performance evaluation with integrated social performance. Ongoing research and experimentation are important for further advancing this multidimensional approach to contribute to the improvement of a human-centred built environment.

Ultimately, the long-term goal of this study is to develop an integrated, data-driven, and occupant-centric approach to evaluate building performance and to enable more informed and effective decision-making to guide the development of environmentally and socially sustainable built environments that contribute to the health, well-being, and quality of life of their occupants.

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Modeling of conventional timber drying using alternative methods

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Abstract: Architects are increasingly specifying sustainable solid wood products within buildings. Many specify a high degree of uniform appearance. This contrasts with standard timber outdoor yard-based air-drying processes that can result in non-uniform appearance. Timber discolouration that has resulted from the drying process leads to the discarding of a high-quality natural resource. The lower recovery rates resulting from defects significantly lower economic yields and increase reprocessing costs. The conventional rack based drying process is subject to multiple environmental factors that can cause this degradation. Rack surveys can map and reveal the location and severity of timber defects resulting from the drying process, but in some cases, it is difficult to understand the reason that certain defects happen under different drying conditions. Almost all those defects are the result of heat and moisture flows throughout the timber racks. Historically, computational fluid dynamics software has been used to simulate the drying processes, however, these tools only explore the flow of heat and not the significant changes in moisture that occurs in timber during the drying process. Recognizing this deficiency, this research explores the alternative use of hygrothermal simulation software tools to view the flow of heat and moisture through racks of drying timber located in an outdoor environment. Traditionally, these tools have been used to inform envelope design of buildings. Liaising with software developers from Germany, this research is exploring the capability of two-dimensional hygrothermal simulation tools to mimic moisture affecting discoloration patterns during the timber drying process.

Keywords: Timber; Moisture Content; Modelling;

1. Introduction:

This article explores the use of modern hygrothermal calculation methods to simulate the flow of heat and moisture through a solid wood product during the drying process. Architects, engineers and other design and construction professionals are increasingly specifying the use of timber in the construction of buildings due to concerns around sustainability and lower carbon emissions. This results in a multitude of different design types with varying uses of timber, from timber buildings with solid timber frames, through to timber-rich buildings that use timber for interior fit-outs and detailing but have a lower structural usage of the material. Current design, stylistic and market trends dictate that most processed materials used for internal fit-outs be of consistent visual quality both in color and visual consistency, timber can be an exception to this rule, as a number of studies identify that particularly in the case of timber, variance in surface colour and visual texture aligns closely with consumer preferences (Jonsson *et al.*, 2008; Nyrud and Bringslimark, 2010), and the presence of natural features

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such as knots are not always a limiting factor in consumer perceptions (Broman, 2001). Architects and other design professionals are not always educated on the specific properties of timber, resulting in the specification of materials that are not always suitable for purpose (Bysheim and Nyrud, 2008).

Where timber is used for its visual properties, it is important that the timber is free from significant visual defects such as visible staining, checking/splitting, discolouration and other visual defects that are introduced by means other than natural timber growth processes. Visual defects arising as a result of normal growth processes are seen in a more favourable light by the customer than process induced defects (Høibø and Nyrud, 2010). One major source of visual defects can be from the timber production process, where individual processes in the timber sawing and drying processes result in specific defects being inadvertently introduced to the timber.

Discolouration of timber is usually not a significant issue as it should be possible to quickly identify sources of that discoloration and correct the process to exclude that discoloration. However, in some cases, it can become a major issue where it involves unknown or seemingly unidentifiable factors. Process induced discoloration can also present as one of several different forms, as shown in Figure 8, which can be the result of conditions present in the drying process. The timber drying process usually involves the application of heat to remove moisture from timber of high moisture content (MC%). Kiln drying is one of the most commonly used methods worldwide, but in many cases, timber is still dried by racking the timber and drying under outdoor ambient conditions. In these cases, on-site climatic conditions provide the temperature, relative humidity and ventilation conditions to drive the majority of the timber drying process.

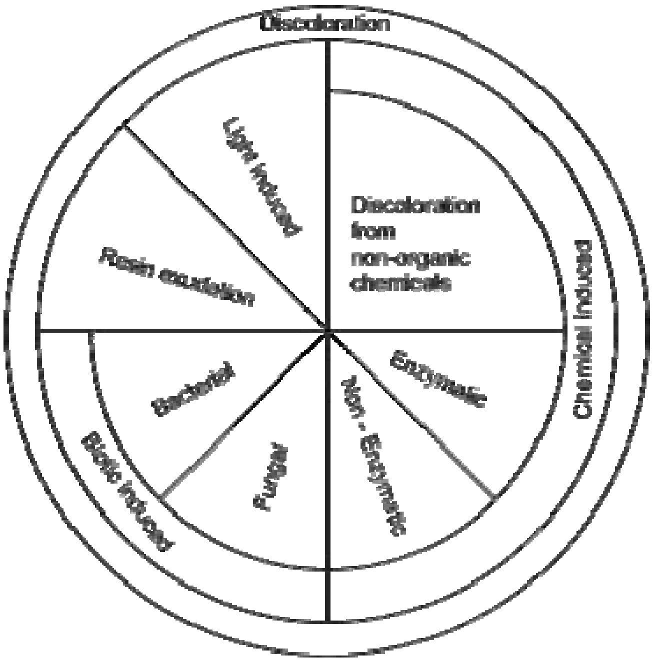

Figure 8 - Timber discoloration types (adapted from (Hon and Minemura, 2000)

The types of discoloration shown in Figure 1 can be further classified into two major types, those that require moisture to occur and those that do not require moisture to occur. In the cases where moisture is required for discolouration to occur, the drying process itself can drive that discoloration, and it may be the case that the movement of moisture through the timber can both shift chemical concentration gradients and/or accelerate chemical reactions that produce coloured compounds as a result. A question this raises then, is it possible to use standard industry available software to simulate the flow of heat and moisture during the drying process to identify the location and dimensions of any potential market limiting discolourations, and thereby simulate the appearance of discolouration patterns with drying timber?

The impetus for this investigation the ongoing problem of discolouration in Tasmanian Blackwood, *Acacia melanoxylon*, a species primarily used for its visual properties that can display several different types of discolouration resulting from an unknown source within the drying process. Currently, the scale of the discoloration problem is that several of the largest sawmill businesses that process and dry Blackwood timber are experiencing up to 30% of the timber produced is displaying market limiting discolouration. Timber that is discoloured in this way must either be re-graded as a lower value timber, reprocessed, (where possible), to remove as much of the discoloured material as possible, or discarded. Until recently, Blackwood discolouration was not perceived to be a significant problem, as most commercial uses for Blackwood involved the staining of the timber to enhance the natural colours which usually obscured any discoloration that was still visible (Lee, 2020).

Blackwood, like many other Australian species is conventionally dried in racks stored in an open-air yard after milling. This is done in preference to other drying methods as it has historically been shown to result in fewer drying defects in the final product. The incidence of different types of discolouration in Blackwood timber depends on several factors including the grain orientation, dimensions of the boards, method of drying (kiln drying, yard drying, or shed drying), and other factors.

Production of Tasmanian Blackwood is limited to 10,000m^3 per year as it is considered a specialty timber by the Tasmanian state government. The largest sawmills producing blackwood board-stock apply the conventional yard-drying method, as shown in Figure 9. This process is used to dry the green sawn logs from their fiber saturation point to a moisture content of 20%, in either an exposed yard, or under cover. The sawn timber is then further refined and dried further in a kiln to final moisture content around 12%. These methods and moisture content expectations are specified in Australian Standard 2796.1-1999 Timber – Hardwood – Sawn and milled Products specification–(Standards_Australia, 1999). Kiln drying does not appear to change the incidence of discoloration and was not a variable that was considered as part of this study. All the timber examined as part of this study were processed with exactly the same kiln drying processes.

A year-long survey timber production for one Tasmanian based timber company (not yet published) has provided a baseline dataset for analysis of the significant discolouration issue. The two sites use open-air yard drying combined with kiln drying and surface finishing to produce high visual grade timber. The two types of discolouration of most concern were ‘light’ sticker mark and ‘dark’ sticker mark as shown in Figure 10 below.

Figure 9 – Racks of timber undergoing yard-drying

Figure 10 - Blackwood timber displaying left to right - dark sticker marks, light sticker marks.

Along with several other factors, a seasonal/weather dependent effect has been identified to play a role in the occurrence of discolouration, as shown in **Error! Reference source not found.**. The figure shows the greatest incidence of discolouration occurred during the summer drying period, whilst the winter drying period showed the least presence of discolouration. Identifying the possible impact of the seasonal factors confirmed the need to explore the flow of heat and moisture through the solid wood products during the drying process.

Tasmanian Blackwood (*Acacia melanoxylon*) is a timber that has a large range of natural colours even within single trees (Bradbury, 2010), making it difficult to establish the natural colour of the timber. Further to this, sectioning and colorimetric analysis of the timber boards observed after the drying process was completed, revealed patterns of discoloration through the dried timber boards. These patterns are generally unique to the two major discoloration types, dependant on several other factors (board location in the rack, rack position in the yard, time of year board was dried, etc). As timber colour also changes naturally during the drying process, it is impossible to say exactly what the natural colour of the timber should be after drying. Further to this, under certain conditions, phenolic compounds can undergo oxidation through several mechanisms which can induce polymerisation producing more complex photochromic compounds (compounds containing more light-reactive chemical bonds showing up as colour). When present in sufficient quantities, these reactions can occur at ambient conditions (Arbenz and Avérous, 2015), which may lead to darkening of materials with high initial phenolic compounds.

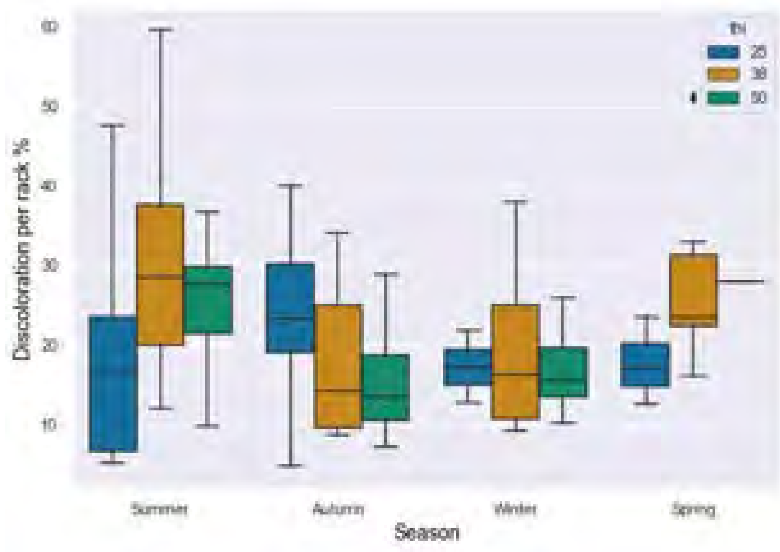

Figure 11 - Blackwood discoloration per rack by season

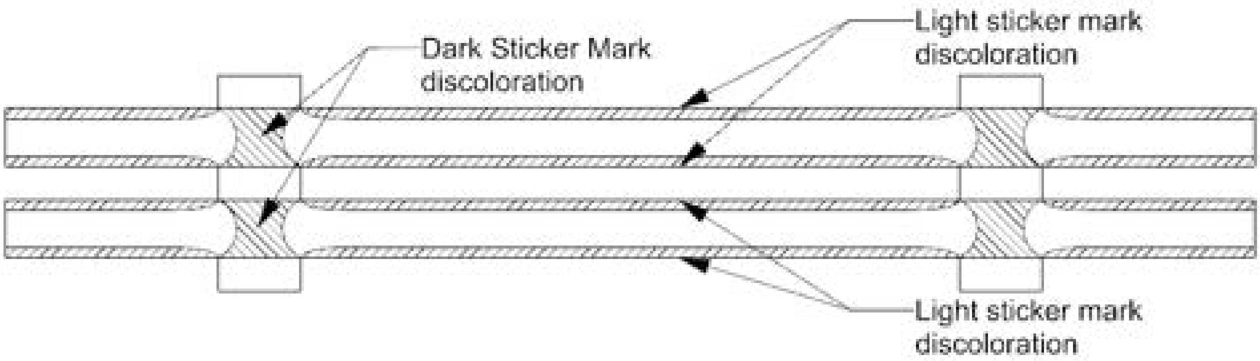

Figure 12 – Location of two types of sticker mark in Blackwood (*Acacia melanoxylon*)

In a parallel research activity chemical analysis was conducted on discoloured Blackwood samples identified in the site-based research mentioned above. This analysis was undertaken to determine whether there were significant chemical differences between the darkened and non-darkened timber. Several different methods were used to analyse the chemical compositions of the timber between discoloured and non-discoloured timber, finding a variety of different compounds (including unknown compounds), with the main conclusions being that:

> "The production of degradation products of flavonoids (colour altering compounds detected in the analysis) is driven by the combination of absorption of UV-vis light, moisture content, temperature and interaction with oxygen."
>
> "The above results clearly suggest the observed chemical differences are a result of differential rates of chemical oxidation of the wood over time. By using stickers, the protection of the wood in localized regions from UV exposure, oxygen access and differential exposure to moisture is highly likely to slow the local rate of chemical oxidation, which would result in visible differences in coloration from different concentrations of coloured oxidation products." (Nolan *et al.*, 2022)

As the results of the colorimetric and chemical analyses were indicative of the action of both heat and moisture, it was decided to use transient hygrothermal (moisture and heat) calculation methods to analyse the drying of the timber racks. It was considered that the hygrothermal simulation method may provide greater insights than the typically used fluid mechanics calculation methods. Transient hygrothermal simulation tools have been used to examine heat, moisture and mould risks within building envelopes for the last three decades. An initial analysis of hygrothermal software tools highlighted that one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) computer simulation tools were available(Nath and Dewsbury, 2019). It was quickly identified that 1D tools were not appropriate as simulation method would need to explore the flow of heat and moisture in at least two dimensions. 3D tools may provide a more comprehensive simulation method, but their relative cost made these tools unsuitable at this early stage of the research. Since 2017, the Architectural Science Laboratory at the University of Tasmania has collaborated with the Hygrothermal team from the Fraunhofer Institute of Building Physics. Due to this collaborative arrangement, WUFI 2D was selected for this stage of the research. WUFI 2D which was developed in the 1990's and has undergone significant calibration studies(Olaoye *et al.*, 2021; Nath *et al.*, 2022). However, as this research is the first of its kind, all parties agreed that further calibration may be required. The WUFI 2D software allows for the use of site measured environmental conditions (hourly air temperature, relative humidity, barometric pressure, wind speed, wind direction and precipitation) as the input climatic data, which would allow the analysis to account for not just seasonality but real-world weather events (Delgado *et al.*, 2010). This level of inputs and hygrothermal simulation results may provide further insights that might identify irregularities in the site-based data analysis that could be further accounted for. Furthermore, if the 2D hygrothermal simulation method could predict discolouration locations that matched the site observed data, an exploration of timber stacking methods and sticker types could be undertaken in an effort to reduce the occurrence of sticker mark and reduce processing losses.

Timber drying is a subject that has been studied in great depth, however there are many ways to dry timber and what is usually simulated is the most commercially profitable method which in most cases is kiln drying (Perré, 2007; Campean, 2010). Blackwood however, is typically yard or shed dried in conditions that change with the weather and as such, any computer simulation must take those conditions into consideration.

2. Method

Typically, transient two-dimension hygrothermal simulation when used for building envelope design or analysis requires the careful consideration of inputs for the site climate data, the properties if the materials and the interior conditions. In this task, the interior conditions of the timber rack would be created by the flow of air, moisture, and heat through the simulation model. The subsections below discuss each of the input parameters explored.

2.1. Selection of 2D simulation sectional arrangement

As the two dimensional simulation software requires the input parameters to consider which axes to create in the model, determining which axis to complete a sectional hygrothermal simulation through was an initial challenge, as sufficient material and rack information was required for the simulation to obtain meaningful results. A vertical section through the rack, perpendicular to the long axis of the rack could be taken with two different variations – (i) one through the position of the stickers and (ii) one without the stickers. The option through the position of the stickers would not account for the long axis of the boards and may not show the area of the discoloration. The option without stickers would show the drying action in a more detailed manner but would not show the effect of the stickers. A horizontal section through the rack could either show the stickers or the boards, but neither in conjunction with each other. A vertical section through the long axis of the rack was therefore selected as the most appropriate, as it cuts through all of the relevant components of the rack. An example of the timber rack cross-sections that were explored is shown in Figure 6. Figure 7 shows the final make-up of the long-axis section that was created for this research. Then orange shading represents the timber and stickers, and the light blue shading representing the air between each board.

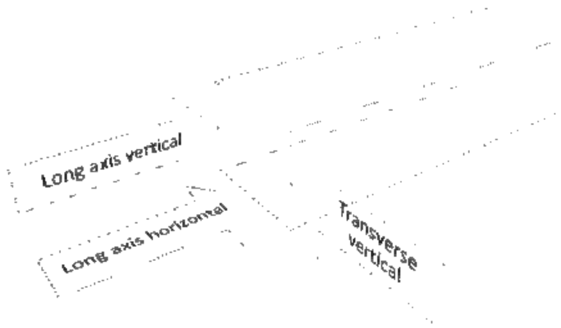

Figure 13 - Simulation sections

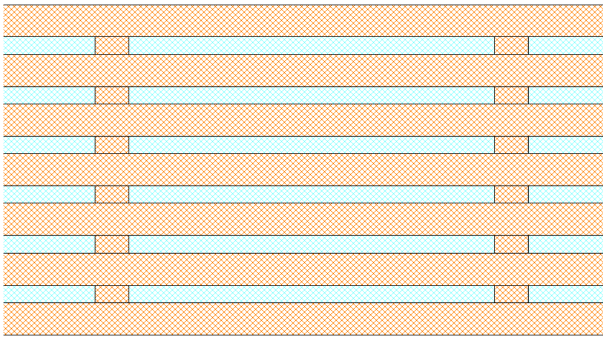

Figure 14 - Long axis vertical section showing boards, stickers and air gaps

2.2. Climate variables

One of the main advantages of using the WUFI 2D hygrothermal simulation software for this research, was the capacity to incorporate the hourly measured site environmental data for the simulation climate file. In this initial exploration of this type of use for the software, simulations were completed for two-year cycles, incorporating hourly air temperature, precipitation and relative humidity %. As the rack to be simulated was protected from overhead solar radiation, the solar radiation data was not included at this stage. The orientation of the racks in the simulation was East-West, to replicate the conditions in the drying yards investigated in the rack survey.

2.3. Material Properties

The WUFI materials database includes material properties for conduction, mass, thermal capacitance, water vapour diffusion resistivity, Moisture storage function, Liquid transport Coefficient, Suction/Redistribution, Porosity, and others. As the properties for mass of the blackwood timber was known, timber materials within the WUFI 2D materials database were examined for listed materials with a similar value. Oak, longditudinal and Oak Radial were selected as being closest in , and the properties Bulk Density, Porosity and built in moisture were modified.

3. Results

The results of the 2D transient hygrothermal simulation showed drying of the timber layers through the simulated rack of timber. Figure 15 Rack drying simulation of total water content below shows the overall moisture content of all the simulated materials over time. A transition stage can clearly be seen (indicated by the orange vertical line) when free moisture within the material is reduced to a minimum and chemically bound moisture is then slowly reduced. This simulated pattern of drying was found to be very similar in nature to the observed drying patterns for boards located that the observed sawmill.

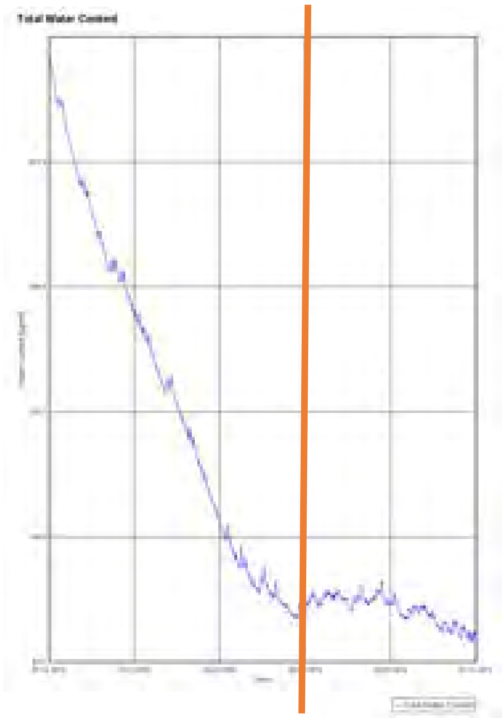

Figure 15 Rack drying simulation of total water content

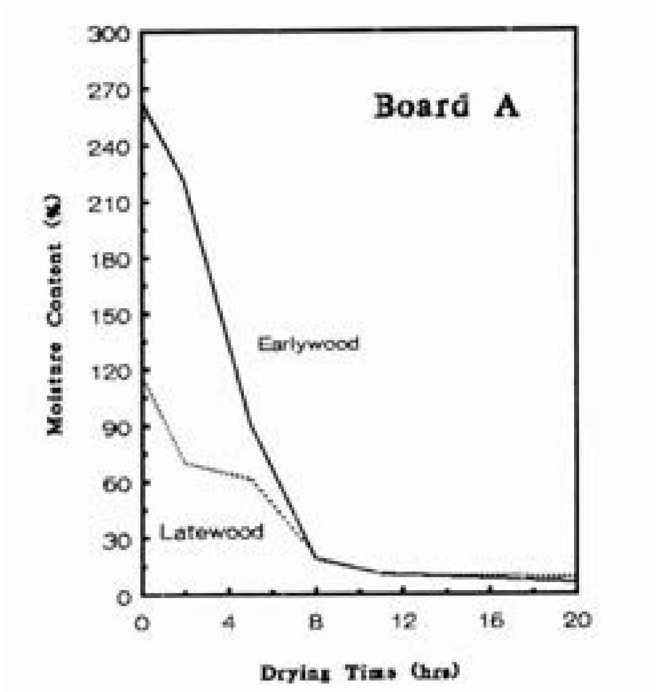

Figure 16 – Moisture content during kiln drying (Gui *et al.*, 1994)

Figure 17 shows a three dimensional representation of the moisture content of the simulated rack at the start of the drying process. Sticks/stickers separating the layers of timber start off at equilibrium moisture content whereas the timber that needs to be air dried starts off at 100% Moisture Content. Relative humidity of the air layers in between boards is set by the climate file used for the simulation. The simulation can be paused to examine conditions at any point during the simulation. Figure 18 shows the simulated moisture content of the pack after 6 months of simulated drying, at the transition zone indicated by the orange line in Figure 15 Rack drying simulation of total water content.

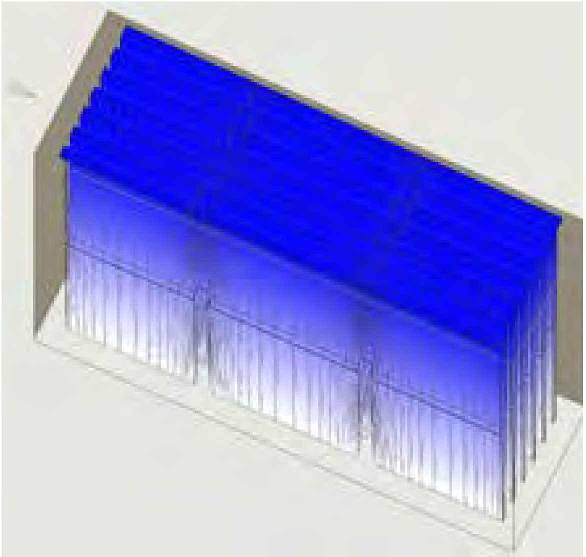

Figure 17 - 3D representation of rack moisture content at start of simulation

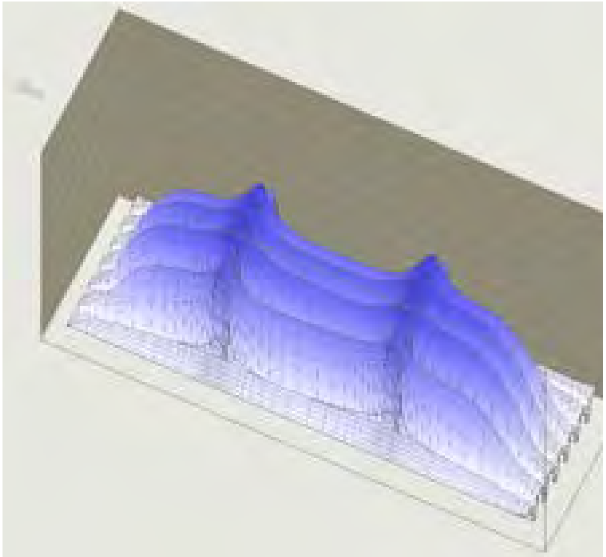

Figure 18 - 3D representation of rack moisture content after 6 months of simulated drying

Figure 19 shows the difference in moisture content on the face of the board in between the stickers and underneath the stickers. As can be seen in Figure 11, the difference in moisture content between stickers and under the stickers at around 4,500 hours of simulation is significantly different. The potential for mould growth was also calculated for each point in the model according to temperature and humidity relative to isopleth lines based on ideal fungal growth conditions as shown in Figure 20.

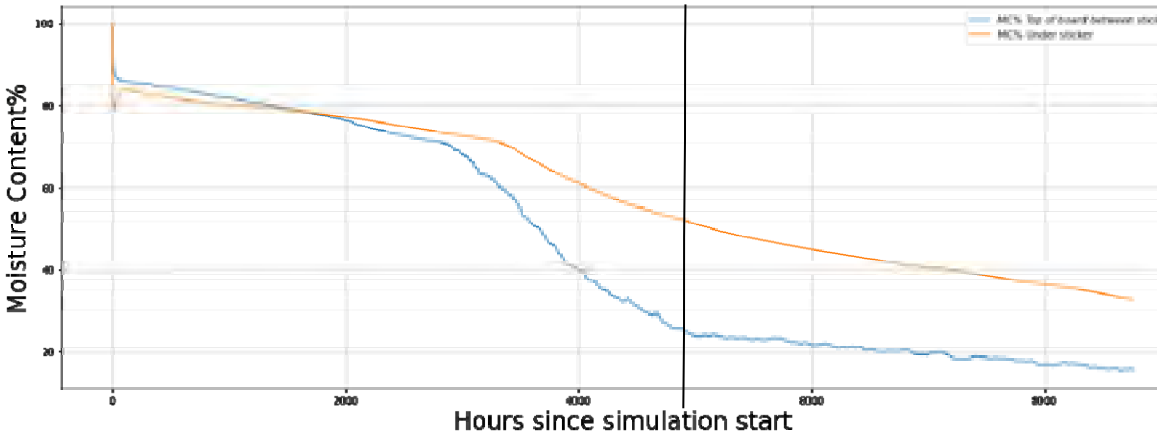

Figure 19 – Simulated moisture content during yard drying showing content at sticker and between stickers

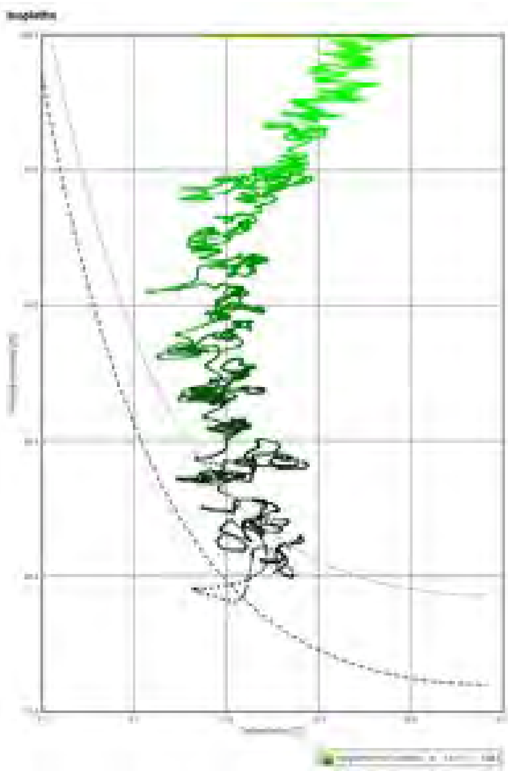

Figure 20 - Isopleths for interior of simulated rack drying

4. Discussion

4.1. Validity of model

The validity of the model for drying of green timber is slightly different to that of pre-dried materials. In green timber, water molecules are found both in the cell lumens and bound by chemical interaction to the cell wall (Redman, 2017). Drying of green timber is a two-stage process whereby firstly the water in the cells is removed (in yard drying by passive climatic mechanisms), and then the bound water is removed, either by continuing the yard drying process for a long period, or by a more energy intensive method such as kiln drying. The point where only the bound water is still present in the timber is called the fiber saturation point (FSP), and when a drying process is plotted, the point where FSP is reached can be seen as an abrupt change in line slope of the moisture content over time. This is due to an increase on the amount of energy required for the removal of the moisture in the timber. FSP varies between different species of timber, and to some extent, drying conditions. The resultant vertical bar in the moisture content graph shown in Figure 15 Rack drying simulation of total water content clearly indicates the transition to the FSP state.

4.2. Indication of moisture movement through timber as a driver for discoloration.

The figures included in Section 3 are derived from an hourly 2D hygrothermal simulation of the racked timber drying process, which can be played back as a three-dimensional video that can be viewed from any angle. The transient 2D hygrothermal model provides an excellent basis for understanding how drying conditions occur within the timber and how that may be driving the discoloration at the same points displayed in the real-world examples. It does not explain the exact cause which may be either the concentration of phenolic compounds or polymerisation reactions caused by conditions within affected areas, but it certainly highlights the unevenness of the conditions within the drying timber and which points are likely to be badly affected. In the case of Blackwood, the two different types of discoloration occur at different frequencies within overall timber racks, for example – dark sticker mark is experienced at a higher rate closer to the top and the outside of the pack where more extreme temperature and humidity fluctuations occur, whereas the light sticker mark occurs seemingly at random throughout the racks.

Figure 20 shows the temperature and humidity conditions throughout the simulated drying compared with two isopleth lines showing ideal conditions for mould growth. While these isopleth lines are highly dependent on the values of the model parameters and nutrient conditions as well as the actual fungal species occurring on site, this can provide a very useful metric for estimating mould growth in building materials. Yard drying of timber however takes place in the open air and is subject to constant environmental conditions including wind-wash which removes mould and fungal spores from materials that might otherwise be at high risk from mould growth.

Moisture conditions both at mid-board and under the stickers varies greatly at different points in the drying process. This is most obviously shown as a three-dimensional graph in Figure 18 but numerically is best displayed in Figure 19, indicating that even towards the end of the drying period there can be a 20% difference in moisture content between where discolouration does and does not occur. This potentially allows for migration and reaction of extractive chemicals via several potential methods leading to localized concentrations of extractive chemicals which may well be affecting reaction rates between them.

5. Conclusions

The aim of this research was to explore if a hygrothermal simulation method could be used to mimic the yard-based air-drying process of green sawn timber and the occurrence of discolouration during the drying process. The observational analysis identified where discolouration was occurring within the yard dried timber. The drying process of the induvial boards, as simulated by the transient 2D hygrothermal simulation software strongly correlated with the well documented drying of timber to the Fibre Saturation Point suggesting the validity of the simulation method. The 2D hygrothermal cross-sectional analysis showed a strong correlation between the timber moisture content and where discolouration was identified during the site observations.

This preliminary use of a transient multi-year hourly 2D hygrothermal simulation software has produced graphical results for temperature, relative humidity, moisture content and vapor pressure. The results from the moisture content analysis closely resemble the location of more than one individual type of discoloration recorded in the site based observational analysis. Whereas previous research has focused on possible chemical and biotic causes, this research has demonstrated that discolouration may in fact be driven by heat and moisture transport mechanisms within the drying timber. The next stage of this research is to explore the impact of different materials and cross-sectional profiles of stickers to identify strategies that may reduce the incidence of discolouration and reduce process cased losses. Whereas these simulations have been completed for a two-year cycle, as identified in observational analysis, some differences occur due to seasonal variation. Future research should explore these issues.

6. Acknowledgements

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MyComfort App: the application of personal thermal comfort models for older people in an online mobile tool

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Abstract: By analysing datasets at the individual level, personal thermal comfort models help to unmask the differences between individuals in an environment, enabling a better understanding of specific comfort needs and collecting diagnostic information to identify user acceptability problems. This information, in turn, can be applied in the decision-making process involved in optimizing thermal environments to improve comfort satisfaction and energy efficiency. In this context, this paper investigates the application of personal thermal comfort models in a mobile tool and discusses the tool's benefits in aiding the adaptation of older people's environments to increase their comfort. MyComfort App is based on a study of 28 personal comfort models for a subset of older South Australians, who participated in a house environmental monitoring in 2019. The App uses individualized machine learning models to allow the automatic calculation of thermal preference for the older individuals. This online user interface provides personal thermal comfort prediction as well as a catalogue of strategies related to personal actions, technology, building operation and design, which could aid the control and adaptation of older person's environments. Testing the App on one personal thermal comfort model proved to be successful in allowing the accessible and automatic calculation of thermal preference for the selected participants. Although still not validated by the end users, the App shows potential to aid designers in the decision-making process, as well as guide caregivers to anticipate needs and control of thermal environments independently.

Keywords: personal comfort models, thermal comfort, older people, machine learning.

1. Introduction

The proportion of older people (i.e., those aged 65 or over) in the world's population is increasing due to historically low fertility rates combined with increased life expectancy. To respond to these demographic trends, a growing body of policy and research over the last decades has accepted that ageing-in-place is most beneficial in the interests of older people's independence, health and wellbeing, as well as to reduce the economic burden on governments and society for the provision of aged care facilities. While there are several guidelines that provide information about designing dwellings to suit ageing-in-place, information to aid older people's thermal comfort and related wellbeing is not always considered.

Traditionally, thermal comfort standards adopt aggregate modelling approaches (such as the PMV model) as the bases on which to establish the requirements for human occupancy in the built environment. Aggregate models explain thermal comfort at a population level, which can result in limitations in real scenarios as individual thermal perceptions can vary significantly. In recent years, a growing number of studies have been conducted to address these limitations by developing 'personal comfort models'. Instead of an average response from a large population, personalised models predict individuals' thermal comfort by using a single person's direct feedback. Nonetheless, studies on personal comfort models have focused on younger adults, generally in office environments (Arakawa Martins *et al.*, 2022b). This presents a critical research gap because intergroup heterogeneity in personal capabilities and needs tends to be greater among older people (World Health Organization, 2015), causing the use of aggregate models for older adults to result in even more frequent exposure to unacceptable thermal environments. These, in turn, can interact with multiple comorbidities, leading to adverse health outcomes and/or premature institutional care. Thus, personalising models hold the promise of a more accurate way to predict older people's thermal comfort and to better manage their thermal environments.

By analysing datasets at the individual level, personal thermal comfort models help to unmask the differences between individuals in an environment, enabling a better understanding of specific comfort needs and collecting diagnostic information to identify user acceptability problems. This information, in turn, can be applied in the decision-making process involved in designing and optimizing thermal environments to improve comfort satisfaction and energy efficiency.

Therefore, drawing from the exploration of personal comfort models, this paper investigates a possible application opportunity and its benefits in older people's context and real settings. Hence, this paper aims to answer the following research question: *how can personal comfort models for older people be used to aid the control and adaptation of older people's environments to increase comfort and health and well-being?*

The investigation explores the use of the models in a web-based mobile tool, that allows the automatic calculation of thermal preference for older individuals, aimed at aiding the control and adaptation for older people's environments to increase their comfort. Although potentially useful for other demographics, the App is destined for designers, caregivers or health care professionals, and was developed using, as references, a series of user-interfaces and mobile apps in the related fields.

The methodology used in this study, as well as the results and limitations, are described in detail below.

2. Tools available today

Several applications and interfaces have been developed in the field of thermal comfort prediction. The Center for the Built Environment (CBE) Thermal Comfort Tool (available at https://comfort.cbe.berkeley.edu/), for instance, is a free online tool that allows the calculation and evaluation of thermal comfort according to the ASHRAE Standard 55 (Tartarini *et al.*, 2020). It includes models such as the PMV and the adaptive comfort model, as well as visualization features involving psychrometric and temperature-humidity charts. The developers aimed to address the field's lack of tools that could be used to calculate thermal comfort indices without prior coding skills. The tool's end users comprise of engineers, architects, researchers, educators, facility managers and policy makers (Schiavon *et al.*, 2013). Applying a simple and accessible interface, users can input their own measured or simulated data and automatically visualise outcomes in the same browser screen.

The Arup Advanced Comfort Tool (available at https://comfort.arup.com/) is a similar free web-based interface that allows the prediction of thermal comfort under changing and non-uniform thermal environmental conditions, including stratification, radiant asymmetry, and effects of personal environmental controls. Based on human psychophysiological models, the tool also provides the option of individual thermal comfort calculation based on personal characteristics such as sex, age, and body fat percentile values, displaying the comfort indices on a thermal sensation timeline (Jones *et al.*, 2020; Jones *et al.*, 2021).

Nevertheless, none of the available tools provide comfort prediction specifically for older people, let alone individualised or personalised predictions.

In the context of older people’s health, several other interfaces are aimed at caregivers and health professionals to provide them with information and strategies to increase health and wellbeing, as well as to monitor vitals and symptoms of specific diseases. For caregivers, for instance, a review by Wozney *et al.* (2018) gathered references of eight commercially-available apps addressed to Alzheimer disease or other related dementias (ADRD) caregivers. The apps are generally static, providing text-based informational resources to understand and deal with older adults’ symptoms or specific behaviours. Two examples are the Dementia Caregiver Solutions app (Personalized Dementia Solutions Inc., 2021) and the Alzheimer's Daily Companion app (Home Instead Senior Care, 2021).

Furthermore, health care professionals have a number of applications commercially available that provide tools to aid decision-making in a systematic and objective way, such as well-known evidence-based apps palliMEDS for palliative care medicine guidelines (NPS MedicineWise and caring@home, 2021), UpToDate for general clinical decision support resources (UpToDate Inc., 2021) or MDCalc for medical equation calculation and guidelines (MDCalc, 2021). The latter, for instance, has relevant calculation capabilities in a user-friendly interface that allows quick and accurate estimations for several health indices.

Other related health mobile applications, aimed at the general public, deliver relevant functionalities and features, such as personal data recording, tracking and visualizing. The PainScale app (Boston Scientific Corporation, 2021), for instance, allows users to log and track chronic pain in order to identity triggers, minimize related daily disruptions, and get personalised reports and insights to better manage health conditions. It is commonly used for the management of Fibromyalgia syndrome among older people.

Resources and tools for caregivers to manage the thermal comfort of older adults in the form of mobile applications remain, however, inexistent in the market today.

3. Research methodology

3.1. Data collection

To investigate the thermal environments of older people in South Australia and collect datasets for the development of the personal thermal comfort models, a field study was conducted involving 71 older people (23 males and 48 females) from 57 households located in South Australia, recruited through press releases in various media formats (e.g., newspaper and radio calls for volunteers and tear-off posters). All participants were aged 65 years or above, lived independently (i.e., not in aged care facilities), and were required to be able to communicate in English. The dwellings were located in hot dry (BSk), warm temperate (Csa) and cool temperate (Csb) climate zones, according to the Köppen–Geiger climate classification system, or Climate Zones 4, 5 and 6, respectively, according to the Australian National Construction Code (Australian Building Codes Board, 2019). The data collection started in mid-January 2019 and lasted 9 months until mid-October 2019, comprising both hot/warm and cold/cool seasons, which provided the range of variations in environmental conditions necessary for a comprehensive analysis.

The data collection process involved the following tools:

(a) A questionnaire about individual socio-economic information, as well as chronic disease and symptoms, behaviours, preferences and responses during hot and cold weather, applied by the project team.

(b) An open-ended interview about the house details (directed by a checklist), including the collection of energy bills, building plans, elevations, and photos, applied by the candidate.

(c) The installation of indoor environment data loggers, which allowed the subsequent environmental monitoring (i.e., dry-bulb temperature, globe temperature, air speed, relative humidity, CO_2 and Volatile Organic Compounds measurements) of each house's main living room and bedroom, every 30 minutes and whenever a participant answered a thermal comfort survey, for 9 months.

(d) The installation of a thermal comfort survey tablet, which allowed the participants to answer thermal comfort surveys electronically at anytime, for 9 months.

Details of the data collection tools have been published by Soebarto *et al.* (2020) and Soebarto *et al.* (2019).

3.2. Modelling methodology chosen

To develop personal thermal comfort models for the older adults involved in the study, deep learning (also known as artificial neural networks) (Goodfellow *et al.*, 2016) was applied. Although other high-performance machine learning techniques could have been used (e.g., Random Forests or Support Vector Machine) for thermal preference prediction, an extensive review of personal thermal comfort models highlighted a lack of exploration of artificial neural networks (Arakawa Martins *et al.*, 2022b). The overall modelling process was based on the framework for personal thermal comfort model development described by Kim *et al.* (2018) and the framework for machine leaning model development described by Raschka (2018). The overall steps involved are shown in Figure 1.

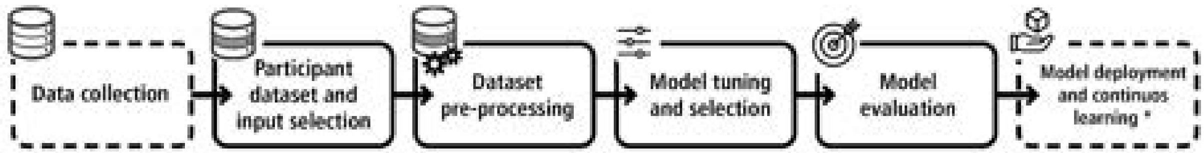

Figure 1 - Overall modelling process steps. *Model continuous learning, although present in the referenced frameworks, were out of scope of this study.

The models were programmed to perform a multiclass classification task. This meant that their task was to specify to which of the k categories an example (or data point) belongs. In general terms, deep learning models are shown data points (i.e., the training set) and follow a set of non-linear mathematical expressions between hidden layers of representation units (or "neurons") to produce an output in the form of a probability for each classification category. A function then measures the error between the outputs and the desired probability patterns and the model modifies its internal parameters to reduce the error (also called the "loss"). The model is then shown a never-before-seen set of data points (i.e., the testing set) and produces a new and final set of probability outputs (LeCun *et al.*, 2015; Goodfellow *et al.*, 2016).

Therefore, in this study, the models are programmed to classify occupants' thermal preference (TPV) on a 3-point-scale ("preferring to be cooler", "preferring no change" or "preferring to be warmer") using up to 7 input variables (dry bulb temperature, radiant temperature, relative humidity, air speed, clothing level, metabolic rate and health/wellbeing perception). The survey's TPV was used as the ground truth to train and validate the models and later evaluate the predicted values using the testing set. The models have an input layer, a hidden layer, and an output layer, and use Rectified Linear Unit (ReLU) (Agarap, 2018) as the activation function between the input layer and the hidden layer and Softmax as the activation function between the hidden layer and the output layer. Cross Entropy function was used to measure the error of the classification rounds and Stochastic Gradient Descent was used as the optimiser algorithm minimises the loss.

The k-fold cross-validation technique, with k=5, was used during training. The technique was chosen due to its low complexity, robustness and frequent use in machine learning related approaches.

Anaconda version 2019.3 (Anaconda, 2019) was utilised as the package management platform and Jupyter Notebooks (Thomas Kluyver, 2016) was used as the scripting and computing platform for the development of all models, using Python version 3.7 and PyTorch tensor library (Paszke *et al.*, 2017). Further details on the chosen modelling methodology in this study have been previously published by Arakawa Martins *et al.* (2022c) and Arakawa Martins *et al.* (2022a) .

3.3. Model development

After the initial data collection, the collected dataset was separated into 71 individual datasets to be analysed, corresponding to each individual participant dataset. The chosen modelling process, however, required that each participant voted at least 6 times in each of the three thermal preference classes (wanting to be cooler, no change, warmer), to allow a minimum of 5-fold cross-validation during model training, plus a minimum of 1 vote per category for testing (Raschka, 2018). Excluding the participants who did not meet this requirement resulted in 28 individual datasets out of the 71 participants to be selected for modelling.

The input features were then selected to cover a combination of the environmental factors traditionally used in aggregate models such as the PMV (i.e., dry bulb temperature, radiant temperature, relative humidity, air speed), in addition to a selection of the personal factors captured in the study (i.e., clothing, metabolic rate and health perception). Other personal characteristics such as age and sex were incorporated into a corrected version of metabolic rates, which were also used as input variables.

Data were subsequently pre-processed, involving undersampling and normalization. Datasets were then randomly split into training, validation and testing sets to allow data cross-validation and avoid drawbacks such as overfitting (i.e., when the model fits well against its training data, including its noise, thus performing poorly when tested against new data). The models were then scripted and their hyperparameters were tuned and selected according to their predictive performance, measured using Accuracy (Ferri *et al.*, 2009), Cohen's Kappa Coefficient (Cohen, 1960) and the Area Under the Receiver Operating Characteristics Curve (AUC) (Ben-David, 2008). Finally, tuned models were tested using the testing set and final performance was recorded using the same performance measures listed above.

3.4. MyComfort App development from personal thermal comfort models

MyComfort Apps were developed to cover a calculator feature, such as the ones present in the beforementioned *CBE Thermal Comfort Tool*, the *Arup Advanced Comfort Tool* or the *MDCalc* app. In addition, the app was developed to deliver evidence-based information and strategies to help users act upon the predictions, similar to the guidelines present in the beforementioned apps for caregivers and health professionals. Additionally, a feature that allows users to save input data was added to provide the tracking of environmental conditions, which, in turn, can give insights on the building's performance, issues and possible causes.

To develop the calculator feature of the app, first the final state of each artificial neural network model, which includes all final calculated weights and biases, were transferred from the *Jupyter Notebook* (Thomas Kluyver,

2016) (i.e., the computing environment used), developed in Python language, to a spreadsheet in *Microsoft Excel* (Microsoft Corporation, 2021), where the neural network was reconstructed. The spreadsheet was then imported to the online developing tool *Open As App* (Open As App GmbH, 2021), where a mobile interface was developed based on the personal models. The app, therefore, allows an easy and automatic way to calculate personal thermal comfort predictions without prior knowledge of Python or Excel.

Figure 2 - Personal thermal comfort mobile tool development steps

The application allows users to input values to the six variables used in the models (i.e., dry bulb temperature, radiant temperature, relative humidity, air speed, metabolic rate and clothing level). The models' equations are then solved automatically according to these inputs, and the app provides the thermal preference prediction according to the calculated probabilities for each thermal preference category. The app displays that the older person in question prefers to be warmer when the probability of "preferring to be warmer" is equal to or higher than 50%; it displays that they want to be cooler when the probability of "preferring to be cooler" is equal to or higher than 50%; and it displays that they want no change when both probabilities of preferring to be warmer and cooler are lower than 50%. This is only possible because simultaneous non-null probabilities of "preferring to be cooler" and "preferring to warmer" are not possible in these specific models' predictions. This means that, when the probability of preferring to be warmer is higher than 50%, the probability of preferring to be cooler is always 0%, and vice-versa. The app also displays these three probabilities below the main prediction, to allow the users to assess the urgency or risks associated to different probability breakdowns.

The app was designed to be used by designers, caregivers, or healthcare professionals. Each user type might profit of specific features of the app, as shown in Figure .

Figure 3 - Online user interface and user types

4. Results

4.1. Modelling results

From the exploration of 28 personal thermal comfort models for older adults, the study found that the models developed using dry bulb temperature, radiant temperature, relative humidity, air speed (i.e., environmental variables), clothing level, metabolic rate and health/wellbeing perception (i.e., personal variables) as input variables presented, on average, an accuracy of 74%, a Cohen's Kappa Coefficient of 61% and an AUC of 0.83. This represented a significant improvement in predictive performance when compared to the generalised Predicted Mean Vote (PMV) model, which presented an average accuracy of 50%, an average Cohen's Kappa Coefficient of 24%, and an average AUC of 0.62.

A detailed analysis of the modelling results, including each individual personal comfort model performance, has been previously published by Arakawa Martins et al. (2022c).

4.2. App example and features

An example of the app was developed from a personal thermal comfort model of one of the study's participants. This personal comfort model has optimal performance indicators (i.e., accuracy, AUC and Cohen's Kappa Coefficient), thus being chosen as an example. The app can be accessed via a mobile device, by first downloading and installing the *Open As App* application. After installing, the App for the participant can be accessed by scanning the QR Code below (Figure). A web-browser version of the app can also be accessed through the link *https://oaa.app.link/launch-app-f65992fc-4e0a-4a01-ab93-fb32ac94266b* . The participant's name was changed to the fictitious name "Tina" to preserve privacy.

Figure 7 – QR Code to access the app for "Tina"

The MyComfort app has a single screen to allow easy access to the information provided. Users are first asked to fill out the input fields to calculate the older person's thermal preference at that moment. The temperature, radiant temperature, relative humidity and air speed inputs can be logged using the toggle buttons (i.e., "+" or "-") or by typing the values using an on-screen automatically-activated number keyboard, as shown in Figure . The activity and clothing levels can be inserted by using sliders or the number keyboard. Note that the activity level is internally converted to metabolic rate to be used as an input in the thermal preference calculation.

Figure 4 - Personal Thermal Comfort app calculator screen

Once the inputs are inserted, the thermal preference prediction is displayed automatically below the inputs. As previously mentioned, the app also displays the thermal preference categories' probabilities below the main prediction, as seen in Figure , to allow the users to assess the urgency or risks associated to different probability breakdowns. In case the predictions are "prefer to be warmer" or "prefer to be cooler", the app displays, below the probability predictions, a set of thematic strategies and guidelines to help increase comfort. By tapping on the themes, the app displays an overlay screen with more details on specific strategies. These evidence-based strategies were derived from the "Thermal Comfort at Home: A guide for older South Australians" (Soebarto *et al.*, 2021). The strategies relate to personal and behavioural themes, as well as design and technological guidelines. Taping the "back" arrow on the top left-hand corner allows the user to return to the main screen. No strategies are shown when the prediction is "preferring no change".

Figure 5 - Personal Thermal Comfort app prediction output and guidelines screen

The app also provides a "Help" button, which activates an overlay "Help" screen with the definition of each input and how to access or measure it. For each participant, the average of each indoor environmental input from the monitoring datasets, for each season, will be included in the "Help" screen to aid the calculation when right-here-right-now measurements are not available. To exit this screen, the user must press "OK" at the end of the screen. An "Upload" button is also included to save the inputs inserted by the user in a server, which can be accessed by developers for analysis and sent back to users by request. Figure presents these features.

Figure 6 - Personal Thermal Comfort app "Help" and "Upload" buttons, and "Help" screen

5. Discussion

5.1. The App's potential applications

The conversion of the selected personal thermal comfort model in a web-based smart phone's App proved to be successful in allowing the accessible and automatic calculation of thermal preference for the selected participant. Although still not validated by the end users, the App showed potential to aid designers in the decision-making process, as well as guide caregivers to anticipate needs and control thermal environments independently.

Regarding the use of this web tool by designers, the tool could be integrated to building performance simulation workflows. The Energy Management System (EMS) component in EnergyPlus (Gunay *et al.*, 2015) or co-simulation methods (Peng and Hsieh, 2017; Kontes *et al.*, 2018) are recent research topics that could aid the integration of predictive models and related databases with simulation tools used for validating design and construction options in specific and individual scenarios. In addition, when measured data is used as inputs in the model (instead of assumptions or approximations), the web tool has enhanced reliability to be used by designers when testing environment's possibilities. Consequently, improving building design, construction and operation could also result in a decrease in the reliance on heating and cooling systems and related fuel consumption.

From the health care perspective, web tools such as the one presented in this study can be considered practical contributions to the worldwide trend and interest in high-performing person-centred approaches for health care delivery (Health Innovation Network South London, 2017; Godfrey *et al.*, 2018; Santana *et al.*, 2018). As accurately described by the Health Innovation Network South London (2017):

"*Person-centred care is not just about giving people whatever they want or providing information. It is about considering people's desires, values, family situations, social circumstances and lifestyles; seeing the person as an individual, and working together to develop appropriate solutions*."

Australian health care organizations have also recognised person-centred care as the basis for achieving better health outcomes and experiences to patients, carers, and families. The National Safety and Quality Health Service (NSQHS) Standards, for instance, identifies seven main attributes that are important to achieve “person-centredness”: (1) comprehensive care delivery; (2) clear purpose, strategy and strong leadership; (3) people, capability and a person-centred culture; (4) person-centred governance systems; (5) strong external partnerships; (6) person-centred technology and built environments; and (7) measurement for improvement. The work developed using personal thermal comfort models and web-tools could be considered as a contribution for principle 6, providing technology that enhances patient experience and outcomes and aiding person-centred design principles to the built environment, as prescribed by the Australian Comission on Safety and Quality in Health Care (2018) documentation on the topic.

5.2. Considerations and potential barriers regarding the use of clothing level as an App input

Apart from potential practical contributions to the field of thermal comfort, design and health care, the development of the personal models and the application on a mobile tool highlighted important insights on the use of clothing level as one of the input variables for the models, as well as the way this data should be interpreted in future field studies. As observed in the example model, the higher the clothing level, the higher the probability of the participant to prefer to be warmer because a higher clothing level indicates a cool or cold thermal sensation. This represents a rather counterintuitive correlation between these variables, since it is commonly expected that one would prefer to be warmer when they are less clothed.

This relationship between variables emphasizes three main insights. Firstly, it appears that the "clothing level" collected through survey answers from participants represents an adaptive behaviour taken by them to act upon their thermal preference at the moment, rather than representing their static clothing insulation status (i.e., the “clo” input in many traditional models). This means that, in this study, increasing clothing level is a result of feeling cold and preferring to be warmer, rather than the cause of a warm sensation and a preference to be cooler, which is what is normally expected in models such as the PMV. In other words, in the personal model, people wear more clothing layers because they feel cold; whereas in the PMV, people are predicted to vote ‘cool’ or ‘cold’ because they wear fewer clothing layers Therefore, not only is the dependent/independent relationship reversed (i.e., the cause-and-effect relationship), but the correlation is also negative in the personal models and positive in PMV model. Consequently, for the mobile app to accurately predict the person’s thermal preference at the moment, the clothing level has to be considered as an adaptive behaviour already taken by the person in question before the prediction is made. This relationship is also observed when analysing the data from the entire cohort.

This leads to a second consideration on the subject. This difference between how clothing level interacts in the current study’s models and in the PMV model can partially explain the errors found in the PMV predictions when compared to participants actual thermal sensation votes. In addition to the generalization limitations of the PMV model, using the field work surveys’ "clothing level" as a representation of “clo” in the PMV model equation is likely to result in the wrong PMV prediction. This highlights an important difference between field study and experimental (i.e., climate chamber) data collection procedures, which require especial considerations depending on the final application envisaged.

Thirdly, the explorations emphasized how the thermal preference of wanting to be warmer was more sensitive to clothing than other thermal preferences. Changing clothing levels appeared to be a more common adaptive behaviour when temperatures decreased and the probability of preference for warmer was higher, than when temperatures increased and the probability of preference for cooler was higher. This can be seen for the whole cohort dataset, where lighter clothing levels are not as common in lower thermal sensations (e.g., cool, slight cool) than higher clothing levels are in higher thermal sensations (e.g., warm, slight warm). This is also observed for the example model, as shown by the Clothing Level probability density distributions in Figure 0. The Clothing Level graph shows that higher clothing levels are more likely to be related to "preferring to be warmer" than lower clothing level are to the other two thermal preference categories. Adaptive clothing behaviours and their relationship with environmental conditions and seasonal sensitivity, however, can vary among participants, and should be analysed at the individual level to aid the correct use of applications such as the mobile app envisioned here.

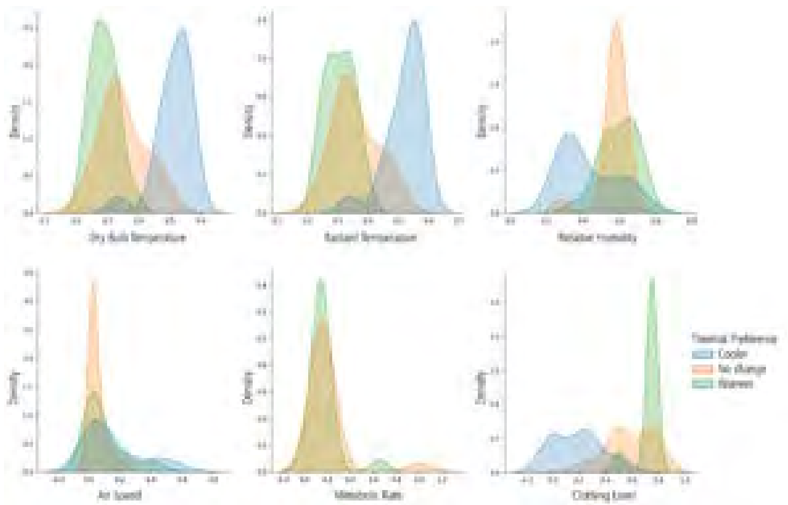

Figure 0 - Probability density distributions for the personal models' inputs, according to each thermal preference category, for the example model. Inputs are normalized from 0 to 1.

It is advised, therefore, that future studies on modelling and tool development consider clothing insulation and/or clothing level as a behavioural and adaptational thermal comfort variable, whose use differs from their traditional applications in aggregate models such as the PMV.

6. Limitations and future research opportunities

Although basing this mobile tool in the beforementioned references, the app presented here is an exploration of the models' application only, and still requires further testing in real scenarios, considering usability, readability, and accessibility (e.g., appropriate font and button size, colours and contrast) (Lidwell *et al.*, 2010). It is also noteworthy that the development platform *Open As App*, despite numerous feature possibilities, still poses limitations in user-experience design. Further explorations should be the considered in future research opportunities.

In addition, although the strategies provided in the tool are evidence-based, derived from the "Thermal Comfort at Home: A guide for older South Australians" (Soebarto *et al.*, 2021), the language and level of details might still require validation from designers and caregivers, since the document was originally developed with the input of older people only.

It is also important to highlight that each individual person is required to be monitored for data collection before the personal model is developed and later converted into an individual App by a researcher/developed. This could result in limitations for deployment of the tool. Further research is, therefore, required for the development of a method that allows the end-user to upload their own data and train a model automatically. Similar conceptual system architecture and frameworks for data collection and automatic (or continuous) model training have been previously envisaged by Kim *et al.* (2018).

7. Conclusion

The investigation explored the use of personal models in a web-based mobile tool, that allows the automatic calculation of thermal preference for older individuals. Although still not validated for usability and accessibility, the app has the potential to aid designers in the decision-making process and can be used in combination with building simulation results. Caregivers can also profit from the app, which can guide the control of environments without disturbing patients and helps track and record events for future consultation. Finally, users can profit from the app as a resource for information and guidelines on personal, technological and design strategies that can help increase comfort and decrease heating and cooling energy use.

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Optimizing thermal comfort and indoor air quality in school classrooms

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Abstract: Recent studies from Victoria provided some baseline ventilation data for schools and noted that ventilation in many of the classrooms are below recommended minimum values. The Covid-19 pandemic has brought about an increased focus on indoor air quality in schools as a result of which many schools in Victoria have been engaging in fit out works to improve the air quality by various means such as introducing portable filters, leaving windows and doors open and bringing in outdoor air mechanically through air inlets. However, introducing outdoor air without pre-conditioning can cause thermal discomfort to the occupants in the classroom. This paper examined the effect of providing fresh air through air inlets to school classrooms using computational fluid dynamins (CFD) simulations. A number of variations were tested by changing the location of the cassette units and the location and number of inlets and outlets. The results showed that though the existing equipment is suited for extreme summer conditions, they are undersized for extreme winter. There was only 4.1% increase in the efficiency with the change in the arrangement in terms of the location of the cassette units and the location and the number of openings for outside air and return air. The use of Direct Outside Air System (DOAS) or a heat recovery system is recommended to address these issues. The findings will assist in developing standards regarding the installation of outside air systems for improving thermal comfort for children in school classrooms while ensuring good ventilation and indoor air quality.

Keywords: thermal comfort; indoor air quality; school classrooms; computational fluid dynamics

1. Introduction

Climate change has deteriorated the air quality of cities leading to increased temperature, increased level of carbon dioxide and other pollutants such as dust and allergens. Extreme weather events such as heat waves, thunderstorms and bushfire smoke are rising. Increasing frequency of such extreme weather events will force people to spend even more time indoor. Children under 15 years spend over six hours per day in school buildings and are particularly vulnerable to the effects of poor thermal comfort and indoor air quality. Thermal comfort and ventilation are essential consideration in the design of school buildings, as they can affect the health and cognitive performance of students. A recent study conducted in five Victorian schools monitored indoor conditions and measured student attention and concentration performance using a neuropsychological assessment, d2 Test of Attention (Woo et al., 2022). The results established a low to moderate correlation between ventilation rates and student performance across the four school terms, particularly speed and accuracy, demonstrating that IAQ does impact student concentration performance.

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Stepwise multiple regression analysis showed that 15% of the variance in speed and accuracy is explained by the four indoor condition parameters of PM2.5 ($p < .05$), mean radiant temperature ($p < .001$), relative humidity ($p < .001$) and air velocity ($p < .05$) (Woo et al., 2022).

Generally, the criteria and recommendations in the international standards have been adopted as normative references by Australian national standards, guidelines and codes of practice. The thermal comfort standards prescribe numeric and descriptive criteria for comfort primarily for mechanically conditioned buildings – 19.7°C-26.7°C, 20% -60% RH. ASHRAE Standard 55 (2010) does not provide specific guidance for naturally conditioned spaces. However, CIBSE Guide A prescribes summer design temperatures and over-heating criteria for free-running buildings, where 25°C is an acceptable indoor temperature (Andamon et al., 2014).

The perception of air quality can be strongly influenced by temperature and humidity. For example, high temperature and humidity counteract increased ventilation rate, and thus degrade perceived indoor air quality. Carbon dioxide (CO_2) concentration is commonly used as a surrogate indicator for assessing indoor air quality. ASHRAE Standard 62.1 (2006) recommends a steady-state CO_2 concentration no greater than about 700 ppm above outdoor air levels with ventilation rate to be held to 5 Ls−1 per person for classrooms (age 9 plus). CIBSE BB101 (Daniels, 2018) Guidelines stipulate daily average of 1000 ppm maximum for mechanical ventilation and cannot exceed a daily average of not more than 1500 ppm for natural ventilation system. Australian Standard AS 1668.2 (2012) specifies a minimum floor area requirement per occupant and recommends minimum outdoor airflow rate between 10 and 12 Ls^{-1} per person. However, a recent study conducted in Victoria involving 10 school classrooms showed that ventilation rates ranged from 1.6 Ls^{-1} to 11.5 Ls^{-1} per person with 7 out of the 10 classrooms showing ventilation rates below the recommended minimum (Rajagopalan et al., 2021). Though designed to be naturally ventilated, often classrooms are installed with heating systems and retrofitted with split air conditioning systems. There has been an increasing tendency to retrofit naturally ventilated classrooms with air conditioning units due to community complaints about thermal discomfort during the summer. However, much of these artificial heating and cooling systems do not have the provision to deliver fresh air ventilation to the classrooms. Currently, most schools rely on teachers opening the windows to provide fresh air to students. But that is not always practical during extreme weather events. The Covid-19 pandemic has brought about an increased focus on indoor air quality in schools due to the significance of viral transmission via small airborne microdroplets. Many schools in Victoria have been engaging in fit out works to improve the air quality by bringing in outdoor air mechanically through air inlets. However, introducing outdoor air without pre-conditioning can cause thermal discomfort to the occupants in the classroom. This can be investigated carefully by trialling different types, numbers and position of air inlets. This paper aims to examine the effect of introducing outside air and various air inlet arrangements on thermal comfort and ventilation using computational fluid dynamics (CFD) simulations. The results are expected to improve thermal comfort of children in school classrooms while ensuring good ventilation and indoor air quality.

2. Methodology

This study focused on thermal comfort and ventilation of a school classroom that uses outdoor air which is not pre-conditioned. A number of scenarios were explored by varying the size and position of air inlet to understand the implication of such arrangements on thermal comfort and indoor air quality. A typical classroom is simulated using Computational Fluid Dynamics software SimScale that uses cloud services for modelling and analysis. Steady state simulation using k-ω SST turbulence model is used. The model combines the k-ω turbulence model and k-epsilon turbulence model such that the k-ω is used in the inner region of the boundary layer and switches to the k-epsilon in the free shear flow. The use of a k-ω formulation in the inner parts of the boundary layer makes the model directly usable all the way down to the wall through the viscous sub-layer, hence the SST k-ω model can be used as a Low RE-turbulence model without any extra damping functions. k-ω SST turbulence model simplifies the equation to provide better results with less complications (SimScale 2021). Camel+ software is used to calculate the design heating and cooling loads, equipment sizing and psychrometric analysis.

2.1. Classroom details

A corner classroom 8.5 m x 8.75 m, located in a primary school building in Melbourne is used as the test case (Figure 1). The building is single storeyed and the classroom has two external walls exposed to outside. The heating ventilation and air conditioning (HVAC) equipment used in the room is a 2 x Panasonic 6kW R32 Mini Cassette 2023 capable of delivering a total of 12kW to the room. The room has a heat load of 11.9 kW and cooling load of 10.6 kW. Windows were single glazed with total area of 13.68 m^2 and with U value of $5.8W/m^2$.

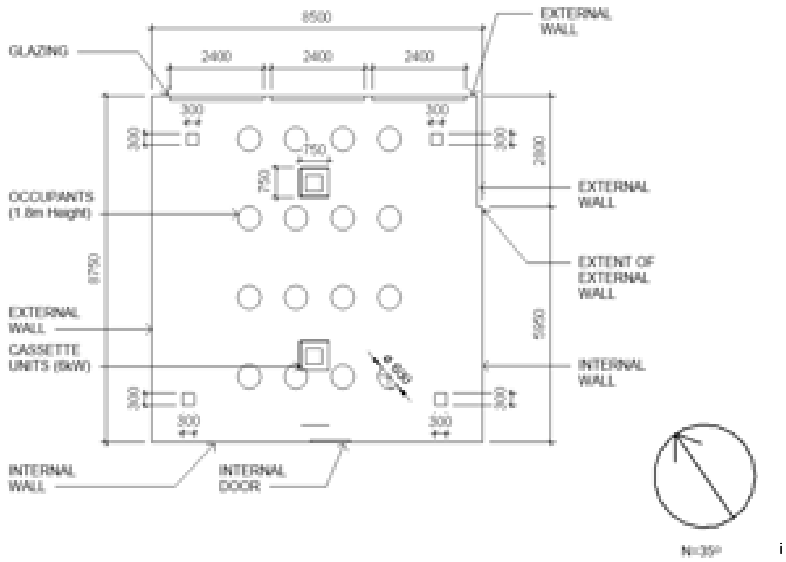


Figure 21: Plan of the classroom

A design flow rate of 591 LS^{-1} for the supply air and 312 LS^{-1} for the outside air is acquired from the Camel+ results. The selected equipment can supply 700 LS^{-1} in the turbo mode which is the supply air flow rate during the extreme weather conditions. Outside air is directly supplied to the room without any conditioning due to the limited capacity of equipment to handle outdoor air as the equipment can only handle maximum of 25% of the supply air. The selected equipment has an average flow rate of 450 LS^{-1} and 25% of the supply air is 112.5 LS^{-1}. In total, the outside air both the units can handle is 225 LS^{-1} while the remaining 87 LS^{-1} outside air needs to be supplied individually. An alternative option is to increase the size of the equipment from 6 kW to 9kW which makes it 18kW for the room to comply outside air requirement. The increase in the equipment capacity increases the overall cost of the equipment and the operational costs for the building. Additionally, the introduction of outside air can impact occupant comfort. Due to these reasons, HVAC designers sometimes split the outside air between the units and supply the rest to the room directly. On some occasions, outside air is directly supplied to the room especially where split air-conditioners are not capable of handling additional outside air to it. This study performs an analysis of such arrangement and investigates the possibilities of reducing discomfort for the occupants by considering extreme conditions of the year.

2.2. Boundary conditions

Peak summer and winter day conditions were selected for simulation. For the selected summer day, the maximum, minimum and average temperatures were 39°C, 25°C and 30.7°C respectively. For the winter day, the minimum and average temperatures were 2°C and 7.3°C. Initial conditions of the domain is assumed to be 24°C for summer and 20°C for winter. Ambient temperature is assumed to be 39°C for summer and 2°C for winter. For external walls, heat transfer coefficient is assumed to be $0.4W/m^2$ and initial boundary temperatures were 29°C for summer and 15°C for winter. Total number of students occupying the classroom was assumed to be 26. For the 4-way cassette unit located in the ceiling, fixed flow rate was assumed based on the maximum flow for the unit installed. The maximum flow rate was divided by four to cater for each direction of the cassette unit and the resulting flow rate is $0.175\ m^3/s$. The outlet temperature is fixed based on the Camel+ heat load calculations where the bypass factor for the unit is assumed as 0.28. The outlet temperatures are 15.5°C during summer and 21°C during winter. For inlet temperatures, maximum achievable temperatures by the equipment during heating and cooling is assumed. For the outdoor fresh air intake, volumetric flow rate is calculated as $10\ LS^{-1}$ per person as per AS 1668.2 2012. The overall flow rate for this room is a constant for all the variations which is $312\ LS^{-1}$. This flow rate is split between the number of outlet sides converted to $0.312\ m^3/s$ as input. The domain was divided into 4.5 million mesh cells.

2.3. Modelling scenarios

Seven different scenarios were tested by varying the location of the cassette unit; number and location of outside air inlets and return air outlets. Figure 2 illustrates these scenarios.

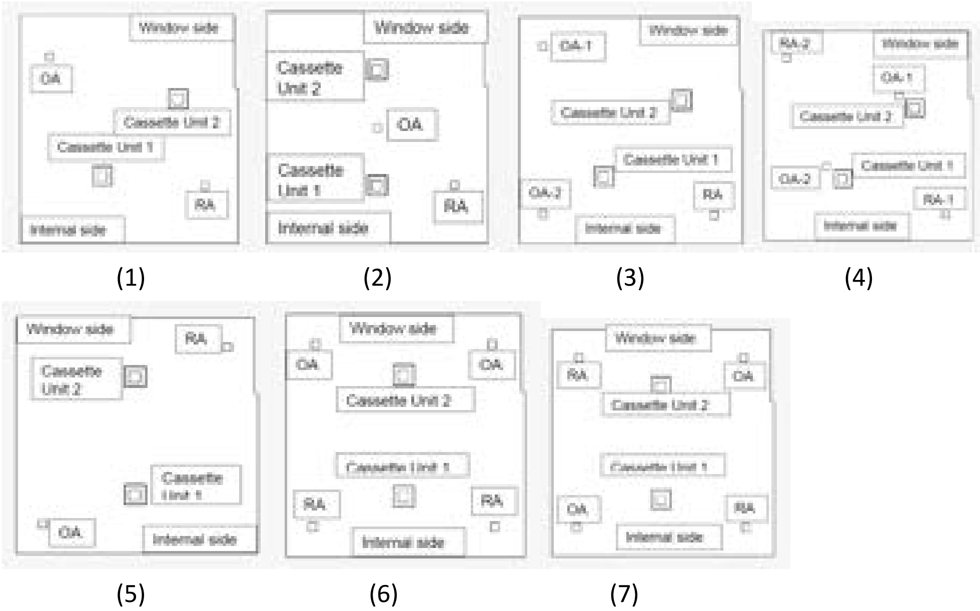


Figure 2: Various scenarios tested

3. Results

3.1. Validation

For validating the model, a simulation case was run without the inclusion of outside air inlet to replicate an existing school classroom located in Melbourne. The results were compared with indoor temperature data monitored in the classroom during the hottest day in February and coldest day in July 2019. The monitoring was conducted with stationary battery-operated datalogger (HOBO MX1102). The temperature data from the simulation showed similar trends to the temperature monitored for those two days.

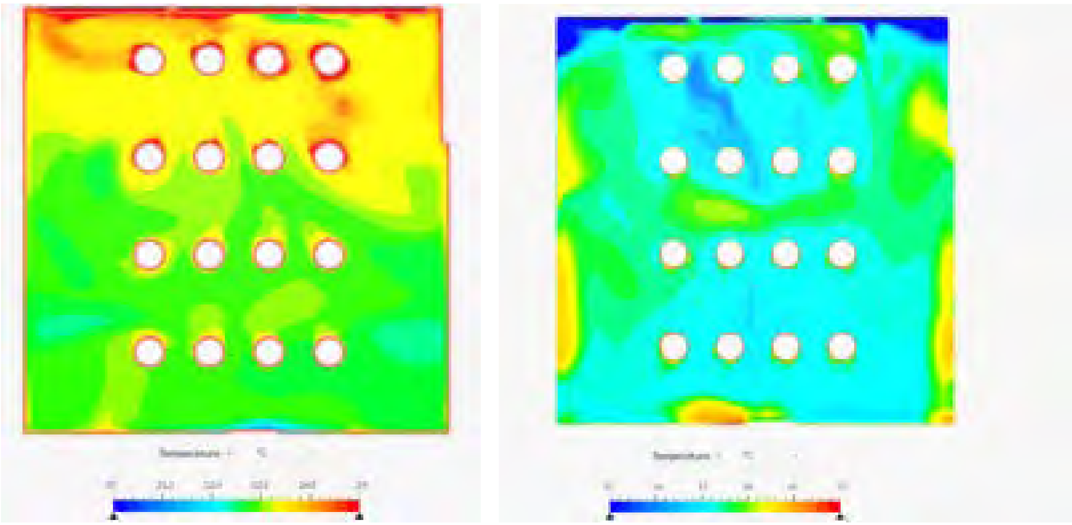
3.1. Temperature distribution

Table 1 shows average temperature at working plane for various scenarios. The ideal arrangement for summer is Scenario 2 with average temperature of 23.7°C. For Scenario 2, the equipment can handle instances where maximum temperature reaches above 39°C and temperature below the required setpoint temperature can be achieved even during extreme days.

Table 1: temperatures for various scenarios during summer and winter

Scenarios	**Summer**		**Winter**	
	T_{min}	T_{avg}	T_{min}	T_{avg}
1	21.1	23	10.2	16.4
2	20.9	23.7	10.2	16.9
3	20.6	22.9	9.8	16.5
4	21.5	23.5	10.2	16.6
5	21.5	23	10	16
6	20.2	22.7	9.5	17
7	21.2	23.2	9.7	16.6

Figure 3 (a) shows the temperature distribution of Scenario 2 during summer. Higher temperature can be observed around the windows as a result of solar radiation passing through the single glazed window. However, there is an even distribution of the temperature on the other areas.



(a) (b)

Figure 3: Temperature distribution (a) for Scenario 2 during summer; (b) Variation 6 during winter

The ideal arrangement for winter is Scenario 6 where average temperature is 16.98°C which is 3.02°C below the setpoint. All the simulations have demonstrated that the room is not capable of handling extreme winter days. Figure 3(b) shows the temperature distribution of the room during winter and there is better distribution of temperature throughout the areas where students are seated.

3.2. Predicted Mean Vote

Predicted mean vote indicates the extent of comfort for the occupants. Table 2 shows the predicted mean vote profiles for various scenarios during summer and winter. Although there is high temperature near the window area as seen in Figure 3a, the PMV values (Figure 4a) are still below the acceptable range. The simulation results indicate that the winter extreme is generally cold. This can also mean that heat loads do not account for extreme conditions of the year as it is designed based on year-round average ambient conditions. Even though extreme heat loads occur only during a fraction of the entire year, the equipment should be capable of handling this effectively with low efficiency. The colder environments are confirmed through multiple simulation runs and verification of inputs. Air velocity values were analysed to verify the factors influencing PMV values. The average velocity is around 0.15m/s which is not excessive. Therefore, it can be noted that the low PMV values are because of low temperature.

Table 2: PMV values for various scenarios during summer and winter.

Scenarios	Summer			Winter		
	min	ave	max	min	avg	max
1	-0.606	0.538	6.276	-4.38	-2.374	-0.582
2	-2.169	0.311	6.765	-3.626	-2.213	-0.594
3	-2.337	-0.161	6.371	-5.156	-2.356	-0.526
4	-1.33	0.143	6.491	-3.594	-2.245	-0.480
5	-1.538	-0.071	6.353	-5.078-	-2.468	-0.847
6	-2.541	-0.201	6.275	-4.689	-2.264	-0.652
7	-1.496	0.048	6.428	-1.496	-2.336	-0.684

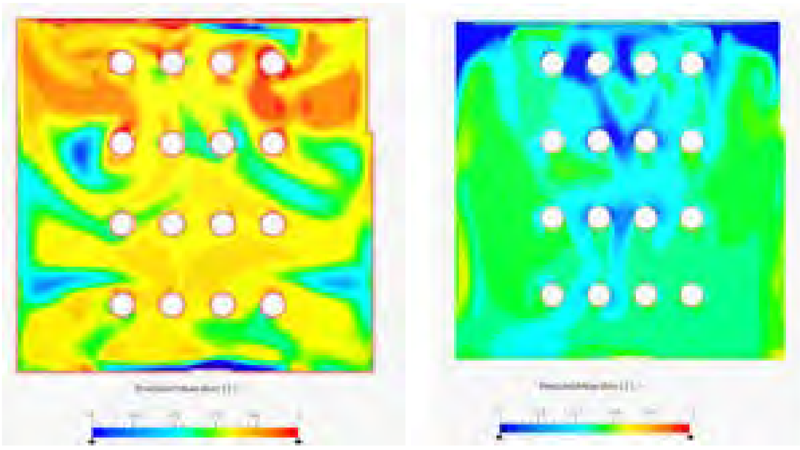


Figure 4: PMV distribution of Variation 2 (a) Summer (b) winter

Figure 4 shows the PMV distribution for Scenario 2 which was selected as the best scenario. During winter, The PMV distribution ranges from -1 to -3 as shown in Figure 4(b). Though this is on the colder side, the distribution is even.

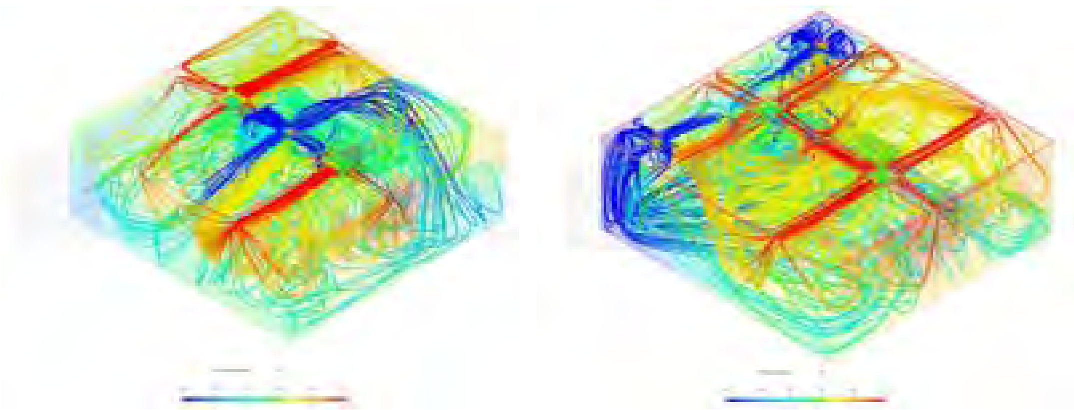
3.1. Mean age of air

The mean age of air is a reasonable measurement to identify if the air is stagnant in the room and to verify if minimum ventilation standards are met or not. AS 1668 require a minimum Outdoor air flow of 10 Ls−1 per person which is equivalent to 15 air changes per hour (ACH) for the classroom. The maximum age of fluid corresponding to 15 ACH is 4 minutes. Table 3 shows the mean age of air for all the scenarios. Scenarios 2 and 6 have the shortest mean age of air values making it the preferred arrangements.

Table 3: Mean age of air during summer and winter

Scenarios	**Summer**	**Winter**
	Mean age (minutes)	**Mean age (minutes)**
1	2.22	2.23
2	3.06	2.17
3	2.15	2.17
4	2.3	2.32
5	2.22	2.25
6	2.17	2.05
7	2.05	2.21

Figure 5 is an illustration of particle tracing which gives an indication of how the temperature changes across the room. An important factor to consider is the possibility of condensation when there is sudden difference in air temperatures.



(a) (b)

Figure 5: Particle tracing during winter for (a) Variation 2 (b) variation 6

Another simulation run was conducted with the same settings for Scenario 6 and with ambient winter condition of 2°C with the inclusion of Direct Outside Air System (DOAS). The flow rate of the cassette units was reduced from the full flow mode of 700 Ls^{-1} to the actual design flow rate of 592 Ls^{-1} split between the two units. The inlet temperature of outside air is assumed to be 17°C with the introduction of the DOAS. It can be clearly observed from Figure 6 that the temperature distribution is even across the room and the room has attained comfortable temperature during the extreme winter conditions with very minimal supply air flow rate, minimising the possibility of condensation and discomfort to the occupants. This enables a greater control of the indoor environment, but with increased capital and operational costs.

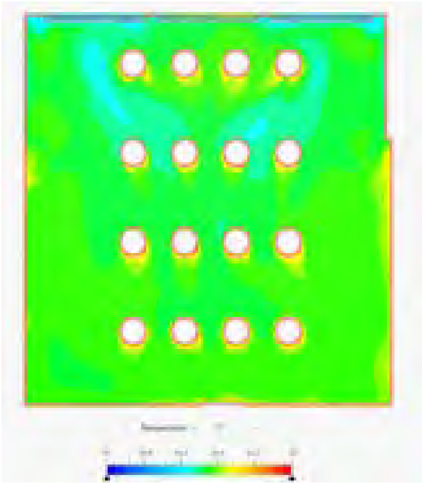


Figure 6:Temperature distribution with DOAS system introduced in Variation 6

4. Discussion

Due to the lack of clarity on ventilation standards, the HVAC industry has been using different workaround to save capital costs that will compromise thermal comfort and indoor air quality. The findings from this study highlight the necessity of providing proper guidelines in the National Construction Code and the Australian Standards regarding the installation of outside air systems. Recent studies have suggested that provision of mechanical or hybrid ventilation should be part of the standards for designing new schools. Such provision of mechanical ventilation caters for adverse weather conditions when doors and windows are closed. The perceived cost associated with implementing mechanical ventilation strategy can be considered as a barrier, which will be outweighed by the long-term health and socio-economic benefits. An integrated approach is required for designing and operating the HVAC systems.

The simulations conducted in this study provided insights about the temperature, comfort, and ventilation conditions of classrooms and how the arrangements of air inlets and outlets impact the performance. The realistic arrangement of the room will need to cater for both summer and winter. The results showed that though the HVAC equipment can cool the space easily it is unable to meet the loads on winter days. Another important factor to consider is the possibility of condensation when there is sudden difference in air temperatures. Therefore Scenarios 2 was not suitable due to the possibility of condensation as the air is directly in contact with the cassette unit air flow which has a temperature difference of more than 10°C. This interaction can be verified from the particle trace in Figure 5. Considering this, Scenarios 6 and 7 are the most suited arrangements. The results show that the use of two 300mm x 300mm return air outlets instead of one outlet will increases the distribution of the flow in the room by 4.1%. For even distribution of air, outside air outlet can be placed towards the external wall and the return air outlet can be placed completely on the opposite side of the room. The cassette unit placed in the centre in the same line of alignment was found to have the maximum effectiveness according to the simulation results.

To address thermal comfort and potential condensation issues during winter, a dedicated DOAS system which conditions the outside air to a certain extent before passing it to the room is recommended. If there are multiple spaces in the same building which requires exhaust, a heat recovery unit can be used to transfer the heat to the outdoor air which can greatly reduce the energy required for the room’s air conditioner and also improve the thermal comfort of the occupants.

5. Conclusions

The study used CFD simulations to investigate the performance of HVAC systems that uses outside air directly fed into the rooms and evaluate how ventilation and thermal comfort in school classrooms can be optimized. Even though the system helps to save cost by not treating the air prior to entering the room, it causes thermal discomfort for the occupants and possible formation of condensation. The results show that room’s heat loads, and the equipment selection are suited for normal air-conditioning operation. The equipment is also capable of catering for extreme summer but are undersized for winter’s extreme conditions. Several variations by changing the location of the cassette units and the number of inlets and outlets suggested that there is only 4.1% increase in the efficiency with the change in the arrangement in terms of the location of the cassette units and the location and the number of outside air and return air openings. The use of Direct Outside Air System (DOAS) or a heat recovery system is recommended to address these issues. The results using such system showed that average temperature during winter increased 17.2%.

This study has limitations as only cassette units with square diffusers were modelled though there are other types of diffusers like swirl diffuser, linear slot diffusers with wall mounted split air conditioner. A comparison of capital and maintenance cost of the proposed variations and the introduction of DOAS can provide more insights for retrofitting existing buildings and new design. Furthermore, a thermal comfort survey of the occupants will help to see how simulated comfort correlated with the comfort perceived by the occupants.

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Regulation for comfort: an investigation of policy and practice in Australian homes

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Abstract: On average, 40% of energy consumed in residential buildings in Australia is expended towards space conditioning to ensure comfort and well-being of occupants. While national regulations have focused on the thermal efficiency of the building fabric, that is assessed in relation to predicted energy based on heating and cooling setpoints, less attention is paid to the actual practices and outcomes for occupants in these buildings. Previously published findings from a two-year monitoring study of 40 homes in western Sydney (by the authors) indicate that while some occupants adopted adaptive practices such as adjusting clothing and using ceiling fans before resorting to air-conditioning, a lower tolerance of 'imperfect' conditions and availability of air-conditioning on standby led to increased usage for others. In this paper we reflect on occupant practices as they relate to the regulatory landscape and systems such as NATHERS in Australia to investigate how thermal comfort is perceived, mandated and provided for in residential settings. We compare actual occupant practices elicited from the aforementioned study against the assumptions built into the Australian regulatory systems to identify differences. Computer-based modelling is used to study how these alternate occupancy settings impact energy, comfort and implications for the building fabric. The paper highlights the implications of rating assumptions - such as bedrooms are only occupied at night, and unrealistically low thermostat settings in winter - which are out of touch with observed and prevailing practices. The resulting underestimation of energy use has the potential to compromise the thermal performance and specifications of the building envelope by the equivalent of a one star under NATHERS. Our findings call for changes in the regulations whereby bedrooms be assessed with a night time heating set point of 18°C instead of 15°C and are also tested for comfort during the day, and that the necessary improvements to the building fabric to account for these changes are mandated.

Keywords: residential energy, comfort, rating tools, occupants.

1. Introduction

The family home ideal can be thought of as a comfortable and safe environment for its occupants. In the last few decades, the expectation of energy efficiency and net zero emissions outcomes have also been added to this list. These latter imperatives are even more critical as we see a more urgent impetus via the IPCC's latest report calling for sufficiency (reducing the energy consumed) and distinguishing this approach from reliance on more efficient technologies such as PV to generate the energy we need in the

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built environment (Cabeza et al, 2022). On average, 40% of energy consumed in residential buildings in Australia is expended towards space conditioning to ensure comfort and well-being of occupants (DISER, 2021). While national regulations have focused on the thermal efficiency of the building fabric, less attention is paid to the actual practices and outcomes for occupants in these buildings.

Sustainable performance for houses has largely been rated using the NATHERS (Nationwide House Energy Rating System) since the 1990s. The system has been embedded into Vol 2 of the National Construction Code (NCC) which deals with Class 1 (houses) buildings since 2003 and Class 10, not the subject of this paper, since 2010. In NSW, BASIX or Building Sustainability Index, was introduced by the government of New South Wales, on 1 July 2004 to regulate the energy efficiency of residential buildings, which also included a NATHERS performance pathway for compliance. As noted on its website, BASIX assesses the *'energy and water use and thermal comfort of your residential development'* (DPIE, 2023). Here the predicted NATHERS 'heating and cooling caps' or *predicted heating and cooling annual energy use* is used as a proxy for thermal comfort - evaluating the extent to which the building design and envelope would need to rely on heating and cooling to deliver thermal comfort based on stipulated heating or cooling setpoints. This approach whereby building envelope performance in residential buildings is benchmarked in terms of predicted annual heating and cooling energy is reinforced in the National Construction Code NCC Vol 2. Applicable (in various versions) across most states and territories, the predicted annual heating and cooling energy is translated to 'stars' bands or ratings.

A number of studies (Moore et al, 2015; O'Leary et al, 2016 and Miller et al, 2021) have investigated the gap between predicted and actual performance of residences and have highlighted discrepancies due a mismatch between what is built and what is modelled, occupant behaviour and expectations out of sync with regulatory assumptions, and inadequacy of the standards to deal with variations in climate.

The intersection of these house performance rating systems and this paper is in the area of thermal comfort as assessed by residential rating tools in Australia. In 2018, the World Health Organisation proposed temperature limits for safe and well-balanced internal conditions for houses, the lower limit being 18°C (WHO, 2018). Their guidelines considered research on health implications like allergies. Barlow et al (2023) have recently published work that shows that more than 80% of monitored Australian houses, in temperate zones with high levels of population, have winter temperatures that are lower than this 18°C limit. Although their research does not nominate the spaces where these temperatures were monitored, another matter of interest is how comfort is assessed in various rooms, given a historic assumption of delineating spaces in homes as day time zones and others as night time zones

2. Study Approach

In a quest to understand occupant practices as they relate to the regulatory landscape within NATHERS, we compare actual occupant practices against the assumptions built into the Australian regulatory systems to identify differences. We focus on two aspects - monitored data in specific spaces (rooms) in Australian houses with a view to understanding occupancy and temperature settings, and the predicted energy consequence of mitigating thermal discomfort in bedrooms. We also provide insights to the energy penalty incurred when bedrooms are more frequently used in the daytime in the context of modern Australian family life.

Our study of occupant practices draws on real, monitored data from households from a two-year monitoring study of 40 homes in western Sydney from between 2019 to 2021 (Thomas et al 2022a).

The homes form part of an 830 home estate and were all furnished with a energy efficient ground source heat pump air-conditioning system and designed to comply with the prevailing BASIX requirements of 2013. Previously published research (Thomas et al 2022b) indicates that while some occupants adopted adaptive practices such as adjusting clothing and using ceiling fans before resorting to air-conditioning, a lower tolerance of 'imperfect' conditions and availability of air-conditioning on standby can also result in increased usage of conditioning. These homes in Western Sydney were monitored for their energy use by end use including air-conditioning, with additional sensors tracking temperature, humidity, air quality as well as occupancy in the living room and the main bedroom of the house. The data collected enables us to selectively understand practices when the house is occupied, both in relation to rooms occupied, coincident temperatures tolerated or maintained in these spaces when AC is in use and when it is not during those times. The study period commenced in September 2019 prior to the Covid pandemic, and included the shut-down periods of Lockdown 1: 2020-03-23 – 2020-05-30 and Lockdown 2: 2021-06-23 – 2021-10-11, and the period in between.

Given that NATHERS heating and cooling set points are set as a proxy for thermal comfort, and most buildings tend to "just comply" with the regulatory yardstick (Moore et al, 2019), the study seeks to understand the impact any variation observed would have on the thermal performance and star rating of the house. Given the latest revisions of the NCC effective from 1 October 2023 already improve the required performance to 7 stars, in the present analysis of the monitored study, we focus on understanding observed occupant practices and compare these to those that are built in to the assumptions of NATHERS, especially in relation to the heating and cooling set points as well as occupancy patterns in the homes. Any observed tendency of the occupants to use heating or cooling to a greater extent emphasizes that the thermal efficiency of the building fabric will need to be more efficient to combat its use.

Under the current NATHERS regime, the heating set point in living rooms is 20°C between 7 am and midnight. In bedrooms, the heating set point is 18°C between 7-9am and 4pm to midnight and interestingly drops to 15°C between midnight to 7am. The upper limit for the cooling setpoint is the neutral temperature based on the adaptive model equation, which is 24.5.C for Western Sydney – climate zone 28. Across the year, with an assumption of non-occupancy, living rooms are not tested for thermal comfort between midnight and 7am, likewise bedrooms are not tested during the daytime hours of 9am to 4pm.

Findings from our study of 40 monitored homes are presented below, and are used to inform the rationale for the various changes to NATHERS settings we then investigate. Computer-based modelling is used to study how these alternate settings impact energy, comfort and implications for the building fabric. A run plan was set up to test the impact within NATHERS (see Table 1) on three selected house plans. As a starting point, the base case was considered to be each home already performing at a 7-star level as per NCC 2022 and the runs were completed using the AccuRate engine version 2.4.3.21SP1 with all settings exactly as per the NATHERS regulatory mode. Star bands are calculated from simulated energy use following the NATHERS procedure.

3. A Review of monitored practice from 40 homes in Western Sydney

3.1. Observed Temperatures

The box and whisker plots in Figure 22 and Figure 23 provide an indication of the temperatures observed in the bedrooms and living rooms across all 40 study homes when these spaces are occupied. Coincident hourly internal temperatures from comfort sensor monitoring and the on/off status of the AC system based on submeter energy monitoring for the AC channel for all 40 houses are shown. Spaces are deemed occupied when the coincident IR occupancy sensor registers motion. Our analysis includes both Covid and non-Covid periods as this is not expected to influence occupant practices in relation to resorting to AC or the temperatures maintained or tolerated with or without it. The plots are separated for Winter months of June July and August and Summer months of December January and February during the two-year study period, and broken down into the hour blocks currently used in NATHERS for thermostat setpoints in these rooms to allow for easy comparison.

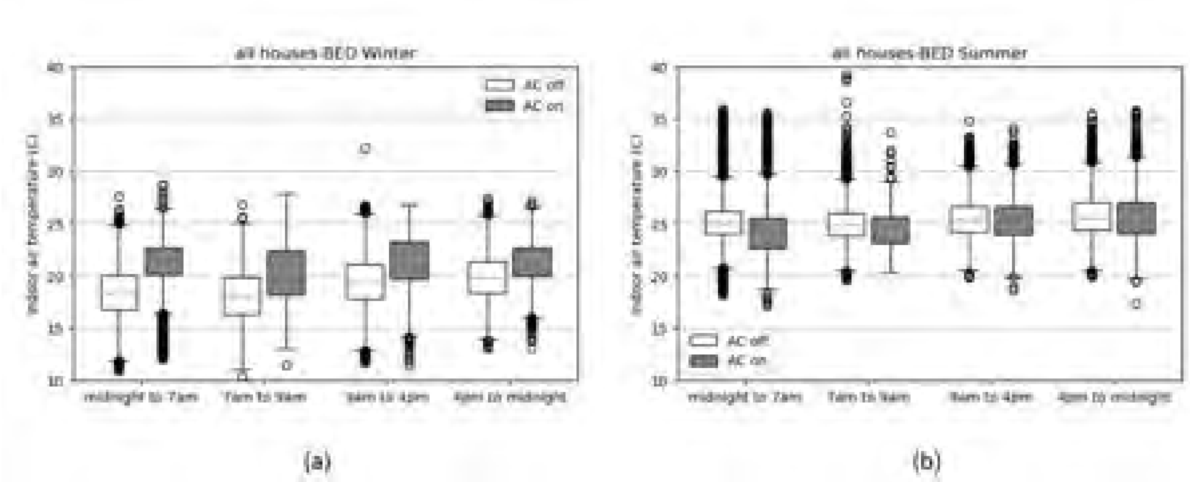


Figure 22: Box and Whisker plot of indoor air temperature observations during Winter and Summer in the Bedrooms (data source: Fairwater Living Laboratory)

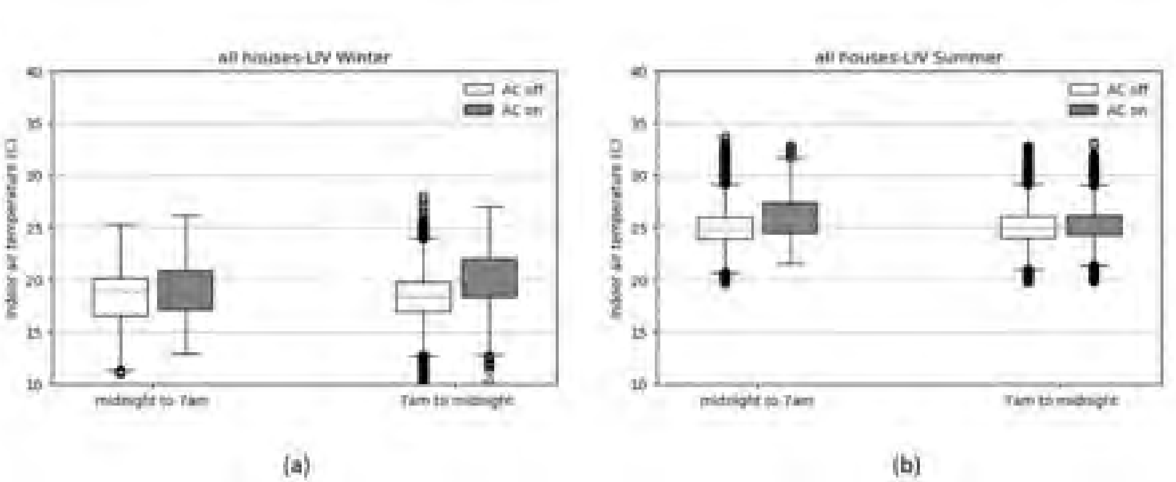


Figure 23: Box and Whisker plot of indoor air temperature observations during Winter and Summer in the Living Rooms (data source: Fairwater Living Laboratory)

In winter, the observed median bedroom temperature at night (midnight to 7am), whether AC is on or not, is higher than the NATHERS assumed overnight heating setpoint of 15 ° C (Figure 22), and 75% of the occupied nighttime hours are above ~16°C without AC and above ~20°C with AC on. If the AC thermostat in the bedrooms was set to 15°C overnight, as assumed by NATHERS, the night-time temperatures coincident with the AC operating would be clustered below or close to the thermostat setpoint temperature of 15°C. This is not consistent with the monitored data which shows that almost all nighttime bedroom temperatures with the AC on are well above 15°C, indicating the thermostat setting for the AC must be considerably higher in practice. In the periods 7am-9am and 4pm-midnight where the NATHERS bedroom thermostat assumption is 18°C, more than 75% of observed hours with the AC on are above this temperature, indicating that the actual bedroom thermostat setting is higher than 18°C.

In summer, the NATHERS cooling setpoint is 24.5°C for climate zone 28 as per NATHERS adaptive comfort settings. If occupant practice was consistent with this assumption, room temperatures with AC on would be clustered close to or below this temperature. The observed temperatures at night in summer in the bedrooms whether AC is on or not are below 26°C 75% of the time, indicating reasonable agreement with the assumption.

In the living room, the daytime NATHERS assumed thermostat settings are 20°C for winter and 24.5°C in summer. As seen in Figure 23, 75% of daytime hours with the AC on are above 18°C in winter and below 26°C in summer. There are limited instances where the living room is occupied between midnight and 7am, however the pattern observed in the bedrooms is similar here.

3.2. Occupancy

Figure 24 shows the average percentage of houses across the 40 study homes where occupancy sensor readings were observed by time of day in the Living Rooms and main Bedroom, regardless of AC on/off status. As the study period extended before during and after Covid lockdowns a breakdown is provided - during the pre Covid-19 lockdown period from 1 September 2019 to 21 March 2020 (a and b); Lockdown 2 from 23 June 2021 to 11 October 2021 (c and d) and the period between lockdowns from 1 June 2020 to 22 June 2021 (e and f). It should be noted that the results for Lockdowns 1 and 2 are very similar, and only Lockdown 2 is shown below as this was the longer of the two periods and the mandated restrictions on movement and gathering were more consistent across this period.

The monitored data clearly indicates that on average there is high level of occupancy across the study houses – in the living rooms (plots a, c and e) for all hours (typically 60 to 80%) between the period of 7am and midnight. This is consistent before and during covid lockdowns and also across the two year study period. This level of occupancy validates the approach under NATHERS to test for comfort in living rooms for all "waking hours" in the living rooms zones. Night time occupancy of the living zones indicates occupancy levels remain low in all scenarios (below 20%.)

With respect to occupancy in the bedrooms it should be noted that the night time movement in the bedrooms is grossly under reported by occupant sensors which relied on occupant movement as occupants remain motionless for much of the time that they are asleep. Consequently, we have also included the calculated occupancy between midnight and 7am in the bedrooms based on whether the houses were occupied for the previous evening – these are depicted as crosshatched areas (See Figure 24 b, d and f). These observations consistently suggest 85-90% occupancy overnight.

While day time occupancy in the bedrooms is highest between 7am and 9am and 4pm and midnight, the sensor data also shows that occupancy in the daytime 9am to 4pm is consistently above 30% on average even prior to Covid. Analysis of the data for individual houses shows that the bedroom only appears to be consistently unoccupied (<20% occupancy) in two houses between 9am and 4pm in the period prior to Covid. In addition, approximately 20% of the houses have a bedroom occupancy above 60% for several hours between 9am and 4pm.

The exact reasons for occupancy in bedrooms are unclear, but household surveys across the 40 households prior to Covid are suggestive of a high level of occupancy of homes at various hours of the day. Only 47% of the household members nominated typical "out of home" daytime occupations such as "employed full time away from home" or "full time student". 36% of all the household members were nominated as "stay at home", or "work from home" or "pre-schooler at home". Our results already call in to question the implied assumption of non-occupancy of bedrooms within NATHERS and its settings whereby comfort is not tested between 9am and 4pm in the bedrooms.

As can be seen in Figure 3, average daytime occupancy in bedrooms is above 40-50% during the Covid-19 lockdown and at least 35-40% when considering homes in the periods between the two lock downs. Examination of the individual house occupancy results indicates that there are no houses with daytime bedroom occupancy levels below 20% during lockdown, only two houses with low bedroom occupancy between lockdowns, and there are several houses with high day time bedroom occupancy (>60%) during both these periods.

The Covid-19 lockdown, and 'between lockdown' occupancy sensor results seen in the study (Figures 3 d and f) point to the new normal of increased occupancy of zones typically considered as night time zones, in addition to the living zones especially as work from home increases. This practice of occupying and adapting bedrooms and alternate spaces in the home for work was also corroborated in our occupancy survey. These observations highlight a further shift in the way bedrooms are used and further emphasise that day time comfort in these spaces must not be ignored.

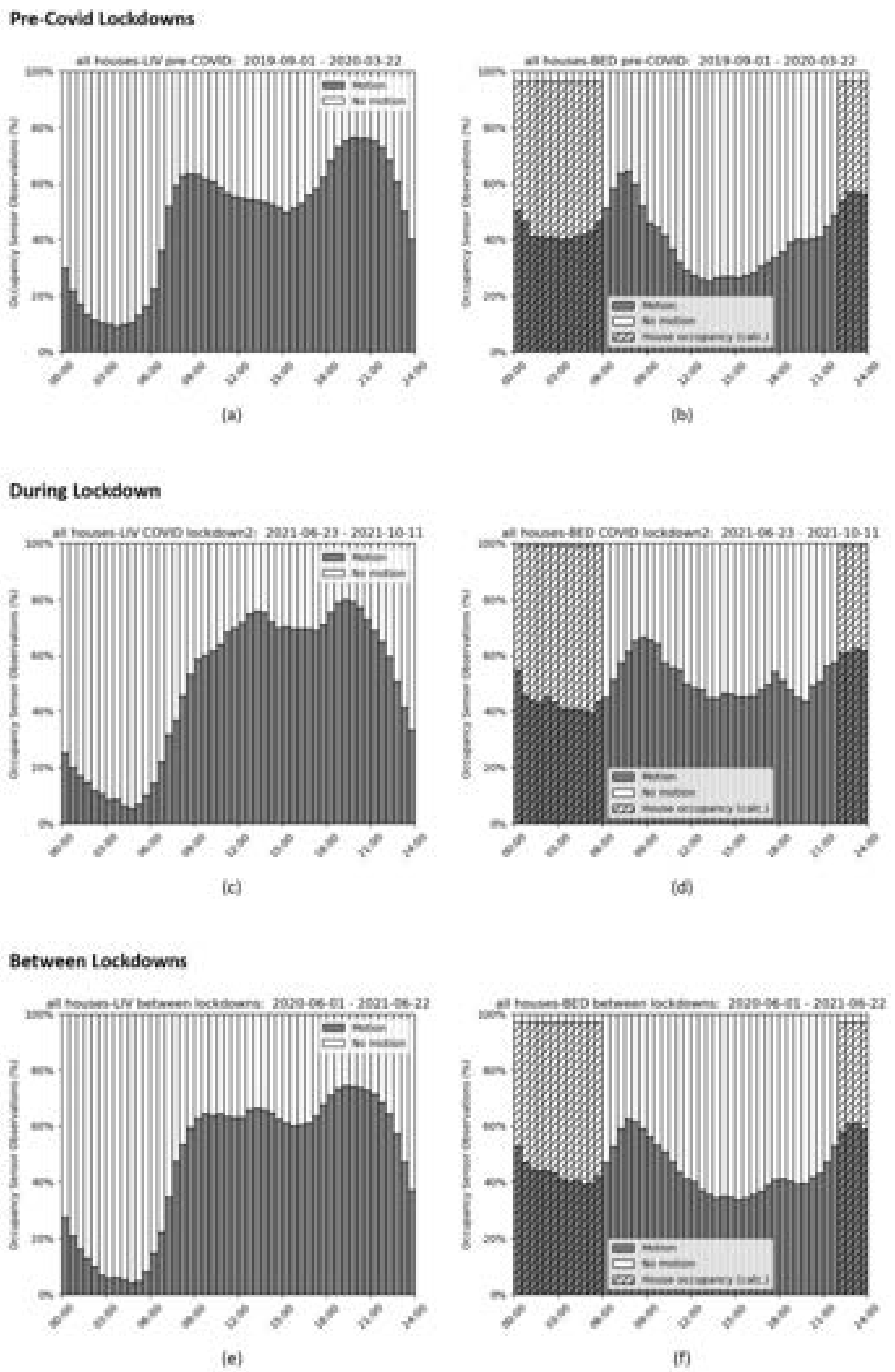


Figure 24: 24 hour Occupancy Sensor Observations in Living and Bedrooms (data source: Fairwater Living Laboratory)

4. Simulation and Modelling outcomes

5.1. Description of the modelling assumptions

On the basis of the results in Section 4, two major departures from NATHERS modelling assumptions were identified for testing:

- The first relating to thermostat setting for heating at night between midnight and 7am in the bedroom or night time zones
- And the second, relating to the need for testing for comfort in the bedroom zones during the day between 9am and 4pm where no testing is currently done within NATHERS.

Table 11: NATHERS Simulation Run Plan and Settings

Run	Description	Heating Set Points		Cooling Setpoints	
		Bedroom	**Living Room**	**Bedroom**	**Living Room**
Base Case 7 stars Code compliant* for CZ28	Base Case NATHERS thermostat settings unchanged for all zones	7.00-9.00: 18C 9.00-16.00: N/A 16.00-24.00: 18C 24.00-7.00: 15C	7.00-24.00: 20C 24.00-7.00 N/A	7.00-9.00: 24.5C 9.00-16.00: N/A 16.00-24.00: 24.5C 24.00-7.00: 24.5C	7.00-24.00: 24.5C 24.00-7.00 N/A
Run 2	Run 1 + **All bedroom zones** thermostat setpoints set to 18C from midnight-7am	7.00-9.00: 18C 9.00-16.00: N/A 16.00-24.00: 18C **24.00-7.00: 18C**	7.00-24.00: 20C 24.00-7.00 N/A	7.00-9.00: 24.5C 9.00-16.00: N/A 16.00-24.00: 24.5C 24.00-7.00: 24.5C	7.00-24.00: 24.5C 24.00-7.00 N/A
Run 3	Run 2+ **Master Bed room zones** @ 24 hr occupancy; apply daytime thermostat between 9am-4pm	7.00-9.00: 18C **9.00-16.00: 20C** 16.00-24.00: 18C **24.00-7.00: 18C**	7.00-24.00: 20C 24.00-7.00 N/A	7.00-9.00: 24.5C **9.00-16.00: 24.5C** 16.00-24.00: 24.5C 24.00-7.00: 24.5C	7.00-24.00: 24.5C 24.00-7.00 N/A
Run 4	Run 2+ **All bedroom zones** @ 24 hr occupancy, apply daytime thermostat between 9am-4pm	7.00-9.00: 18C **9.00-16.00: 20C** 16.00-24.00: 18C **24.00-7.00: 18C**	7.00-24.00: 20C 24.00-7.00 N/A	7.00-9.00: 24.5C **9.00-16.00: 24.5C** 16.00-24.00: 24.5C 24.00-7.00: 24.5C	7.00-24.00: 24.5C 24.00-7.00 N/A

The Simulation Run Plan and Settings are set out in Table 1.

Three house plans (Figure 25) were selected to test the implications of the altered thermostat settings and occupancy for bedrooms within the climate zone of interest. Each have four bedrooms and were tested for an east facing orientation for the main bedroom. While House B is a single floor house, House A and C are double storeyed and representative of our study houses, and many western Sydney developments where main living zones are on the ground floor and bedrooms are on the upper floor. To control for other impacts, the street and garage orientation is East facing, making the master suite typically east facing and the main living zone predominantly west. As previously noted all three house models were set up so the Base Case in each house would "just comply to 7 Stars as per NATHERS heating and cooling caps for 2022. In all cases construction included, bulk ceiling insulation (R4.0) and thermally broken double-glazed window (U value 2.5W/K.m2, SHGC 0.39) and construction of external walls were either insulated brick veneer (R2.96) or insulated FC Cladding (R2.91), with a concrete ground floor slab and intermediate floors as Hebel floors for Houses A and C.

Figure 25: House Layout Plans

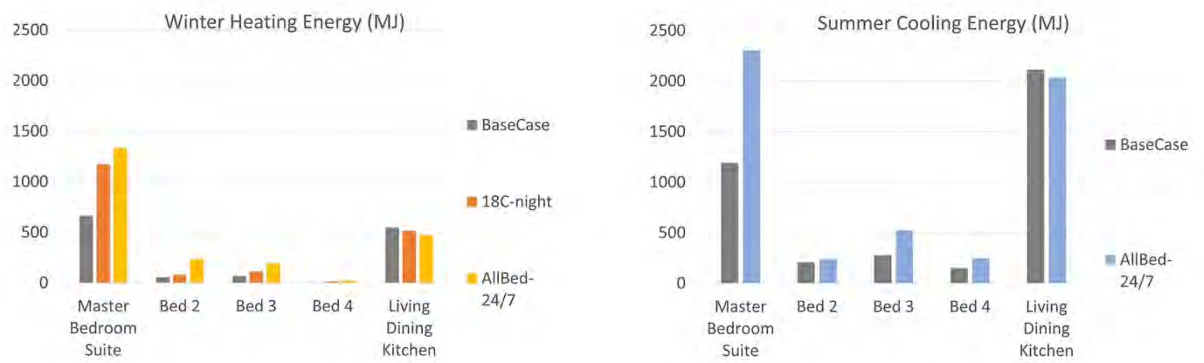
Based on the monitored data, the heating setpoint of 15°C was considered too low. A revised heating setpoint for night time could arguably be set based anywhere from 18 °C which is the lower quartile threshold when AC is off or even 20 °C based on the lower quartile threshold when AC is on. However, from a health perspective and in keeping with WHO guidelines: *"For countries with temperate or colder climates, 18°C has been proposed as a safe and well-balanced indoor temperature to protect the health of general populations during cold seasons"* (WHO, 2018) we have chosen to adopt the 18°C setpoint. Consequently, for subsequent runs, the AccuRate engine input scratch file was edited to adjust the heating set point from 15 to 18°C for midnight to 7am for all bedrooms (Run 2, 3 and 4). When rethinking the bedrooms as daytime spaces between 9-4pm, we then set the heating and cooling setpoints to be 20°C and 24.5°C in line with the other daytime zones under NATHERS. The progressive impact of applying this first to the Master bed and then to All bedrooms is set out for Runs 3 and 4.

5.2. Results

Table 12: Annual Heating and Cooling Energy and Star Rating for Study Houses

	HOUSE A *Total Area 234 m², Conditioned Area 161m²*							***HOUSE B*** *Total Area 201 m², Conditioned Area 128m²*							***HOUSE C*** *Total Area 302 m², Conditioned Area 210m²*						
	Heating Energy MJ/m2-yr		*Cooling Energy MJ/m2-yr*		*Total Energy MJ/m2-yr*		*Stars*	*Heating Energy MJ/m2-yr*		*Cooling Energy MJ/m2-yr*		*Total Energy MJ/m2-yr*		*Stars*	*Heating Energy MJ/m2-yr*		*Cooling Energy MJ/m2-yr*		*Total Energy MJ/m2-yr*		*Stars*
Base Case	**21.1**		**36.5**		**57.6**		7	**43.2**		**23.8**		**66.9**		*7*	**24.7**		38.4		**63.1**		*7*
Run 2	**24.3**	*15%*	**36.6**	*0%*	**60.8**	*6%*	6.8	**48.1**	*11%*	**23.8**	*0%*	**71.8**	*7%*	*6.8*	**29.8**	*20%*	**38.5**	*0%*	**68.2**	*8%*	*6.7*
Run 3	**24.9**	*18%*	**42.8**	*17%*	**67.7**	*18%*	6.4	**49.2**	*14%*	**25.6**	*8%*	**74.8**	*12%*	*6.6*	**30.8**	*25%*	**41.4**	*8%*	**72.2**	*14%*	*6.5*
Run 4	**25.8**	23%	**44.9**	23%	**70.7**	23%	6.2	**53.1**	23%	**26.8**	13%	**79.9**	19%	*6.4*	**31.9**	29%	**47.5**	24%	**79.4**	26%	*6.1*

% change shown above refers to the increase in energy with respect to the Base Case set at the updated compliance level of 7 stars.



(a) (b)

Figure 26: HOUSE A – Step Change in Seasonal Heating and Cooling Energy with reference to its 7-star BaseCase. (Source: Authors)

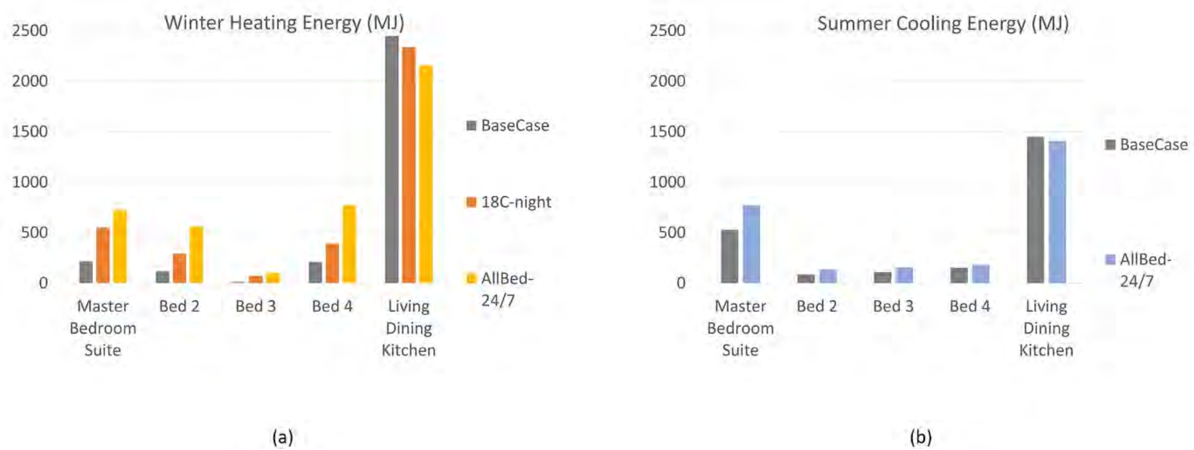


Figure 27: HOUSE B – Step Change in Seasonal Heating and Cooling Energy with reference to its 7-star BaseCase. (Source: Authors)

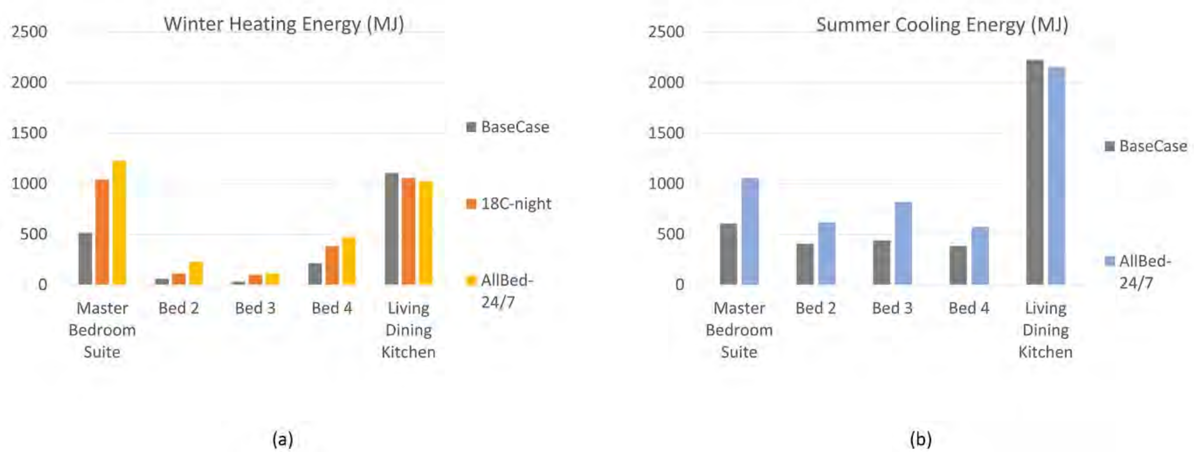


Figure 28: HOUSE C – Step Change in Seasonal Heating and Cooling Energy with reference to its 7-star BaseCase. (Source: Authors)

When considering the performance of the homes in annual terms, Table shows that changing the night time thermostat results in a 6%-8% increase with respect to the base case, and when combined with the consideration of day time use of bedrooms, this increases to 19-26%.

When considering just the three winter months, in comparison to their base case, the heating energy in winter across bedrooms in the three houses increased by 75% in House A, 100% in House C and 130% in House–B – roughly double on average when setpoint changed from 15-18C. See Figure 26, Figure 27, and Figure 28. During the same period, the combined effect of set point at night and bedrooms occupied during the day is at least double to over three times the heating energy of the base case in the three homes studied (126% in House A, 148% in House C and 291% in House B.

Considering the bedrooms to be occupied over the day in summer also has a significant effect, with the increase at individual bedroom level anywhere between 30% and 100% of the base case and an average increase of 40% across the three houses.

5. Discussion and Conclusion

The results for occupant practices in the monitored homes reveal that some settings within NATHERS are out of touch with observed and prevailing practices and could be compromising the intended thermal performance of houses.

Heating set points: The results for monitored temperatures clearly show that the adopted heating setpoints are higher than the NATHERS heating setpoint of 15°C overnight, and once heating is deployed, space temperatures are maintained around 20C. As such the present NATHERS assumption is not reflective of user practices. While it is true that people do adapt to colder temperatures with the benefit of quilts and sweaters and other adaptive practices, the focus of this paper is on ensuring mandatory stringencies to ensure building fabric performance is not compromised especially once heating is deployed. Moreover, we argue that the fabric must be tested for comfort against at least the minimum health guideline of 18°C for night time and agree that NATHERS daytime heating setpoint continue to be 20°C.

The impact and significance of changing the thermostat from 15 to 18°C at night is best understood at the seasonal level for Winter. Given that unconstrained energy estimates in NATHERS are a proxy for thermal discomfort, the doubling of heating energy in the Bedroom zones across the Winter season shows the scale of increased discomfort if the 18°C yardstick was applied to assess night-time performance of code compliant homes under the new NCC. When considered in terms of annual energy, the energy impact of changing the set point from 15 to 18°C seems small (roughly 6-8% as seen in Table 1). However, given health risks previously discussed and the race to lower energy consumption in homes, this is not an energy penalty that can be ignored, but rather one that should be combated with improved building design and thermal performance.

Daytime comfort in bedrooms: Bedrooms may be envisaged as places for sleeping in an idealised world. However, increased pressure on rents, adult children staying at home, requirements and choices for multiple family members working from home, requirements such as caring for children or invalids in bedrooms would suggest that bedrooms are increasingly used as multi-functional spaces (Dincer et al, 2023). As reinforced through our occupancy results, bedrooms must no longer be considered simply as the "night-time" zone envisaged in NATHERS, wherein the heating/cooling energy requirements are not tested between 9am and 4pm.

As shown in our modelling results, the building fabric in the three homes that would be assessed to be code compliant would in fact, incur additional energy penalty when bedrooms are considered to be occupied in the daytime. This indicates that the treatment of bedrooms merely as night-time zones, means the rating tool is ignoring the daytime discomfort both in winter and in summer in the bedrooms and overlooking the need for an improved building fabric that would be required to combat this.

Study limitations: We acknowledge our findings in this paper depict implications for just one climate zone and further research will be required to ascertain the impact under different climate zones, house types and future weather scenarios. Further work is envisaged in this respect. Nonetheless our analysis for Western Sydney climate is noteworthy as it is one of the regions that is experiencing exponential development in the country. (Morrison and Van den Nouwelant, 2020)

The question of night-time heating set point may be perceived as less important in the context of warming temperatures. However, further to the prevalence of cold in Australian homes and health imperative previously discussed (Barlow et al, 2023 and WHO, 2018), it should also be noted that predictions for climate change continue to acknowledge cold snaps with risks from cold being greater for people with health and economic vulnerabilities (Baker et al, 2020). Moreover, the concern for warming temperatures in future summer only reinforces the need to pay careful attention to the bedroom zones in the interest of ensuring all spaces in homes remain resilient to a changing climate.

As a further caveat, we note that our present analysis remains unquestioning of air-tightness in the houses. While the NCC implies an infiltration rate of 10ach, previously published research (Ambrose and Syme, 2015) of blower door tests in Australian homes suggest infiltration could be as high as 30 ach. If indeed efforts are not taken to ensure infiltration matches modelled assumptions then our results particularly for heating would be under predicted, and the building fabric would need to work harder to compensate for infiltration losses.

Although our monitored data already suggests a tolerance of temperatures around 25-26°C in summer, the cooling setpoint of 24.5°C prescribed under NATHERS has been retained in the present analysis. From the perspective of future warming climates, we acknowledge that the 24.5 cooling setpoint would be expected to increase based on the adaptive model of comfort. However, we anticipate using the current setpoint within present day weather files ensures a more stringent building fabric, that could then be expected to remain resilient in a warming climate.

Implications for the Rating System: Assuming the current energy budget under NCC 2022, our findings show that a home in western Sydney that is assessed to be compliant under current settings would drop by nearly a full star band with an accompanying energy penalty of up to 26% per annum from the combined effect of night time heating setpoint and day time use of bedrooms

Our findings point to an underestimation of energy use which has the potential to compromise the thermal performance and specifications of the building envelope. We call for an update to NATHERS settings to ensure bedroom thermal comfort and fabric performance is not overlooked **and we would recommend bedrooms be assessed with a night time heating set point of 18°C instead of 15°C and also stress the need to test for comfort in bedrooms during the day.**

The urgency for reduction in CO_2 emissions from this sector means that it is imperative that current energy budget must not be diluted. Given the star bands are based on a particular energy budget per climate that seeks to steer the housing stock towards its decarbonisation strategy, we also take the view that these budgets cannot be increased when testing for comfort. In other words, in the face of increased energy predictions from revised settings, we argue **further improvements to the building fabric are needed to maintain the overall thermal efficiency into the future.**

Additionally, with a view to sufficiency, and as discussed elsewhere (see Thomas 2022b), rating tools and policy must protect adaptive and sustainable practices through requiring homes with effective natural ventilation that include adaptive opportunities such as secure openable windows, ceiling fans as well as encourage indoor–outdoor living opportunities to acclimatise occupants to a wider range of temperatures and support occupant education and engagement towards such practices.

Considerations for existing homes: While our discussion up to this point have been in relation to the rating scheme for newly built homes, the findings are also relevant to existing homes. Firstly, it is worth noting the vulnerability of the building fabric will apply to a greater extent to homes that were deemed compliant even at 5-star level (2006 onwards) and 6-star level (since 2010 depending on jurisdictions) and until new provisions come into effect. We also suggest that as NATHERS turns its attention to existing homes, the system carefully consider the manner in which occupants use their homes is correctly reflected, especially as the tool is expected to inform retrofitting decisions. For instance, our past experience has shown that it has been possible to comply with 5 and 6- star requirements with single glazed windows in a western Sydney climate. Recognizing the energy penalty and consequences to bedroom discomfort could become the impetus to consideration of double glazing and other improvements to the building fabric from a thermal comfort point of view well before offsetting energy used with solar panels when retrofitting homes in these climates.

In conclusion: While NATHERS is designed to benchmark thermal performance and is not in itself a predictor of actual energy use, it is only useful as a rating system if it delivers the CO2 emission reductions we need towards Australia's low energy trajectory. Settings within NATHERS must therefore be reflective of user practices especially as they establish policy settings for building envelope stringencies. The reality suggests that in contemporary households the design and comfort in all spaces especially bedrooms must be taken more seriously than is currently acknowledged in the tool. Our study points to an underestimation of energy use has the potential to compromise the thermal performance and specifications of the building envelope by the equivalent of a one star under NATHERS. Our findings call for changes to regulatory settings that ensures bedrooms be tested for comfort more stringently as outlined above, and that the necessary improvements to the building fabric to account for these changes are mandated.

6. Acknowledgements

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Rethinking architectural typologies in times of change – Integrating food production with high-rise residential development for resilience

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Abstract: Despite importing more than 90% of its food to meet its local needs, Singapore is ranked the fourth most food secured country in the world, according to the 2017 edition of the Global Food Security Index. Singapore achieves this by adopting a successful food security strategy that is heavily dependent on the global food supply chain and diversification of sources. Yet, considering the recent coronavirus pandemic and the growing threats from the impacts of climate change, a new strategy is needed. Such complex problems will require a design-led approach, leveraging on methods such as foresight, scenario planning and transition design. This paper examines the resiliency of Singapore's food security and explores, through a scenario planning study, the possible roadmap for Singapore to enhance its food security through integrated architectural typologies. Approximately 80% of Singapore's population live in public housing. This presents a unique opportunity as the government has control over a large building stock. How might the Singapore government increase production of leafy green vegetables through Plant Factories with Artificial Lighting (PFAL) integrated with public housing. In a land-scarce country like Singapore, this presents an unique opportunity for agriculture to be practiced in a highly urbanised setting without using additional land.

Keywords: Integrated urban food systems. Design-led solutions. Food security. Plant factories with artificial lighting.

1. Introduction

In 2017, Singapore, which imports 90% of its food from more than 160 countries (SFA) to meet local needs, was ranked the fourth most food secured country in the world (SFA). It achieves this through a heavy dependence on international trade, ensuring that Singaporeans have access to readily available and affordable food that is safe and nutritious.

Climate change and its impact is a topic of growing concern. Increasingly, the reports produce by the IPCC shows that the impact of climate change is far more serious than we had anticipated. Yet, despite the numerous Conference of Parties (COP) in recent years, impactful change has been slow to materialise. The coronavirus pandemic exposed the challenges of a highly globalised supply chain and the lack of resilience in many countries. In a time of pandemic and climate change, Singapore faces unprecedented challenges that diplomacy and financial might have limited influence over.

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The war between Ukraine and Russia has seen the rise of food prices and energy globally. In 2022, Malaysia who supplies 39% of Singapore's needs (SFA), banned the export of chickens to Singapore to ensure domestic sufficiency (Ramli, R.M.A.B., 2022). It is important for Singapore to ramp up the infrastructure needed for producing more of its own food, which will take time and considerable effort. Such a move will allow Singapore to adapt better and faster when the imported supply is reduced or when the increased in price justifies the shift to self-sufficiency.

The perennial argument for the dependence on global trade for its food security has been the lack of land for agriculture and the need to maximise value for whatever land that the country possess. Singapore has a unique characteristic which is that 80% of its population live in government developed high-rise residential housing, commonly referred to as HDB flats as they are developed by the Housing & Development Board (HDB) of Singapore. Though an anomaly, Singapore may serve as case study for how urban planning and architectural typologies might be reconsidered and tested especially in these times of unprecedented change. In this highly organised and considered city, how might we understand the systems that might be required for change at a macro level?

2. Methodology

The effects of climate change will result in more intense weather events. Over the past few years, we have witnessed more of such extreme events such as Australia's Black Summer in 2019-2020, which are consistent with climate change because of human activities. Commonwealth Scientific and Industrial Research Organisation (CSIRO) reports that Australia is experiencing longer fire seasons and extreme fire years are occurring more often (CSIRO, 2021). This is consistent with the IPCC reports. In the past year, we have witnessed more extreme weather events from the drought in the northern hemisphere in 2022 to the extreme heat in South Asia in 2023 (Ramirez, R., 2023).

It is also expected that global warming will impact the quantity and quality of livestock production due to several factors. The rise in temperature will likely see a drop in the nutritional quality of the feed, as well as am increase or change in diseases and pests (due to the change of ecosystems). Physiological changes to the animals are also expected due to the change in temperature, which might impact their growth and production (IPCC, 2018). Current global warming will continue for centuries or even for millennials even if the net emission of greenhouse gases is zero today, but with the current rate of increase of greenhouse gas emissions, it is unlikely that the limit of 1.5°C can be met (IPCC, 2018).

In the face of unprecedented changes that climate change brings, there is a need for a design-led approach in envisioning potential solutions in different scenarios. These changes are likely to be at a systemic level, which will take immense resources, which includes time and finances, to realise. It is imperative to envision future scenarios and therefore solutions that are to come in time. Design-led solutions such as Foresight and Scenario Planning are of increasing relevance and importance, as methodologies in creating a preferred future.

This paper examines the amount of food that is consumed by the country and what it means to be able to produce enough of a type of food for self-sufficiency. It extrapolates the amount of food that is consumed locally against the production capacity of a PFAL. It also attempts to address the issue of land scarcity of the country and projects the infrastructural and technological needs that is required to meet local food consumption demands beyond what is currently provisioned for. Addressing scenarios in stemming from climate change and the events that disrupted the global food supply chain such as the global coronavirus pandemic, through scenario planning, this paper explores ways that the Singapore government may leverage on physical assets that it has control over to increase the resilience of the country's food security.

3. Singapore

Singapore is a small island-nation with little natural resources. It measures 722.5 km² (Singstat, 2018) with a population of 5.638 million people (Singstat, 2018), and is the third densest country in the world (World Bank Open Data, 2018). Despite importing more than 90% of its food to meet its local needs, Singapore is ranked the fourth most food secured country in the world, according to the 2017 edition of the Global Food Security Index (GFSI) (SFA, 2018). Singapore achieves this by adopting a food security strategy that is heavily dependent on global trade.

Singapore imports most of its meat from Brazil and Brazil is the leading source for imported beef at 52%, chicken at 46% and pork at 30%. The 2[nd] leading supplier of pork is Indonesia at 18% and Australia is right behind, at 14%. Malaysia is the main supplier of duck to Singapore and accounts for 95% of its imports. Malaysia is also the 2[nd] largest source of chicken imports at 39% and is almost the exclusive source of imported hen shell eggs at 99%. Australia is the 2[nd] leading exporter of beef to Singapore (28%) behind Brazil and is the leading source of mutton at 88% (SFA, 2018).

Singapore's strategic shift to depend on food imports to meet local needs is a double edge sword. On one hand, it has the advantage of the free market system, which allows it to source for food at competitive prices from global sources. On the other, the strategy renders it vulnerable to global volatility and the resultant knock-on effect on price (IPCC, 2018). This hit home in 2008 with the global food crisis that saw the price of produce increase at an 'unprecedented rate'. It was combination of factors such as emerging countries' rapid economic growth, which drove up the global demand of food as well as the global economic uncertainty resulting from the global economic crisis. The prices of food, such as rice doubled during this period. Prices of imported food in Singapore, in general, rose nearly 8% in the year between December 2007 and 2008 (IPCC, 2018). Singapore was only spared the worst of it as the proportion of the household income spent on food is smaller than most other countries and Singapore has a stockpiling system for rice import, which allowed the government to maintain the price of one of its staple foods. The Singapore government also has in a place, a 'whole-of-government' approach in ensuring food security and supply. This was put into action during the pandemic and the Singapore government managed to diversify its supply. The government also work with industry partners both locally and globally to source for new food supplies. This has largely been a very successful strategy.

However, new challenges arose with effects brought upon by climate change which puts the Singapore strategy in doubt. In 2018, warmer weather reduced chicken and egg supply coming from Malaysia. To ensure adequate supply for their own country, the Malaysian government banned the export of eggs to Singapore. This had a significant impact on Singapore as approximately 73% of eggs consumed are supplied by Malaysia. The recent viral outbreak in the Johor straits where Singapore has many floating fish farms, forced a barramundi farming to cease its operations. This was on top of the plankton bloom that occurred in 2015 and 2010 that wiped out our severely affected the local aquaculture (Migration, 2016). This highlights the challenges that a highly urbanised country like Singapore faces (Qing, A. and Begum, S., 2023).

In 2019, Singapore announced the '30 by 30' initiative, which is to increase Singapore's food production to meet 30% of local nutritional needs. This was a significant shift with the intention to triple local food production within 11 years. As part of the initiative, the Singapore government is investing heavily into high-tech indoor farms, aquaculture and encouraging roof top farms. This also involves the development of the Lim Chu Kang area, which the government has zoned for agriculture activities, from traditional farming to multi-story indoor farms. However, the total amount of land set aside for agricultural activities is about 1% (approximately 7.2 km^2) of the total land area of Singapore, which is very little to support 5.638 million people. Moreover, the threat from climate change and global unrest persists. How might the Singapore government further enhance its food security with its limited hinterland and the increasing impact of climate change on traditional farming?

A unique feature of Singapore is that approximately 80% of its population lives in public housing. HDB manages a total of 1.017 million dwelling units over 25 HDB towns in Singapore (HDB, 2017). HDB towns are planned to be self-sufficient, meeting the needs of the residents, from social to educational, recreational and to some extent, work. It is interesting to note that these residential units that are 'sold' to residents, are essential leaseholds on the units and the residents have no rights to the land, which is held by the government. This essentially means that the government has ultimate control over the development. The Singapore government owns much of the land in the country through government-linked companies or statutory boards, which develop the land into properties for commercial and industrial usage. The commercial aspect of such properties makes integrating agricultural food production trickier as compared to public housing as there are competing needs and the potential of pollution.

The integration of indoor farming within the public housing stock is plausible as the government of Singapore, is the developer of these housing and has control over the development large number of physical assets. This will enable the Singapore government to dramatically enhance its food production resulting in greater food security while addressing the constraint of land and impact of weather changes brought about by climate change. This paper examines the feasibility of this hypothesis through a series of tests to understand the extent of the intervention required as well as the possible configurations that may render it plausible.

4. Plant factory with artificial light

Indoor farming generally refers to the large-scale practice of agriculture indoors. Indoor farming encompasses a range of set-ups and can include everything from a low-tech greenhouse farm to a high-tech plant factory with artificial lighting (PFAL). A PFAL is air-tight and independent of the climate, soil, and sun conditions, which allows for total control of the entire farming process.

Within the air-conditioned space are culture shelves stacked vertically with electric lamps (now commonly high-efficiency LED) beneath each shelf to enable the plants to grow hydroponically. The facility includes other equipment such as air-circulation fans, units that supply nutrient solution, and CO^2 for plant growth, which is all controlled by an environment control unit (Kozai et al. 2016). This allows the system to optimise the growing of the plants as the conditions and nutrient supply can be adjusted accordingly. The facility, being almost airtight allows it to eliminate dust and pests from entering the facility, where the plants are cultivated, enabling a higher level of quality and environment control. There are variations of the system, and some uses vertical towers to grow their produce, instead of horizontal shelves, which is commonly used.

Due to a combination of factors arising from climate change as well as the projected increase in the global population, the Food and Agriculture Organisation of the United Nations (FAO) projects that by 2050, the arable land per capita will drop by more than half as compared to 1970 (FAO, 2012). The global urban population is expected to rise with 68% of that living in urban areas in 2050, as compared to 55%

currently (UN, 2018). Access to food will be an issue and PFAL is potentially a solution for food security in future cities.

With a completely internalised climate maintained by an environmental control system and adjusted for optimal production, there is a certainty in the output of produce from a PFAL. The fully controlled environment also allows the growers to understand clear cause-effect relationship as a result to fully optimise food production (Kozai et al. 2016). A PFAL can also be used in areas where it is unsuitable to plant outdoors, like deserts and very cold areas. In an urban environment, PFALs can even be set up in unused or underutilised areas, such as the underside of expressway flyovers. It does not have to be concerned with the condition of the soil. With the advancement of technology, (such as LED (Kozai et al. 2016) and artificial intelligence will bring greater efficiency and production, and in turn, a higher adoption rate. The increased interest and research into PFAL development is already seeing trials run for growing other vegetables such as medicinal plants, which will carry a higher value and hence a higher return.

4.1. General layout and operations

The first task was to understand the general layout of a PFAL and the percentage of space that it requires. To understand the spatial implications is critical for realistic projection of the amount of food that can be produced within typical spaces produced by HDB. The two main spaces within the PFAL, are the culture and operations rooms (Figure 4.1). The culture room houses the racks of culture beds, where the plants are cultivated. The operations room houses the ancillary operations and forms the barrier between the external and the cultivation room. These two rooms are clean rooms, and the spaces are arranged to facilitate the efficient movement of the plants between them. Strict procedures and infrastructure are put in place to ensure that both rooms are clean rooms and remain so. In general, for most of the PFALs examined, the allocation ratio of space for culture to operations is 50-50%.

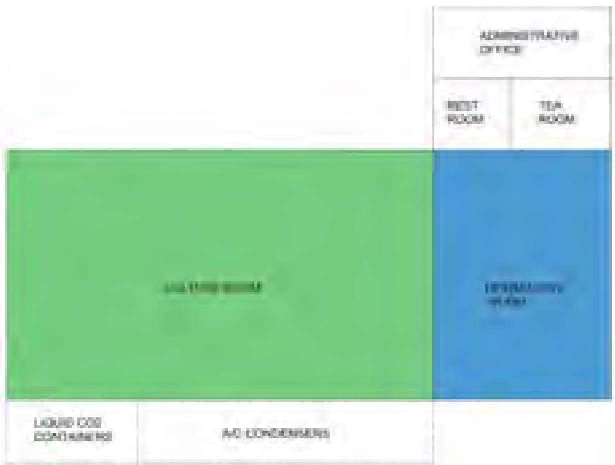

Figure 4.1 Layout of a PFAL (not to scale) (Kozai et al. 2016)

5. PFALs integrated with high-rise residential development

The subject of this proposal is Tengah Plantation Grove, which is part of Singapore's newest HDB town, Tengah. The specific plots (Plot 01 – Blocks 116A - 119C and Plot 02 – Blocks 120A – 122C) were launched in November 2018 in a built-to-order (BTO) exercise by HDB. The objective of this exploration is to understand the production capacity of the entire development. Thereafter, it is worked out, based on the rate of HDB's development of flats over the past 10 years, the time that is required for Singapore to achieve self-sufficiency in green leafy vegetable production through PFAL integrated HDB housing.

Figure 5.1 Plot layout plan (left)
Figure 5.2 PFAL footprint per block and size (right)

5.1. Proposal – integrating PFALs into new HDB flats

To ensure a realistic extrapolation of the production capacity, the exercise began by assuming an efficient rectilinear block footprint for each of the blocks (Figure 5.2). This exploration can then be extrapolated for future HDB developments as HDB has very clear guidelines for the layout of flats. We utilise a floor-to-floor height of 2.8m which a standard for HDB development, except for the first level (BCA, 2018). This allows for a clear floor-to-ceiling height of 2.6m within the unit (factoring in 15cm for the thickness of the slab and another 5cm for floor finishes). 15 cm is allocated for the depth of each rack and a clear space of 30cm in between each tier. In all, each HDB unit can accommodate 5-tier cultivation racks. This allows the study to estimate the for the total cultivation area achievable within each unit, based on a 5-tier cultivation rack. (Figure 5.3).

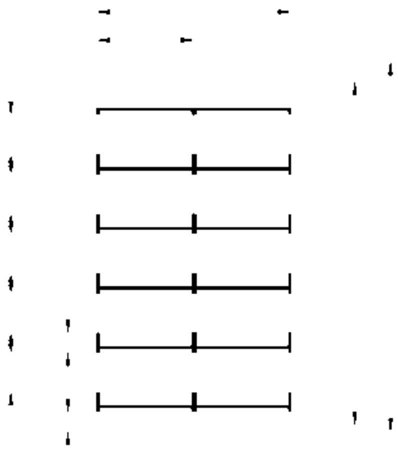

Figure 5.3 PFAL tier heights in the unit (measurements in millimeters)

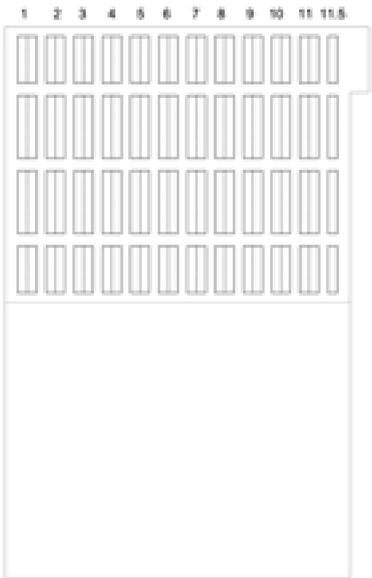

Figure 5.4 PFAL Cultivation rack layout plan for Block 122C in Plot 02 (not to scale)

Calculation of cultivating area per sqm (5 tiers)	
Block 122C	
Total footprint	1220 sqm
Efficiency	50%
Total of tiers for cultivation	5
Calculation of total planting area	
Row 1 (1.5m x 3.75m x 11.5 columns x 5 tiers)	323.44
Row 2 (1.5m x 5m x 11.5 columns x 5 tiers)	431.25
Row 3 (1.5m x 5m x 11.5 columns x 5 tiers)	431.25
Row 4 (1.5m x 3.75m x 11.5 columns x 5 tiers)	323.44
Total (sqm)	1509.38
Cultivating area per sqm of overall space	1.24 sqm
(1509.38 sqm / 1220 sqm)	

Figure 5.5 PFAL total cultivation area per square meter

The exploration looked at production across one single level of both plots. Basing on a 50%-50% ratio allocation of space for culture to operations (Fig 5.4), the resultant cultivating area per sqm of the overall space is 1.24m²(Fig 5.5). Extrapolating that across all blocks, the resultant total cultivation area for one level across both plots is 32,922 m² (Fig 5.6).

The production capacity (in weight) of the cultivation rack is as follows: [**Number of plants/m² (culture bed area)] x [Number of tiers] x [20 harvests per year] x [0.9 (ratio of saleable plants to transplanted plants)] x [Weight of plants]**. The number of plants per square meter assumed for the calculation is ten and the choice of vegetable is lettuce, which has an average weight of 80g. (Kozai et al. 2016). The resulting annual production capacity per level of the integrated PFALs is 474 tonnes (Fig 5.7).

Plot	Block	Total PFAL Footprint	Total cultivation area (total PFAL footprint x cultivation area per sqm of PFAL footprint - 1.24sqm)
1	116A	2360	2926.4
	116B	2090	2591.6
	117A	1390	1723.6
	118A	1810	2244.4
	118B	1180	1463.2
	119A	1720	2132.8
	119B	1550	1922
	119C	1840	2281.6
2	120A	1370	1698.8
	120B	1470	1822.8
	120C	1190	1475.6
	121A	1620	2008.8
	121B	1130	1401.2
	121C	1730	2145.2
	122A	1400	1736
	122B	1480	1835.2
	122C	1220	1512.8
		Total cultivating area of one level for Plots 01 & 02 (sqm)	32922

Figure 5.6 Total cultivation area of one level for Plots 01 & 02

Annual Production Capacity per level	
Annual Production Capacity Formula	
[Number of plants/m² (culture bed area)] x [Number of tiers] x [20 harvests per year] x [0.9 (ratio of saleable plants to transplanted plants)] x [Weight of plants].	
Number of plants per m²	10
Number of harvests per year	20
Ratio of saleable plants to transplanted plants	0.9
Weight of plants (lettuce - kg)	0.08
Total cultivation bed area (m²)	32922
Total production (kg)	474076.8
Total production (tonnes)	474

Figure 5.7 Annual production capacity per level for Plots 01 & 02

5.2. Meeting Singapore's green leafy vegetable demand through integrating PFALs into new HDB flats

HDB completed 174,370 units in the 10 years between 2008 and 2017 (Table 5.11) (SFA, 2018). The 10-year average for the number of units completed is 17,437. There is a significant difference in the number of units completed in 2008 (1769 units) and in 2017 (31,325 units), but the growth has been steady. The statistics also show that after years of steady growth, the number of units being awarded for construction, started to decrease steadily since 2014. Over the period of these ten years, both steady growth and decline have been captured. Based on the number of units awarded per year, the ten-year average of 17,437 is a safe assumption as it is also closer to the annual average of the lower end of the spectrum of the units awarded in 2008-2010 and 2016-2017 (average of 15880.2 units).

Completed units by HDB

Year	No. of units completed	No. of units under construction	No. of units [illegible]
2008	[illegible]	[illegible]	[illegible]
2009	[illegible]	[illegible]	[illegible]
2010	[illegible]	[illegible]	[illegible]
2011	[illegible]	[illegible]	[illegible]
2012	[illegible]	[illegible]	[illegible]
2013	[illegible]	[illegible]	[illegible]
2014	[illegible]	[illegible]	[illegible]
2015	[illegible]	[illegible]	[illegible]
2016	[illegible]	[illegible]	[illegible]
2017	[illegible]		

Total	[illegible]

Figure 5.8 Completion status of HDB development (data.gov.sg)

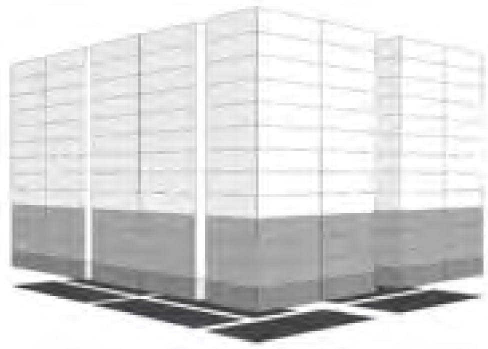

Figure 5.9 Four levels used for PFALs in Tengah Plantation Grove

Singapore's total green leafy vegetable consumption in the year 2017 is 91,456 tonnes (SFA, 2018). If the production is conducted on four levels (Fig. 5.9), the total food production for Tengah Plantation Grove can achieve an annual yield of 1896 tonnes. Assuming that this is implemented across all HDB developments for the year, adding 4 levels of PFALs integrated with HDB flats will yield an annual production of 20408 tonnes (Fig 5.10). Based on the past 10-year average rate of HDB development, this will allow Singapore to achieve self-sufficiency to meet green leafy vegetable demand in just under 5 years.

Singapore Leafy Green Vegetable Demand (Figures from 2017)					
	Import (Tonnes)	% of total	Local Production (Tonnes)	% of total	Total demand (Tonnes)
Singapore's Demand for Leafy Green Vegetables (SFA, 2018)	79, 678	87.12	11,778	12.88	91,456

HDB 10 Year Average Completion between 2008-2017 (units)	17437
Tengah Plantation Grove (units)	1620
Percentage (%)	9.29%
Potential annual production capacity from total number of units built (number of times)	10.76

Tengah Plantation Grove Production Capacity	Levels	Tonnes	Annual Production from all HDB developments (Tonnes)	Number of Years to achieve self-sufficiency
	1	474	5102	18
	2	948	10204	9
	3	1422	15306	6
	4	1896	20408	5
	5	2370	25510	4
	6	2844	30612	3

Figure 5.10 Calculation of number of stories required for PFALs

6. Conclusion

The integration of PFALs within new HDB development will allow Singapore to move towards self-sufficiency in food production without the need to dedicate additional land for agriculture. The cost of such an endeavour can be seen as a tradeoff for the need to use additional land for agriculture and can be absorbed into the building of the public housing. As it is an integrated development, the infrastructure (structure and shell) cost is comparatively lower as compared to building from scratch as the development cost can be shared with the residential development.

From an operational and environmental standpoint, agricultural production via a PFAL, integrated with public housing is much easier as compared to traditional forms of agriculture as it there is very little pollution involved. Water usage of a PFAL is low and integrated PFALs can leverage on rainwater collected from the rooftops of the HDB as its source. HDB's SolarNova programme (HDB, 2018) can be tapped on to provide the electricity used for the PFALs. It is also a prime example of how initiatives can be rolled out by the government, leveraging on the buildings that HDB manages. From a social perspective, the proposal can potentially bring employment to where people live. As the working conditions in a PFAL is controlled and comfortable, it can create gainful employment opportunities to older residents, living in the vicinity, and engage people with special needs. This is akin to an initiative by Citizen Farm with the Autism Resource Centre and the Down Syndrome Association of Singapore (Citizen Box, 2018). Having food produced where people live, also provides an opportunity for people to have a better understanding of how food is produced.

6.1. Future research

Though an anomaly, Singapore may serve as a case study for how urban planning and architectural typologies might be challenged, reconsidered, and tested. This proposal is a springboard to examine the other food types that can be produced in this integrated model. In the immediacy, the next step of research would be to examine the feasibility of integrating aquaponics within public housing and other food types, to balance the nutritional demand of the country. As the figures in Fig 5.10 shows, the resultant output and timeline towards self-sufficiency can be projected, depending on the food type chosen that might strengthen Singapore's food security.

The above proposition extrapolates the potential of integrated developments to enhance Singapore's food security and does not exclude the current modes of food production such as traditional farming and even roof top farming. This scenario is especially important to understand how the country might significantly increase its resilience in the face of climate change and global unrest. Further research will also need to be done to imagine and examine the new architectural typologies and how community and social needs are to be designed for. Beyond recreational needs, how might the need typology enhance community bonding and their relationship to the environment and where their food comes from?

Work can also be done to examine novel models that other countries employ, to understand how it might fit within the Singapore context to achieve greater self-sufficiency in its food security. Systemic changes are needed to address the challenges climate change brings, therefore, there is an urgent need to employ design-led approaches such as foresight and transition design to explore future scenarios and the adaptations needed to achieve a preferred future. There is little room for reactive responses as systemic level changes take planning, time, and finances. (Heinrichs et al, 2010).

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Socialized Housing Adequacy from the Lens of Potential Housing Intenders: The Case of Davao City, Philippines.

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Abstract: The growing Philippine housing backlog has resulted in increasing socialized housing developments, the country's primary mode of housing delivery. While it aims to address the Filipino's dream of home ownership, it is necessary to consider what the potential users think of the current housing provision. This study asked 401 individuals regarding their perception of the current socialized housing and determined their willingness to live in such developments. Principal Component Analysis was used to group the 53 housing variables into components. Confirmatory Factor Analysis was utilized to determine if the variables manifest a specific construct and Multiple Linear Regression Analysis helped determine which factors significantly explain the perception. Additionally, the qualitative perception was noted and grouped into themes to further explain the results of the perception index. About 63% of respondents expressed interest in moving to a socialized housing development while 37% do not intend to live in a socialized housing development. Overall, the housing intenders perceive the current housing provision as "satisfactory" while the non-intenders rated it as "neither satisfactory nor unsatisfactory". The quality of the dwelling unit, social environment, acquisition and financing, were found to be significant factors in the respondents' perceptions. Despite being a practical housing choice, many respondents expressed that the current socialized housing provision is small, low in quality, and unaffordable. With a rise in row-house socialized housing developments, prioritizing the potential residents' voices is crucial. The study underscores embedding aspirants' preferences to ensure new projects match their needs, enhancing contentment, sustainability, and suitability.

Keywords: Socialized housing; housing intenders; housing perception; housing adequacy.

1. Introduction

1.1. Background

When envisioning their lives in 2040, Filipinos aspire to a shared vision of a comfortable existence encompassing homeownership, sufficient travel funds, and emergency savings, as indicated by the Ambisyon Natin 2040 (NEDA, 2016). Nevertheless, like many global populations, Filipinos encounter challenges in terms of both the affordability and sufficiency of housing.

Part of the strategies of the government to combat the growing housing backlog is to provide enabling laws to expedite housing production. The Local Government Code of 1991 or RA 7160 (Official Gazette, 1991) was enacted to strengthen the housing provision through the devolution of the national

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government's responsibility to the Local Government Units (LGUs). In the following year, the enactment of the Urban Development and Housing Act (UDHA) of 1992, or RA 7279 identified socialized housing as one of the primary modes of housing delivery (Official Gazette of the Republic of the Philippines, 1992). It caters to the needs of the low-income group, specifically the bottom 30% of the income decile (Housing and Urban Development Coordinating Council (HUDCC), 2018). To ensure its affordability, this housing segment is mandated to be sold within a specified price ceiling and following a minimum standard of house construction. Currently, socialized housing with a minimum of 24 sqm floor area has a price cap of Php 480,000 (HUDCC, 2018). This type of housing may be afforded through housing subsidies and housing loans with special interest rates.

The government was optimistic about the early implementation of RA 7279 as it mandates private housing developers to allot twenty percent (20%) of the area of their projects for socialized housing. In 2016, RA 7279 was amended by the passing of RA 10884, or the Balance Housing Act reducing the socialized housing compliance to 15% and adding a 5% socialized housing compliance for condominium housing projects. However, while the socialized housing developments led by the private sector increased, a huge housing backlog is still recorded. In a recent estimate of the Philippine housing backlog, the projected accumulated need for housing is 15.08 million units in 2022. Among this need, 5.11 million belong to the socialized housing segment (Padojinog and Yap,2020).

Criticism has been received by the LGUs for "the lack of political will which has impeded the proper implementation of the national policy on balanced housing development" (Buendia, 1998 as cited by Pampanga and Majid, 2014). While this is aimed toward socialized housing production, this has turned the private sector to be the primary driver of housing production (Carino and Corpuz, 2009). The privatization of socialized housing production not only made homeownership for Filipinos more difficult, but it has also driven the affordability of these units beyond the capacity of the socialized housing beneficiaries (Yares, 2021). Since 1992, there have been six (6) adjustments to the socialized housing price ceiling as rallied by the private housing developers. Twenty years later, Arcilla (2018) had a parallel sentiment with Buendia (1998) claiming that "through the socialized housing program, a systematic spatial, political, and economic displacement of the poor is institutionalized to facilitate private gain and commodify housing for the poor". The privatization of housing production, coupled with second-rate construction quality to keep up with the price ceiling and profit has compounded into the bigger issue in the housing sector. This has left some of the socialized housing units developed by the National Housing Authority, the housing production arm of the government, to be unoccupied because of their "substandard and unsuitable" condition (Arcilla, 2018).

1.2. The use of perception and satisfaction studies for housing developments

Households judge their housing conditions based on the actual housing situation and housing norms, often expressing high contentment if the households' current housing situation meets the norms. On the other hand, incongruence with housing situations and norms may result in a housing deficit, which in turn gives rise to housing dissatisfaction (Morris & Winter, 1975). On a larger scale, improving the housing quality of a neighbourhood may notably impact the residents' social identity (Hauge, 2009).

In 2015, Ibem et al (2015) suggested that housing adequacy and residential satisfaction can be used interchangeably or as surrogates for each other. This observation carries substantial implications for policy formulation and research, implying that either concept can yield analogous results, thereby informing sound judgments on housing quality, residents' quality of life, housing adaptation dynamics, project effectiveness, and housing providers' prowess in addressing user needs.

The study of Mohit, et al (2010) argued that the notion of residential satisfaction is composed of the indices of satisfaction which respondents perceive with (1) dwelling unit features, (2) dwelling unit support services, (3) public facilities, (4) social environment, and (5) neighbourhood facilities. Similarly, Karim's study (2013) exhibits a parallel configuration where he grouped 45 variables into five broad components relating to the (1) dwelling unit features, (2) dwelling unit support services, (3) public facilities, (4) neighbourhood facilities and (5) social environment.

It has also been found that different population groups often have different predictors of satisfaction. This has been the case in looking at high-rise versus low-rise units (Francescato et al, 1975), public housing versus non-public housing sites (Anderson and Weidemann, 1997), as well as when looking only at demographic differences within the same site. Similarly, certain age groups like the elderly have a different set of satisfaction predictors than the family respondents as manifested in the study of Anderson and Weidemann (1997).

By understanding how residents perceive housing conditions and challenges, housing satisfaction studies contribute substantively to diverse Sustainable Development Goals (SDGs), encompassing poverty alleviation (Goal 1), enhanced well-being (Goal 3), sustainable urban development (Goal 11), responsible consumption (Goal 12), equitable justice (Goal 16), and productive partnerships (Goal 17). Such studies enable policymakers to design targeted interventions, create inclusive communities, enhance resource efficiency, and promote equitable and sustainable societies, harmonizing with the overarching SDG framework for 2030 (UNDP, 2015).

1.3. The research locale.

The research is conducted in Davao City, distinctly the largest city in the Philippines in terms of its land area. The city is the third most populous city in the country next to Quezon City and the country's capital, the City of Manila. Davao City is located in the southern part of the Philippines on the island of Mindanao. Home to 1.77 million residents (PSA, 2023), Davao City continues to receive local immigrants from its neighbouring towns and cities being the regional centre of the Davao Region. This has led to the growing housing need in the city coupled with sprawling housing developments in city suburbs.

Figure 29: Actual photo of a typical socialized housing unit with an 18 sqm floor area and 35 sqm lot.

1.4. The research gap and question.

There has been a wide range of literature discussing housing affordability (or its unaffordability), and housing supply and backlogs. While housing provision in terms of quantity is a major concern, housing adequacy in terms of quality also needs to be evaluated in the Philippine context. Studies agree that the best respondents for residential satisfaction are the end-users themselves. A study of residential satisfaction in Davao City found that the residents were “highly satisfied” with the current socialized housing (Yares, 2023). However, this level of satisfaction is quite questionable when it was found that the same end-users were not the qualified beneficiaries of the program but those who were overqualified in terms of allowable income (Yares, 2021). Nonetheless, aside from the residential satisfaction of a socialized housing end-user, it is also valuable to get feedback from the prospective end-users. Hauge (2009) expressed that urban planning and housing design can be carried out with a perspective on how to include the insights of people who are excluded from society.

This study intends to fill the gap in the delivery of socialized housing by evaluating the program's efficacy through the perspective of its potential beneficiaries. The primary objective is to measure how satisfactorily the public perceives the current socialized housing and identify the factors that influenced them. Furthermore, this study hopes to come up with empirically grounded insights, allowing the voices of those aspiring for housing to be heard. Recognizing the intenders' priorities and preferences, the study offers invaluable guidance to policymakers in their decision to help make socialized housing more sustainable.

2. Methods

2.1. Respondents of the study

In this study, random sampling has been used to select the respondents of the survey. A total of 401 individuals (n=401) was selected based on Yamane's formula from a total of 1.77 million (N=1,776,949) population (PSA, 2020), with a confidence level of 95%. As a criterion for selection, respondents who filled in the survey questionnaires were all living in Davao City in any housing accommodation except socialized housing.

2.2. Research design and data gathered

The research design is mainly a mix of quantitative and qualitative as the respondents were asked to answer a structured survey questionnaire containing both closed and open-ended questions.

Photos of sample projects within the city were shown to respondents with corresponding information on the lot and floor area of the housing unit as a reference. They were then asked to answer a pen-and-paper survey questionnaire on how satisfactorily they perceived the socialized housing projects. The survey questionnaires were composed of two sections, the first section inquired about the respondents' socio-demographic data (i.e., age, sex, marital status, income range, etc.). The second part is influenced by the study of Mohit (2010) but contains 53 housing variables that fit the horizontal development context. The respondents rated these latent variables using a five-point Likert scale. Inspired by the earlier study of Anderson and Weidemann (1997), the respondents were asked the questions (1) Would you move to a place like this? and (2) What is your general perception of socialized housing? Qualitative data were also recorded as respondents wrote down the cause of their respective ratings.

The data was gathered from February to April 2019 with continuing direct observation until the writing of this paper.

2.3. Analysis of data

To get the respondents' profiles, the socio-demographic data was tabulated both for those who wished to live in a socialized housing project and those who did not.

For each group of respondents, the 53 housing variables were subjected to Exploratory Factor Analysis (EFA) using Principal Component Analysis (PCA) to examine whether the variables relating to perception can be grouped into components. A parallel analysis was employed to ascertain that the creation of components was not by chance. The internal consistency of the derived components was measured using Cronbach's alpha. The Confirmatory Factor Analysis (CFA) was also utilized to determine if the variables manifest a specific construct. Variables retained after the CFA were converted to indices of the components and subjected to a Multiple Linear Regression Analysis (MLRA) using a stepwise method to determine which housing variables significantly influence such perception. This was triangulated with the qualitative data obtained from the survey when the respondents answered the open-ended question on what they thought about the housing project.

3. Results and Discussion

The total number of respondents who answered the survey is 401. Of these, around 6 out of every 10 (n=254, 63%) were considered intenders as they indicated their intention to move to socialized housing developments while almost 4 out of every 10 respondents (n=147, 37%) answered that they did not want to move to such development. The perceptions of the two groups of respondents were analyzed in a similar manner.

3.1. Socio-demographic profile of the respondents

The socio-demographic data of the first group (the intenders) of respondents revealed that the majority were around the age of 21-30 (42%) followed by the age 31-40 (21%), most are female (62%), single (52%) and have a college degree (63%). The non-intenders on the other hand are mostly composed of individuals aged 21-30 (34%) and 31-40 (27%), female (67%), single (42%), and have obtained a college degree (66%). The income profile of both sets of respondents varies with the majority from Php 10-30K and Php 10-35K for intenders non-intenders, respectively. Both groups are currently living in a single-detached household and are occupying an owned or owner-like accommodation (either personally or by parents).

3.2. Perception Index of the two groups of respondents

Answering the question, how satisfactorily do you perceive the current socialized housing developments, the 401 respondents have a combined perception index of 66.78. For descriptive interpretation, the range 0-20 is described as "very unsatisfactory"; 21-40 for "unsatisfactory"; 41-60 for "neither satisfactory nor unsatisfactory"; 61-80 for "satisfactory"; and 81-100 for "very satisfactory. Given this range, the combined perception index of the 401 respondents is equivalent to a "satisfactory" rating. However, looking at the responses per group, the perception index differs significantly across housing intenders (74.17) and non-intenders (54.01). From the range of satisfaction, it will be observed that the housing intenders view the provided socialized housing as "satisfactory" while non-intenders see it as "neither satisfactory nor satisfactory".

Table 13 Perception Indices of Respondents

Respondents	Overall Perception Index	Descriptive Interpretation
Housing Intenders	74.17	Satisfactory
Non-Intenders	54.01	Neither Satisfactory nor Unsatisfactory
All	66.78	Satisfactory

3.3. Factors affecting the housing intenders' perception of socialized housing.

The original 53 variables having a Likert scale of 1-5 where 1 is very unsatisfactory and 5 is very satisfactory were all subjected to an EFA using PCA. The result of the EFA generated 9 components with 51 variables having a factor loading greater than 0.40. To confirm if the 9 components were not made by chance, a Parallel Analysis was used where the eigenvalues generated from the PCA were compared to the random eigenvalues of the Parallel Analysis. Components in the PCA having an eigenvalue more than that of the Parallel Analysis were considered, resulting in five (5) retained components. The PCA was repeated with a fixed component of five (5) because of the Parallel Analysis. To confirm the internal reliability of the grouped components and assess how closely related the set of variables are as a group, Cronbach's alpha was computed per component. As a result, the 51 retained variables under 5 components have a good consistency having an alpha ranging from 0.8-0.9 as shown in Table 2. These components and their retained variables were subjected to a CFA to validate the construct of the model. Variables with a factor loading of less than 0.70 were omitted, resulting in 24 retained variables, still under 5 components with their final descriptions (see Table 3).

Table 14 Internal reliability of components after PCA

	Intenders		Non-Intenders	
Components	Cronbach's Alpha	N of Items	Cronbach's Alpha	N of Items
Dwelling Unit	.853	8	.869	7
Acquisition & Financing	.956	4	.950	4
Proximity to Public Facilities	.930	12	.914	16
Social Environment & Neighborhood Support Facilities	.929	16		
Subdivision Management	.937	10		
Neighborhood Support Facilities and Subdivision Management			.934	18
Social Environment			.895	6

Indices of the final components with 24 retained variables were computed (Table 3) and used as predictors for the MLRA model with the overall perception index per group of respondents (Table 1) as the dependent variable. The result of the MLRA revealed that two components; (1) Social Environment, and (2) Acquisition and Financing, are significant predictors (p = 0.000) of housing intenders' perception of socialized housing. It is also noted that the model's coefficient of determination (R square) has a value of 0.328 which means around 32.8% of the variance in the dependent variable is explained by the significant factors. Factors composing the component Social Environment include safety, security, peace and order, and crime prevention with a component index of 75.77 (Table 3). Meanwhile, another significant component, Acquisition and Financing, has factors like contract or selling price, monthly amortization, the process of application for financing, and the availability of different modes of payment having the second largest component index, 69.55 (Table 3).

Table 15: Housing intenders retained variables after the Confirmatory Factor Analysis (CFA)

Proximity to Public Facilities 69.27*	Social Environment 75.77*	Management System 66.06*	Dwelling Unit 66.43*	Acquisition & Financing 69.65*
Distance to Workplace Distance to the Bus station Distance to Fire Station Distance to Restaurants Distance to Public Market Distance to Police Station Distance to nearest Shopping Center Distance to Place of Worship Distance to the nearest town centre	Safety Security Peace and Order Crime Prevention	HOA Management HOA Rules and Restrictions HOA Community Activities Maintenance of Facilities	Construction Materials Size of the Housing Unit House Quality & Workmanship	Contract Price Monthly amortization Application for Financing Payment method Facility

*Computed index per component

That Social Environment and Acquisition and Financing were significant in the perception of the intenders why they rated the socialized housing program as satisfactory can be further explained by the general comments towards the housing program. A thematic analysis was conducted using the intenders' remarks resulting in three themes as the most common sentiments. First is the view of socialized housing as a good and practical means of homeownership. Respondents say that socialized housing can be a good option for starting families. Comparing it to other housing products in the market, intenders say that socialized housing units are relatively affordable especially since they can be mortgage under the Home Development Mutual Fund (HDMF), one of the major home financing agencies in the country.

Figure 30: Villa Grande Subdivision, a socialized housing development in Toril District, Davao City

Additionally, housing intenders view socialized housing as a peaceful place to live highlighting that subdivisions are organized, referring to how subdivision projects have their own road networks and open spaces. Graphically representing these comments, Figure 3 shows a word cloud generated from the intenders' comments showing "good", "practical", "affordable" and "peaceful" as the biggest words. Others, however, provided a caveat that they wish to live in socialized housing if they can afford it, implying its unaffordability for the moment.

3.4. Factors affecting the perception of non-intenders for socialized housing.

Of the total surveyed, about 4 out of 10 (37%) respondents indicated their disinterest in socialized housing. In the same manner as the previous group (housing intenders), the data collected were analyzed starting with the EFA using PCA. All 53 housing variables were loaded completely into 11 components, unlike the intenders which were initially loaded into 9 components. Consistently, the Parallel Analysis resulted in five (5) components like the first group. Internal consistency of variables categorized in the same components was also computed revealing an acceptable result ranging from 0.8-0.9 (Table 2). Performing the CFA, the original 53 variables were reduced to 19 to fit the construct of the model. These 19 variables under 5 components loaded almost like the first group except for components Management Systems and Proximity to Public Facilities which has fewer retained variables (see Table 4). Under the

MLRA, the component "Dwelling Unit" turned out to be a significant factor in why non-intenders perceived the socialized housing to be "neither satisfactory nor unsatisfactory". Meanwhile, consistent with the first group of respondents, "Acquisition and Financing" turned out to be a significant predictor (p=0.001). The multiple correlation coefficient (R) between the predicted values of housing perception and the actual observed values was found to be 0.410, indicating a moderate positive relationship between the independent variables and housing perception. Moreover, the coefficient of determination (R square) was calculated to be 0.168, indicating that approximately 16.8% of the variance in housing perception is explained by the independent variables included in the model.

The significant predictor, the Dwelling Unit, recorded a component index equivalent to "Neither Satisfactory nor unsatisfactory" at 57.28. This is made of variables like living spaces provided, quality of workmanship and construction materials, and the size of the housing unit. The other significant component, Acquisition and Financing barely had a satisfactory rating equivalent to 60.07. It also loaded the same variables as it did with the housing intenders.

Table 16: Non-housing intenders retained variables after the Confirmatory Factor Analysis (CFA)

Management System 56.79*	Proximity to Public Facilities 60.20*	Dwelling Unit 57.28*	Acquisition & Financing 60.07*	Social Environment 66.43*
Pedestrian Walkways Road Drainage Maintenance Traffic Rules Inside the Subdivision HOA Community Activities Maintenance of Facilities	Distance to Restaurants Distance to Shopping Center	Living Spaces provided House Quality/workmanship Construction Materials Size of the Housing Unit	Contract Price Monthly amortization Application for Financing Payment method/facility	Safety Security Peace and order Crime Prevention

*Computed index per component

Qualitative remarks by the second group of respondents were also analysed as depicted in Figure 3 (right). While some of the respondents still believe that socialized housing is a good alternative in providing the poor with decent homes and is good for families who are starting off, most of the recurring themes include the housing unit being small and cramped which the respondents think is only ideal for bachelors and families with 2-3 members. Along with this, some are concerned with ventilation as row houses only have limited window openings and low floor-to-ceiling height. They are also concerned that because of the limited space, future house expansion is not possible with this accommodation. Secondly, comments pointed out the substandard quality of materials and the quality of dwelling unit construction. Some respondents believed that the developers are maximizing their profits at the expense of housing quality. While a few respondents indicated that the housing program is relatively affordable, more respondents are inclined to perceive the socialized housing as expensive and beyond the capacity of low-income families. Others also highlighted that the quality of the constructed houses does not match their price, implying that the current housing product is beyond affordable.

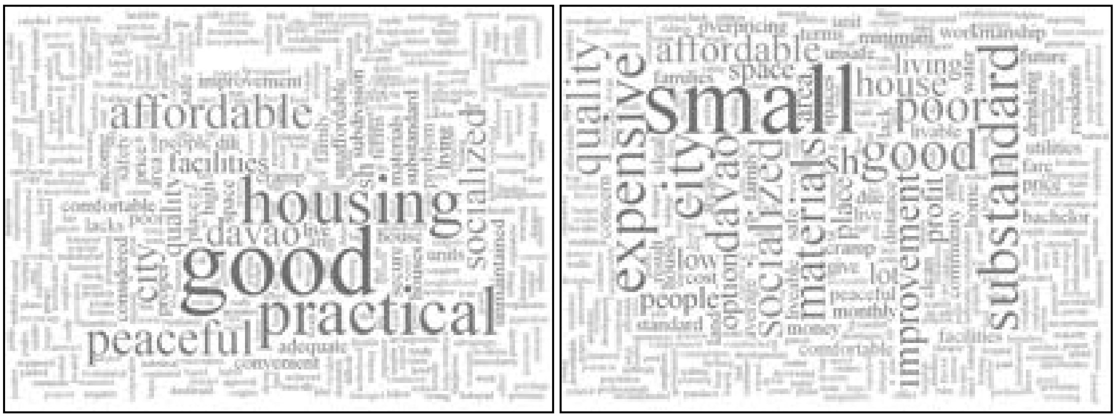

Figure 3: Word cloud generated from the comments of the intenders (left) and non-intenders (right).

3.5. Implications of the results.

The housing intenders have a “satisfactory” perception of the socialized housing provided in Davao City mainly due to its social environment, and acquisition and financing. Perhaps, the perception of safety may be influenced further by the impression that Davao City is the second safest city in Southeast Asia (Sunstar, 2019). Housing intenders value the social environment socialized housing projects offer as it is seen as an organized settlement like other housing developments in a subdivision form. This is consistent with what Hauge (2009) said that a good neighbourhood affects people’s perception of the place. What socialized housing projects provide is a sense of achievement for people especially if the previous accommodation is from informal housing or settlements.

Meanwhile, the second group of respondents (the non-intenders) views the housing provision as “neither satisfactory nor unsatisfactory” influenced by the dwelling unit and the acquisition and financing. In other words, this group of respondents is not entirely convinced that the housing offered by the socialized housing developments is adequate to be rated satisfactory. Consistent with another satisfaction study in Davao City, end-users of socialized housing units also complained of the limited home space in their socialized housing units (Yares, 2023). Often delivered as a studio unit (without interior partition and in some projects, without ceiling), consideration of the existing design standards should be reviewed to address the common perception that the housing unit is cramped and not flexible. As of 2018, the minimum floor area specified by BP 220 is 24 sqm for a row-house development, the housing type commonly available in the city for socialized housing projects. Available socialized housing built before the 2018 standard has floor areas as small as 18 sqm. With the Filipino’s Average Household Size of 4.1 (PSA, 2021) per dwelling unit, adequate living space per person can hardly be accommodated in the available housing. According to the 721 Housing Quality Indicators (2007), a family of four is required to have spaces allocated for two bedrooms, a toilet, and bath, a kitchen, a dining, and a living room to maintain comfort. Considering the standard room size of 6 sqm for bedrooms, 1.2 sqm for the toilet and bath, and 3 sqm for the kitchen (National Building Code of the Philippines, 1977), these spaces would already take up 16.2 sqm. As observed, this does not yet consider space provision for the dining, the living room. In a similar study by Karim (2013) in the case of low-cost apartments in Malaysia, while the residents rated their 41.80 sqm (almost double compared to the Philippines minimum) satisfactory, they still noted the lack of space for study and storage.

While the perception of affordability is a common theme, it shall be noted that views about how it is affordable or unaffordable differ among groups. This goes to show that there is a divided view among the respondents in terms of the prevailing housing price of the offered socialized housing. Expectedly, housing intenders with higher income levels (Php 50,000 or more) view the units as affordable while those that belong to the lower income bracket (Php 25,000 and below) only wish to live in socialized housing developments if it is offered at a lower price. As an effect of its unaffordability and inadequacy to meet the user needs, around 2 out of every 10 socialized housing owners in Davao City were not able to sustain payment and have given up their units (Yares, 2021). With the program targeting beneficiaries belonging to the low-income segment, careful consideration should be given by the newly established Department of Human Settlements and Development (DHSUD) as they review the release of a new price cap for this housing segment which often only considers the clamor of the housing developers (Ordinario, 2021) and not the target beneficiaries.

Recently, the DHSUD has yet again launched another program, the Building Adequate, Liveable, Affordable, and Inclusive (BALAI) Filipino Communities Program whose acronym also means “house”. The program aims to accelerate housing production, enhance housing affordability, and ensure the liveability and sustainability of human settlements delivered through direct and indirect assistance. It also supports the attainment of the Philippine Development Plan 2017-2022, the National Urban Development and Housing Framework, the Philippine New Urban Agenda, and the Ambisyon Natin 2040. With new programs being launched and new departments being created, it is only hope that a real change in the housing reality can be implemented considering the feedback of the stakeholders.

4. Conclusion

Among the socialized housing issues, housing perception and satisfaction are given the least attention. Perhaps because the government’s focus is fixed on housing units produced and production backlogs, leaving housing adequacy from the lens of its users and prospective users. This study revealed that from the perspective of the non-socialized housing users, the program is satisfactory. However, while it provided some insights into areas for improvement, it also highlighted some practices to emulate. This study revealed that the social environment exhibiting safety and security along with the nature of the subdivision being “organized” is one of the aspirations of the intenders. Perhaps living in a planned community provides self-achievement and a sense of social status.

From the perspective of the non-intenders, the program is not yet satisfactory, implying room for the program’s improvement. Specifically in its delivery of the Dwelling Unit and Financing – translated into the housing component features and its affordability. The specified minimum lot and floor area of the socialized housing units limits the possible improvement in the future and compromises the comfort of the family with an average household size. That current housing reality suggests that socialized housing units are relatively small and in a row house form, considerations should be made in the minimum standards of housing floor area while ensuring that the low-income household can still access the product. Lastly, the quality of the housing unit in terms of materials and construction should not be compromised just because it is intended for low-income households.

Over the years, various laws and housing programs have been launched and implemented in trying to address housing inadequacy. Yet again, a lot of these government efforts have failed to achieve their goals, and the country is still grappling with a huge housing problem. Instead of technocrats and legislators mandating what needs to be done, perhaps it is also time to listen to the voices of the people on the ground. And if only to make housing accessible for all, perhaps the government should also explore alternative forms of housing arrangement other than ownership.

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Stop the chop:
A humane response to city tree loss

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Abstract: This paper outlines the rationale and methods used to collect feelings from the School of Architecture community about recent tree losses on the Unitec Te Pūkenga campus, due to land sales for housing. The aim was to use this data to inform a research by design process to propose a memorial to be constructed on-site, as an appropriate reminder of the lost trees and to educate about the importance of trees in our environment. Data took the form of emails shared by staff soon after a significant tree removal and anonymous comments by students that were written on posters created by the authors and put up around the School of Architecture building. In agreement with other authors, social factors such as strength of place attachment is important in considering views on contentious issues such as tree removals – which are equally revered and reviled in the landscape, despite their established benefits of shading, cooling, water absorption etc. Themes were drawn out of the data and connected to the design via Bowring's taxonomy of possible memorial treatments. 'Healing and Repair' was chosen as the best approach matching the themes and a site on the campus was chosen to create a memorial, using research by design methodology. The paper presents sketch plans and perspectives for a design based on Akira Miyawaki's mini forests. It concludes that considering both social and physical aspects of trees encourages a more humane response to city tree loss and may lead to greater environmental stewardship and social resilience. In this case it not only provides a 'living memorial' that addresses climate change, it acknowledges trees as beacons of legibility within the landscape, symbols of meaning, improvers of the environment and significant contributors towards the zero-carbon nexus of lifestyle and well-being.

Keywords: tree removal, tree loss, urban trees, community, memorial

1. **Introduction**

This project seeks to memorialise tree loss within a community through considering their views in a process that culminates in research by design to create a proposed plan for a memorial. In doing so it intends to raise awareness of the importance of tree:people connections and caring. Many people believe that humans and trees are interconnected and even that we mimic each other with trunks and arms. Bowring (2019) paints a picture of strong connection in terms of form, structure and lifecycles, which is at odds with our commonplace treatment of trees as expendable parts of the landscape. Michael Pollan, author of books about nature and people suggests trees have something like a soul (Pollan, 2003, as cited in Bowring, 2019 para. 9). Bowring (2019) concludes "With their anthropomorphism, their souls, their psychological presences, their listening attentiveness, and their agency, trees generate strong affective bonds with humans." (para. 10).

Resilience is the ability to manage adversity in a beneficial way, or to 'bounce back' according to Greene (2002), and Krasny and Tidball (2013) make a case for the interdependence of ecosystem resilience and human systems. Their book, *Greening in the red zone* describes how, world-wide, communities have transformed scenes of destruction into havens of green. In doing so the claim is made that community greening and caring for the natural world is connected to social health and wellbeing. Similarly, in their research into such caring practices at living memorials and community gardens McMillen *et al*. (2016) found practices of urban environmental stewardship to be indicators of social resilience since it fosters flexibility and ecosystem thinking which "…allows for emergent place-based assessment, dialogue, negotiation and change." (p. 21).

Trees are an essential part of the environment and their value to humans is expressed in terms of ecosystem services (see Table 1), which include providing greater comfort and wellbeing through reduction of heat island effects, (eg via shading and cooling) and encouraging biodiversity. This makes what happens to trees of relevance to architectural science due to that focus on the comfort of buildings for people, which trees positively impact on. This is especially as we experience higher temperatures due to global heating. However, as Watkins (2015) acknowledges, trees are very contested, since they can be viewed as providing public good but having private cost (eg maintenance and opportunity cost since where a tree stands a manmade structure cannot easily fit). As a consequence, trees are often polarising, including within New Zealand urban communities. Simply put, some people protest to protect them and others wish to poison them. While they may be seen as an asset (eg leafy suburbs command higher property values compared to less green neighbourhoods and trees help soak up floodwaters) they are also criticised for dropping leaves, growing into power lines, blocking drains and views or damaging property during storm events.

In their research, conducted as a result of the removal of publically administered tree protection in Poland, Paniotova-Maczak *et al*. (2021; 2023) investigated the importance of psychological variables, including place attachment and perceived benefits of trees, as determinants in people's views on tree management – specifically whether decisions about tree removal should be made by Councils or by private landowners. The premise is that with stronger place attachment comes greater tendency to value and protect nature. In comparing a rural and urban community they found higher place attachment in the rural community was linked to favouring tree removal being in the hands of Councils (Paniotova-Maczak *et al*., 2021). This suggests a stronger connection to place in the rural community means people are more invested in their surroundings and therefore want tree rules to be administered by Local Authorities. In a later paper (2023) they also considered environmental worldviews within two urban communities and found an Anthropocentrism (human-centred) worldview to support allowing private landowners to decide about tree removal, with this opinion being stronger with increasing sense of place attachment. This suggests that worldview takes precedence over place attachment in this instance. Overall, these researchers recommend that social factors affecting people's preferences needs inclusion and careful consideration in tree management decisions. Place attachment has potential merit in application to the project we are presenting here since we are seeking community views.

2. Setting the scene for Auckland trees

In Auckland (Tāmaki Makaurau), blanket Tree Rules that required resource consent to remove (or even prune) trees over a certain size, existed under the Resource Management Act (RMA) until 2015 (Stuff, 2015). Vernon Tava (2015), a Green Party MP at the time, claims that when this was removed, as part of a reform of the Act, an alarming number of trees in the private domain were removed 'just in case' such restrictions were to return. Further, a poster included in his blog suggests some arborists at this time also encouraged property owners towards tree removal – referring to trees as “shade baring [sic], leaf dropping, view blocking, hazardous, property damaging, or unwanted…”. The Auckland General Tree Rules applied to trees in both the public and private realm. The site for this research by design project is on land that was part of extensive grounds of a public polytechnic and now much of this land has been sold and is currently being developed into thousands of private dwellings (MHUD, 2023).

Relevant to this study is that as private section sizes have shrunk since the 1930s and house footprints have generally grown since the 1990s (Parliamentary Commissioner for the Environment, 2023), space for trees on private property has become increasingly squeezed. This signals the importance of increasing tree cover in public spaces. Compounding this situation, since 2017 Auckland has been undergoing a radical period of housing intensification predicated on a national housing shortage crisis (Auckland Council, 2023). The resulting increase in non-permeable surfaces is leading to the city’s leafy suburbs being deforested at an alarming rate, suggested (but not substantiated) to be up to 1000 mature trees per week, based on lidar (light detection and ranging method) comparisons (Niall, 2021).

Auckland Council has a policy to increase tree cover, called the *Auckland Ngahere (forest) Strategy* (Auckland Council, 2019) which states a goal of increasing tree cover from the current 17% average over the urban area, to 30%. However, not only is this a lamentably low figure, it is very inequitably distributed with some lower socio-economic suburbs being well south of 17% while more affluent suburbs are close to or exceeding 30% tree cover (Golubiewski *et al.*, 2021). For this strategy to achieve its aim mature tree loss on private property needs to be significantly slowed, and more trees planted – all in a landscape of less available land for planting.

3. Tree symbology and memorials

We suggest that trees are possibly the most symbolised organism by humans. When a healthy tree is removed, while the loss is easily measurable via ecosystem services the emotional symbology is not so easily quantifiable.

Trees can have spiritual, historical, cultural meaning to people and they may be used for legibility or way-finding in the landscape. In Aotearoa/New Zealand Māori mythology regards Tane Māhuta as the God of the forest – representing knowledge and holding his parents, Ranginui (the Sky Father) and Papatūā̄nuku (the Earth Mother), apart to create light and enable growth (Best, 1976). He is represented on Earth by a giant kauri tree (*Agathis australis*) in a Northland forest. Other native forest trees in Aotearoa are believed by Māori to represent human qualities and conditions, eg. totara for leadership and humbleness, maire for strength, kahikatea for shelter and pohutukawa for death and connection to Afterlife (Best, 1976). Yet even with this amount of significance bestowed on trees, they rarely become memorialised in the way buildings and events involving people are.

It is commonplace to use trees as memorials or plant trees within memorials and Jones and Cloke (2002, as cited in Cloke & Pawson, 2008, p. 109) point out “Their size, seasonality, and living qualities lend visual and embodied significance, and they exude streams of sensory data which engage our senses …”. Cloke and Pawson (2008) are geographers who studied the interconnections between trees and memorialisation at sites in Christchurch, New Zealand. They found trees’ organic nature to be both an addition and a distraction in this role as they mould place and its meaning with their presence. This includes physically (via growing), symbolically (via meaning), as characters developing personality, and metaphorically (via conveying relationships). As a result they coined ‘treescape memories’ to better reflect the complexity of the relationship between trees and memorialisation. Bowring (2019) writes about the practice of retaining ‘survivor trees’ as memorials (eg. those standing following the Christchurch earthquake in 2011, or surviving the WW2 bombing of Hiroshima). She explains that the survival of plants in the face of collapsed buildings lends these trees a spectral air. This can be perceived as an invincible force field, creating an atmosphere of the survivor tree being haunted by a tragic past (Bowring, 2019).

It is less common to memorialise tree loss. In one example a ghost gum in Queensland, Australia, named the Tree of Knowledge, became a symbol of the Australian Labor Party due to being the site of early pickets and reading of the Queensland Labour Party Manifesto. The tree was memorialised in 1991 to commemorate the centenary of the 1891 Shearers' Union strike. In an act of vandalism the tree was poisoned in 2006, which has led to the design by m3architecture of *The Memorial for the Tree of Knowledge*. The dead tree remains with its excavated roots protected by glass and its few canopy branches surrounded by a box-shaped frame filled with charred wooden pickets, indicating the extent of canopy the tree had in 1891 (Etherington, 2009). In a further example, Similarly, in Auckland the One-Tree Hill sabotage of the colonially-planted *Pinus radiata* in 2000 has led to a (better protected) native tree planting, in memorium.

Forty-nine dead Atlantic white cedar trees were erected in Madison Square Park in Manhatten by artist Maya Lin in 2021 to raise awareness of climate change and extinction (Madison Square Park Conservancy, n.d.). This exhibit evokes the concept of 'solastalgia' which translates as distress due to lived experience of negative impacts of environmental change (www.wikipedia.com). In another response to solastalgia, a funeral was held for the death of a glacier in Iceland (Quaglia, 2022).

Table 1: Benefits of Trees (Auckland Council, 2019).

Social	Environmental
Improve health & wellbeing	Enhance biodiversity
Reduce the urban heat island effect	Improve air quality
Provide shade	Carbon sequestration
Enhance visual amenity	Improve water quality
Economic	**Cultural**
Increase property values	Support education
Reduce flood risk	Local food growing
Reduce energy costs	Sustain and enhance mauri
Reduce healthcare costs	Cultural heritage

Figure 1: Mulch piles from felled trees (Authors' photo)

4. The site

Much of the historically significant Unitec Institute of Technology (now Unitec Te Pūkenga) site in Mt Albert, Auckland (approximately 50Ha), which has been chosen for this project, has recently been sold for residential development through an agreement between Unitec and the Ministry for Housing and Urban Development (MHUD, 2023). As a result, the park-like campus has turned into a construction zone. With this has come significant loss of mature trees that made up the, unoffical, Unitec arboretum. The disinterest to consult by Crown and developers, coupled with somewhat clandestine removals has led to a mood of disempowerment among those watching on. This research springboards off responses from concerned parties at the time of tree felling – asking for a process of consideration of the issues involved.

The tree removal leaves the campus somewhat denuded visually and concern has been expressed about loss of ecosystem services, especially the ability of trees to absorb water, given recent storm and flooding events in Auckland in 2023. There is also indication that campus-goers had connections with the lost trees, as evidenced by emails (with permission), Facebook posts and other media around the time of the tree felling. For example, they talked about having favourite flowering trees, walking through the trees and seeing them as symbols of legibility within the landscape. In addition, people were incensed by the trees being shredded into mulch rather than salvaged for use as a building material (see Figure 1). Of particular poignancy was the loss of four London plane trees (*Platanus* x *acerifolia*) estimated to be approximately 150 years old, dating back to an earlier land use when the site was a mental asylum and working farm (see Figures 2,3,4). The London plane trees were included among many mature trees felled towards the end of 2022 (see Figure 5).

Figure 2: London plane trees prior to felling

Figure 3: Trees after felling (Authors' photos)

Figure 4: Plane trees (far left) seen from the Marae

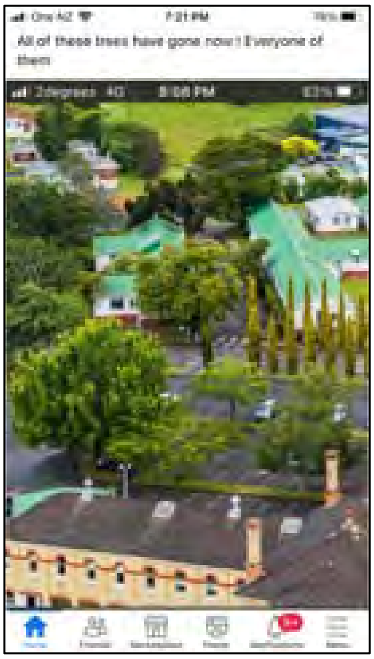

Figure 5: Facebook post about other tree losses on campus (Authors' photos)

5. Project method and analysis

5.1. Project

The project has been undertaken by a final year Unitec student in the Bachelor of Landscape Architecture programme. By identifying the emotional triggers people have within the School of Architecture about the trees, a community view of the tree loss, albeit limited, will be built up. Mixed methods were used, comprising collection of data and interpretation via themes (including use of 'word clouds'), sourcing case studies and relevant literature, and research by design to result in a proposal for the memorial.

5.2. Data collection and analysis.

In April 2023 posters showing the ghost outline of trees that were felled on a campus road in September 2022 were put up in the School of Architecture building at Unitec and pens supplied as an invite to students who wanted to add a graffiti comment on the poster (see Figure 6). Permission to use text from emails circulated by staff at the time of the tree felling in September 2022 was also obtained. Single words or groups of words were extracted for analysis.

At first the words and phrases were inputted to an App that created 'word clouds' (www.wordclouds.com). These presented the words as a circle shape with increasing font size indicating greater frequency (see Figure 7). Additionally, as a comparison to the campus-generated data, the response comments to two online newspaper articles on wider Auckland tree topics were also extracted and turned into word clouds. However, this indicated the news article comments were more focused on the larger issue of development and housing densification, rather than on people's emotional response to tree loss. This data was therefore dropped from the project as were the word clouds, which while visually strong interpretive accuracy.

The focus shifted back to the data collected from the School of Architecture at Unitec (ie. staff emails and student comments from the posters) and this data was organized into emerging themes, as represented by: Sad emotions, Negative emotions, Ecosystem services, Positive outcomes, Anthropomorphism/ symbolism, and Decolonization (this last theme was only evident in the student comments). Deconstructing this, sad emotions were dominated by loss, negative emotions by anger, ecosystem services refers to the benefits trees offer people, positive outcomes sought to find some value in what has happened or suggest alternative ways of managing the trees, anthropomorphism/symbolism regarded trees as having human qualities and/or special meaning beyond the usual. Decolonisation was the final theme, which emerged only in the student comments. In this context it refers to the preference in some quarters of NZ society to favour native flora over introduced colonial species.

Negative emotions were the greatest in number from the staff emails, perhaps reflecting that staff are generally more long term inhabitants of the place, compared to students. This fits with place attachment theory, as discussed earlier, since staff have stronger connections to this site (Paniotova-Maczak *et al*., 2021). It is also likely to be due to the more immediate timing of the emails, which were sent within a week of the felling of the plane trees and others. Negative emotions were also commonplace among the student comments – with both groups using words such as "willful destruction", "criminal", "tragic", "pointless", "stupid". Sadness came through strongly in both groups and especially that the trees are "missed". "Shame" was present both as feeling disappointed and as something to project onto another (eg. "shame on you"). Accusations were evident in both groups, eg. "poor planning", "agenda", "lack [of] consultation", "increased heat and reduced shelter in our climate change world", "negative effects on the stream and sediment controls".

Of interest were the comments that evidenced that respondants saw the trees as significant beings that were needed by humans at a fundamental level (eg. "earth's lungs", "breathing") and that they created an atmosphere and acted as a marker within the landscape (eg. "miss walking through", "poise", "framing", "greeting", "touching the sky"). This finding of the importance of trees and the perception of their human qualities within this community resonates with other researchers (eg. Bowring, 2019; Cloke and Pawson, 2008). It is important, however to acknowledge that a significant research limitation exists in that the participants who made comments are more likely to be people who cared more about trees and potentially had stronger place attachment.

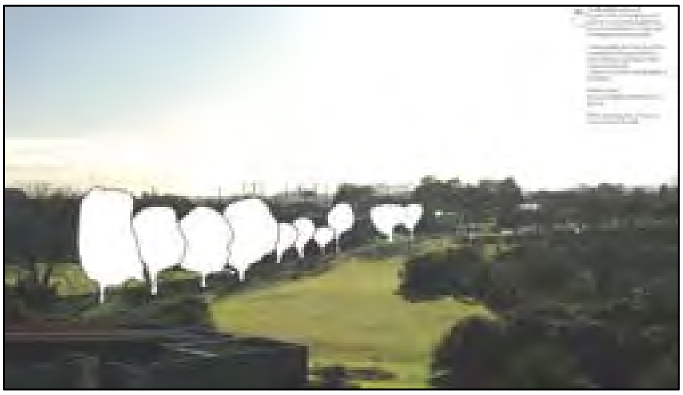

Figure 6: Authors' poster inviting students' graffiti comments on tree loss

Figure 7: Word cloud of poster comments (Generated by Author)

5.3. Design

Bowring (2022) situates landscape architecture as the discipline that draws together the many facets of memorialisation – eg social scientists, geographers, psychologists, stating that "… design becomes part of the dynamic of the urban memory field" (p. 375). In this recent review chapter, *Dealing with difficult memories,* she presents a taxonomy of possible memorial treatments, based on four authors' work. These range from memorials that seek to forget to those intent on remembering the event. Within these extremes Bowring (2022) proposes that design intent can be on a sliding scale from 'Oblivion' through 'Healing and repair', 'Curation and care' and, finally, 'Emphasis'. From her definitions and examples we determined the best fit for a design intent for the Unitec tree memorial to be 'Healing and repair'. Susser and Schneider (2003, as cited in Bowring, 2022, p. 382) propose that violence and wounding requires healing and they propose the possibility of "…imaginative construction in the face of destruction."

Roggema (2016) defines open-ended, complex and persistent problems, such as those associated with social processes, as 'wicked problems' and proposes that design offers an ideal way to approach these. Specifically, research by design is suggested, alongside a clear definition of it as "… a type of academic investigation through which design is explored as a method of inquiry…" (p. 3). Research by design is used here in proposing, through mapping and drawing, a memorial design encompassing the feelings of the people within the School of Architecture community of Unitec Institute of Technology.

The 'tiny forest' or Miyawaki forest movement is based on a forest management system developed in the 1970s by Japanese botanist and ecologist Akira Miyawaki. These densely planted mini woodlands are lately being suggested as a viable antidote to some climate change issues, eg. via providing shelter and shade, sequestering carbon in the soil and wood, soaking up rainwater, and increasing biodiversity (Buckley, 2023). According to Buckley (2023), they can be as small as the area of a basketball court yet contain as many as 1400 native shrubs and saplings crowded together. Their growing popularity in the UK and Europe is being matched or surpassed by plantings in Japan, Africa, Sth America, Russia, the Middle East and India. They have potential to transform waste and wasted land (eg. landfill sites, motorway shoulders, parking areas, school grounds) and offer the promise of extraordinarily fast growth (up to ten times faster) due to the intense planting and the improvement of soil through addition of leaf litter and fast buildup of soil microfauna and above ground reptiles and birdlife, bringing in new species (Buckley, 2023).

The Miyawaki forest concept matches both with the Unitec site and the analysis of data from the posters and emails. This includes the focus on the ecosystem services provided by the trees, the inclination to look forward and find solutions, the symbolism of trees supporting each other and humans, and the anger at waste and futility being replaced by regeneration and diversity. Fitting with Bowring's (2022) 'Healing and repair' it can become a bandaid metaphor for the dug-up and battered campus. It is scalable to on-going land development and includes plant species unique to New Zealand/Aoteroa, therefore helping to bridge the many cultures that call NZ home. Importantly, it is a positive response both to climate change and to repairing the wound caused by tree removal. In addition, as identified by Cloke and Pawson (2008) "Trees can be socially constructed as markers of memory, but they also make active contributions to the relational agency of place-related nature…" (p. 107). Although these authors are referring to trees being planted as or as part of memorials to events, not trees, their words are relevant in this context, especially discourse about the evolving and unruly nature of trees as they grow and carry memories of past events into the future, creating 'treescape memories'.

Although it first seemed desirable to choose a site for the Miyawaki forest memorial in the land to be retained by Unitec, site analysis revealed few suitable places. Even the area near where the plane trees had been growing was rejected as being too close to new infrastructure. Instead it was decided to site it as a connection between two proposed green spaces for the new intensive housing blocks that will eventually occupy the land. A site was found and mapped (see Figure 8 and 9) in the north-west of the site where a historic listed building (the pumphouse for the previous mental asylum) is likely to be transformed into a café with nearby playground. This is slightly raised and includes basalt outcrops from the eruption of nearby Ōwairaka Maunga (Mt Albert), 120,000 years ago. The area is currently thick with self-sown weed trees such as *Acacia* sp. and *Casuarina* sp. (see Figure 10 and 11). Through successive design iterations it was decided that these will be felled and the thicker trunks used as natural play elements (both lying and standing) in a clearing that will ultimately be surrounded by a mini native forest (25m diameter) that connects to a smaller Miyawaki forest, ensuring visibility safety for users.

Figure 8: Location map showing campus boundaries before and after the land sale (blue dot indicates the site chosen). (Source: Auckland Council Geomaps)

Figure 9: Location map showing chosen site for the memorial design. (Source: Auckland Council Geomaps)

Figure 10: Within the proposed site for Miyawaki forest

Figure 11: Looking into the proposed site with memorial showing lava flow (basalt) at bottom centre and *Acacia* and *Casuarina* spp. (woody weeds). weed species (trees

and herbaceous).
(Authors' photos)

The preparation and planting will follow the principles of Miyawaki forests, ie soil analysis (soil texture has been determined to be a sandy silt loam – typical of volcanic soils in this region) and improvement, determining potential natural vegetation (PNV) and consideration for the way plants interact together, called phytosociology (Nargi, 2019). In assessing PNV we looked at remnant Auckland lava forest, a globally rare ecosystem, which is found nearby (within 1km) under the North-Western motorway interchange – also due to the Ōwairaka eruption. A plant species list will include layers of species unique to this ecosystem type (Urban Ark, 2023). By planting very densely the plants will grow faster as they compete for light. Ferns, mosses and other plants such as climbers and epiphytes will also naturally colonise the area due to wind, rain and bird dispersal and the ideal conditions of moisture retention and shade. A plan view (Figure 12) and perspective (Figure 13) show how the Miyawaki Forest Memorial will look and function. An simple interpretative panel will be erected to provide information on the memorial.

igure 12: Plan view (NTS) of Miyawaki forest memorial showing ground layout of planting versus open space for reflection and play.
(Created by Authors)

6. Conclusion and reflection

Figure 13: Perspective (NTS) showing Miyawaki forest memorial with rocks and logs for natural play and space for enjoyment and reflecting. (Created by Authors)

This project set out to consider people's feelings about tree loss within their community (in this case a tertiary educational institute) and to use this to drive a research by design process to design a memorial to tree loss that respects those feelings, commemorates the tree loss and educates about the importance of trees in our climate-changing environment. Survivor trees are imbued with a 'stickiness' of memory and meaning (Bowring, 2019), which is similar to what is being projected by the Queensland memorial tree example described earlier. In our example the trees are gone. Worse, they were reduced to the indignity of becoming piles of mulch, so the design approach, guided by our interpretation of the data collected, has been different.

Although there were clear limitations with the data-gathering process in that the pool of participants (staff and students from the School of Architecture) was both limited and biased in that they largely expressed strong place attachment, this does not diminish the process since it was intended to seek and reflect people's views and memories of the trees, rather than to draw sides on the contentious issue of tree removal. The developing themes from the data were valuable in helping to direct the design of the memorial towards something strongly regenerative, plant and ecology-rich, symbolic and yet also playful and future-focused.

The taxonomy of memorials presented by Bowring (2022) was useful in directing us towards a certain approach (healing and repair). Following this, Roggema's (2016) identification of 'wicked problems' and subsequent proposal of research by design as the appropriate method for solving such problems led to multiple solutions being proposed. From here the Miyawaki forest concept emerged as the most fitting memorial response – one that transfers the energy contained in the lost trees back into this new forest, both through its growth and through the enjoyment of those who will visit and reflect or play, in essence caring for this environment. Certainly this fits with te ao Māori (Māori worldview) and, given the evidence connecting trees with human well-being, this should be of benefit to all through building social resilience, as identified by McMillen *et al*. (2016).

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Sustainability and Health: The nexus of carbon-neutral architecture and well-being

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Abstract: Within the imperative surrounding contemporary concepts for environmental and social sustainability and the affordable housing crisis, an opportunity exists to explore low-cost, low-skill labour use as a transferable housing solution to support vulnerable communities. In this scenario, recognising the intricate nature of the domestic construction industry is critical: involving the interweaving balance between material culture, the social networks of construction and the boundaries between architecture, structure, materials, and building in a digitally enabled domestic construction industry. Amongst the challenges this scenario poses is to broaden education modes, using technological enablement and aligning them to communicate architectural science in its application to political economy, societal equity and the environment. This paper explores ways to use a digitally designed and fabricated unit to embed youth training through participation in the assembly process and as future training ambassadors as the project develops. It enquires how digital tools engender new pathways for collaboration between designers and makers and incorporate end-users needs, facilitating the permeation of capacity-building access via a construction material (timber) that has traditionally circumvented formal-driven social structures.

Keywords: Digital Design. Digital Fabrication, Youth Homelessness Design, Affordable Housing.

1. Introduction

The sustainable development goals of the United Nations identify good health and well-being, the education of future generations, the creation of job opportunities for youth, and the reduction of inequalities. They also put forward responsible innovation and production and are doing so to provide for sustainable communities—the removal of disparities and the provision of sustainable communities (United Nations, n.d.).

Within the imperative surrounding contemporary concepts for environmental and social sustainability and the affordable housing crisis, an opportunity exists to explore low-cost, low-skill labour use as a transferable housing solution to support vulnerable communities. In this scenario, recognising the intricate nature of the domestic construction industry is vital: involving the interweaving balance between material culture, the social networks of construction and the boundaries between architecture, structure, materials, and building in a digitally enabled domestic construction industry. Amongst the challenges this scenario poses is to broaden

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education modes, using technological enablement and aligning them to communicate architectural science in its application to political economy, societal equity and the environment.

This paper explores ways to use a digitally designed and fabricated unit to embed youth training and work experience opportunities through participation in the assembly process and as future training ambassadors as the project develops. Specifically, it a) explores scoping opportunities in the use of digital design to digital fabrication techniques in its application to vulnerable sectors of the community, namely youth at risk of homelessness, diverting pathways to homelessness through low-cost temporary accommodation, and b) provides alternate low-cost and rapid temporary accommodation supply to leverage existing property assets (e.g. short-term leasing arrangements on Municipal owned land for utilisation for temporary affordable housing for vulnerable community members) without large capital outlay.

The subsequent objectives are to (a.1) formulate a protocol for users to customise their units while considering performance-based inputs; (a.2) prepare an approach for youth empowerment enabled via training opportunities in process participation and develop higher-level skills through train-the-trainer programs. It enquires how digital tools in architecture can engender new pathways for collaboration between designers and makers and incorporate end-users' needs, facilitating the permeation of capacity-building access via a construction material (timber) that has traditionally circumvented formal-driven social structures.

The research presented in this paper was inspired by studies on digital materiality, design and fabrication (Burry et al., 2020; Klinger, 2013; Mota, 2011; Neeley et al., 2013; Schwartz, 2016), DIY and Makers (Camburn and Wood, 2018; Anderson, 2012).and the participatory design and democratic practices of mass customisation (Corser, 2012) as a way to equalise power relations and give voice to those who may be invisible, as explained by Greenbaum and Loi ((Greenbaum and Loi, 2012).

Through a Faculty Research Development Grant, this research has been carried out by the paper's authors in a collaborative effort with Research Assistants Dr Alessandro Liuti and Darcy Zelenko.

2. ROOM (Resolve Once Output Many) and Carbon neutral architecture

The Australian guide *Climate Active Carbon Neutral Standard for Buildings* defines carbon neutrality as reducing greenhouse gas emissions where possible and using carbon offsets to achieve net zero overall omissions (Commonwealth of Australia, 2022). The ROOM project, amongst its objectives, is to seek as close as possible to carbon neutrality and, in doing so, act as a source of carbon offsetting. Its primary purpose is to serve as an accommodation option for youth at risk of homelessness.

ROOM (Research Once Output Many) is a project proposing using digital technologies based on digital design to design fabrication for a customisable temporary, transportable, and adaptable small independent unit intended in its original configuration to be for separate accommodation for youth at risk of homelessness. The unit is customisable by inverting a traditional supply chain approach in encouraging end-user input into the design phase. It is customisable and adaptable to being site-specific and adaptable by reconfiguration to repurpose the unit to other potential uses. These uses may include modification to further application in stand-alone housing or adaptation as a parasitic architecture to improve energy efficiency or extend existing structures' capacity. The proposition is to reuse offcuts or discarded building construction or manufacturing materials in repurposing or upcycling. The reuse of materials extends the output lifecycle, thereby reducing the carbon footprint of material production and application.

Despite the significant impact of COVID-19, a pilot project was commenced, which sought to use small timber lengths joined without mechanical fixings. A 1:100 scale timber frame using 1.8 mm Victorian Ash laser ply replicated 18 mm plywood sheets. The sheets can be cut using a CNC (Computer Numerical Control) router and are made to identify the issues raised by the computer-supported design and fabrication proposition. Software applications and computer numerical control (CNC) machining were limited to that available within the existing dictates of a tertiary education fabrication laboratory. Modelling was done using Rhinoceros 3D, and a full-bed MultiCam CNC routing machine did the cutting.

The purpose of the physical model was to analyse one possible design output while investigating the areas needing verification, such as the nodal connections. The physical model was not intended to validate a pre-established design solution but to analyse the workflow's robustness and end-use purpose.

3. Vulnerable communities

The *Australian Charities and Not-for-Profits Commission* defines vulnerable people as "people under 18 or other individuals who may be unable to take care of themselves or protect themselves against the harm of exploitation" (External Conduct Standard 4: Protection of vulnerable individuals | ACNC, n.d.). A key aspect is to recognise and respond to vulnerability in youth at risk of homelessness before it progresses to public welfare and structural homelessness. At-risk youth depend on their existing direct support networks, friends, family, work, education environments and mental health professionals despite some being the instigators of their issues. Based on research in Canada and the United States, O'Grady and Gaetz have identified several causation factors ranging from abuse, poverty, discrimination, and interaction with the child welfare system (O'Grady and Gaetz, 2009). Young people have limited choices for employment, incur challenges in seeking training and education, and are below the level of qualifying for affordable housing. The approach of assisting young people to improve relationships, retain or develop a connection to their community, and leverage education is a recent policy and program approach.

In 2021, the Australian government created the pilot *Reconnect Program*, funding 96 early intervention services nationally. The *Reconnect Program is* proposed to build community and early intervention capacity to address youth homelessness. It sought to build community infrastructure and strengthen agencies and organisations in early intervention strategies (Department of Social Services, Australian Government, 2023).

Independent or supported accommodation and existing facilities such as emergency and crisis accommodation are ill-suited to those youth at risk of homelessness. Additionally, there is a lack of supply to meet the demand for homeless housing, let alone that suitable for youth. The ROOM project is a potential response mechanism to provide independent but connected accommodation leveraging existing land availability adjacent to or directly connected to existing capacity in a household or expanding specialist supply options for housing support agencies, such as emergency or transition youth-based housing. The proposal is to produce a tiny home customisable to the end user and site whilst incorporating user design input and user assembly. The proposal seeks a low carbon footprint by incorporating construction and manufacturing waste materials and pursuing sustainability through future adaptability.

4. Health, Well-being, and Education

The Reconnect program seeks to permit at-risk youth to remain within their existing support networks but connect them to individual or family counselling, health services and employment training. ROOM provides a temporary unit suitable for individual accommodation or as a support to continuing or pursuing education.

The ROOM project seeks to engender youth empowerment. It does this by providing design control of a young person's living environment in a customised unit fit for purpose and engendering a sense of ownership by participating in the assembly of a unit of their design. The involvement in the design and assembly process engenders an educative function, not only in an individual's capacity building but also in empowering them via additional training to feedback their skills in a train-the-trainer program. An individual may then train other individuals and expand the program. This process aligns with the World Health Organisation's physical and mental health pursuits in recognising mental health as a universal human right that promotes individual and community resilience (World Health Organisation, 2022).

5. Opportunity

Amongst the many issues faced by youth at risk of homelessness is the inability to access independent living. Housing affordability is at a crisis point for the general community. Discourse in solution response is an increase in supply through government land release, government and private capital funding and provisioning by not-for-profit housing agencies. These frameworks seek to increase affordability access and housing supply.

ROOM accounts for the lack of new land for development and the suitability of such land release in the metropolitan periphery. However, youth homelessness vulnerability is not limited in its scope. It is applicable in urban, peri-urban and rural environments.

ROOM provides an opportunity to leverage existing underutilised land. Such land exists via traditional freestanding housing, which may be found in social and private housing. Australian planning regimes allow dependent persons' units as second dwellings. These may be utilised for single occupancy by a young person dependent on the person in the main home. Opportunity, therefore, exists to leverage existing land. However, awareness and advocacy are still required, as exemplified in the approach underpinning not-for-profit housing agencies such as Kid Under Cover.

ROOM also recognises the requirement for response immediacy and the difference between a temporary and permanent housing solution.

ROOM intends to provide an immediate but temporary response that embeds youth empowerment by these users participating upstream in the design process and end stream in a building assembly. In linking these two aspects of the supply chain, a feedback loop is created for design and delivery improvement opportunities and for an individual to demonstrate capacity.

6. Technology, social responsibility, and social sustainability

The utilisation and application of digital technology is promoted as a tool for productivity gains, production efficiency and economic benefit (Klinger, 2013). These promotions are more often predicated on the economics of societal benefits aligned with production efficiency, consumption, and market impact. Rarely does it extend to turning the lens to private and social benefits in application to directly addressing fundamental human rights and social justice. In recognising other approaches such as WikiHouse and X-frame, this project retains the imperative of looking at a social disadvantage in its applicability to social disadvantage in Australia.

ROOM recognises that existing capacity exists by tapping into technology already embedded in the construction industry. This capacity exists in the uptake of digital design to CNC fabrication of the joinery sector of the construction industry. A balance may be tapped between material culture, the social networks of construction and the boundaries between architecture, structure, materials, and building in a digitally enabled domestic construction industry for a social justice application in providing accommodation options for youth at risk of homelessness. In addition, tapping innovation and broad application are afforded by open-source engagement.

7. Resource sustainability

ROOM is aligned with several resource sustainability aspirations. By being supported under the planning provisions for in-place dependent secondary accommodation, it is required to ensure land use minimisation. Its intended use as a temporary small living unit embeds material reduction resources, permutations of use flexibility and resource adaptation.

ROOM desires to leverage resources by incorporating material reuse and recycling towards built fabric based on zero carbon imperatives, contributing to a positive environmental impact.

Design with leftovers is a crucial challenge for students, users, and architects. Making and designing with surplus, leftovers and scrap materials from manufacturing processes that would otherwise have been used as firewood means designing through a more adaptable and versatile arrangement of components. ROOM shows how excess textile, stone, timber, and consumer waste can be given a second life, demonstrating how manufacturing waste can create high-quality products on a larger scale.

ROOM was based on the concept that the outcomes follow specific resource availability, not vice versa. For this reason, the components of a typical unit are classified into key variables and invariables. The first consists of the framing, which requires a material whose characteristics can be traced and used for the structural calculation. The recommendation is to use offcuts of timber manufacturing, thus allowing a consistent approach to resource minimisation. The key invariables are each structural element's small components, which allows the timber industry to use offcuts. The key variables comprise all the other parts.

The ROOM project embeds the once-ignored approach remaining prevalent in the construction industry of economic circularity and economic redundancy in the construction industry. The end of life of each unit is considered through the Design For Disassembly principles of ROOM.

8. The pilot project

The project started with whether we could develop a design system, rather than a single solution, through a simple workflow that included some basic design strategies that users could utilise while customising their unit. The aim was to build a digital design and fabrication flow that, given some specific constraints, could (1) easily accommodate changes to the manufacturing instructions between each unit, (2) cost the same to mass-customise as it does to mass-produce the same quantity of identical products; (3) be assembled and disassembled by non-specialists and without specialised tools; (4) be easily disassembled and reused.

We built the initial workflow in *Grasshopper*, a visual programming language running within the *Rhinoceros 3D* computer-aided design (CAD) application.

The final version of the pilot workflow (Figure 31) is based on clusters of variables, starting with the general dimensions of the unit (internal height and plan dimensions) and the cross-section key parameters. The vertical structure is given an initial value (that can be modified as needed). The initial workflow includes one door and window location. The openings' presence changes the walls' internal structure; therefore, it is an initial input to be considered.

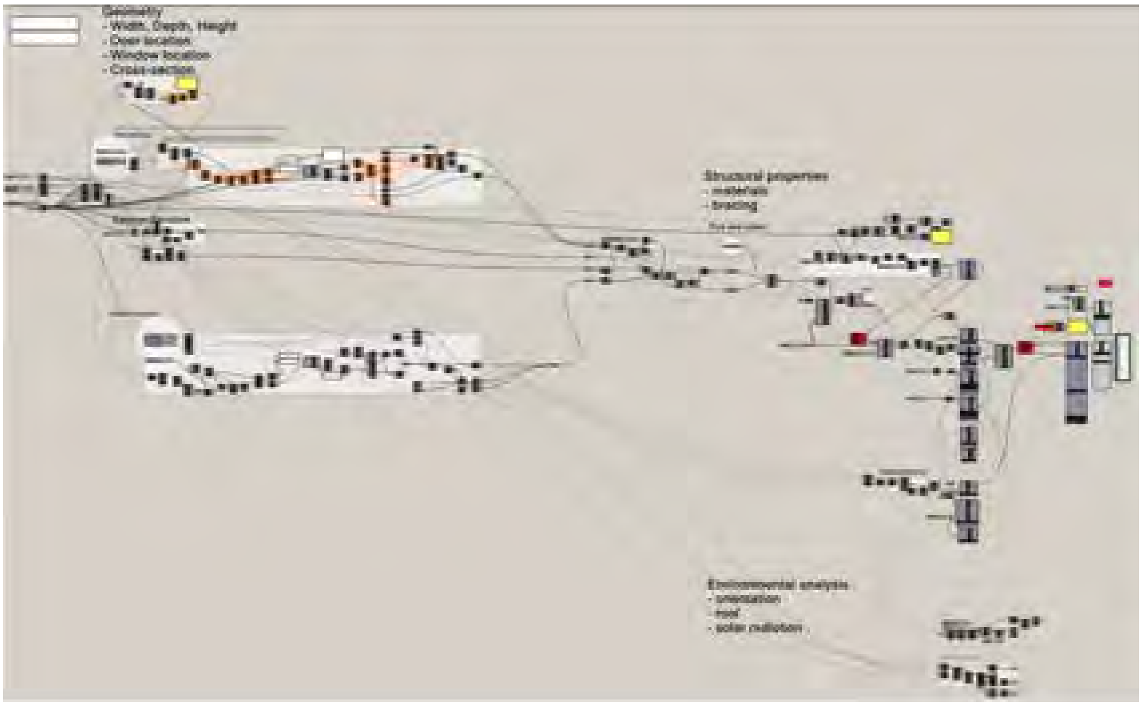

Figure 31: ROOM workflow.

The ROOM components comprise sub-framing, wall framing, roof framing and internal furniture. The floor framing structure was initially conceived as the roof, entirely digitally fabricated from small timber pieces (**Error! Reference source not found.** left; element count: 33; total CNC cut length: 70m). It was then replaced with a more efficient system of traditional bearers with a unique CNC joint to the footing and the vertical structure, thus transferring the complexity of the digital fabrication only where needed, while taking advantage of the traditional construction systems of bearers and joists. The first iteration of the bearers allowed for fixing on the top layer and running the services along the bottom, but the simplicity of production and assembly was deemed more relevant to the project's scope. Therefore, the more straightforward solution (**Error! Reference source not found.**, right) was chosen.

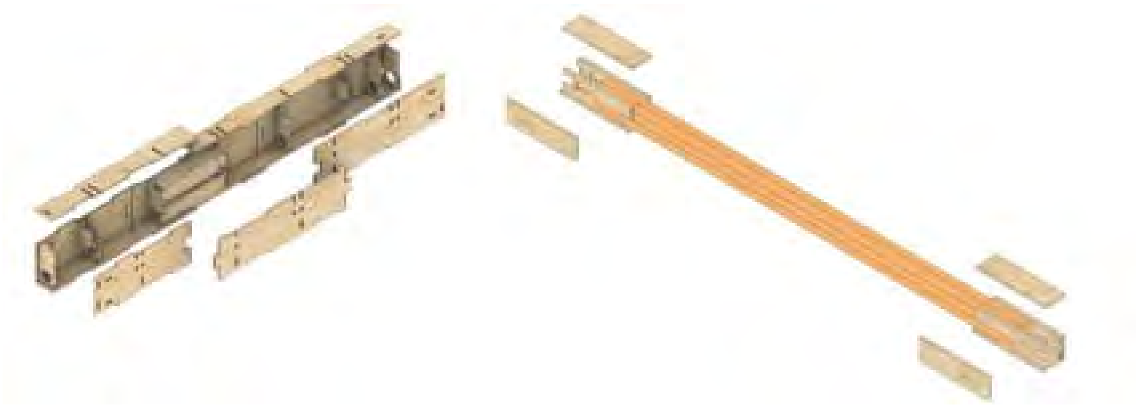

Figure 32: Bearer comparison - initial design (left) and final simplification (right).

The roof truss aggregates 19 elements for a total CNC cut length of 76 m. It is designed with bottom slots to facilitate the insertion of the ceiling battens (**Error! Reference source not found.**). The inclination of the top chord can be customised in the workflow and optimised as needed. The overhang can be adapted for wall shading in winter and solar gain in summer. The maximum overhang is assumed not to exceed 900 mm to avoid tension at the nodes.

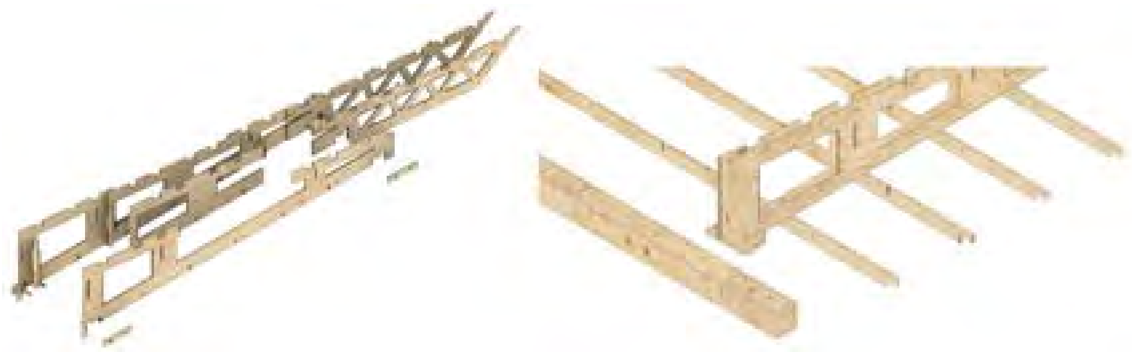

Figure 33: Exploded view of a typical beam (left); connection to the ceiling battens (right).

The typical nodal connection counts 18 elements for a total cut length of 20m. Footing solutions and other connections are selected off-the-shelf for low-cost and easy assembly. The users can choose the preferred (or available) cladding and insulation materials.

Several options were studied to simulate how a typical ROOM unit could be aggregated to other units to set up diverse scenarios (e.g. two to four-person accommodation). The workflow was then rearranged to make it possible to remove one wall and connect with a second (or more) unit, with or without an internal additional space that could be used as the entrance and separation between the two rooms. The straightforward option is to leave the two units disconnected and use the space between them as a small terrace or two-unit entrance (Figure 34).

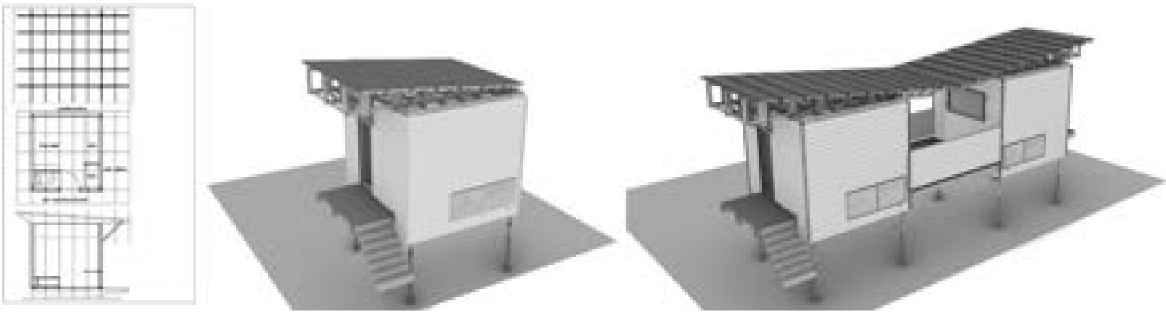

Figure 34: Basic plan and section views (left). Single unit (centre). An aggregation (right).

9. Conclusions

The ROOM pilot project put forward a framework for applying digitally enabled design and fabrication to respond to the increasing societal problem of youth homelessness. It does this by offering a self-build accommodation unit, like a tiny home, to help youth at risk of homelessness to remain within their existing support networks and activate support services targeted to individual needs. End-user participation in the design and assembly of the unit creates a method by which the young person may participate in training and verify their capacity to a potential future employer. It builds capacity that responds to significant supply challenges to an increasing demand. In more general terms, the pilot aims to integrate teaching and learning in the making. Its fundamental goals are to provide an education vehicle for youth and verification capacity and, in doing so, build resilience. The broader application is to assemble to make design a creative capital within the next generation.

By expanding the involvement into a train-the-trainer approach, the project extends to community development and to design and build a moral sense of service to a community. The refrain lies in enabling fast and cost-effective construction, which is easy to assemble, dismantle, and reusable. It looks at design application in terms of cost minimisation, sustainable practices, and the circular economy for a positive social benefit.

The pilot exposed several challenges and questions which could not be pursued due to the limitations of resources, timing, and scope. Amongst the findings were the resourcing implications of offcut timber and its structural integrity.

The design is based on the ability to assemble the system without prior knowledge or construction skills and mechanical fixings. The project identified that a critical area of focus lay in the nodes or points of connection. These had to be responsive to structural actions, load transfer and frame stability. Due to these nodes' importance, it became clear that these nodal connectors had to be strictly controlled and required expertise and non-site-based manufacturing.

Although it was not tested, the kit of parts responds to the framing of being both a (partial) solution to youth homelessness and a manifesto against consumerism, planned obsolescence and waste.

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Testing of new feedback methods for architects on school design – methodology and preliminary results

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Abstract: Architects and designers need feedback from completed buildings to improve the sustainability of future designs. Besides quantitative measures like energy performance, embodied energy, and water use, sustainability also includes assessment of qualitative aspects such as occupant wellbeing, psychological and physical comfort and social and community connection. For this research, school buildings were selected as a test typology due to the large body of pre-existing qualitative research, multi-disciplinary research community, worldwide application and long-term effects on people. A prior literature review determined gaps in the comprehensiveness of available feedback methods for schools. A prior survey of Australian architects ascertained aspects upon which they desire feedback and showed that existing feedback methods omit aspects architects believe are necessary to improve future designs. This paper presents methodology and preliminary results of new feedback methods designed to provide comprehensive, designer-friendly, and easy-to-analyse feedback. These methods included on-line surveys for older children, teachers, administrators and parents, a drawing-voice activity for younger children, and other visual response methods for all grades. They are compared to more traditional methods including instrument recording of classroom indoor environment indicators, walk-around interviews with staff and a traditional style post-occupancy evaluation survey of staff. The overall results of this study will illuminate the strengths and limitations of more traditional feedback methods and offer insight into alternate feedback methods that gather design-related experiential information.

Keywords: Sustainability; feedback; post-occupancy; architect or designer.

1. Introduction

The importance of feedback on completed buildings for architects and designers to improve the sustainability of future designs is well recognized in the literature (Clements-Croome, 2019) (Fairley, 2015) (Vischer and Preiser, 2005) (Federal Facilities, 2001). Buildings produced by the construction industry are all prototypes (Cohen *et al.*, 2001), and numerous modifications are made between designs, further complicated by the different context for each project – including geographical, economical, social, and organizational factors. Due to these complexities, architects require feedback to ascertain whether each change has led to improved outcomes or conversely, had a detrimental impact.

However, despite its necessity, post-occupancy feedback often remains inaccessible or is presented in a format not useful to architects. This situation can be attributed to a variety of reasons, including:

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- A focus on energy performance and comfort (Brown, 2018).
- Limited assessment of qualitative aspects and a lack of agreement on methods for that assessment (Whittem *et al.*, 2022).
- Omission of areas important to architects, such as the way people use and behave in a space (Hay *et al.*, 2017) or concerns related to a particular typology such as sightlines or security concerns in a hospital (Fay *et al.*, 2017).
- Questionnaire results which provide general feedback and do not show locations of specific successes and problems (Kelly *et al.*, 2011).
- Published in media or locations such as academic journals which may not be accessible to architects, nor formatted to provide design guidelines. (Li *et al.*, 2018) (Hamilton, 2007).
- A focus on particular aspects across many buildings rather than detailed examination of a particular building (Li *et al.*, 2018)

In addition, barriers to architects obtaining their own post-occupancy feedback have been well documented, including:

- An industry culture that views a building as completed at handover (Cooper, 2001).
- Feedback results are held behind a paywall, such as the BUS Occupant Survey (currently held by ARUP) (Leaman, 2021a) or the Victorian School Building Authority POEs (completed by Aurecon) (Delestrez, 2022) which are the intellectual property of those firms and the architect is not permitted access to the results.
- No allocation of project budget to post-occupancy studies and client unwillingness to pay for them as they consider benefits would go to the design team or the next client (Bordass, 2004).
- Lack of profit margin in small architectural practices from which to fund feedback studies (Woodroffe and Tucker, 2007) (Whittem and Roetzel, 2019).
- Constructors fear uncovering problems which they would be required to rectify or be subject to court action (Bordass, 2004).
- Architects and insurers have concerns that POEs may lead to reputational harm or professional indemnity liability (Hay *et al.*, 2017).

This research examines feedback on school designs as an initial typology for the following reasons: firstly, the design of schools significantly impacts the education of all individuals; secondly, there is an existing extensive body of research with an active research community; thirdly, school buildings influence how future generations perceive sustainability; lastly, the owners of these building assets typically operate with long-term horizons.

This research builds on previous work which reviewed the academic literature for the comprehensiveness of building aspects examined in post-occupancy studies of school buildings (Whittem *et al.*, 2022). The conceptual review used the Integral Sustainable Design (ISD) framework to check for comprehensiveness. ISD was developed by DeKay (DeKay, 2011) as a design guide for buildings because, at that time, sustainability rating schemes focussed on quantitative measures and technical solutions and ignored qualitative and experiential aspects of buildings. ISD is based on Integral Theory (Wilber, 2001) which proposes that all human knowledge can be placed on a four-quadrant matrix with axes of objective to subjective and individual to shown in Figure 1.

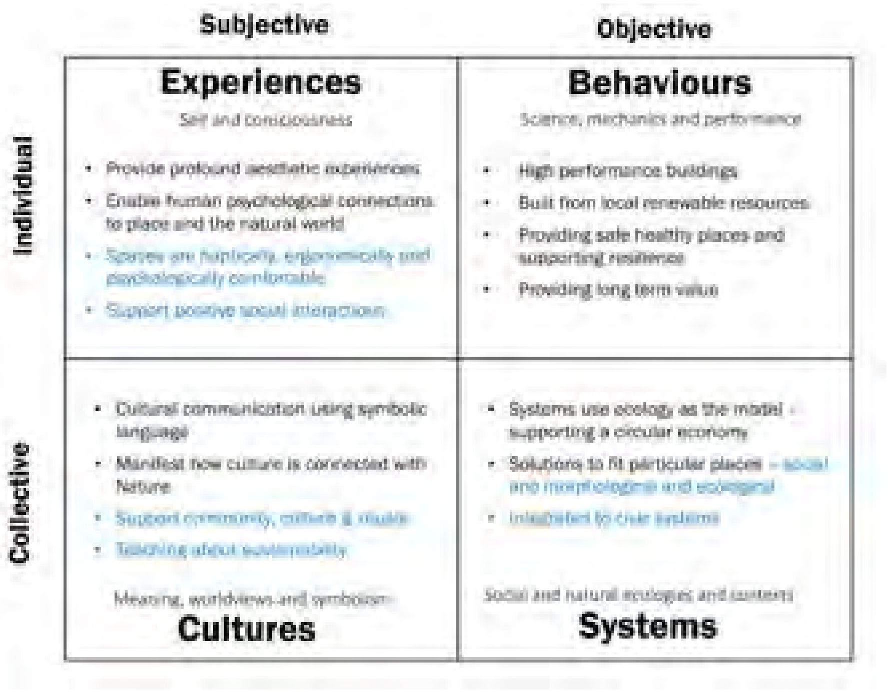

Figure 1 : Aims of Integral Sustainable Design (DeKay, 2011) as extended by author (Whittem *et al.*, 2022)

The review identified areas where evaluation methods and criteria are well established and agreed, such as instrumental measurement of energy (Dias Pereira *et al.*, 2014) and water use (Fayyad and John, 2019)thermal comfort (Kim and de Dear, 2018) , acoustics (Wilson *et al.*, 2019) and lighting (Ackley *et al.*, 2020), comfort experience (Sadick and Issa, 2017a), waste management (Global Sustainability Standards Board, 2020), and green stormwater infrastructure (Taguchi *et al.*, 2020) (objective right-quadrant ISD aspects). Aspects exhibiting some research with criteria proposed included school food gardens (Ledesma *et al.*, 2020), ecosystem services (Wong *et al.*, 2018), wellbeing (Sadick and Issa, 2017b; Rolfe *et al.*, 2022), control (Hellwig, 2015), spatial aesthetics (Şenyiğit and Basri Memduhoğlu, 2020), sustainability culture (Tucker and Izadpanahi, 2017), and learning culture (Young *et al.*, 2021). Areas with limited research and lacking proposed assessment criteria included socialization (Walden, 2015), sense of place (Cole *et al.*, 2021), support for rituals (Chen, 2016), physical externalities (Baird, 1996), and community services (D'Ayala *et al.*, 2020).

Following the literature review, a survey was conducted of Australian architects to determine their preferences for feedback regarding design of school projects (publication in review). The survey questions were designed using broad language to prevent influencing the responses. The findings revealed that beyond energy and thermal performance measures, architects expressed a desire for user feedback related to functionality, flexibility and variety of spaces. This also included various aspects of comfort, including emotional and psychological responses, as well as support for both established and novel pedagogy, community engagement and sustainability education. However, it is worth noting that a later question regarding the evaluation of schools for sustainability generated a range of criteria more focussed in the upper right objective performance quadrant.

In response to the need for feedback on under-researched aspects of schools, the need to address architect preferences and the need for incorporation of spatial information valuable to architects for design and planning, new feedback methods and instruments were developed. In addition, prior research has found that the amount and depth of post-occupancy feedback acquired is determined by the size of the architecture firm and clients, with smaller firms not having the resources for in-depth studies (Whittem and Roetzel, 2019) (Woodroffe and Tucker, 2007). Therefore, an additional consideration was the need to develop post-occupancy feedback methods that are user-friendly and effective for architects to readily implement on their own. The developed methods have been tested through a case study of a Victorian school in conjunction with instrument data collection, time-consuming visual methods, and traditional post-occupancy feedback methods. This paper reports on the methods along with preliminary findings from the data analysis.

2. Methodology

A case study was conducted at a school in Victoria, Australia, to evaluate the new feedback methods against certain existing methods.

The study recognizes the importance to obtain views from diverse members of the school community, both to satisfy architect requests and to ensure that the lived experience of the school environment is properly investigated (Cleveland *et al.*, 2016), in other words:

> …. if the environment provided by the school for learning is to be comprehensively understood, it seems important for all those involved, including parents, learning support and other staff, as well as students and teachers, to participate in any investigation. (Woolner *et al.*, 2010)

There is a challenge here between obtaining comprehensive information and the length of surveys which must be kept as short as possible to avoid impacts on response numbers.

Increasingly, visual methods are being used in education environment research (Woolner *et al.*, 2010) and are particularly useful for participants who struggle with written language or who raise ideas not imagined by researchers when designing written surveys (Barriage *et al.*, 2017). A critical literature review of visual research methods used in related fields was conducted to determine what methods would be most suitable for the ages of the children in the case study and which would provide useful information for architects. Woolner makes a convincing argument that several methods should be used concurrently to overcome any bias or deficiency of a particular method (Woolner *et al.*, 2010). The case studies in Sanoff's *Visual Research Methods in Design* were illuminating as many related to children and school design (Sanoff, 2016). Photo-elicitation and photo-voice in particular have been used extensively in ethnographic research with children for many reasons including allowing children to engage with complex feelings, reducing power asymmetry and engendering confidence (Brown *et al.*, 2020). The picture(drawing)-voice activity was utilised in this study as being suitable for younger children who do not have the reading and writing skills to complete a written on-line survey. In this case it was also important to compare the spatial questions in the ISD comprehensive on-line surveys to other visual ways (*Places I Like* poster exercise) of obtaining similar information. Methods identified in the literature review as potential alternatives for this purpose included techniques such as image sorting (Mannay and Pauwels, 2020), cognitive mapping, and the utilization of wish poems combined with drawings of typical and ideal school environments (Sanoff, 2016).

Other methods found in the literature review were determined to be impractical for architects to use due to extensive analysis time required or onerous ethics approval requirements. Moreover, some of these methods were not suitable for the intended purpose or engagement with children. These included auto-photographic method, photo-elicitation, visual narratives, pictorial diaries, bio-documentary filmmaking, participative video, artefacts/sandboxing/dolls houses (Mannay and Pauwels, 2020), scale model kit, simulation games, VR, houses layout game (Sanoff, 2016), found object photographs (Moss and Pini, 2016), interview-infused participatory photo elicitation, drawing with mapping and transparency overlays, pen-casting (recording of self-descriptions during drawing process) and slideshow photo-stories (mark-up student photos on screen while recording discussion) (Blackmore *et al.*, 2013).

Table 1 lists the selected activities undertaken and the number of respondents:

Table 17: Case Study: Research methods used and number of participants.

Research Method	Qualitative/ Quantitative/Spatial	Stakeholder Group	Dates	Number of Respondents
Instrument Measurement of Indoor Environment	Quantitative		Aug 2022 – Feb 2023	8 classrooms & 2 hubs
School overall data questionnaire	Quantitative	Administrators & Owner	Apr 2023	1
Teacher Survey 1 On Line	Qualitative	Teachers	Jan-Feb 2023	13
Administrator & non-class teachers Survey 1 On-Line	Qualitative	Administrators & non-class teachers	Jan-Feb 2023	10
Traditional POE Survey – Teachers & Administrators Survey 2– On-line	Qualitative	Teachers & Administrators	Jan-Feb 2023	13
Children's On-line Survey – grades 3-6	Qualitative & Quantitative	Children	Feb-Mar 2023	94
Parents On-line survey	Qualitative	Parents	Feb-Mar 2023	14
Walkaround Interviews – Administrators, cleaner/janitor & teachers,	Qualitative	Administrator, cleaner & teachers	Feb-Apr 2023	5
Picture-Voice Activity – grades Prep-2	Qualitative/Spatial	Children	Feb-Mar 2023	79
Places I Like plans	Spatial	Children	Dec 2022	8 classes
Graffiti plans	Qualitative/Spatial	Children	Dec 2022 – Feb 2023	8 classes

The research was approved by Deakin University Human Ethics Advisory Group approval number SEBE 2022-53- and Victorian Department of Education and Training Approval Number 2022004648.

2.1. Instrument Measurement

Instrument data was collected from each classroom continuously with durations ranging from one to two weeks during each winter, spring, and summer seasons. The monitoring equipment used included two Ethera Mini XT devices which were installed at child desk height. A typical location is shown in Figure 1. They measure Formaldehyde, Carbon Dioxide (CO_2), LVOC (Light Volatile Organic Compounds), Temperature, Humidity, Air Pressure, Lux, average and maximum noise.

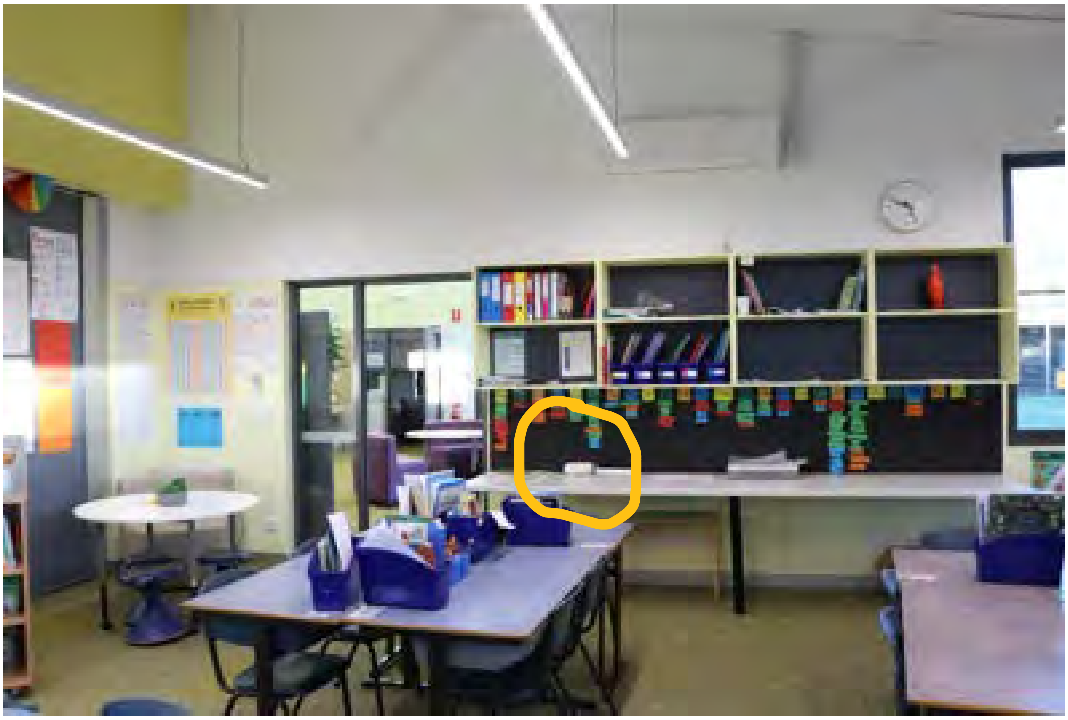

Figure 1 Typical location of Ethera Mini XT

In addition, air velocity was measured using two TSI AirPro AP500sensors. The latter instruments were located out of reach on high cupboards due to the age of the children, the delicacy of the instruments and the need to leave them unattended to minimize disruption to classes. Comfort carts set up to ASHRAE standard and recently calibrated were also used in some classrooms during the month of August 2022. Under ISD these instrument measurements belong in the upper right objective-individual quadrant. They were included in the case study for comparison to user subjective opinions of indoor environment quality elicited in the on-line surveys.

2.2. School Overall Data Questionnaire

This questionnaire, provided as a Word document, was supplied to the school Business Manager and asked for specific data regarding consumption of electricity, gas and water prior to and post the new construction. It also asked about repairs, maintenance and cleaning expenditure before and after the new build. These questions, relating to the ISD individual-objective or performance quadrant, were in direct response to specific requests from architects in the survey, who desired confirmation that their new buildings exhibited improved sustainability. Additionally, the questionnaire included questions regarding out-of-school hours community use and demands which are aspects from the systems (collective-objective) quadrant.

2.3. Teacher & Administrator On-Line Surveys

Two similar new ISD comprehensive surveys were administered – one to the classroom teachers and one to the administrators and other teachers. The questions were developed to answer the desires in the architects' survey, including spatial responses, and cover specific areas identified in the literature review. A separate on-line survey based upon a conventional POE survey, similar to the BUS Occupant survey (Leaman, 2021b) (originally designed for office workers) was administered. On-line surveys would be a time-efficient way for architects to obtain their own post-occupancy feedback. The questions in the survey related largely to the personal experience of the buildings, building support for pedagogy, and school and sustainability culture from the subjective-individual and subjective-collective ISD quadrants.

2.4. Walkaround interviews

Traditional walkaround interviews were conducted where the building is used as a text to prompt interviewees regarding positive and negative feedback on the facility (Watson, 2003). Three interviews were conducted: one with the principal and janitor/cleaner, one with teachers and a third "virtual" walkaround interview with the business manager due to her unavailability on the other days. These transcripts are to be analysed thematically (Braun and Clarke, 2006) and the results compared to the on-line surveys for responses regarding aspects in common and differences. Conducting and analysing walkaround interviews is considerably more time-intensive compared to on-line surveys, making it a less probable choice for architects to utilize.

2.5. Children's on-line survey

An on-line ISD comprehensive survey for the children was administered to grades 3 to 6 (4 classes) on the advice of the school leadership team who considered the questions and format and capabilities of the children. The questions in this survey were also generated based on the architect's survey and included spatial questions such as "Click on your favourite place inside" "Why is it your favourite place?" and other qualitative responses. Educational researchers were consulted regarding the questions, and they suggested the inclusion of happy and sad face graphics for the Likert style quantitative questions. It is not usual to survey children of these ages regarding building characteristics as some researchers regard their responses as unreliable (Leaman, 2021a), although the prevalence of the view that children should be consulted regarding spaces and planning is increasing (Brown *et al.*, 2020). Similar to the teacher and administrator surveys, the children's questions regarded their (individual-subjective) personal experience of the buildings and playground and support for their learning activities.

2.6. Parent's On-Line Survey

The parent's on-line survey was short and aimed to obtain responses on ISD comprehensive topics such as whether the school facility is welcoming, safety, traffic flows and preferred places to wait for children. These questions related to the ISD cultural and systems quadrants.

2.7. Picture-Voice Activity

This activity was conducted with grades Prep to 2, a decision made by the leadership team who deemed them not sufficiently proficient in reading and writing to participate in the on-line survey. The activity was conducted in class time on a class-by-class basis. It was introduced with an explanation about who designs school buildings and why architects need to hear from children with an example picture drawn on the white board. The children were requested to draw a picture regarding something about the school or the classroom that is important to them. Then they were asked to explain their picture to the researcher who recorded their explanations and asked clarifying questions. The recordings were used to prevent mis-interpretation of the visual artifacts by the researcher (Brown *et al.*, 2020). The researcher took photographs of the drawings to enable children to retain the originals. The analysis of this data would pose a time-challenge for architects. Picture-voice allows participants an active role in both producing and interpreting images (Shaw, 2020) similar to photo-voice which is a well-established visual research method with younger children (Mannay and Pauwels, 2020).

2.8. *Places I Like* Plans

All classes were provided with an A0 plan of their building and a plan of the entire school grounds. Each child was issued with two blue and two yellow adhesive dots. Teachers administered the activity and were requested to instruct the children "Please put a blue dot on your favourite place inside and outside" "Please put a yellow dot on the place you most dislike inside and outside". This activity was conducted for comparison to similar questions in the children's on-line survey. This activity was developed based on similar activities pioneered by Woolner (2010) with an older cohort (11-16 year olds).

2.8. Graffiti Plans

All classes were provided with an additional plan of the whole school grounds and teachers were requested to instruct the children as follows: "children can write on it things they like, draw themselves in their favourite spots or add features (e.g. a covered walk way, veggie garden, play equipment)". This activity was intended to provide rich qualitative and in-depth information as a comparison to *Places I Like* and the on-line survey and follows similar methods developed by Woolner (2010). Administration and analysis of this activity is regarded as too time consuming for architects' feedback purposes, however, may be useful for consultation with children at the briefing stage of new projects.

2.9. Case Study School

The case study school is a Victorian Department of Education primary school (grades Prep to 6 – children 5 years to 11 years old). The school is situated in the outskirts of Melbourne. The school's infrastructure includes three recently completed buildings, a BER (Building the Education Revolution) Programme building, dating from about 2010, and an older multi-purpose hall. The new buildings were finalised in early 2020 and include a teaching building, an administration block and a language/art block. This gives an opportunity to compare responses between the two teaching buildings. Due to remote learning during Covid and the extensive Victorian lockdowns, the school community's transition into the new buildings was delayed . Consequently, the first full school year within these new buildings was 2021, interrupted by the circuit breaker lockdown that occurred on 15-17 February 2021 (Wright, 2021).

The new buildings are slab on ground, steel framed brick veneer with double glazing to most windows. The BER building is also slab on ground steel framed brick-veneer with single glazing and louvred windows in strategic locations

Figure 2 shows a simplified plan.

Figure 2: Simplified plan of case study school buildings and grounds. Drawn by author based on plans supplied by architects (classroom names changed for privacy).

The school operates on a traditional format of one teacher to each class, and there are no composite grades nor team-teaching. The new teaching building was designed to permit this along with other more flexible arrangements and all classrooms have doors connecting to interior “Hub” spaces. Individual teachers have complete control of gas heaters, split system air conditioners and window and door opening and closing in their classrooms. All gas heaters are vented to the exterior and rated 0.00 for carbon monoxide. Each classroom is also equipped with a particulate matter filter, introduced during Covid 19. The building has no mechanical ventilation and relies on the opening of windows and doors. Teachers would be understandably reluctant to do this in a Melbourne winter.

3. Preliminary Results

3.1. Instrument Measurement: Carbon Dioxide levels - CO2

Early examination of the instrument data from the winter period in the new building showed some alarmingly high CO_2 levels in some classrooms at regular times during the day. In one classroom, the CO2 levels exceeded 1500ppm for an average of 3.5 hours during each school day (a school day is 6.5 hours long including breaks). The mean number of hours over 1500ppm for the 6 classrooms was 1.6 per school day, although one classroom never exceeded 1500ppm. Two classrooms exceeded 2500ppm on a number of occasions.

Table 2: Average hours per school day with CO2 > 1500ppm by classroom – Winter season

Classroom	G4	Prep A	Prep B	G3	G2	G1	Mean
Number of Hours	2.21	0.46	0.00	1.12	3.52	2.23	1.59

(classroom names changed for privacy)

This was brought to the attention of the school principal at the time. In addition, teachers were instructed regarding the dangers of high CO_2 levels and the need for ventilation during a pupil-free training day in early 2023. Data regarding other factors – humidity, temperature, etc. has not yet been fully processed at the time of writing, although a cursory review indicates that for the winter period temperature ranged between 15 and 19 ^oC during school hours and relative humidity was in the range of 50-60%.

3.2. School overall data questionnaire

As described above, the school overall data questionnaire was intended to elicit information regarding energy and water consumption before and after construction of the new building. In the case study school, the business manager ascertained that the most recent complete year prior to Covid and the build was the calendar year 2018. She was able to obtain total expenditure figures in AUD dollars for electricity, water and gas for 2018 and 2022. However, there were limitations in providing data of units consumed as well as the corresponding unit rates, as these were not accessible through on-line sources. Searching through archived paper invoices was deemed impractical for this study. While the researcher was able to obtain electricity and gas consumption data for the 2022 year from the current suppliers, it was noted that the school had changed suppliers since 2018 and neither the business manager nor the vendor could identify the previous supplier.

Maintenance expenditure was significantly increased in 2022 as compared to 2018, due to a number of large non-recurring items, including repainting the entire BER building, installing pergolas, and plumbing costs due to roof leaks in the new buildings, all of which could be argued were capital costs associated with the building project. Excluding these items, maintenance costs were similar to the average cost for 2017 and 2018.

3.3. Teacher/Administrator and Parent Surveys

It is clear from preliminary analysis that certain questions in the new surveys will require further development.

As an example, in the thermal comfort section, a higher level of dissatisfaction was displayed through the new survey. This was evident through a question which asked “Are you ever too hot/too cold?” and asked respondents to specify when this occurs (Summer/Winter, Morning/Afternoon). This contrasted with the traditional survey, where participants were asked to rate conditions on a 7-point Likert scale.

While the traditional survey has no questions regarding noise or acoustics, the new survey question “Is the sound level in the building comfortable - Yes, Maybe No” provided insufficient information with almost half of the respondents answering “Maybe”.

Within the new survey, when the lighting-related questions were combined with the location-based questions, a notable response pattern emerged. Responses indicating insufficient lighting aligned with the instances when the sun was situated on the opposite side of the building. Conversely, instances of excessive light were reported when the sun was positioned on the respondent’s side. The traditional survey gave more detailed information about the lighting conditions, including Likert scales ranging from “Too Little” to “Too Much” for natural and artificial light, as well as from “None” to “Too Much” for glare caused by lights and the sky. The findings indicate a high level of satisfaction with the lighting, although it is important to note that the number of respondents for the traditional survey only represent half of the adult population of the school.

Although only 14 people answered the parents' survey, results were strongly positive for the questions regarding how welcoming the school feels, pedestrian access and access to after school care, which is supported by the reasons given in the qualitative answers.

3.4. Children's On-Line Survey

The analysis of the qualitative and spatial questions for the children's on-line survey will require much additional time. The total number of child respondents (94) provides an adequate sample size for conducting statistical analysis of the quantitative questions. These questions used a 5-point Likert scale accompanied by happy and sad face graphics, appear to have been effective in eliciting valuable feedback. For example, for the statements "My building has enough space for me to use digital devices" and "My building has fast enough internet", the answers were overwhelmingly positive or neutral with only 8 and 14 students respectively disagreeing. The question "Can you hear the teacher well in the classroom?" received a clear positive response with 91% answering "Always" or "Mostly".

In contrast, for the question "Does any part of the building remind you of nature?", the responses were evenly divided, with 50% responding "Yes" and 50% responding "No". Similarly, the questions regarding the presence of various sustainability items within the school were structured with Yes/No choices. This format likely contributed to the reduced number of responses. For instance, while 82% answered the question regarding recycling bins in the classroom, only 42% answered the question about energy saving devices indicating that a response of "Don't Know" should have been offered.

Heat Map questions of class location will allow correlation of thermal comfort questions on a class by class basis. For the heat map question of favourite place in the school grounds, there is strong preference for a limited number of areas. Interestingly, there is a portion of overlap with places students dislike to go.

Although the indoor air quality questions are the same as for the teachers and suffer from the same deficiencies, a critical part of this research will be comparison of the instrument data to the student responses, to determine if the student on-line survey is an adequate alternative for instrument measurement.

3.5. Walkaround Interviews

Preliminary findings of the walkaround interviews appear to align closely with the results from the teacher/administrator on-line surveys. However, in some cases, the walkaround interviews provide more detailed information about specific problems and successes in the design of particular spaces in the building. Notably, participants appeared more concerned about functionality issues and support for their teaching practices than aesthetic or comfort considerations.

For example, having spaces for children's bags in the hubs would allow for more wall room in the classroom for displays, L-shaped classrooms require careful positioning of the teacher's desk to ensure all parts of the classroom are visible and lack of an electrical outlet near the smartboard creates difficulties with connection of teacher laptops when low on power.

3.6. Picture-Voice Activity

The picture-voice activity with the younger children is yielding interesting findings. Many of them included particular fixtures in their drawings of the classroom that they feel are important. These fixtures include items such as smart boards (which the teachers use extensively at this school), ceiling fans, air-conditioners, heaters, child-sized tables and chairs, as well as windows and doors. When asked why exterior doors were important, for example, they cited safety concerns or a wish for direct access to the outside for play at recess and lunch. Some of the younger children drew imaginative playground fixtures, such as ponds and water features, or robots and spaceships. There were a large number that drew either the separate school library or the in-class library as being important. This information must be analysed in conjunction with the children's recorded explanations of why they feel the items drawn are important. These explanations may or may not reveal information valuable as feedback to architects.

3.7. Places I Like & Graffiti Plans

The lack of recorded commentary from the children regarding their drawings on the graffiti plans makes them harder to interpret. In retrospect it may have been more effective for the researcher to provide an explanation and supervise the activity. Some classes appear to have simply drawn and labelled themselves in their favourite place, resulting in duplication of the "Places I Like" activity. On the graffiti plans with detailed drawings, there is a consistent inclusion of additional features such as handball, netball, cricket and other courts within the playground. Some children drew new buildings for various purposes, including a library. The older classes have added commentary around broken playground equipment (which is soon to be replaced following an engagement process with the children and community) and providing reasons for liking or disliking certain areas.

4. Discussion

The above results indicate that the various on-line surveys were mostly successful in providing both more comprehensive information than traditional methods and additional information desired by architects. All quadrants of the ISD framework are represented in responses to the various adult surveys.

Regarding the school overall data questionnaire, the time elapsed since the build is too great to facilitate the collection of this information for the case study. This suggests that in order to receive this feedback, architects would need to collect this data at the project's initiation and collaborate with the school management to secure equivalent data after the year post-completion while the information remains current and available.

As mentioned above, some questions in the new on-line survey instruments provided good data on aspects omitted from traditional surveys relating to aspects identified in the comprehensive literature review or architects survey. In other cases, the new survey questions will need revision. Regarding the thermal comfort questions, it may be better to use Likert scales similar to traditional POE surveys coupled with spatial-related questions about class or office locations, to provide a more comprehensive understanding of discomfort. This approach would need to factor in time and season, in order to identify problematic spaces. Importantly, it must be noted that thermal comfort equipment in these classrooms is entirely under the teacher's control. In this case, in a building which appears to have good thermal design, instances of dissatisfaction likely represent a failure of education or procedure.

While the traditional POE survey has no questions regarding noise or acoustics, the new survey question for teachers provided insufficient information and did not allow for a 'sometimes' or temporal component. Speech intelligibility is critical for children's learning therefore a clearer question, such as: "Do acoustic levels in the building support children's understanding and your teaching?" with a Likert scale from Unsatisfactory to Excellent, would result in more definite answers. The differently worded question regarding acoustics in the children's survey "Can you hear the teacher well in the classroom? Always, Mostly, Sometimes, Never" was much more successful.

In the children's on-line survey, the heat map question of favourite place in the school grounds appears to have elicited a segment of overlap with places students dislike. Although gender information was not requested, it could potentially offer insights into this phenomenon. Further clarity may be gained through analysis of the qualitative responses to the question "Why don't you like to go there?". The picture-voice activity, while producing some interesting results, is judged as too time-consuming for architects to use. However, the results will provide a comparison to the information in the on-line survey, and thus possible differences between younger and older children. The parents who answered the parents' survey can be regarded as self-selecting, some due to positive feelings about the school. Thus, as well as being an insufficient sample of the parent population for statistical analysis, the results may be biased in a positive direction.

5. Conclusion

While there is a need for further extensive data analysis, this paper demonstrates that the evaluation of responses to the new questions and surveys, in comparison to existing data-gathering methods, has identified questions that yield comparable data and others that require refinement. Furthermore, this paper has highlighted the questions that delve into areas previously unexplored which appear to be successful or those which need development to provide the information desired. With development, this will be an easy and effective method for architects to obtain feedback on their own projects.

Methods which were found to be too time consuming for architects to administer or analyse include walkthrough interviews, picture-voice, and possibly graffiti plans, although this latter may provide useful information at brief development stage. The benefits of comparing the various feedback methods for this study include enabling comparison of effectiveness of eliciting particular information, triangulation of results, richness of responses to qualitative questions versus clear responses in quantitative questions, and spatial questions providing valuable context for other question responses.

In conclusion, these new comprehensive ISD on-line surveys hold potential as an innovative way for architects to independently obtain post-occupancy feedback that are much less time-consuming to administer and analyse than other methods. These methods also offer valuable insights into the physical environment of schools and user responses to them.

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The building-health nexus in water damaged buildings

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Abstract: In 2018 a parliamentary inquiry was conducted by the Commonwealth of Australia into biotoxin illness (Chronic Inflammatory Response Syndrome, or CIRS) from water damaged buildings (WDBs). CIRS manifests across multiple organs and symptoms and is diagnosed. Due to the complex patient profile and uncertainties in establishing microbial contamination thresholds, CIRS has not been recognised and is little heard outside of integrative medical practitioners. The Inquiry recommended that further medical research should be supported. In 2022, the National Health and Medical Research Council (NHMRC) funded a targeted call for research to an interdisciplinary team led by Macquarie University. Though this research is underway, it already expands the discussion on healthy buildings from its well known allegenenic, pathogenic and toxicological effects to now accommodate CIRS. The paper is situated at the confluence of the two emerging field of condensation research and CIRS, explaining why the architectural scientist plays a pivotal role in delivering buildings that will not be prejudicial to the health of CIRS patients.

Keywords: water damaged buildings, chronic inflammatory response syndrome (CIRS), mould, contamination

1. Background

The first listed objective of the *Building Act 1993* (Victoria) is 'to protect the safety and health of people who use buildings and places of public entertainment'. Although structural and fire safety are well understood concepts with clear compliance requirements in the National Construction Code and referenced standards, it has been difficult to find definitive guidance around how buildings are to be designed and constructed to protect the health of its occupants from moisture damage.

Cladding Safety Victoria, whilst in the process of rectifying 168 buildings in the state with combustible cladding, recently reported that they found half of these buildings had leaking balconies (CSV, 2023). Where timber structure had been compromised by fungal decay which compromised structural safety, the need for rectification was clear. However, when mould was reportedly found, it was unclear whether and what the method of remediation should be.

Thus even though the building legislation is developed around the interest of safeguarding public safety and health, safety is far more well defined, and the standards also much more well articulated, compared to health. At present, the health ramifications of microbial contamination arising from excessive moisture is largely unsettled in building legislation and practice.

Last year, the UK the coroner's inquest into the death of 2-year-old Awaab Ishak from mould in the family's social housing led the coroner to reflect, "It was apparent that updated information regarding the current health risks relating to damp and mould are not widely available or known to the housing sector. … In my opinion there is a risk that future deaths will occur unless action is taken" (Kearsley, 2022). In terms of the health risks to occupants, we believe the situation in Australia is not too different from the UK.

This paper is positioned at the emerging confluence of mathematical modeling of mould germination and the impact of mould on the health of occupants with particular emphasis on biotoxin illness. It is necessary to consider both these factors to meet the National Construction Code's condensation management performance requirement which is that "risks associated with water vapour and *condensation* must be managed to minimise their impact on the health of occupants" (Vol. One F8P1 and Vol. Two H4P7).

2. Mould growth models

Relative humidity (RH) is a measure of humidity in air, a parameter that is distinct from water activity (a_w) which measures humidity in a porous solid material. Conditions that would affect equilibrium are the differences in temperature between air and surface that are common in uninsulated or thermally bridged materials. Barbosa-Cánovas, Jr, Schmidt, & Labuza, (2008) provide the mathematical formulation to determine the water activity based on substrate and the dew point temperatures. In situations where humidity has large fluctuations, timber moisture content is also known to show a hysteresis effect (Thybring & Fredriksson, 2023). Where building materials achieve equilibrium with the air, RH and water activity values are practically synonymous and so RH is used as the main parameter in mould growth models.

The condensation management provisions of the Australian National Construction Code (ABCB, 2022) will be in force between Oct 2023 and May 2024, depending on state and territory. The new verification method introduces the AIRAH DA07 (AIRAH, 2020) reproduction of ASHRAE 160:2016 (ASHRAE, 2016) *Criteria for Moisture-Control and Design Analysis in Buildings*. The material sensitivity of this standard is based on the experiments in VTT Finland (Ojanen et. al., 2010) using 9 materials: pine sapwood, spruce board, concrete, aerated concrete, cellular concrete, polyurethane insulation, glass wool, polyester wool, expanded polystyrene (EPS). The mould index is in turn based on an original formulation by Hukka and Viitanen (1999) which can be represented as time isopleths of temperature and humidity in the following Figure 1. The red dot reflects the reference conditions by Ojanen et al of 1.4 weeks (or 9.7 days) for a change of mould index from M=1 to MI=3 at 22°C 97%RH. The dashed line shows all other temperature and RH combinations that will result in the same change in mould index over the same length of time.

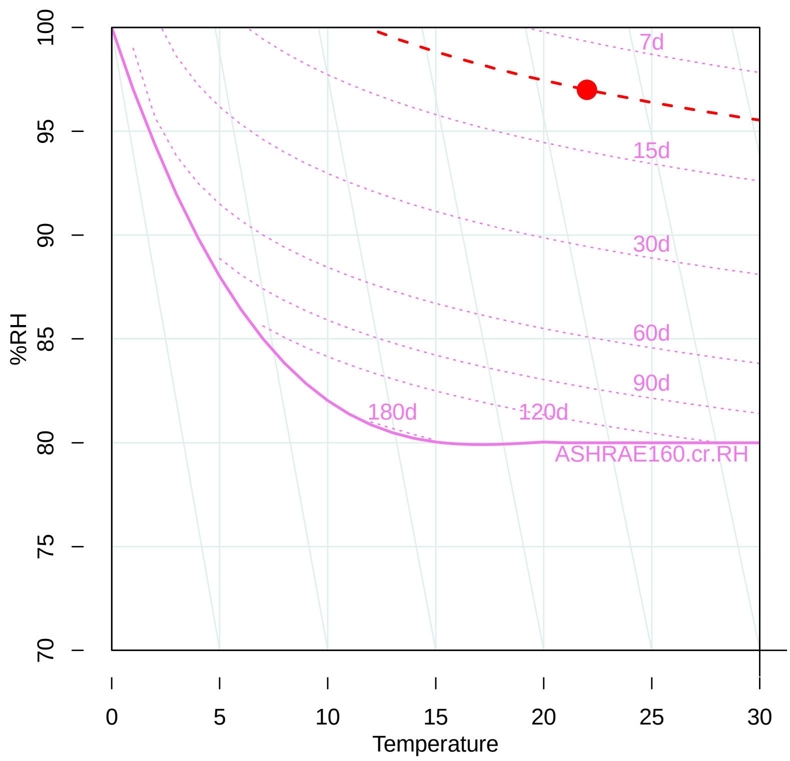

Figure 1: Time-based isopleths for change of Mould Index MI=1 to MI=3 (similar to MI=0 to MI=1) in ASHRAE 160

The Fraunhoffer Institute of Building Physics developed another mathematical model (Sedlbauer, 2001) known as the Isopleth Method and implemented this in the WUFI-Bio hygrothermal software. The method was referenced in the *WHO Guidelines for Dampness and Mould* (WHO (World Health Organisation), 2009), and is here overlaid on the ASHRAE160 below. Both sets of ispoleths relate to similar conditions of germination (equivalent to change of mould index from MI=0 to MI=1) on pine.

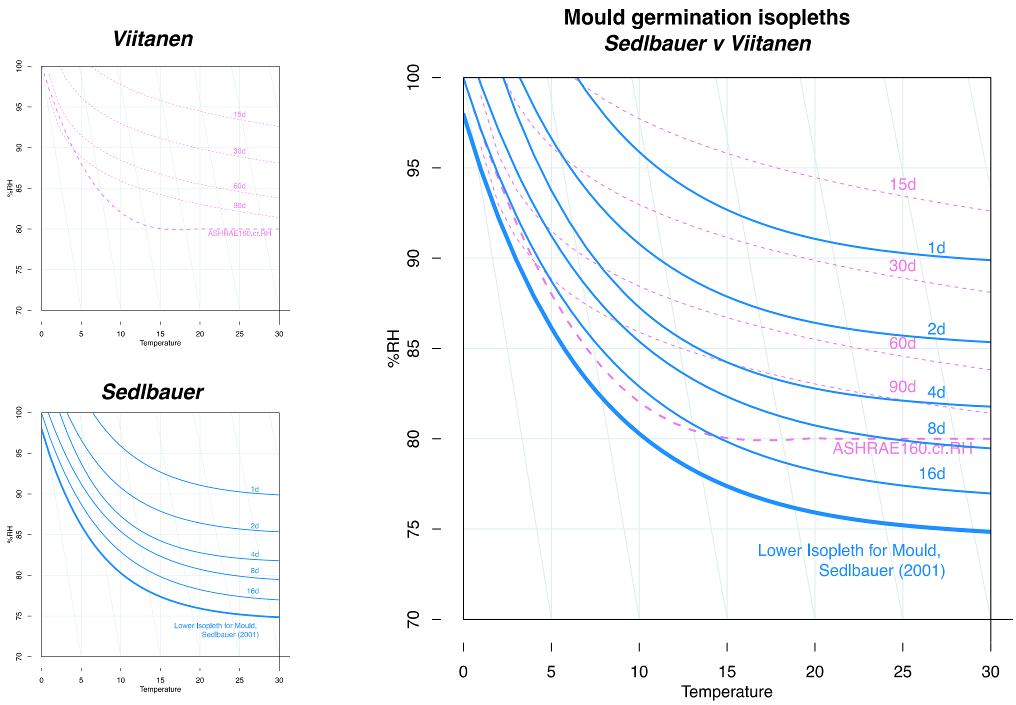

Figure 2: Composite time-based isopleths

The 2 models reflect very different lengths of time. For example, conditions for mould germination within 2 days using the Fraunhoffer model would take about 30-60 days with the VTT model. Recent validation work has reflected that the Viitanen/VTT model needed to be adjusted to be much more sensitive to reflect mould risks in UK houses (Menneer et al., 2022), whereas the Sedlbauer/Fraunhoffer model on the other hand was found to properly predict mould growth in an office environment in a cold climate in China (Lv et al., 2020). To the authors' knowledge no validation of either model has been undertaken in Australia.

Figures 3 and 4 show Australia Bureau of Meteorology observations graphed as (1) RH time series with bands indicating continuous 'run' periods of high humidity (>65%RH) for over 48h, (2) psychrometric chart with twice daily observations (9am and 3pm) connected by a line and with observations of 'runs' as red circles, and (3) mould isopleths with individual observations as points, continuous 'runs' of high humidity as lines, and bubbles indicating the number of days in a run positioned at the average T and RH of the run. If one were to adopt the more conservative Sedlbauer/Fraunhoffer model, most locations in Australia will encounter an annual risk of mould germination from ambient conditions alone. When additional vapour loads from daily occupant activities are added (estimated at 10 litres per person per day by the ABCB), the risk of mould growth is exacerbated.

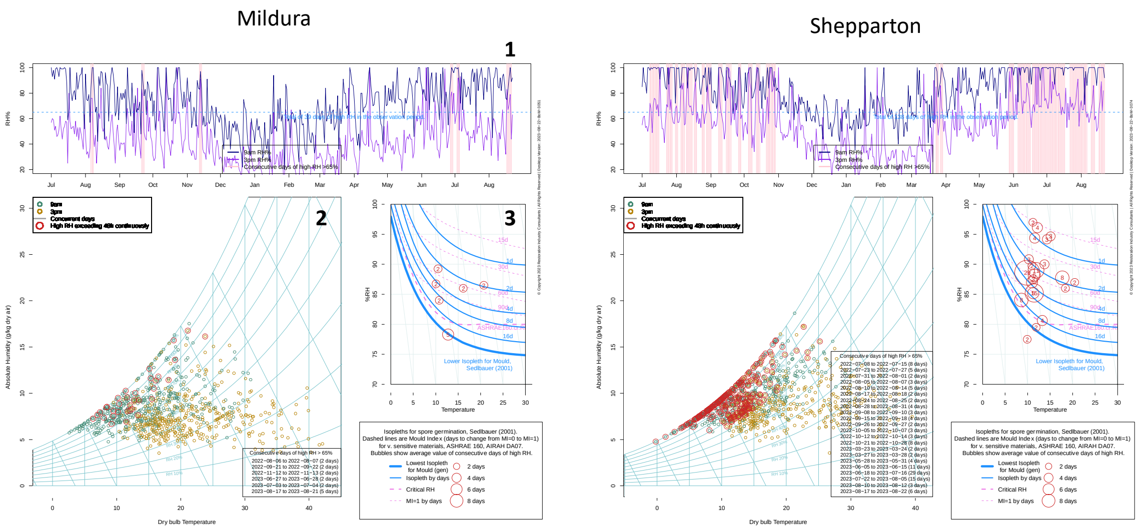

Figure 3: Bureau of Meteorology observations for 2 locations in Victoria (Mildura and Shepparton weather stations) over the period July 2022 – August 2023.

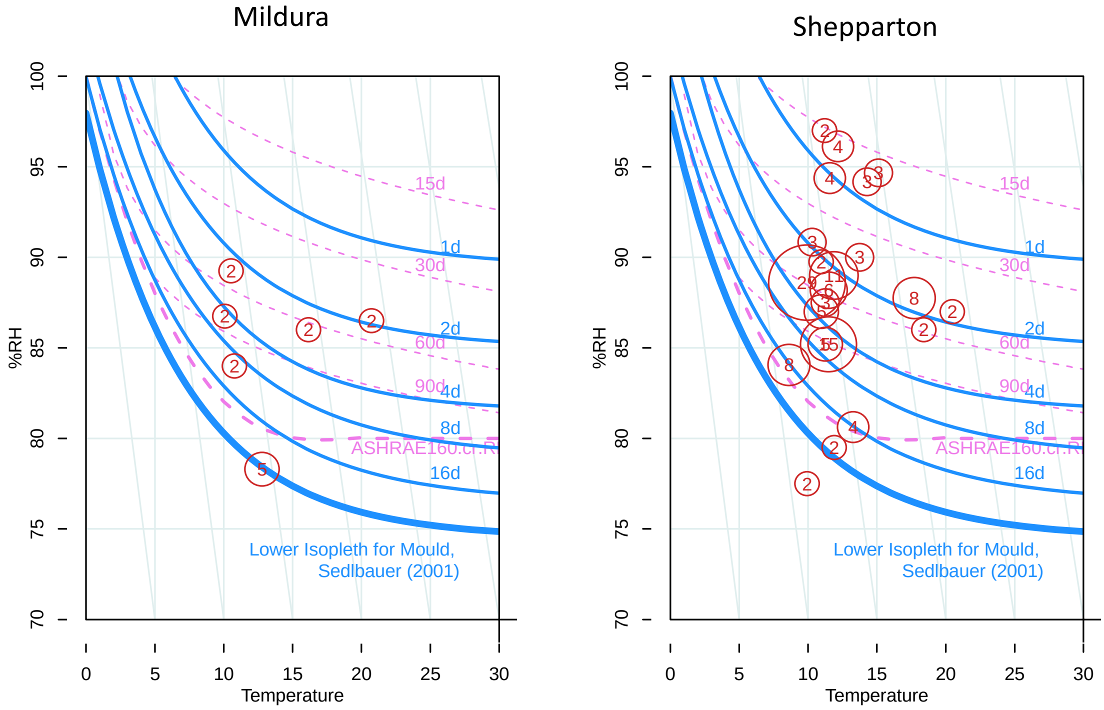

Figure 3: Comparison of continuous periods of high humidity between Mildura and Shepparton. Numbers in bubbles indicate the continuous number of days of high humidity.

There is much more work that needs to be undertaken to achieve a rigorous hygrothermal model to evaluate the mould risk. Although AIRAH-DA07/ASHRAE-160 offers a NCC compliance pathway, it is worth noting that this model may not have the granularity to satisfy the building legislation for buildings to not be a risk to health of any person.

3. Health impact of mould

Mould is recognised as causing a wide range of health effects, reflected in the health advice from Australian States and Territories, as seen in Table 1.

Table 1: State and Territory Governments advise on the health effects of mould (Commonwealth of Australia, 2018).

Jurisdiction	**Health effects**
Australian Capital Territory	• Nasal congestion; • Sneezing, coughing, and/or wheezing; • respiratory infections; and • worsening of asthma and allergic conditions. • People with certain pre-existing conditions may be more susceptible to mould.
New South Wales	• If sensitive or allergic: • running or blocked nose; • irritation of the eyes and skin; and/or wheezing. • For people with asthma inhaling mould spores may cause an asthma attack. • People with weakened immune systems are more at risk of severe reaction such as infection.
Northern Territory	• If sensitive to mould: o stuffy nose; o irritated eyes; o wheezing; and/or o skin irritation. • If allergic to mould: o shortness of breath; and/or o mould infections (if you have a weak immune system or chronic lung condition).
Queensland	'Health problems, especially for people with asthma, sensitivities or allergies.'
South Australia	• Allergic reactions; • coughs; congestion; and/or runny nose; • eye and skin irritation; and • headaches. • If immuno-compromised or suffering from a respiratory disease: o fever; and/or o breathing problems.

Tasmania	'Damp, condensation and mould can make you sick, especially in winter when colds and flus are common.'
Victoria	• Nasal congestion; • sneezing, coughing, and/or wheezing; • respiratory infections; and/or • worsening of asthma and allergic conditions. • People with allergies, asthma, lung disease or weakened immune systems are more susceptible.
Western Australia	• Asthma attacks; • watery, itchy and red eyes; • respiratory infections; • rashes (dermatitis); • sinus problems; and/or • blocked nose."

The effects of mould on building occupants are varied but can be summarised to the following four effects. Mould could (1) be allergenic to some such as asthmatics; (2) be invasively pathogenic to others; (3) cause toxicosis through skin contact, inhalation or ingestion; or (4) the biotoxins from microbes in water damaged buildings could cause a persistent inflammatory response.

The World Health Organisation (WHO, 2009) in its extensive literature review concluded that, 'sufficient epidemiological evidence is available from studies conducted in different countries and under different climatic conditions to show that the occupants of damp or mouldy buildings, both houses and public buildings, are at increased risk of respiratory symptoms, respiratory infections and exacerbation of asthma.' (p.93) This is one of the most cited health impacts of mould in damp buildings and underpins a number of position statements, such as that of the AIHA (American Industrial Hygiene Association, 2013). The burden of disease from asthma associated with damp homes in Australia is estimated by the Healthy Housing Centre of Research Excellence to be in the region of AUD$1.5 billion for medical care and AUD$7.5 billion for loss of income (Bentley, 2023).

In 2018, a Parliamentary Inquiry was convened into Biotoxin Illness in Water-Damaged Buildings. The terms of reference for this inquiry included investigation into the prevalence of CIRS (or biotoxin-related illness) and the treatment options available, together with research into the causes from water damaged buildings. Up to this point, CIRS had not been broadly recognised by the medical community in Australia (McGowan, 2018).

Following the inquiry, the Commonwealth endorsed the inquiry findings to raise awareness of CIRS amongst the medical community, and to have building codes and standards constantly updated in step with increased understanding of this built environmental illness (Commonwealth of Australia, 2018). As a result, the NHMRC (National Health and Medical Research Council) awarded a $1m grant led by Macquarie University for a 3-year, longitudinal case-control study to explore possible new diagnostic biomarkers in the genomic, immunological, pro-inflammatory, and environmental domains. The links between mould modelling and the longitudinal biomarkers from before, during, and after exposure to dampness and mould in water-damaged buildings will be used to identify new biomarkers for diagnostic and prognostic purposes as well as response to treatment and create a patient outcomes registry to house all clinical and biological information collected from patients. The ability to connect the biotoxin in buildings with its health rammifications will be a crucial step in achieving the condensation management performance requirement of the NCC (Vol. One F8P1, Vol. Two & HP H4P7) which is that “Risks associated with water vapour and *condensation* must be managed to minimise their impact on the health of occupants.”

4. CIRS, or biotoxin illness

CIRS-WDB, (Chronic Inflammatory Response Syndrome) was first coined by Ritchie Shoemaker, a physician who found mould patients presenting similar symptoms to those who suffered from toxic algae bloom (dinoflagellate toxin exposure) he had treated elsewhere. Biotoxins from mould accumulate in genetically susceptible individuals with an over-sensitised immune response that places the patient under chronic inflammation. According to Shoemaker, genetically susceptible patients suffer more from the friendly fire of their overactive defence mechanism than from the invading biotoxin itself. He created a protocol around the diagnosis and treatment for CIRS, and has estimated that 24% of the population possess the genetic disposition to develop CIRS if exposed to a water damaged building (R. Shoemaker, 2011).

In the absence of recognition of CIRS from the general medical community, patients have largely suffered in silence and turned to support groups on social media. Toxic Mould Support Australia (TMSA), is a Facebook group that started in 2013, administered by volunteers who have suffered mould illness from exposure to water damaged buildings. As at July 2023, the group comprised some 14,600 members, providing an invaluable hub containing thousands of firsthand occupant accounts.

Among the TMSA community, autoimmune conditions, brain fog, sinus problems, allergies, fatigue, rage, neurological symptoms, gut issues, depression, anxiety, rashes and other skin breakouts, were the most commonly reported symptoms of exposure to water damaged buildings. These symptoms often reached levels that dramatically limited their ability to function within society, often leading to job cessation, financial insecurity, and high medical costs. Occupants of WDBs also widely reported near-instantaneous relief from symptoms upon leaving the water damaged building, even if only for a few hours, and that these symptoms returned, sometimes with a vengeance, upon re-entry into the building. A recurring sentiment was the cruel irony that 'living in mould' made one so sick that, unable to leave, they were forced to remain in the mouldy environment (Law et. al 2021).

A primer on CIRS was written by the then group administrator (Di Lizio, 2020). CIRS is an immune reaction triggered by biotoxins, manifested across multiple organs and symptoms. As a result of the NHMRC funded research into biotoxins, a more definitive connection between water damaged buildings and health can be established.

For a CIRS patient, the need to vacate from water damaged buildings is the non-negotiable prerequisite for treatment. In an experiment to test the efficacy of a biotoxin binder cholestyramine, 14 patients in a double-blind, placebo-controlled, clinical trial (R. C. Shoemaker & House, 2006), patients were (1) exposed to a water damaged building, (2) treated with cholestyramine, (3) ceased cholestyramine, (4) re-exposed to the building that caused the sick building syndrome and (5) treated with cholestyramine again. The researchers noted, "Health status continued to show marked improvement following CSM [cholestyramine] therapy while the study participants avoided re-exposure to the WDBs [water damaged buildings]. However, all participants relapsed within 7 days of re-exposure to the WDBs."

In their comprehensive literature review on the deleterious effects of biocontaminants, Thrasher and Crawley (Thrasher & Crawley, 2009) reached a similar conclusion, urging that the "medical profession must recognise the importance of immediate removal of occupants from the toxic environment." Thrasher also cautioned that it was virtually impossible to eradicate a systemic mould problem from a building. A systemic mould problem arises from a building with designed-in and/or built-in water-related problems.

5. Unhealthy Premises

It is of immense consequence that a dwelling may be deemed not only uninhabitable, but irreparable as well. This sentiment is not an exaggeration. There have been instances where restoration works only temporarily removed mould without dealing with the root cause. This was seen from the American experience with Hurricane Sandy, "Since there is no current standard requiring that mould workers be trained and mould remediated to evidence-based standards, residents in mould-infested homes are left largely to fend for themselves—not just to remediate mould, but potentially to rebuild for a second time." (ALIGN, 2013)

Depending on which Australian state/territory one is in, the law differs on which officer has the statutory capacity to decide if a building is unhealthy.

In states that have adopted the National Model Building Act in entirety, such as Victoria, the Building Act has provisions for a municipal or relevant building surveyor to cause a building notice to be served if a building poses danger to the health of any member of the public or any person using the building (s.106 of the *Building Act 1993*).

In Tasmania, the s.86 of the *Public Health Act 1997* empowers the environmental health officer (EHO) to make the determination whether “premises are so unhealthy that no person can safely occupy them”. Following this determination, an interim closure order may be issued by the council until a building surveyor provides a rectification report, on which basis the local government authority will decide and order the premises be either rectified or demolished.

The severity of such a decision, one which could condemn a building, places profound responsibility on the EHO. The Tasmania government published a “Guide to Assessing Unhealthy Premises” (DHHS (Department of Health and Human Services) Tasmania, 2015) outlining the procedures for decision making, and even provided a metric for determining the severity of mould — under $1m^2$, up to $10m^2$, over $10m^2$, and possibly hidden — but did not categorically state which one of these would make the premises meet the criteria of being ‘so unhealthy that nobody could safely occupy them.’ This lack of guidance leaves the EHO open to legal challenge should the building owner contest their decision in the courts.

The difference between the Victoria *Building Act 1993* and Tasmania *Public Health Act 1997* boils down to whether the building is deemed unhealthy to anyone, or to everyone. In the context of ensuring that buildings are fit for occupation health wise, the precautionary principle is more prominent in states like Victoria where habitable buildings are expected to be universally healthy, rather than Tasmania where buildings are only deemed uninhabitable when universally unhealthy. In circumstances where mould affects some patients but not others, particularly where only some respond with allergic or inflammatory reactions, the unhealthy premises clause of the Tasmanian *Public Health Act 1997* cannot be convincingly applied.

It follows that the verification method of compliance to NCC 2022’s *Condensation Management* provisions will fit within the legislative framework of Tasmania, but will not have the granularity and sensitivity to meet the legislative expectations (as distinct and difference from NCC compliance) in Victoria.

6. Restoration and Repairs to Mould Damage

When mould is discovered, a homeowner is confronted with the complex and costly undertaking of uncovering and remediating the root cause of a water damage problem. Even with thorough removal of the mould contamination, unless the underlying moisture problem has been resolved, mould would simply recolonise in a matter of days or weeks. If the house was tenanted, some landlords would rather conceal the problem, strenuously resisting any admission that their buildings were the cause of the tenants' illnesses.

Even if the cause of water damage could be identified, the average homeowner will not be able to navigate the interactions between building practitioners to know which party was responsible and whether the cost of litigation was worth pursuing all parties for damages. To make matters worse, home building insurance may not be of any help since most policies have exclusion clauses for mould occurrence apart from listed events. This means that if the homeowner cannot establish causation from a listed event, the owners will be looking at out of pocket expenses to rectify mould damage.

The general consensus on the Facebook group Toxic Mould Support Australia (TMSA) appears to be that any kind of water damage or intrusion needed to be fully rectified within 48 hours to pre-empt a mould problem. Outside of this window, members said that mould progressed beyond surface level and was very much irreparable without removal and replacement of building materials.

It was widely reported by TMSA group members that remediation action rarely occurred within the necessary window of 48 hours. Many group members expressed that landlords refused to fund the work required to properly remediate a mould problem, instead offering more band-aid level solutions such as concealment by paint rather than fixing its root cause.

Overall, not many TMSA members were in a financial position or emotional headspace for a prolonged legal battle over mould. Even though there was an intuitive sense that a mouldy residence was problematic, the lack of awareness of CIRS in mainstream medicine, together with a highly complicated construction litigation process, had resulted in these occupants opting to accept substandard living conditions instead of fighting what they felt to be an incomprehensible system.

In Victoria, the *Residential Tenancies Regulation 2021* has updated a new minimum standard that 'each room in the rented premises must be free from mould and damp caused by or related to the building structure'. Tenants Victoria (TV) plays a unique dual role of providing legal assistance to renters and also advocating for them. TV had and continues to receive a large number of mould-related complaints, with mould regularly being in the 10 most frequent complaints or inquiries in the 10,000 or so inquiries TV receives each year (Beveridge, 2023).

The updated tenancy regulations also classified mould repairs as an urgent repair to be attended to as soon as possible, as opposed to a non-urgent repair for which the rental provider has 14 days. However, this appears not to be taken as seriously by the majority of landlords. In a special publication *The Mould Report (Tenants Victoria, 2023)*, TV disclosed that 31% of landlords outrightly refused repairs, and a further 55% prevaricated (i.e. did not respond to or delayed the mould repairs).

TV CEO, Jennifer Beveridge wrote in a magazine published by the Council to Homeless Persons, 'The seasonal increase in the occurrence of mould, the nebulous nature of its source and its frequent invisibility helps in reinforcing the age-old power imbalances between the renter and landlord.' (Beveridge, 2023)

CIRS is extremely debilitating and the impact on a CIRS patient to have access to work, medical treatment, mould sampling, remediation, renovation and reconstruction are all intertwined with their lack of legal recourse to hold anyone responsible for the state of water damaged buildings.

7. Where to now for Architectural Science

The predicament facing vulnerable tenants or hapless homeowners can be illustrated with the quip saying of Everybody, Anybody, Somebody and Nobody.

> Moisture damaged buildings have such important health implications that Everybody assumes Somebody would take responsibility. Anybody could see the problem, Somebody should be responsible, but Nobody would. Anybody could have helped, because as long as Somebody told Everybody what to do, then Nobody would have the problem. So even though it affects Anybody and Everybody, it always ends up as Somebody's problem and Nobody's business.

The 'Somebodys' involved with healthy building would primarily be the builders, building surveyors and architects/building designers.

It might be hopeful though naive to assume that builders, under the *Domestic Building Contracts Act 1995*, would honour the implied warranty to deliver houses and apartments which are free from defects. A builder's obligation to honour warranties is premised on remaining solvent. For context, in Victoria there were 364 building and construction insolvencies in 2021, or an average of one insolvency a day (Master Builders Victoria, 2022). When volume builder Porter Davis collapsed, some 2,500 claims were filed (Godde, 2023). Even if the builder is solvent, the wait time to take conciliatory action against an unresponsive builder through Domestic Building Disputes Resolution Victoria (DBDRV) involves a wait time of months (Clayton, 2023), and only thereafter to be able to take building action through the Victorian Civil Administrative Tribunal (VCAT) with a 8 month median wait time, which can drag to years to schedule a hearing for building disputes (Lucas, 2022).

In Victoria, the municipal building surveyor (MBS) or relevant building surveyor (RBS) have broad powers to issue building notices if of the opinion that a circumstance exists where the building is a danger to the health of any person using the building (s.106(d)). Despite this, it does not appear that building surveyors are supported if they endeavour to exceed the minimum standards. As a case in point, In Building Appeals Board (BAB) Case No. 454512, the relevant building surveyor (RBS) requested to undertake a cladding inspection as the builder had undertaken product substitution of the cladding, and the RBS was concerned that the builder might have failed to install the product per the installation requirements. When the builder refused the request, the RBS issued a Building Notice and Building Order. On appeal, the BAB cancelled the Notice and Order, which amongst other reasons, was because cladding installation was not a mandatory inspection stage, and instead of an invasive inspection, the RBS 'could request the builder to declare the product has been installed in accordance with the manufacturer's manual'.

In the absence of a builder remaining solvent to fulfil its duty, or building surveyor having the authority for a broad duty of care, it thus largely falls on architects as the main practitioner able to exceed the minimum standards of the NCC to deliver healthy buildings by design and specification. In the case of the condensation management verification method, this will also mean exceeding AIRAH DA07 with an increased sensitivity for mould germination and growth.

Most architectural scientists are competent around building physics, and comfortably switch between concepts of thermal comfort, lighting, air tightness, condensation, psychrometry and the like. Fewer are as comfortable with discussing mould germination and growth, toxins from various microbes, contamination thresholds, inflammatory cytokines and the like. Within the context of microbial contamination, the study of healthy buildings is a fertile and untapped domain that the NHMRC research into biotoxin markers in water damaged buildings is only starting to coallesce. There is a critical lack of guidance documents in Australia which are equivalent to overseas remediation standards, position documents, consensus statements and the like.

If 'Anybody' in the construction industry is in a position to deliver healthy buildings, it would largely be the architects, guided by the architectural scientists. It may still be a few more iterations of the NCC before condensation management, weatherproofing, waterproofing and damp-proofing provisions can ensure that buildings are universally healthy, even for the most sensitive of CIRS sufferers. However, in the meantime, there is a growing awareness amongst the CIRS community around the pressing need for healthy homes that need to exceed the minimum standards of the code.

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The unintended consequences of novated design construct procurement and the impact on the education of graduate architects in Victoria

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Abstract: In the practice of the building industry, Novated Design and Construct (NDC) contracts have gained widespread usage and are well-established in the Victorian market across many building classifications. This study draws insights from a comprehensive approach that includes interviews, desktop research, transcript analysis, and key takeaways from ongoing research. A notable concern arises from the bespoke nature of NDC Contracts, which demands a nuanced understanding of their contents and associated risks. This prompts a critical examination of the architecture profession's foundation, debunking the notion of the lone genius designer. Instead, the evolving role casts architects as both designers and coordinators of documentation, carrying shared liability. This paradigm shift necessitates an expanded education framework, beyond the current confines, warranting the development of a structured 'apprenticeship' model. Over the past three decades, the construction industry has undergone profound transformations, resulting in heightened complexity to construct the built environment. To comprehend this complexity, the prevailing siloed discussions and contract author-centric approaches must be disrupted. It is imperative that education, both initial and ongoing, equips professionals with the requisite skills to thrive in an evolving remodelling. This research underscores the urgency for adaptive education, ensuring that architects are adept at navigating intricate contracts and industry dynamics, thus promoting sustainable architectural practices and an improved built environment.

Keywords: Architectural education, Novation, Procurement, Architect

1. Introduction

1.1 Prevalence of novation

Novated Design and Construct (NDC) contracts have become the preferred method of procurement in many countries, including Australia (Australian Institute of Architects 2022a; Doloi 2008; Poulton 2022). The proliferation of this type of contract over the past decade—a variation of the Design and Construct (DC) contract (Australian Institute of Architects 2022b)—has created significant changes to the role and relevance of design consultants—and in particular architects. In Victoria, this has extended from large scale projects through to government schools projects—the latter have been considered the ‘bread and butter’ for small to medium sized architectural practices.

Sustainability and Health: the nexus of carbon-neutral architecture and well-being: 56th International Conference of the Architectural Science Association 2023, M. Dewsbury, D. Tanton (eds.), pp. 656 - 666.

> Novation occurs when the contract between the architect and the principal is extinguished and is replaced by a contract with a new client (the building contractor) usually on the same terms, bringing about a transfer of contractual rights and obligations (Australian Institute of Architects 2019, 1).

Professional practice subjects in architectural education traditionally adhere to a model where architects are actively involved in all phases of a project also referred to as Traditional Architectural Services (See Figure 1). This means that graduates from accredited Architecture programs and individuals seeking registration as an architect in Australia are expected to possess a comprehensive understanding of the entire project process, from initiation to completion (AACA 2021a)—whether this is reflected in their logbook experience or not. In addition to these, a new suite of competency standards has been introduced and put into practice for accreditation panels for architecture schools across Australia, starting in late 2023 and State-based ARB examinations, commencing in 2024.

> The practice of architecture continually faces new challenges and, as such, needs to be inherently dynamic. The context in which architects work is ever-changing, and our communities' expectations of the built environment continue to evolve. It is important, therefore, that we maintain standards of competency that ensure our knowledge and skills keep pace with these many changes, always with the intent to drive further improvements in our built environment (AACA 2021b).

The multitude of procurement methods may be touched on in professional practice subjects at university, but the legal implication of these contracts in something evident in the feedback from registration boards, informing the content of future accreditation requirements. This is also an area of expertise that few graduates have experience of.

The research in this paper stems from an extensive literature review focused on novated design and constructed buildings, conducted as part of a research project in the Faculty of Architecture Building and Planning at the University of Melbourne. The primary goal of the project was to investigate the implications of different points of novation in Class 9b buildings.

Regarding that initial research, the results were inconclusive. We found that the decision to novate a project was often influenced by arbitrary factors (i.e. those that are outside the production of documentation). Notably, even when dealing with experienced clients, the determination of the point novation exhibited considerable variability, ranging from as late as 90% completion (driven by the need for use of a soon to be demolished building for teaching) to as early as 50%, when architectural documents were hastily completed to meet external accreditation deadlines for a program of study. These are for buildings that will never be sold for profit (such as the Class 2 buildings highlighted in the *Building Confidence Report*) and require ongoing maintenance—i.e., the value of the building is for ongoing use by the university for the purposes of administrative, research and educational spaces.

Literature and discussion surrounding novation is still evolving, especially in light of the impact felt by architects following the release of the *Building Confidence Report* by Shergold and Weir (2018). Significantly this has had initial impact in New South Wales (NSW) with the amendments to the Architects Act and the introduction of the *Design Practitioners Act* (NSW Government 2023). NSW now specifies classes by which an architect is registered to design—it is anticipated that this will be adopted across Australia as we move to a national model.

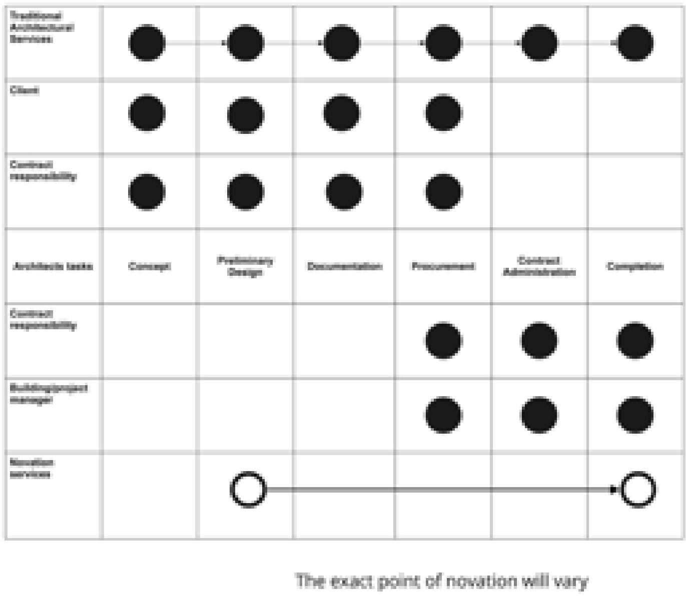

Figure 1: Figure 1 provides a visual representation of how the point of novation affects various project tasks. It features two sections: one at the top with black circles representing interactions in a project with Traditional Architectural Services and another at the bottom with a white circle indicating possible points of novation during a project. In the upper section, the diagram shows that at the procurement (tender) stage, there is a transition in the contractual relationship. Initially, there is the agreement between the client and the architect, but at procurement, this relationship is an agreement between the client and the builder, with the architect serving as the contract arbiter. This stage also expects a certain level of complete documentation. In the lower section of the diagram, the white circle highlights where the point of novation may occur in the project timeline. It illustrates that the closer the novation point is to the concept or preliminary design phase, the less complete and resolved the project drawings are likely to be.

1.2 Literature and reporting

In the last decade, there have been several reports commissioned to address failures in the construction industry including Shergold & Weir's ***Building Confidence Report*** (2018) and the Victorian Government's response ***Framework to Reform*** (2019).

While these reports brought together a vast range of issues—material substitution, liability, oversight, inexperience with performance-based solutions, and a lack of understanding of the National Construction Code (NCC)—the work demonstrated the significance of role and liability changes and the general lack of understanding of change to the broader audience. Most of these findings apply to Class 2 Buildings which has been the fastest growing market of construction in Australia over the past 20 years (Shergold and Weir 2018, 11).

The reports under consideration highlight the use of NDC contracts, which remains an important underlying factor. Material substitution emerged as a crucial element, highlighted by the Lacrosse incident and subsequent investigations revealed the presence of flammable cladding in numerous buildings (estimated as 1600 building sites in Victoria alone). Figure 2 describes the timeline of events and the reporting on these failures such as the Victorian Cladding Taskforce (The State of Victoria Department of Environment, Land, Water and Planning 2017), Building Confidence Report (Shergold and Weir 2018), Framework to reform (*Framework for Reform: Modernising Victoria's Building System* 2021; Victorian State Government 2019) and Integrity of private building surveyors and their role in enforcement—A response to the Building Confidence Report Discussion Paper (Commonwealth of Australia and States and Territories 2021).

For the built environment, professionals that carry Professional Indemnity (PI) Insurance have experienced an increase in their PI premiums and encountered limitations on design activity, such as the exclusion of external façade coverage in architects' insurance policies. The Lacrosse hearings specifically addressed the roles and responsibilities of each of these professional groups (Victorian Civil and Administrative Tribunal, 2018).

Figure 2: The timeline of recent events concerning failures in the construction industry and their reports.

1.3 Impact on graduate architects

The shift away from administrative roles for architects has had a considerable impact on the post-graduation experience of individuals in the period leading up to their registration as architects. One notable consequence of limited on-site experience is the gradual erosion of skills within younger members of the architectural profession. Currently, our understanding of this phenomenon is based on anecdotal evidence gathered through discussions with architects and examiners of ARB interviews. The authors are actively working on developing an empirical method to substantiate this observation Architects Registration Boards.

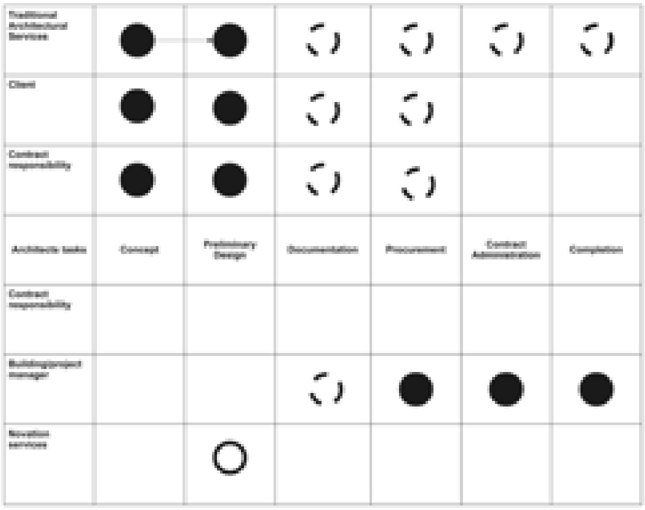

Figure 3: Diagram illustrating the change in responsibility if the point of novation is at the end of preliminary design. Solid circles represent defined activity and roles. Dash lines indicate roles and responsibilities that requires negotiation. The white circle indicates the point of novation.

2. Novation

2.1 Complexity of projects in 21st century

Construction lawyer Wendy Poulton describes NDC in the Australian context as “often used and little understood” (Poulton 2022). She continues:

> It remains a common law concept, largely unregulated by legislation, and there is little reported case law. All this means that we lack definitive guidance on what novation is, and how this complicated transfer of rights and obligations works—for example, novation could take place at 5% completion of design documentation, or at 95%. Every novation is different. The requirements applicable to each novation depend on the design and construct contract, consultancy agreement, scope of services and novation deed in play on that individual project (2022).

To understand the impact of the point of novation, this research looked at the typical sequence of architects' tasks proposed by RIBA's plan of work (RIBA Architecture.com 2020) to develop the design and delivery phases of a building project. Based on this sequence of tasks as outlined in the plan of work, Figure 3 describes the sequence of the traditional architectural services and the impact of the point of novation and the element of risk when the consultant and level of documentation of the different phases are ambiguous.

Another factor to add to this complexity is the language and terms used between disciplines. While schematic design, design development and construction documentation are relatively well understood within the practice of architecture—this doesn't necessarily transfer to other disciplines such as construction management. After all, what is 'design'?

2.2 Code of Novation

Historically, architects had responsibility for both the design and the construction administration of a building. However, that role has since changed as construction projects have grown in complexity and scale (Burr and Jones 2010). Construction management firms have increasingly garnered more authority and responsibility, whereas architects have adopted a subordinate role (Ahuja, Nikolova, and Clegg 2020).

The Code of Novation (Australian Institute of Architects 2022a) was developed from a national survey sent out to members of the Australian Institute of Architects (AIA) in 2019 to survey member experiences working with novated contracts. The draft Code was refined via working with stakeholders including developers, consultants, contractors, project managers government and industry bodies and legal experts.

The objective of the Code was to outline the scope and diversity of experience regarding novated projects, commonly employed in many sectors, including commercial, government, and education projects. The survey findings revealed that a significant majority (over 64%) of member practices generated more than half of their revenue from design and construct contracts involving novation—constituting a substantial portion of Australia's construction sector, representing 9% of the national economy or over $360 billion in GDP (Australian Institute of Architects, 2022).

One of the key factors highlighted in this study is the importance of a comprehensive design phase that should be completed prior to the point of novation. Depending on the scale and complexity of the project, it may be necessary to finalize construction documentation for major components or all elements. It is recommended that the Principal and Consultants establish a mutual agreement and define the required level of completion for key design work packages—before the novation process (Australian Institute of Architects, 2022).

According to the Code, the completion of the Design Development phase (100% DD) is deemed achieved when the design scope aligns with the agreed brief and/or Principals Project Requirements (PPR) (Australian Institute of Architects, 2022, p. 4).

> Put simply, the contract you sign can only protect you if it has been negotiated fairly and if you enforce your contractual rights when you are being prevented from performing your role. It is vital for those in the profession to support each other in order to reach a common position on what is acceptable and to lift the benchmark for fair contracting (Weir 2021)

While the concept of 'novated design' offers several advantages, such as early contractor involvement, there is still no widespread consensus on the fundamental principles of the NDC procurement method. This uncertainty is particularly problematic in an environment that increasingly relies on customized contracts, as highlighted by the ARBV (Architects Registration Board of Victoria 2022)

The existence of NDC contracts and the potential for insufficient documentation resulting from early novation raise significant concern. Subcontractors often struggle with inadequate or misaligned design information during the tendering phase, leading them to inflate their prices as a precaution against potential risks. To address this issue, postponing the novation point can lead to improved coordination, detailed specifications, and enhanced construction details. This, in turn, provides subcontractors with a more comprehensive understanding of tender prices and expected project outcomes, as suggested by the Australian Institute of Architects (2022a, 4). While there are comprehensive guidelines around Novation—these are not enforced in Victoria and the question of value needs to be considered.

With a larger percentage of projects using the NDC model, there are fewer opportunities for graduates to be on site during the contract administration stage. With fewer graduates exposed to this area of expertise—we are slowly deskilling the profession in this area.

3. Value

The time cost/quality/triangle is one of the basic principles of Project Management. When this balance is altered—say with a focus on cost and time—quality will suffer. One of the recommendations by the AIA when using a novated contract is the need to have in place an independent representative to assess quality (the traditional role of an architect (Australian Institute of Architects 2018). Compromising quality can undermine the very objectives of the project – typically in terms of sustainability or accessibility (Day and Huppatz 2022). This is an area that requires further investigation with post occupancy surveys with an analysis of 'value'. In discussing what is success and failure in a project—Atkinson deems that without quality a project cannot be successful. However—'quality' in a developer driven market is an opaque term.

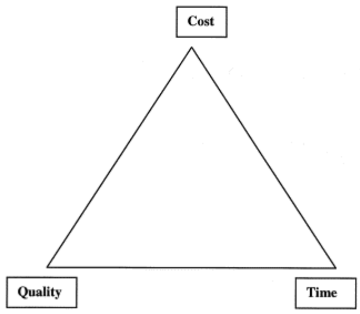

Figure 4: From (Atkinson 1999), The time cost quality triangle. Atkinson argues that cost and time are actions with quality as a phenomenon and that this model requires revision. Without 'quality' a project is not fit for purpose – a notion that underpins the Building Confidence Report.

4. Accreditation and registration

4.1 Changes to the AACA

Accreditation in Australia is controlled by the AACA and organised through the various registration boards at state and territory level. These bodies protect and control the use of the title 'Architect'. However, anyone can undertake the 'work' or 'activities' of an architect as long as they don't use the title. In the USA this is controlled more tightly where the 'work' of an architect can only be done by an architect (Leach 2015)—with the exception of California.

4.2 The finite system of education

Training architects faces challenges due to limitations within the education system, as pointed out by Leach (2015). Another key issue lies in the distinction between 'educating students about architecture' and 'training students for a career as architects' in the system of education and university structure. There is a strong demand for a flexible model of education supporting a global marketplace—reinforced by systems such as the Bologna Accord model (AACRAO 2023). The challenge is the management across scales—while education is global—the accreditation principles are definitively local.

As the tertiary education system continues to globalize—such as the incorporation of the Bologna Accord, professionally accredited courses like architecture are increasingly compelled to fit a substantial amount of content into a compressed two-year timeframe (the standard Master of Architecture program)—and in the case of Architecture in Australia, also aligning with the AACA Competencies (AACA 2021a). This places substantial pressure on these programs.

5. Discussion and conclusion

5.1 Accreditation systems

While there are ongoing debates about the value of the title 'Architect' (Deamer 2020), the professional regulation of architects determines what is taught in architecture schools (if they choose to remain accredited). While there are many students that study architecture that will not become registered architects (moving into allied areas of design, media, research or academia)—the prime objective of the degree surely is to train people who want to practice as traditional Architects. There are schools in the USA that are not accredited with NAAB, likewise with ARB in the UK—however this does limit options for graduates in relation to work and their opportunity to obtain licensure. It would be a brave school to challenge the prevailing orthodoxy in Australia without at least an undergraduate program approved by the AACA—especially with government policy geared toward 'job ready' graduates (Australian Government 22 August 2022). Job ready graduates for architecture in Australia in 2023 equals capacity to register as an architect in one or many of the states and territories of Australia.

5.2 Guided space from graduation to registration?

Examination interviews reveal an ongoing deterioration in practical experience on site for candidates. There is discussion about the requirement for a guided apprenticeship model—curating the journey from graduation to registration. In the USA practices such as Gensler University and Khan University, SHoP Architects are designed to fill in "educational gaps about tools, techniques and professional standards" (Cayer 2022). In the UK, schools including the Bartlett School of Architecture, The Mackintosh School of Architecture and the University of Newcastle upon Tyne offer Post Graduate certificates or Diplomas or Part 3 of an architect's education—specialising in the examination of Practice and Management. The Part 3 in the UK is the examination for registration like the structure in Australia.

5.3 What is an architect in the 21st century?

In the ever-evolving construction industry, various project scales require different approaches and contractual setups. In these scenarios, architects may or may not assume the role of the lead principal. Irrespective of their perceived authority on-site, there is a growing concern that many architects lack awareness of their liabilities and responsibilities within these arrangements. They often fail to adequately account for their contributions to projects. The choice of contract for a project depends on its size and complexity. This presents a significant challenge for architects, particularly in the Victorian market, where NDC contracts are becoming increasingly common. The prevailing policy favours NDC as the preferred procurement method, which restricts the architect's role to the design phases only—but there needs to be consensus as to which stage which could be anywhere between town planning through to the end of design development. This limitation has already had negative effects on recent graduates, who have limited exposure to construction sites and insufficient skills in contract administration and the application of 'value management' by project managers has reduced the overall quality of the built environment. Although there have been instances where novation has worked effectively, there is a concerning trend regarding architects losing expertise in professional practice and contract administration.

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Tipping point for condensation water drainage on surfaces and interfaces of insulated wall assemblies – experimental method to define water content limits for hygrothermal simulation models.

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Abstract: If condensation occurs on non-hygroscopic surfaces of insulated wall constructions, droplet runoff may happen if the amount of condensate exceeds certain limits. Depending on the situation this phenomenon may help to dry the wall, but it may also result in material degradation by water accumulating at the bottom where drainage is not intended. The limits for interstitial condensation amounts on non-hygroscopic materials calculated by the dew-point method in European standards differ with values up to 500 g/m². However, it is questionable whether these limits are based on rigorous experiments and whether they are suitable to evaluate hygrothermal simulation results. Therefore, a laboratory test method has been developed to determine the amount of condensate required for water to run off from vertical surfaces or interfaces of insulated assemblies. For this test 14 fibrous insulation materials (9 x mineral wool, 3 x wood fibre, 2 x cellulose) and 4 types of condensation planes (hydrophilic, hydrophobic, smooth, or rough surface) were examined. The results proved to be much lower than in the above-mentioned standards. Mostly, they ranged between 100 and 200 g/m². Furthermore, by correlating the acceptable amount of condensate with the hygrothermal properties of the insulation materials, a simple formula was derived to estimate the material specific limit value, using its moisture equilibrium at 80 % RH. Finally, by comparing the test results with hygrothermal simulation results, it can be concluded that the water content in the critical one-centimetre-thick layer of the assembly, referred to in DIN4108-3 (2018), is appropriate to assess the probability of condensate runoff.

Keywords: Interstitial condensation, condensate runoff, hygrothermal simulation, fibrous insulation.

1. Introduction

The application of hygrothermal simulation tools for moisture control assessment and design have become more widespread in the past three decades. Today, many national and international moisture control standards and guidelines refer to these tools as being the most reliable way to assess the dynamic moisture performance of building envelope components, because they consider hygrothermal inertia as well as vapour and liquid transfer. The most common of the hygrothermal simulation tools have been extensively experimentally validated. Mostly, this has been done by comparing measured and simulated parameters, such as water content, relative humidity (RH) and temperature, at certain positions within the building assembly at defined timesteps. While most building materials are porous and absorb water, there are also material layers that absorb very little water or no

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water, respectively vapour. Examples are plastic foams or films as well as metal sheets or foils. If their surface temperature drops below the ambient dewpoint, condensation will occur in form of small droplets. When the droplets become more numerous and grow larger, there is a chance of water runoff if the amount of condensate exceeds the surface water retention capacity of the specific layer.

This is a well-known fact and may be intended to drain condensate off the surface. However, if there are no provisions to collect or discharge the water, it may accumulate somewhere in the construction and cause damage. In that case, the occurrence of condensation should be limited by vapour control measures to remain below the tipping-point of condensate runoff. Since hygrothermal simulation tools can predict the amount of condensate on non-water absorbing material layers, knowing the water retention capacity of such layers helps to prevent the risk of runoff. Looking at the steady-state vapour diffusion standards in Europe, proves that there is no real consensus on limiting the amount of condensate on non-water absorbing surfaces. The German moisture control standard DIN 4108-3 (2018) specifies a maximum of 500 g/m² and the ISO EN Standard 13788 (2012) warns that more than 200 g/m² bears the risk of runoff. The British Standard BS 5250:2011+A1:2026 contains a table that states even lower limits: Droplets form and begin to run down vertical surfaces between 30 and 50 g/m² of condensate. This is a pretty large range for assessing the risk of condensate runoff. Therefore, the aim of this paper is to establish limit values for hygrothermal simulation analyses that are realistic and take into account the roughness and installation specifics of the material surface/interface in question.

2. Condensation tests

There are numerous studies on the drainage of rainwater on cladding systems or water resistive barriers, (e.g. Straube 2007). However, the authors believe that their results may not be transferable to condensate runoff because field tests of Künzel (2007) identified large differences in the water retention properties of external wall coatings depending on the type of moisture load. While rainwater was repelled form hydrophobic surface coatings and drained immediately, condensate forming very small droplets still adhered to the water repellent surface. From this finding, it may be concluded that experiments looking at the drainage of driving rain or spray water may show different results from those exploring the drainage of water condensing on a surface. Therefore, the following experiments have been designed to study condensate runoff exclusively.

Because there is often confusion about the hygrothermal characteristics of materials and material layers, this paper makes a clear distinction between liquid water absorption and hygroscopic vapour sorption. Liquid water absorption due to capillary action happens only in hydrophilic materials. Hydrophobic materials may have similar pore structures, but they don't absorb liquid water because water will not spread on their surfaces (surface angle of droplets > 90°). Hydrophobic materials may still be hygroscopic, which means they can adsorb water molecules at their interior surfaces.

2.1. Test unit

The test is carried out in an air-conditioned room (constant 23 °C and 65 % RH, dew point 16.1 °C). In this room, a cooling plate (30 cm x 30 cm) is placed vertically, and its surface temperature is controlled to the set temperature by a cryostat cooling circuit. The investigated material is placed in a rectangular, laterally insulated, frame (10 cm x 10 cm with the thickness of 2 cm). The heat conducting metal backside of this frame is placed against the cooled plate with heat conducting paste. In a preliminary test, the cooling plate has been chilled by cryostat with its setpoints between 2 and 7 °C. Significant differences in condensation and runoff patterns due to the temperature dependent viscosity of water or the intensity of condensation could not be detected. Therefore, all further experiments were carried out with the chilled surface controlled with the set-temperature of cryostat at 2 °C. The surface temperature was about 4 - 7 K warmer than the set temperature depending on the test material. In total, four frames are placed on the cooling plate (see Figure 35, left). The foam insulation of the frames helps to avoid thermal bridges at the edge of each frame. On the chilled surface of the metal plate, the surface materials to be investigate can be attached (Figure 35, right). Afterwards, the cavity may be filled with fibrous insulation material which is held in place by rubber bands to ensure direct contact with the surface. The drained condensate is collected in a small vessel under each frame (not shown).

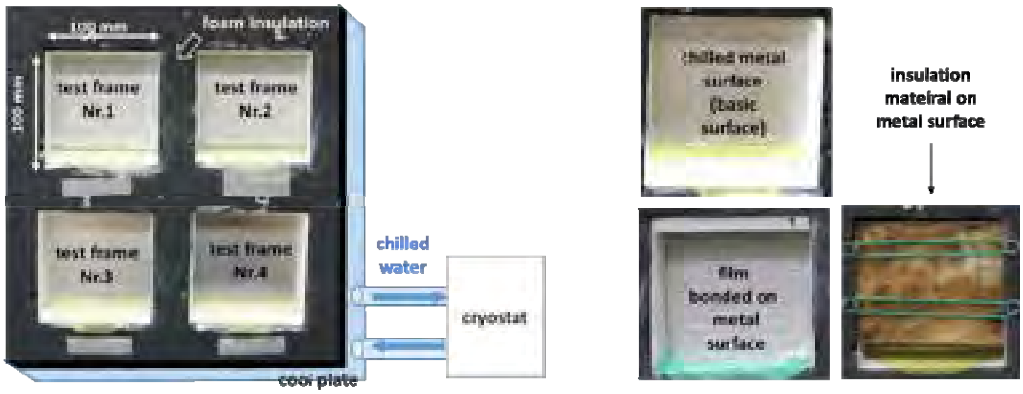


Figure 35: Left: Condensation test unit. Four frames with a metal backside are fixed with heat-conducting paste to a cooled surface. Each frame is surrounded by foam insulation material. Right: Frame with test material. The default surface is a metal plate, on which a film or an insulation material is placed.

2.2 Water retention capacity of surface layers

The condensate remaining on the surface of the substrate is blotted by an absorptive paper, and the weight difference of the paper before and after blotting indicates the amount of retained surface condensation. This amount is divided by the area of the tested material. At first, the amount of condensate adhering to different surface materials and textures is determined separately (without contact to any insulation material). The following four surface materials with different hydrophobicity and roughness are examined and shown in Figure 36.:

- metal (hydrophilic)
- PE film (hydrophobic, smooth)
- film laminated on fleece (hydrophobic, fine structured)
- film reinforced with fabric (hydrophobic, coarse structured)

Figure 36: Tested surface samples from left to right: metal (hydrophilic), PE film (hydrophobic, smooth), film laminated on fleece (hydrophobic, fine structured), film reinforced with fabric (hydrophobic, coarse structured).

As described above, the set temperature of the cryostat and the test duration was varied. As no clear correlation between each of these two factors (temperature and duration) and measured water retention can be established, all measured values are used to evaluate the results and presented as a box plot in Figure 37 . The amounts of water clinging to the surface clearly differ with the surface properties. The hydrophilic metal plate retains more condensate than the hydrophobic PE-film. Increasing the roughness of a hydrophobic surface also leads to a higher condensate retention capacity.

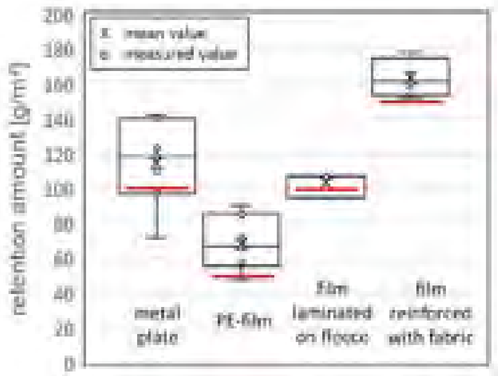


Figure 37: Measured amounts of condensate on four types of surfaces when runoff had started. The boxplot shows the variations of the results, and the red lines indicate the limit values defined in Table 1.

Based on the experimental results described above, a limit value of the condensate retention capacity on each surface is determined and listed in Table 18. These values are for each case below the mean values of all measured retention values on a surface at all temperatures and test durations. It should be noted that the determined retention amounts are lower than the maximum possible level because condensate runoff had already occurred prior to the blotting test. Thus, the obtained amounts of condensate still clinging to the surface represent limit values that are still on the safe side without being overly conservative. Furthermore, the retention capacity on the hydrophobic film laminated on fleece of 100 [g/m²] matches well with the results of Janssens (1998).

Table 18: Limit value of retention amount according to substrate property, determined as minimum of several tests, thus representing limits on the safe side concerning the risk of condensate runoff.

Substrate characteristic	hydrophilic	hydrophobic		
		smooth	fine structured	coarse structured
Investigated substrate	Metal	PE-film	Film laminated on fleece	Film reinforced with fabric
Limit value [g/m³]	100	50	100	150

2.3 Water retention capacity at insulated interfaces

In the next step, the retention capacities for condensate on cold surfaces in contact with 14 different insulation materials are investigated. Table 19 lists the insulation materials with their relevant properties. As representatives of mineral insulation materials, six glass wool variants with bulk densities between 20 and 65 kg/m³ and, three stone wool samples with higher bulk density (111 to 135 kg/m³) are selected. One glass wool and one stone wool product (glass wool #3 and stone wool #2) is exceptionally hydrophilic and, thus, absorbs liquid water, while the others are hydrophobic. As cellulose insulation, a standard product and a hydrophobic product are selected. The tested wood fibre insulation samples represent the variety the most common bio-based building insulation products in Germany. Wood fibre sample #1 is a flexible insulation batt with a density of 60 kg/m³, generally used for cavity insulation. The other two wood fibre samples are rigid insulation boards used as exterior cavity sheathing or external insulation. Their density is higher than the density of cavity insulation materials and they are supposed to be non-water absorbing. This means they repel liquid water but can still adsorb vapour which means they are hygroscopic.

Table 19: Tested materials with their material properties

Insulation material	density	moisture equilibrium		free saturation	water absorption coefficient
		80 % RH	97 % RH		
	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m²√h]
glass wool #1	20	0.7	3.8	372	0*
glass wool #2	22	0.9	4.3	335	0*
glass wool #3	22	n.d.	n.d.	n.d.	5.3
glass wool #4	30	1.1	5.7	510	0*
glass wool #5	35	0.8	3.9	536	0*
glass wool #6	65	n.d.	n.d.	n.d.	0*
stone wool #1	111	0.75	1.4	600	0*
stone wool #2	128	0.9	4.0	929	18.0
stone wool #3	135	0.6	2.0	121	0*
cellulose fibre #1	50	3.7	14.7	173	0*
cellulose fibre #2	50	7.9	20.1	614	12.0
wood fibre #1	60	7.7	48	307	9
wood fibre #2	140	16	35	570	0.14
wood fibre #3	96	10.5	22.3	464	0.2

n.d.: no data, *: hydrophobic

The insulation materials are installed in close contact with the substrate on the cold surface as shown in Figure 38. Loose cellulose is filled into the frame in the amount equivalent to the installation density of 50 kg/m³ and held in place with a fine stainless-steel mesh. The other material samples are fixed with a rubber band. The batt insulation product samples are 10% larger than the frame and fixed by two rubber bands to achieve the same close fit as in practice situations. All insulation samples are distanced from the bottom of the frame by two wires to avoid contact with the drained condensate to avoid water absorption at the footing, which could distort the test results.

Figure 38: Mounting of insulation materials on condensation test equipment.

To detect the influence of substrates such as films or foils, all insulation samples are combined with two types of substrates, the metal plate (hydrophilic) and the PE film (hydrophobic and smooth structure). Once the drained water is visible in the vessel under each frame, the test frame is removed from the cold plate and the amount of retained condensate is determined. By separating the insulation material from the substrate, it is possible to differentiate between the condensed water in the insulation and the water retained by the PE-film or metal plate. In case of the cellulose fibres only the total amount of condensate can be determined because the fibres could not be removed cleanly from the substrate, as individual fibres would still adhere to the substrate.

Figure 39 shows the measured retention amount on the surfaces (PE film or metal plate) and on or in the materials. In 8 of 14 tested insulation materials, condensation ran off within 24 hours. In the case of two wood fibre materials, condensation ran off between 24 and 48 hours. In the remaining four materials, condensation still did not run off after three days (72 hours). The condensation test was terminated after three days, and the amount of water contained in the samples after this period was determined. Except for glass wool #3, all hydrophilic materials contained more than 1000 g/m² of water in the frame, mostly in the insulation. This indicates that hydrophilic insulation materials may not be comparable to hydrophobic materials in terms of condensate retention and water drainage.

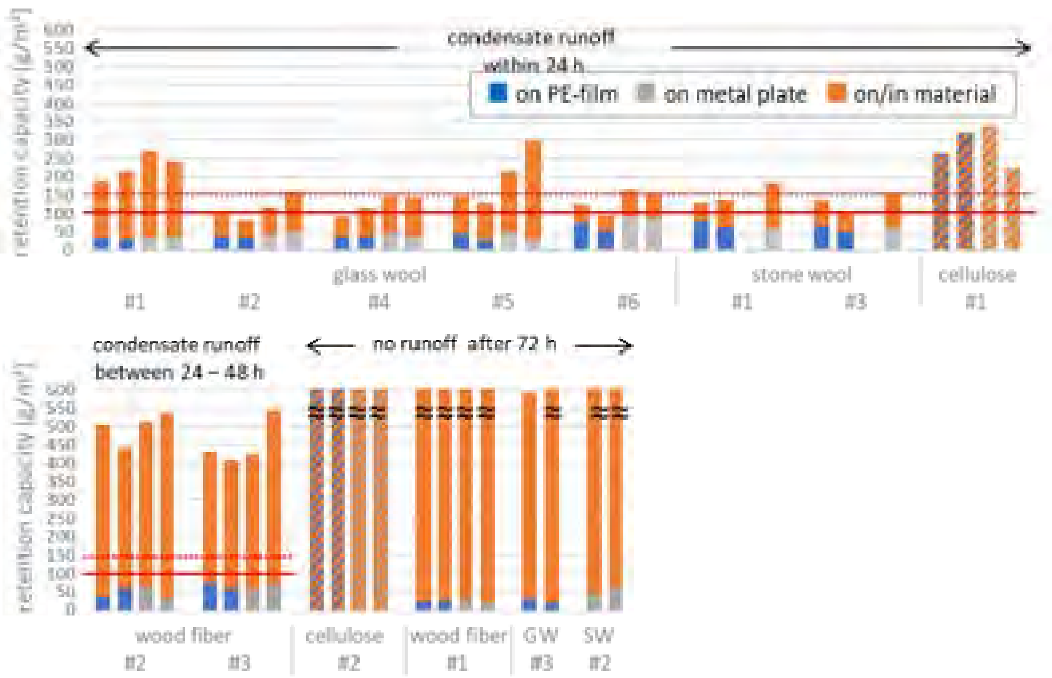


Figure 39: Measured condensate retention on and in the insulation material (orange) and on the PE film (blue) or metal surface (grey). For cellulose these are not differentiable. The red lines at 100 g/m² (solid line) and 150 g/m² (dotted line) refer to the limits defined below.

Regarding the drainage of condensate in insulated cavities closed by a non-water absorbing membrane or sheathing at the cold side, the following can be concluded from the results:

- The current limit value of 200 g/m² according to DIN EN ISO 13788 (2012) appears to be too high for most mineral wool products in the test. Therefore, a lower limit should be introduced here if runoff must be prevented. A safe general limit would be 100 g/m².
- With a hydrophilic surface (metal), the total retention quantity is approx. 150 g/m². The difference of 50 g/m² increase agrees well with the difference of the surface retention capacity without insulation materials.
- Cavities filled with hygroscopic insulation materials seem to buffer a significant part of the vapour diffusion flux. This increases the condensate retention capacity of the building assembly to approx. 500 g/m².

Also the capillary water absorption of the insulation material plays an important role in raising the condensate retention characteristics of insulated cavities. If the water absorption coefficient (A-value) of the insulation material exceeds 5.0 kg/m²√h more than 1000 g/m² of condensate could be retained until the end of the test after 72 hours. However, in our test, only few materials were so hydrophilic.

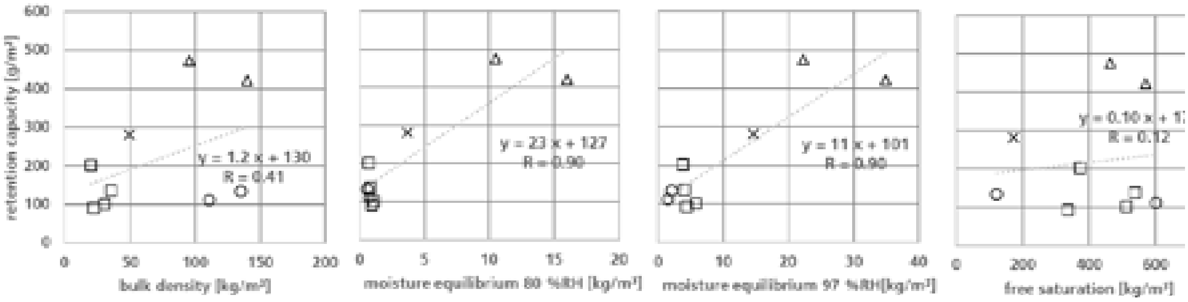
2.4. Essential material properties for the retention capacity of non or weak absorbent insulation materials

The test results indicate that the retention values determined for 10 different hydrophobic insulation materials vary in a wide range from approx. 100 to around 550 g/m². To enable a product-specific and finer evaluation of the condensation runoff risk in addition to the limit value of 100 g/m², which is usually on the safe side, the impact of specific material parameters such as density and hygroscopic vapour sorption on the condensate retention capacity is investigated. Therefore, a correlation analysis is carried out between the retention capacity and bulk density, sorption moisture at 80 % and 97 % RH and at free saturation. The results are shown in Fig. 6 above for the hydrophilic metal plate and below for the hydrophobic PE film, each with a regression line through the measured data. The equations of the regression lines and the respective correlation coefficient R are also given.

The correlation of the retention capacity with the bulk density of the insulation material (Fig. 6 left) is surprisingly low, at only 0.41. Since a higher density indicates a higher number of fibres and thus possibly more "runoff resistance", a stronger influence was expected here. With 0.22 and 0.12 respectively, the correlation of the retention capacity with the free water saturation is even lower and, therefore, this correlation is discarded.

In contrast, a significantly better correlation can be observed between the retention capacity and the sorption moisture both at 80 % RH and 97 % RH. The coefficients here are between close to 0.9 in each case. The sorption moisture level in the higher moisture range thus appears to be the decisive, easily determinable variable that most strongly influences water retention. Since the correlation with the water content at 80 % RH is even slightly higher than at 97 % RH and, moreover, the so-called reference moisture content is known and available for most materials, the following approach uses this correlation.

on PE-film (hydrophobic, smooth)



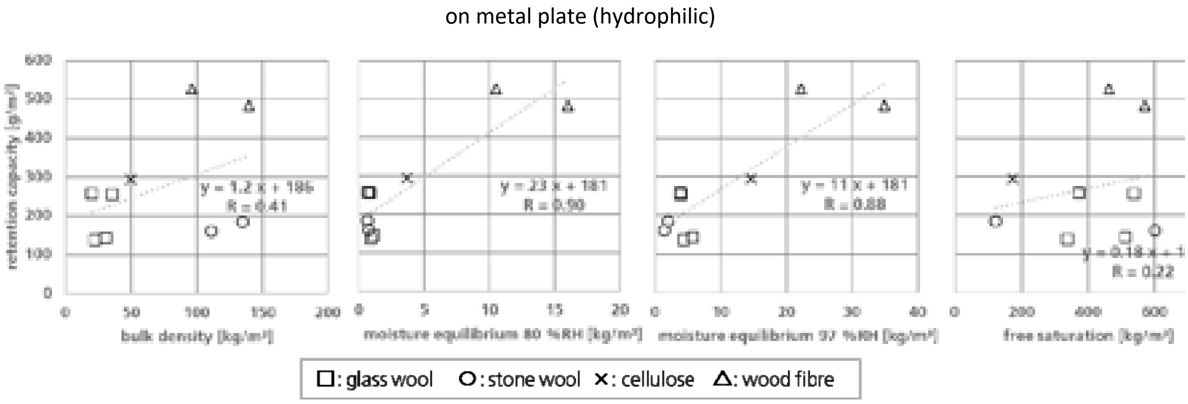


Figure 40: Measured retention amount via material properties (bulk density, free saturation, moisture equilibrium at 80 % and 97 % RH) with regression line and its formula together with correlation coefficient (R). On the left are results examined on metal and on the right on PE foil.

2.5. Interface- and material-specific limit values

With the help of the degrees of regression between retention capacity and reference moisture content u_{80} on metal (hydrophilic) and PE film (hydrophobic, smooth), the empirical correlation to determine the material-specific limit values is defined in such a way that the limit values remain slightly on the safe side compared to the measured data. This results in the following equation for unknown substrate properties.

Retention capacity RC= 20 [mg/kg] x u80 [kg/m³] + 100 [g/m²] (1)

The retention capacity is increased by 20 g/m² for every 1 kg/m³ of additional sorption moisture content at 80 % RH. The base value represents the 100 g/m² always retained regardless of material and substrate properties. For hydrophilic metal substrates, this base value increases to 150 g/m². The difference of 50 g/m² corresponds to the retention quantities determined on free surfaces without insulation material. Figure 41 shows the calculated correlation together with the measured results. The limits are mostly lower and thus slightly on the safe side with the exception of the two glass wool products, where the retention amount is about 10 g/m² lower than the limit curve in each case. However, this seems acceptable in view of the slightly lower values after the start of the runoff.

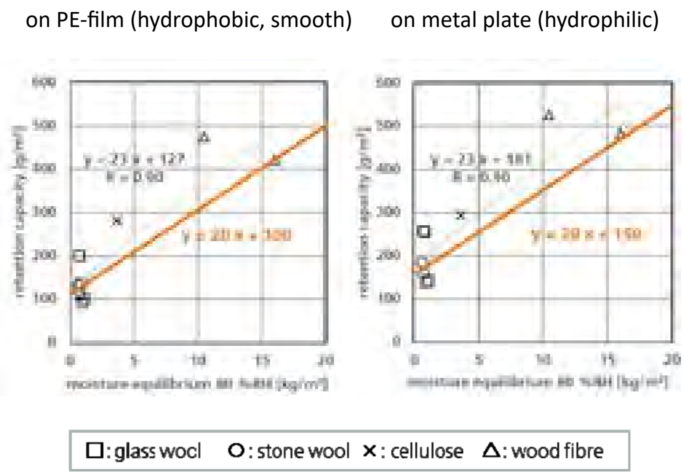


Figure 41: Measured retention capacity plotted over the moisture equilibrium at 80 % RH on hydrophobic and smooth PE film (left) and hydrophilic metal plate (right). The dotted lines represent the regression results, and the orange lines are the resulting limits calculated by equation 2.

It has already been mentioned that the difference in retention capacity on metal and PE film with and without fibre insulation is 50 g/m². In additional tests it could be shown that this correlation also applies for other interface properties. Therefore, the following general equation can be defined:

Retention capacity RC= 20 [mg/kg] x u80 [kg/m³] + b [g/m²] (2)

with:

	100 g/m²	for unknown interface properties
b =	150 g/m²	for hydrophilic or fine structured hydrophobic interfaces
	200 g/m²	for coarse structured (hydrophobic) interfaces

However, an exact classification of the respective surface into the three categories can be difficult in individual cases - for varnished wood, for example, depending on the surface treatment, a coarse or fine texture can be considered. In case of doubt, the value for unknown substrate properties should be selected. If required, the substrate-specific retention capacity can of course also be determined individually in the laboratory.

3. Evaluation by hygrothermal simulation

The laboratory tests are compared to hygrothermal simulation results. The one-dimensional hygrothermal simulation program WUFI® Pro, which has been validated by numerous studies worldwide, is used for the simulation. The boundary conditions are the room air condition (23°C, 65 % RH) and the measured temperature behind the insulation material (approx. 7 °C). The impermeability of the cooling surface is considered by a very high s_d value (s_d = 10000 m). One product of each of the four material types (glass wool, stone wool, cellulose and wood fibre board), for which all required hygrothermal characteristic values are available, is simulated. The total thickness of the insulation layer is consistently 20 mm.

In order to check which choice of the condensation zone thickness is most appropriate, the evaluation of the water content in the insulation layer is carried out for four different condensation zone thicknesses, 1, 5, 10 and 20 mm thickness. This choice means that it takes different lengths of time until the limit value relevant for condensate drainage is exceeded in the respective zone. To simplify the evaluation, it is assumed that all the water in the layer is due to condensation. Since the effect of gravity is not accounted for, the condensate will not run off but stays at the respective position in the building component. Therefore, the risk of runoff must be assessed in a separate step. Fig. 8 shows the increase in the total amount of water in the condensation zones of four different insulation materials, depending on the chosen thickness of the evaluated condensation zone. The retention capacities determined in the laboratory are shown as red lines for the situations on the metal plate and on the PE foil respectively.

For glass and stone wool, the evaluation thicknesses are not relevant to the determination of the time of the first condensation runoff. With the more sorptive materials, cellulose and wood fibres, the curves diverge somewhat further, as not all the water is on the cold side but is stored in larger areas in the material. A too thin evaluation zone would lead to the limit value being exceeded too late here. If an edge layer of only 1 mm thick is evaluated in the hydrophobic cellulose fibre, the water content of this layer exceeds the limit value only after just under 2 days, which contradicts the observation in the laboratory, where condensation had already occurred after 24 hours.

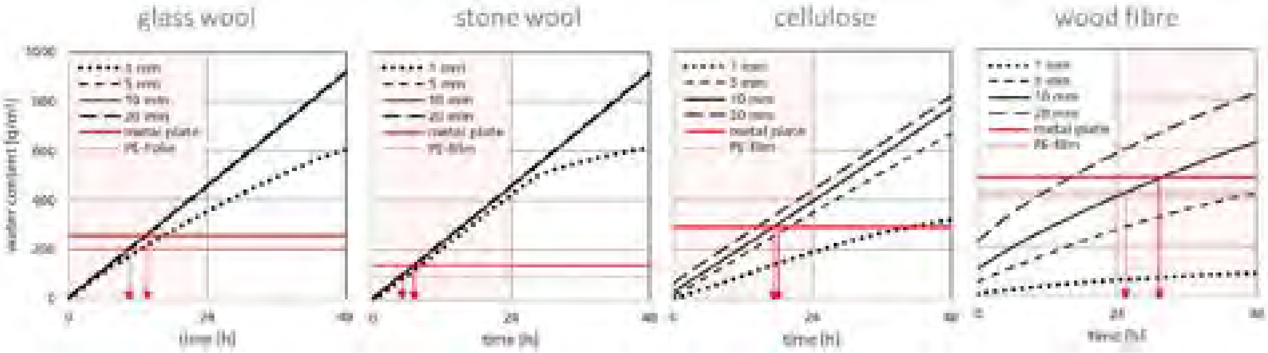


Figure 42: Simulated water content curves in different thicknesses (black) and the measured retention amount (red) on two types of surfaces. Red arrows show the time points at which the water content in a 10 mm layer exceeds the retention amount, i.e. the condensation water is calculated to have run off first time. In the lab test the condensate run off within the time range coloured in red.

When the thicker layers are evaluated, the limit value is exceeded after 14 to 20 hours - i.e. within the time period determined in the laboratory. With wood fibre insulation, the discrepancy between the evaluated layer thicknesses is even more pronounced. If a thin layer of 1 or 5 mm is evaluated, the water content reaches the limit value only after the condensation has run off as determined in the laboratory. In the case of the 2 cm thick layer, on the other hand, the limit value is exceeded too early after about 12-16 hours. In the case of the 1 cm thick layer, the runoff occurs within about 26 to 30 hours, depending on the interface, which is consistent with the laboratory result. Comparable results were also obtained for the other materials not shown.

In summary, the choice of 10 mm for the condensation zone to be evaluated against the condensate runoff limits resulting from the laboratory tests appears to be well suited for evaluating the risk of condensate runoff from hygrothermal simulation results.

4. Conclusions

The results of the condensation tests on vertical non-absorbent surfaces prove that the tipping point for condensate runoff depends on the surface material and its texture as well as on the adjacent insulation material in the cavity. If the condensation plane is not in direct contact with another material, the tipping point is reached at 50 g/m² for smooth polymer surfaces. Smooth metal surfaces and polymer films on fabric can retain up to 100 g/m² and polymer films fortified with a mesh (coarse surface) up to 150 g/m² before runoff occurs. All these values are below the limit of 200 g/m² in EN ISO 13788. According to Straube and Smegal (2007) who conducted drainage test in very small gaps (1 mm), the water being retained in these gaps before run-off occurs can be as low as 25 g/m². However, we didn't not investigate the behaviour of condensate in such small gaps to confirm these finding also for the incidence of interstitial condensation.

If there is no airgap but a hydrophobic fibrous insulation material next to the surface where condensation occurs, the runoff limit for smooth surfaces increases only marginally to about 100 g/m². Generally, condensation on non-water absorbing, non-hygroscopic interfaces of more than 100 g/m² could be chosen as failure criterion if no provisions for safe drainage within the building envelope assembly are provided.

However, this changes if the interface material is hydrophilic or not smooth but having a coarse texture and if the fibre insulation material in contact with the cold interface is hygroscopic or even water absorbing. Hygroscopic materials such as wood fiber or cellulose insulation will slow down or even prevent the process of condensation for a certain period of time by reducing the ambient vapour pressure through vapour absorption. If the material is also absorbing liquid water, it may even wick all the condensate away from the condensation plane. If 100 g/m² is exceeded, the insulation material and substrate properties can be used to check to what extent the limit value is increased in the specific case. The material surcharge is empirically based on the sorption moisture at 80 % RH (u_{80}) via factor 20. As an example, for an insulation material with u_{80} = 2.0 kg/m³, the limit value increases from the base value of 100 g/m² to 140 g/m², irrespective of the substrate properties according to equation (1). In addition, a hydrophilic or coarse textured substrate can further increase the retention capacity by 50 to 100 g/m². This is summarized in equation (2) together with the material dependency. In total, the consideration of the interface and the material type, can increase the limit up to approx. 500 g/m².

To assess the condensation run-off risk at the interface between insulation and external cover layer by hygrothermal simulation, calculation and experimental results were compared. The key factor for a good agreement between calculation and test results is the condensate retention capacity of the insulation layer where condensation actually occurs. A study with varying thickness of the condensation zone in the insulation proved that the choice of a 10 mm thick condensation zone at the exterior end of the insulation layer ensures in the best agreement between calculation and laboratory test results.

5. Acknowledgements

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Towards a circular economy: a review of the current challenges and potential for recycling construction waste materials in New Zealand

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Abstract: Construction and demolition waste has many negative environmental and economic impacts. In order to achieve the New Zealand governmental vision of carbon neutrality by 2050, the transition toward circular economy principles could play a crucial role in mitigating construction waste environmental effects. However, barriers hinder the reuse and recycling of such waste. This paper provides a structured overview of the different challenges. The analysis includes an evaluation of different construction materials' nature and their potential to be reused or recycled. This is set against the environmental impact of those waste materials and how different research projects have aimed to overcome the barriers limiting better use and reuse. The paper reviews how successful projects have taken advantage of the latest research to improve resource circularity. The findings presented reflect on the legislative, cultural, financial, infrastructure, logistical, and technical barriers. The examples reviewed showed how different construction materials' characteristics affect their potential to be recycled or reused. Generally speaking, composite materials are the hardest to be recycled, whereas assembled materials are more suitable to be reused or recycled. The potential use of material passports is also discussed. A detailed map of the obstacles and the possible solutions to maximize the benefits of those potential resources is an outcome of the research presented in the paper. The intention is to support the construction industry stakeholders by evaluating the current situation, thus paving the way toward adopting a viable circular economy approach and 'Closing the Loop' through increased construction waste recycling.

Keywords: *construction and demolition waste (CDW); recycling; circular economy; material passports*

1. Introduction

In the last few decades, negative environmental and economic effects have been linked to the continued growth of the development of the manufacturing process, such as the increase in raw materials and energy consumption along with the emission of greenhouse gases and depletion of valuable resources (Nodehi and Taghvaee, 2022). The evolving transition toward a Circular Economy (CE) concept is considered an attempt to preserve our limited resources and move beyond the traditional linear economic model (Oluleye *et al.*, 2022).

The CE paradigm has recently attracted the attention of many policymakers, companies, scientists, and scholars in many specializations (Geissdoerfer *et al.*, 2017). The circular economy idea proposes an economic framework that is founded on sustainable business models that substitute the traditional 'end-of-life' approach with alternative disposal options (Kirchherr *et al.*, 2017). The waste disposal hierarchy of preferences associated with CE has six levels; Prevention, Reduction, Reuse, Recycling, Recovery (incinerate), and Landfill (Peng *et al.*, 1997).

The building construction industry consumes roughly 40% of raw materials worldwide (Darko and Chan, 2016), contributes about 25% of carbon dioxide emissions, consumes around 40% of the total global energy production (Mahpour, 2018), and is responsible for about 40% of the world's waste production (Nasir *et al.*, 2017). A considerable quantity of construction and demolition waste is consequently produced annually, estimated to be over 10 billion tons, and researches contend that much of it can be recycled (Wang *et al.*, 2019).

Construction waste is a combination of both inert construction waste, such as construction debris, bricks, tiles, rubble, and concrete (Hossain *et al.*, 2017), and non-inert construction waste, such as asbestos, packaging, vegetation, timber, and organic materials (Zheng *et al.*, 2017). Construction and Demolition Waste (C&DW) can be classified according to the production phase, construction, renovation, demolition waste, or the generation source if it results from natural disasters or particular activity (Ghosh *et al.*, 2021).

Globally, 30 % of the world's landfill composition has resulted from the construction industry (Ghaffar *et al.*, 2020). Hence, the unsustainable traditional behaviour of "take, make, dispose", of the building construction industry makes this industry one of the highest waste generator industries (Bilal *et al.*, 2020). Consequently, there is an acute need for managing building construction and demolition waste C&DW to increase resource circulation.

The construction and demolition sector is considered one of the main waste sources in New Zealand. It is difficult to estimate the actual annual amount of the C&DW (Hernandez *et al.*, 2023). According to the New Zealand Ministry for the Environment, in 2023, the total waste generated annually is about 17.49 million tonnes, about 70 % of which is sent to landfill (Ministry of the Environment, 2023). And according to the BRANZ website, construction industry waste comprises about half of the total waste produced in New Zealand distributed to landfill and clean-fill sites (BRANZ, 2023). It is concerning that the construction of one house typically produces about 4 tonnes of waste, while the demolition process for one house produces about 30 tonnes of waste (Rohani, 2019).

Identifying significant challenges to the adoption of construction waste reduction strategies will improve the sector's performance in New Zealand. Hence this review aims to provide a map of the barriers and consequent potential solutions to maximize the efficient of use of materials in New Zealand. This paper is structured into three parts. In the first part, a state-of-the-art summarises the general barriers to reusing and recycling construction materials. The study includes a technical evaluation of different construction materials and their potential to be reused or recycled. In the second part, relevant research projects that have been conducted to help overcome the technical barriers will be presented. Successful commercial projects that used construction waste in the production process will be explored. In the third part of this study, some recommendations are proposed, and the potential use of material passports concept is also discussed.

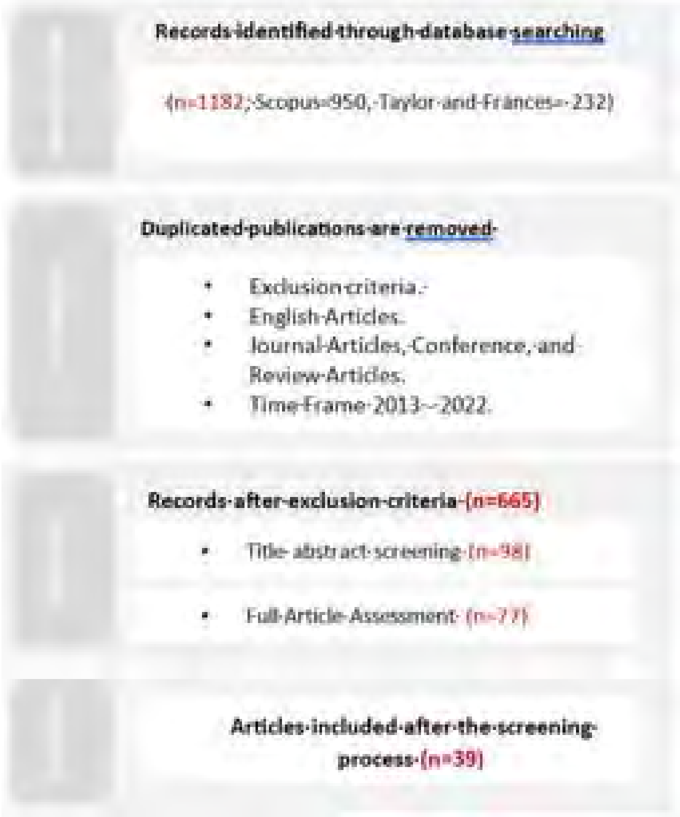

Figure 43. The systematic literature review process.

2. Methodology:

The systematic review process is divided into four main steps, as shown in Figure 1. The first step, identification, included collecting recent articles on the subject published in journals in selected databases; Scopus (www.scopus.com) and Taylor and Francis (www.tandfonline.com). The keywords were defined. A search string was developed and implemented on the platform searching protocol; the search terms were consisted of four main keywords. The first group aimed to find articles containing the keyword “barrier or its synonyms”, The second group aimed to locate articles that included the term “construction waste”, and the third group focused on articles containing the terms (“Reuse*” OR “Recycle*)”. The Boolean connector "AND" enabled the search for multiple keywords within each article. In the screening and eligibility step, the duplicates are removed. The title and abstract of 1182 articles were scrutinized to determine the relevant articles to the scope, and the articles that were not relevant were removed. Articles out of the time frame were removed. The review time frame was limited to the last ten years’ publications (2013-2022) to obtain the most recent research in the field. Based on the abstract screening, unrelated articles to the topic were excluded. In the last step, the resulting full papers were checked, and the remaining articles (n=39) were selected to be investigated in this study.

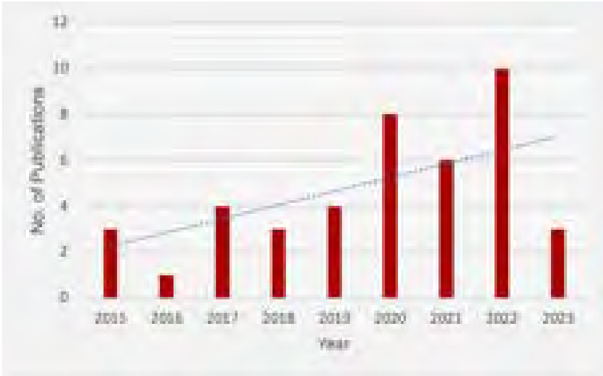

Figure 44. Annual distribution of selected articles from 2013 to 2022.

Figure 45. The journals of selected articles.

2.1 Systematic literature review results

When this study was conducted, at least 39 studies on barriers to reusing or recycling construction waste materials were found. The indication is that research on construction waste management is still growing.

2.1.1 The years distribution of the selected articles

The period covered by this study is from 2013 to 2022. As shown in Figure 2, the number of articles published increased steadily. However, 2022 was a major milestone, with 10 articles. This notable increase could indicates that researchers are committed to understanding the barriers to construction-waste management.

2.1.2 The journals of selected the articles

The analysis revealed that the 39 articles were distributed across 36 different journals, which indicates that reuse and recycle of CD&W challenges are in the scope of AEC publications. This strengthens the interest in investigating them carefully and presenting a comprehensive analysis framework. As shown in Figure 3, at least seven articles focusing on barriers were published in the Cleaner Production Journal, (4), Buildings, the Science of the Total Environment, Earth and Environmental Science, Resource, Conservation and Recycling (3), Procedia Engineering (2) and one publication for each of the rest of the journals. This information could be a helpful focus reference searches for future studies on this topic.

2.1.3 The geographical distribution analysis of the selected articles

By analyzing the geographical distribution of the studies, it was found that 39 studies were conducted in 21 different countries (**Error! Reference source not found.**). A significant number of the studies were conducted in Australia (8), the United Kingdom (6), China (4), Denmark and Italy (4). Geospatial distribution can reflect the global distribution of interest in barriers to construction waste reuse. The lack of studies from African universities may be attributed to language restrictions. It is important to note that other potentially relevant articles were not included in Scopus because of their quality or journal reputation.

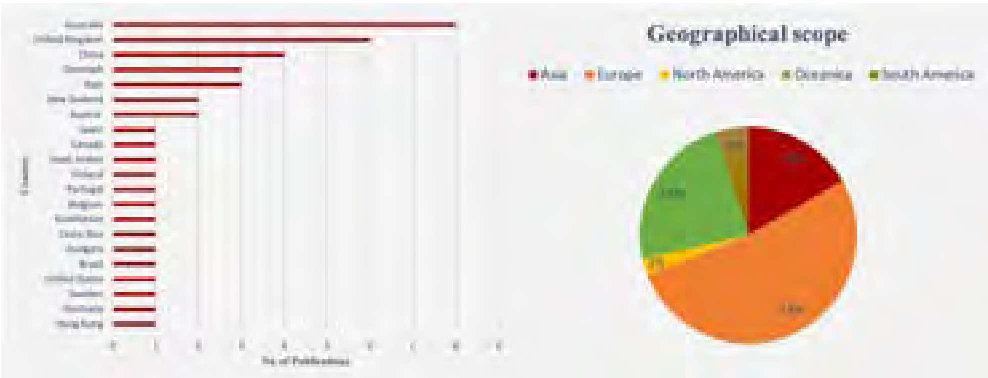

Figure 4. Geospatial distribution of the selected studies.

2.1.4 The main topics of the selected articles

The scope of the selected articles included different topics Figure 5. In 27 Articles, the main topic was the barriers to reusing and recycling construction waste, and the waste management concept was discussed in 19 articles. The concept of circular economy was discussed in 10 articles. Reusing and recycling construction materials were 7 and 2, respectively. Scientometric analysis using VOSviewer shows keywords co-occurrence network analysis in Figure 6.

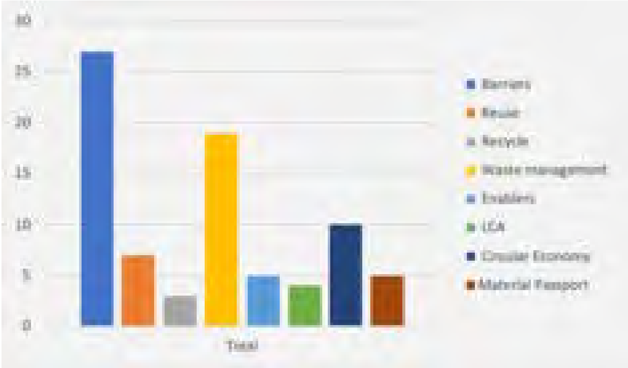

Figure 5. The main topics of selected articles.

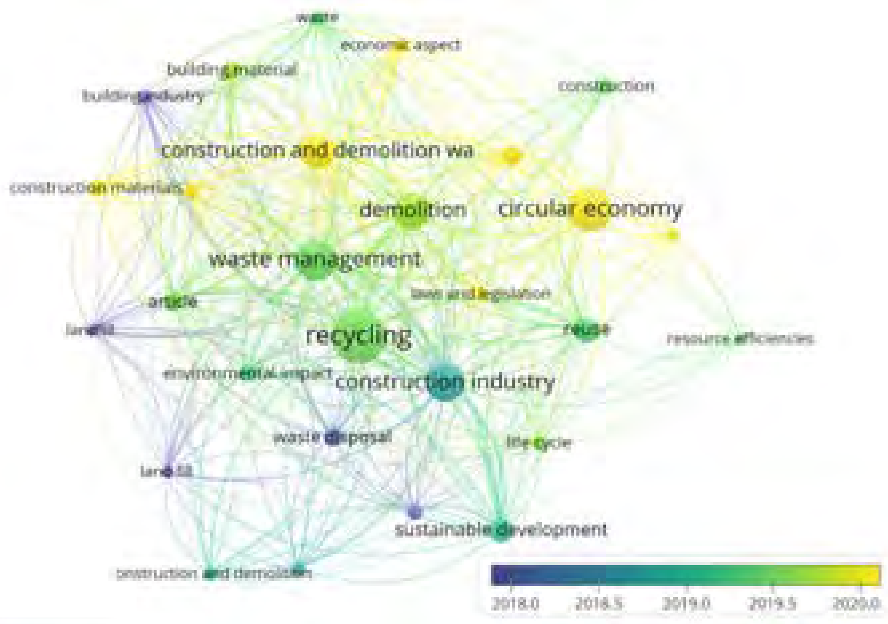

Figure 6. Keywords analysis of the selected articles.

3. Results and discussion of review findings

3.1 The barriers to reusing and recycling the construction waste

On the global level, many authors have investigated the barriers to reusing and recycling construction waste materials. Abarca-Guerrero *et al.* (2022) investigated the literature on the barriers and motivations for reducing construction materials to enhance efficiency and effectiveness in the construction industry. He reported that only a limited number of companies have a waste management plan to guarantee efficient waste handling in the early phase of projects. In China, Huang *et al.* (2018) comprehensively reviewed the existing CDW management policies and analyzed the CDW management using the 3R (reduce, reuse, recycle) principle.

In Australia, Crawford *et al.* (2017) conducted a case study on a housing renovation project in central Australia to recognize the challenges of construction waste management in remote areas. The study identified a range of economic, technical, and cultural barriers to enhancing the ecological efficiency of construction waste management during the demolition phase. Park and Tucker (2017) reported that socio-economic factors are the main barrier. Professionals identify the customers' lack of interest as a key challenge, including an reluctant to pay the increased prices associated with using reused construction materials; Shooshtarian *et al.* (2022) concluded that the lack of financial incentive is the main barrier. Ratnasabapathy *et al.* (2021) point out that the absence of communication and collaboration among different parties and the absence of a user-friendly waste exchange platform (that presents reliable waste data) hinder the effectiveness of C&D waste management practices.

In New Zealand, Low *et al.* (2020) investigated the opportunities and challenges of CW&D management. They concluded that the main issues are the absence of training and education, infrastructure, incentives, and labor health and safety concerns. Moreover, they identify limitations associated with the decentralized resource management approach. While decentralized waste-sharing platforms could improve materials recirculation, expand outreach, and establish a safe marketplace, construction waste websites need to align with centralized regulation to ensure the materials' reliability, quality, and safety. Balador *et al.* (2020) investigated the different influential factors of consumers purchasing behaviour of reclaimed and recycled materials and found that price and self-satisfaction are the most influential factors.

The literature review reveals several barriers that affect the management of construction and demolition waste within the construction industry. According to the literature, the major barriers to construction waste reduction are sorted into six categories: financial, legal, technical, institutional, and socio-cultural.

3.1.1 The financial barriers

The construction sector is cost-driven. Besides the cost, time and quality are the most critical factors that concern the client and the decision-makers (Lock, 2004). Construction companies mainly focus on the economic, not the environmental aspects (Bohne and Wærner, 2014). In the same vein, the high salaries often paid to the labourers in the construction sector discourage the companies from employing labourers to reuse or recycle the recovered materials (Low *et al.*, 2020). There are also doubts about the long-term quality of reused or recycled materials, so many companies prefer traditional materials (Adams *et al.*, 2017). In addition, recycled materials are often not price-competitive in the market compared to traditional materials (Yuan, 2017). The investment cost and feasibility remain crucial concerns for the stockholders' decision in New Zealand's construction sector (Bui *et al.*, 2022). The inadequate financial incentives, such as the reduction of taxes, direct grants, and discounts, could encourage the stockholders to adopt the circular economy approach that will lead to the reuse or recycling of construction waste materials (Bao *et al.*, 2020). It is has been noted that it if often much cheaper to send waste to landfill than to recycle it (Bohne and Wærner, 2014). In response to this, in New Zealand, in July 2022, the landfill cost for C&D waste is about S20/tonne, and the government is planning to raise the fees to 50-60 $ next July. It will be interesting to see what effect this has; increasing construction costs or reducing waste.

3.1.2 The technical barriers

Overcoming the technical barriers will be needed to enable the maximum impact of material circularity. These technical difficulties could be at the building, product, and/or material level (Adams *et al.*, 2017). Guaranteeing the extracted materials' quality is crucial for effectively reusing construction materials (Adams *et al.*, 2017). Insufficient knowledge and consideration of the potential end-of-life uses and immature recycling technologies is another technical barrier. The low quality of extracted materials and the possible contamination with different toxic are also key barriers to reusing CDW (Huang *et al.*, 2018).

Different aspects could be considered as part of the solutions including design of materials, flexibility, and deconstruction at the end of life to enable circularity. While there is a growing interest in these areas, there is a lack of knowledge of how traceability can assist a materials' potential for circularity. However, the concept of a material passport is gradually developing, with evolving understanding of its applications (Adams *et al.*, 2017).

3.1.3 The legislation barriers

One of the main issues is that the current regulations do not encourage and support reusing and recycling construction waste (Huuhka and Hakanen, 2015). Rakhshan *et al.* (2020) argued that bureaucracy is an obstacle to deconstructing projects in South Australia. The approval process is complicated. Reusing recovered materials is hindered, and the current regulations prohibit the storage of salvaged components. Furthermore, there is insufficient commitment and support at the managerial level for implementing effective methods and standards for construction waste efficient handling (Periathamby, 2009). The regulatory jurisdictions have a prohibitive approach towards reusing constriction waste materials (Rakhshan et al., 2020). Park and Tucker (2017) reported that at the level of local jurisdictions, the regulations and legislations discourage the reuse of construction waste due to the complicated requirements and the long process of certification and documentation of the produced materials have important impacts. For contractors the intensive work environment for labours does not encourage sustainable practices, including minimization and sorting of construction waste (Park and Tucker, 2017). In addition, the regulations do not provide adequate incentives to improve their practices. Moreover, the lack of knowledge, guidance, and standards for effective construction waste management is another challenge (Huang et al., 2018). Furthermore, the absence of quality certificates adversely impacts the reuse of construction waste components (Rakhshan et al., 2020).

3.1.4 The Socio-cultural barriers

The socio-cultural challenges include users' and contractors' negative perceptions and low preferences (Mittal and Sangwan, 2014). The absence of awareness of the issues in clients and labourers has led to low demand for recovered materials or components (Rakhshan *et al.*, 2020). The unsatisfactory working environment of collecting, sorting, treatment of construction waste lessens interest in such work (Rakhshan *et al.*, 2020). The workers' and clients' health concerns and possible liability are significant challenges (Mittal and Sangwan, 2014). The abscence of mature market and supplier trust to accept the recovered materials (Akinade *et al.*, 2020). The introduction of material passports could solve the trust problem as the material tracking from production until the end-of-life stage offers reliable information about the salvaged components.

3.1.5 The infrastructure and logistics barriers

The lack of well-established infrastructure in the construction waste management process (collection, separation, transportation, and disposal is one of the main challenges (Adams *et al.*, 2017). The Adams *et al.*, (2017) survey showed that the stockholders consider the fragmented supply chain and the absence of market interest the top challenges. Some researchers Darko and Chan, (2016); Yuan (2017); Luciano *et al*. (2022) reported that the absence tracking mechanism, monitoring, and information reporting system are considered obstacles to reusing construction waste.

3.1.6 The Educational and research institutions' barriers

Several authors reported that institutional barriers play a crucial role in hindering the possibility of reusing construction waste. The designers overlook the waste reduction and the design for deconstruction principles during the design process (Hossain *et al.*, 2020). The absence of end-of-life consideration during tendering, commissioning, design, and construction is deemed to be a significant barrier by designers, researchers, and consultants (Rakhshan *et al.*, 2020). The absence of knowledge, experiences, and skills negatively affects the reuse of the building components (Shooshtarian *et al.*, 2022). Insufficient focus on research and development of recovered construction material is considered a challenge in institutions (Purchase *et al.*, 2022).

4. The construction materials' technical challenges to be reused or recycled

Reuse potential refers to how recovered construction components can maintain their functionality after the end of life. Throughout history, masonry has been extensively reused because of its durability. The reclaimed stones could be reused when constructed using traditional mortars with no Portland cement (Webster and Costello, 2006). Similarly, the brick has a high potential to be reused depending on different factors. The time of dismantling and binding type affect the reuse potential of bricks. Utilizing lime and soft mortars for brick binding or using interlocking bricks to eliminate mortar presents a sustainable and cost-effective comparison to Portland cement mortars (WRAP, 2008). The durability and flexibility nature of steel components (beams, plates, and columns) can lead to high reuse potential at their end-life. Although steel's reuse potential might be hindered by corrosion, fatigue degradation, and rust formation caused by earthquakes, fires, scouring, and degradation, these limitations can be addressed with appropriate maintenance practices. The only feasible way to recover steel components that reinforce concrete building is by reusing pre-cast concrete modules that hold them. However, in most cases, the practical difficulty of separating this steel from other materials often results in minimal potential for reuse (Cooper and Allwood, 2012).

The potential for the reuse of timber components is high when adequately disassembled. The high potential for reusing timber comes with the challenges of decay vulnerability, the difficulty, potential hazards, and risks involved in their deconstruction process. The deconstructing process may require special equipment and extra effort during cleaning and de-nailing to avoid material damage (Baiden et al., 2005). Generalizing concrete's potential for reuse is challenging Because it has a wide range of uses, composition variations, strength levels, and potential impurities from substances like paint and plaster, as well as different forms such as cast-in-situ, pre-cast, or unit materials like blocks and tiles. Cast-in-situ concrete is specifically designed for each project, making it heavy and challenging to handle. Without reinforcement information, analyzing it becomes problematic, and its lack of joints makes dismantling from the structure more susceptible to damage (Hurley and Hobbs, 2005).

5. New Zealand commercial projects to reuse or recycle construction materials

By 2050, to tackle climate change impacts, the New Zealand Government has promised to achieve zero greenhouse gas (GHG) emissions (Bui *et al.*, 2022). Hence, there is a considerable effort from the governmental and private sectors to encourage the circular economy approach in the construction industry, which has a severe environmental negative impact. Different companies play a prominent role in construction waste management to reuse or recycle construction and demolition wastes (table. 1).

Table 1. New Zealand commercial projects to reuse or recycle the C&WD materials

Company	Raw Materials					Location	Material Shape				Reference
	Timber	Bricks	Concrete	Steel	Plaster board		Blocks	Aggregates	Panel	Powder	
Canterbury Clay Bricks		✓				Christchurch	✓				https://claybricks.co.nz
Winstone Wallboards					✓	New Zealand			✓		https://www.gib.co.nz
Green gorilla					✓	Auckland				✓	https://www.greengorilla.co.nz
D&T Macdonald	✓		✓	✓	✓	Waikato		✓		✓	https://www.dandtmacdonald.co.nz
Green Vision Recycling			✓			Auckland		✓		✓	https://greenvisionrecycling.co.nz
Nikau Group	✓		✓			Auckland/ Waikato/ Taranaki		✓		✓	https://www.nikaugroup.com
Atlas Concrete			✓			Auckland		✓		✓	https://atlasconcrete.co.nz
Ward Group			✓			Auckland				✓	http://www.ward-demolition.co.nz

6. The concept of the material passport

The circular economy principle aims to minimize waste contribution and maximize resource utilization in a circular cycle (Ellen MacArther, 2013). Moving from linear to CE requirements in the construction industry, by focusing on the construction life cycle and value chain is essential to improve reuse. According to Farooque *et al.* (2019), Circular Supply Chain Management (CSCM) is influenced by CE principles to increase resource longevity throughout the supply chain. Wijewickrama *et al.*, (2021) stated that the absence of accurate data is the main concern in product supply chain management that could facilitate the circularity of products.

Information availability of material flow, composition, and building stock is crucial for supporting the change toward CE. Currently, various strategies and projects focus on CE implementation. The Building Material Bank (BAMB) project was launched by collaborators from 8 European countries. The goal of BAMB is to transform the construction sector by exploring circular strategies to preserve the values of construction materials and structures. Improved circularity could be achieved by introducing mechanisms to the construction sector, such as Material Passport and 'reversible building design' (Honic et al., 2019).

The materials passport is a digital tool that helps document and track the circularity of various materials, and systems. It provides reliable and standardised information on a materials' characteristics in relation to circularity options. The objective of the combination of MP, information technologies (ITs), and flexible building design is to promote circularity in the construction industry (Hansen et al., 2020). The materials with an MP would be identified, replaced, and reused several times, thereby mitigating the impact of the construction industry.

Furthermore, ensuring comprehensive documentation of material performance during its life cycle in the building as-built drawings, specifications, list of codes and standards, maintenance, quality, and any refurbishment applied to the materials could facilitate the reusing process (Gorgolewski et al., 2006). This could offer valuable insights into the potential for reuse and facilitate the materials circularity in the supply chain (Kovacic and Honic, 2021). Combining RFID & BIM to generate MP, could facilitate the creation of sustainable infrastructure by offering accessibility to updated information through the materials' life cycle. Jayasinghe and Waldmann (2020) reported that by Linking BIM to a database, the reclaimed materials archived in the database could be selected and reused in new structures more effectively and accurately. This technology is in its early stage, but if it becomes prevalent, it could change the construction sector significantly (Kovacic and Honic, 2021).

7. Conclusion

In conclusion, the studies mentioned above highlighted different barriers to reusing or recycling CDW, including the absence of performance information of recovered components, technical challenges, and regulations compliance. Researchers believe that a collaborative approach among designers, owners, manufacturers, and users can help to overcome these obstacles. Traceability of the material throughout the whole lifecycle would be an innovative disruption in the construction sector. Utilizing smart technologies such as Building Information Modelling (BIM) at the design stage and stress sensors or Radio Frequency Identification (RFID) at the material implementation stage can assist by archiving the materials' characteristics and specifications required based on their reuse potential. Adopting the processes would promote circularity by making the relevant information more readily available.

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Urban voids in the CBD of Davao City: Their potential towards sustainable infill development and inner urban regeneration

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Abstract: Suburbanisation is the expansion and spatial reorganisation of a growing metropolitan region. For Davao City, this phenomenon has notably damaged the quality of life in the Poblacion District (local term for Central Business District or CBD) by creating gaps in the city's urban landscape; gaps that is also referred as urban voids. These urban voids present both a problem in the urban space and an opportunity for progressive development. This study aims to explore the potential of urban voids in the local context of Davao City's Poblacion District and its significance in promoting urban revitalisation and avoiding urban blight. In analysing the figure-ground map of the CBD produced solely for this study, five (5) types of urban voids were identified: (a) derelict spaces; (b) infrastructure voids; (c) underutilised public spaces; (d) transitional spaces; and, (e) exceptional cases combining derelict spaces and transitional spaces. Further assessment identified the factors that caused urban voids to include natural, geographic, political, economic, socio-cultural, and dysfunctional factors. Majority of the public perceive these spaces as opportunities rather than liabilities. Hence, active participation and cooperation of all stakeholders is needed to achieve sustainable urban revitalisation initiatives and successfully integrate urban voids into the urban fabric.

Keywords: Urban voids, typologies, placemaking, urban revitalisation.

1. Introduction

1.1. Background of the study

Developing nations are currently facing significant challenges due to rapid increase in urbanisation indicated by its increasing urban population. Urban areas currently house around 55% of the world's population, and this figure is expected to rise to 68% by 2050 (UNDESA, 2018). This shift from rural to urban living could result in an additional 2.5 billion people residing in urban regions by 2050. According to the United Nations (2018), almost 90% of this increase is expected to occur in Asia and Africa.

Urbanisation has reshaped cities on various levels including political, economic, and socio-cultural dimensions. As cities continue to grow, there is a need for customised interventions that consider the existing urban context. Shrinking cities have implemented economic development strategies to optimise the use of vacant lands. However, challenges arise in accommodating population densities and preventing suburban expansion within limited urban spaces and resources. This has led to empty spaces

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in the urban fabric, notably within the city's central core, commonly referred to as urban voids. The term "urban void" encompasses various underused or abandoned spaces, such as vacant lots, derelict structures, and brownfields (Hwang and Lee, 2015, p. 18). The notion of "void" suggests untapped urban areas with potential for reuse, indicating absence, vagueness, or emptiness. These transformations result from the investments and economic progress that support urban centres.

Trancik (1968) suggested three (3) approaches to urban theory that can be used in identifying void spaces in cities: (1) figure-ground; (2) linkage theory; and, (3) place theory. These models identified urban void spaces in the local context and classified the factors that greatly affected the formation of void spaces in the study area. By localising typologies for urban voids, this study will help Davao City and its stakeholders realise the effects of fast urbanisation on the urban fabric. While the city has a large amount of land area available for urban expansion, it is crucial to value potentially high-income parcels of land and its historical value, which remain empty spaces in the existing central business district (CBD). Early identification of urban voids can help facilitate improvement through effective planning and laws in a collective agreement of the stakeholders.

1.2. Statement of the problem and research objectives

Population growth coupled with spatial expansion to the suburbs resulting to increase of unoccupied inner urban areas is one of the urban challenges in Davao City. While the city grapples with planning concerns and strives for sustainable urban environments, the focus on addressing infrastructure, resource security, biodiversity, and social equity is vital. These vacant spaces could potentially enhance economic activity and attract investors. Hence, to explore this, the research aims to explore urban void spaces in the Poblacion District; identifying and understanding their causes, historical use, governmental response, and strategies for beneficial development. Furthermore, it is hoped that in any case for urban revitalisation, the potential of urban voids is integrated in the development of the urban fabric.

2. Methodology

To comprehensively analyse urban void spaces, the research employed a three-step methodology, which incorporates a thorough review of pertinent scholarly works. The initial step involves the identification and categorisation of extant voids within the inner Poblacion District. This was accomplished through mapping, on-site inspection, and direct observation of nearby developments and communities. The subsequent step entailed the execution of a survey within the study area targeting communities, neighborhoods, and both private and government establishments exposed to the previously identified void spaces. This survey aims to assess the extent of public exposure to these spaces, gather opinions regarding their redevelopment, and gauge the level of familiarity with them. Furthermore, the research utilised secondary data provided by government and private agencies, and cited important contributions of other researchers in the field. This supplementary information enriched in understanding of the localisation of urban void spaces, incorporating indicators, definitions, and assessments of these void spaces with the analysis of maps, spatial configurations, zoning and land use, accessibility, and local policies.

3. Results and discussion

3.1. Identifying urban void spaces in Davao City

The study focused on the inner part of the Poblacion District where most of the void spaces identified situate inner economic centre and government processes. Urban voids were identified by analysing the figure-ground map of the CBD area. Referring to several urban design theories, these identified urban voids were evaluated and categorised exploring these spaces in terms of linkage and place evaluation.

Figure 1: Figure ground map of Davao City CBD and the theoretical analysis of urban voids spaces

3.2 Causes of urban void spaces

The emergence of urban void spaces in Davao City can be attributed to urbanisation and suburbanisation, which have led to changes in the population and economic activities within the city's urban centre. The transition significantly impacted the Poblacion District, exhibiting an inversely proportional relationship with the land, spaces, and surrounding structures. Bowman and Pagano (2000) presented varying rationales for expanding cities, encompassing factors such as the burgeoning local economy, in-migration, and city policies promoting land reuse through infill development. Conversely, the contraction of cities is characterised by disinvestment, suburbanisation, deindustrialisation, out-migration, and other related circumstances (Bowman and Pagano, 2000). In general, the impact of global phenomena on post-industrial modern society has resulted in the transformation of various spaces, causing them to lose their original purpose. Exploring this cited urban phenomenon, this research identified four common factors in forming void spaces in the Poblacion District: natural and geographical; political; economic and dysfunctional; and, socio-cultural.

3.2.1. Natural and geographical factors

Natural and geographical factors, like physical barriers and natural disasters can cause urban voids. The city has support systems to address risks in specific locations. However, these measures may only minimise void size and disconnection from the district, rather than thoroughly reconnecting void spaces with the urban landscape.

3.2.2. Political factors

The district's plan for economic growth has led to the creation of empty spaces due to non-compliance with zoning regulations and inadequate land use conversions. Property owners' concerns have made it difficult for the government to implement programs and incentives, resulting in these spaces being repurposed as parking lots. The lack of policy to address idle land taxation discourages owners from redeveloping these areas, leading to an unsustainable and expensive burden on them.

3.2.3. Economic and dysfunctional factors

The economic climate in some urban areas can lead to unused spaces being repurposed during the pandemic. However, certain buildings located in Quirino Avenue of Davao City's CBD have been demolished and replaced with parking or storage facilities, negatively impacting neighbouring establishments and the community. This has decreased and increased land values, making it challenging for property owners to pay taxes and maintain their buildings. High taxes and a lack of economic opportunities can also cause businesses to leave urban areas, leading to more abandoned properties.

3.2.4. Socio-cultural factors

The CBD, or the Poblacion District in the case of Davao City serves as the urban hub of the city. It comprises regions that have played a pivotal role in the locality's historical evolution and swift economic expansion. These areas have significantly met the city's inhabitants' ongoing urban requirements and expectations. The phenomenon described engendered a perception of spatial detachment among specific individuals, as certain areas within the district exhibited neglect, leading to abandonment and prolonged periods of vacancy. The proliferation of criminal activities, dense vegetation, widespread vandalism, and disregard for the once thriving and vibrant communal space have rendered it undesirable for public gatherings and expression of its historical significance.

3.2. Current uses of void spaces

The urban voids spaces in Davao City have a variety of uses that have resulted from changes in function or surrounding land use. After conducting onsite inspection and direct observation, it was found that most of the spaces in the Poblacion District are used for parking and storage. The distribution of the void spaces covers 59 lots or spaces in the district. These are often combined with other uses such as makeshift markets, farm lots, construction and fabrication spaces, and reserved open spaces.

These vacant spaces have transformed in usage, reflecting their evolving transitional functions. It is interesting to note how the surrounding land and the critical development elements mentioned earlier have affected how these areas function. Additionally, Table 1 provides a comprehensive overview of the site attributes of these void spaces and the various temporary uses they have been put to. It can be argued that the multiple uses of these spaces, whether long-term or short-term, indicate that they are being utilised despite their abandonment or being influenced by land uses and nearby developments.

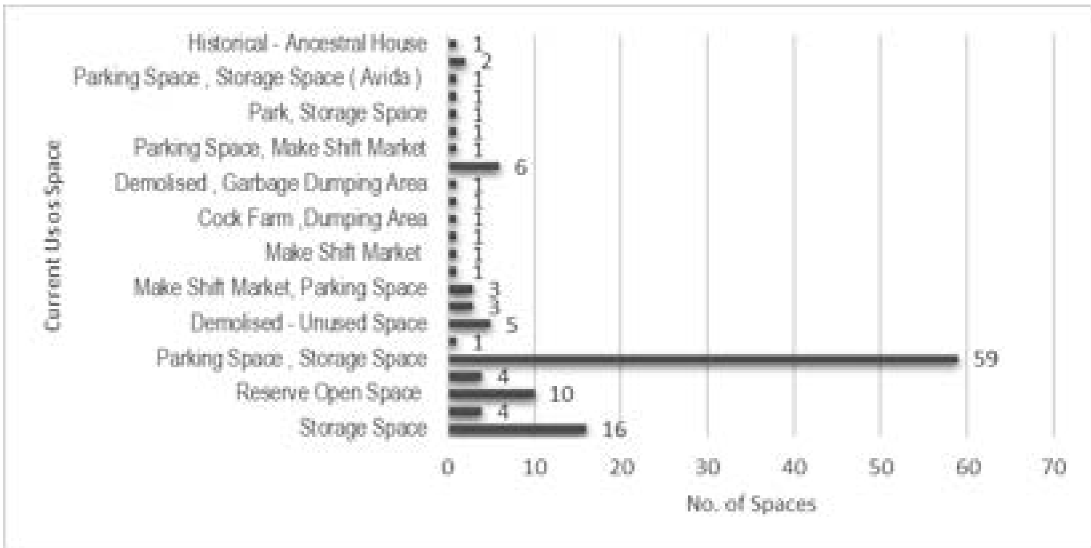

Figure 2**:** Distribution of the current use of void spaces in the CBD

3.3. Mapping urban voids in the Poblacion District

In the inner urban district, the study area covers about 2,118,794.00 square meters. According to the definition, urban voids can include structures that have been abandoned and are currently unoccupied. The study primarily focused on inactive, unused, or underutilised sites. However, it is essential to note that the identified gaps are not limited to these categories and can include abandoned buildings and unfinished structures. Figure 3 shows the Davao City Poblacion District void map within the inner CBD area. The investigation found approximately 135 void spaces. It is worth mentioning that abandoned buildings or structures, which are not discussed further but are included in the mapping as part of the void identification process. The identified urban voids spaces have a total area of 26.6 hectares, which is equivalent to 266,331 square meters of horizontal space. These discovered vacant areas comprise 13% of the subjected urban district's land area. Recent findings have shown a few tendencies that explain their development and maximum concentration on city blocks that contain government centres and significant inner-city arteries.

Figure 3: Urban void map scope in the inner Davao City Poblacion area

3.4. Categorizing urban void spaces

In the Poblacion District of Davao City, void spaces are classified based on various attributes such as use, accessibility, location, form, and status. These spaces play a crucial role in the city's urban design, and if correctly identified and utilised, they can be utilised as public spaces. The district has four (4) types of void spaces and like in other cities, these spaces are critical components of the urban fabric. Although their disconnection varies due to different factors, they can become urban generators for public use if correctly utilised.

The first type of void spaces is derelict spaces, which include abandoned buildings and lots with demolished structures. They make up 40.25% of the vacant space in the district, covering an area of 20,115 square meters. The second type is infrastructure voids, which include all city infrastructural developments and affected lots, linear developments, properties located near rivers and similar features in the district, as well as large roads and unused access freeways. This type accounts for 11.05% of the identified void spaces, covering an area of 122,732 square meters. Thirdly, underutilised public spaces that were part of the planning process but failed to function or were not utilised by the public can also become voids. This includes parks and plazas, multi-purpose spaces, and other public or government-use developments or spaces. This type accounts for 21.71% of the identified vacancies with a total area of 57,825.00 square meters. Lastly, transitional spaces are most prevalent within the district's block locations. This type includes inner block voids, edges, wedges, and spaces between blocks resulting from the city's policy and historical spatial configuration. Transitional spaces comprise 23.62% of all voids and occupy a total area of 180,285 square meters of the study area, see Figure 4 below.

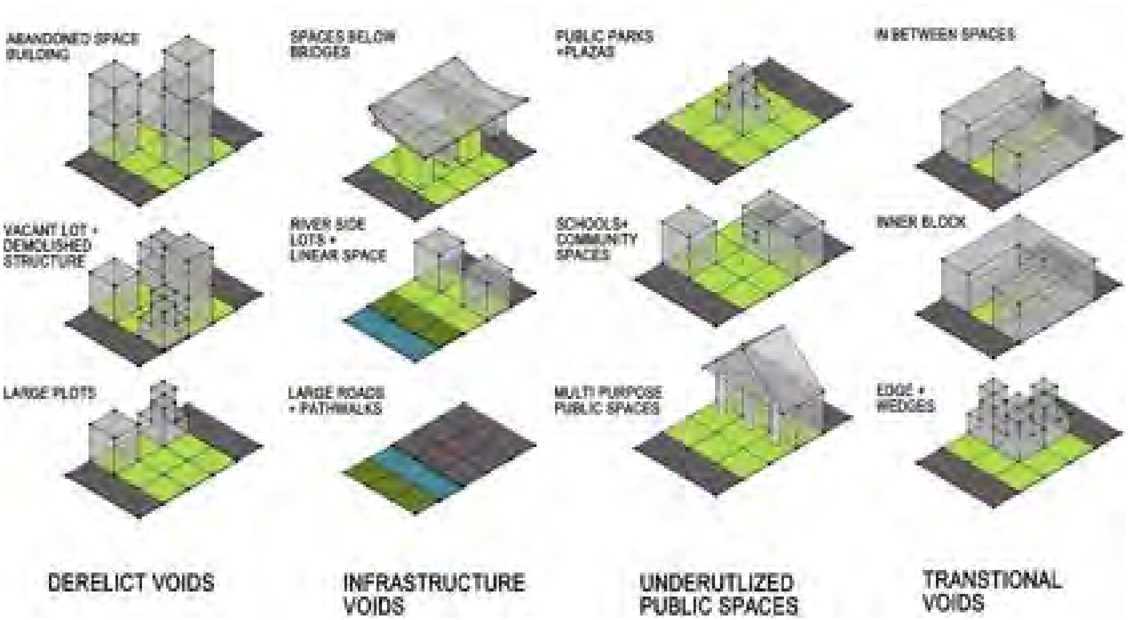

Figure 4: Urban void typologies in Davao City Poblacion District

3.4.1. Derelict voids

The first type of urban voids is called derelict spaces. It refers to private areas left unused and abandoned for a long time. These areas are usually medium to large plots known as vacant spaces, they come in various shapes and sizes. They include lots, structures, transformed land use, and former industrial sites that are now uninhabited. Repurposing these areas often requires a significant investment due to environmental problems. These spaces are typically reserved for private use, such as ample parking lots or storage facilities, either for a short or long period. The category is divided into three subcategories based on location and spatial features: large plots; plots that once contained structures that have since been demolished; and, abandoned spaces and buildings.

Figure 5: Derelict spaces map category and site samples located in Quirino Avenue

3.4.3. Infrastructure voids

Infrastructural urban void spaces are often empty or underutilised places inside a city-built environment that are mostly related to infrastructure systems. These areas often occur because of the urban infrastructure's design, planning, or operational characteristics. Infrastructural voids are spaces that are associated with linear developments in the city. These spaces are commonly situated alongside river development or part of geographical developments. Its subcategories include under bridges or pedestrian overpass, riverside plots, and large roads.

Figure 6: Infrastructure voids map and spaces below bridges at Bangkerohan Avenue and Bolton Street

3.4.4. Underutilised public spaces

This category refers to public spaces the government maintains, such as parks, small plazas, and multi-purpose areas. The public's level of use and expansion is monitored, including both users and government entities. When public spaces are not utilised or maintained, they can become harmful. This can occur due to a lack of support, such as inadequate amenities or the absence of appropriate agencies to ensure sustained functionality. One of the most common issues in urban parks is the presence of blank walls or dead zones around the periphery of the space, despite their functionality. In addition, concerns about inconvenient transit stops and inadequate parking allocation are also frequently observed. Furthermore, underutilised public space voids refer to sections of public land or infrastructure in an urban context that are not utilised optimally or to their total capacity.

Figure 7: Underutilised public spaces category map

3.4.5. Transitional void spaces

Transitional void spaces are often associated with spaces that define the block and its parts. These spaces are the most common void spaces in the district. Although it is only second to the identified derelict spaces, transitional voids have the widest distribution in the district. It forms due to the spatial configuration and character of the Poblacion District as themed spaces, and the provisions of easements and local laws such as parking and accessibility requirements.

Figure 8: Transitional void spaces and sample site along Magallanes Street

3.4.6. Special cases

Combinations of the enumerated typologies are special cases of urban voids. These spaces as identified are some places regarded with their location, current usage, and scale which frequently dictate the formation of vacant spaces. Additionally, the characteristics of the mentioned typologies are frequently employed to describe the boundaries and worth of area in a district. As a result, if circumstances are identified as connecting the public spaces, more options may be available.

As shown in Figure 9, the typologies collectively formed a composite map of void spaces in the Poblacion District showing their locations and distribution. As seen on the map below, the parameters from the typologies established a relationship with nearby spaces. It can be argued that although these spaces have different land uses and programmatic elements, the collective block covering these spaces had a great effect on influencing the status and value of the void spaces towards their surrounding developments or neighbourhoods.

Figure 9**:** Composite map of urban voids in Davao City Poblacion District showing the typologies

3.5. Revitalising urban voids in the Poblacion District

3.5.1. Familiarity with urban void spaces

A survey was conducted to gather residents' opinions on void spaces, their use, associated problems, and recommendations for redevelopment. The survey revealed that respondents could identify void spaces, but some needed clarification, concrete definitions, and synonymous local terms. Despite the increased clarity in identifying voids, most respondents could observe void spaces in their communities in general sense. A minority of the participants exhibited minimal interest in the space, yet they noted distinct observations about its activities and relationship to their community. Common uses observed included informal settlements and vacant or abandoned structures. Problems identified were unwanted vegetation, uneven land development, and safety concerns. Respondents recommended converting these spaces into parks, open spaces, markets, and for art exhibitions. The public's perception of void spaces showed potential for development but was influenced by lighting, vegetation, and accessibility issues. Suggested policy implications include implementing idle land taxes and involving stakeholders in the revitalisation. Moreover, challenges in implementing idle land taxation, such as inconsistent implementation and tax collection issues, must be addressed. Thus, there is a need for community involvement towards effective policy implementation for revitalising the urban void spaces.

3.5.2. Revitalisation in the inner Poblacion District

By utilizing typologies and thematic maps developed in conjunction with community engagement and visionary efforts, the revitalisation of void spaces in Davao City will emerge as a pivotal strategy in preserving the charm of the historic Poblacion District and countering the looming threat of urban blight. This revitalisation initiative breathes fresh vitality into the city's urban core by transforming void spaces into vibrant public spaces. The figures presented below illustrate examples of different urban void spaces, which have been carefully identified and closely monitored as potential sources of activity and opportunities to reconnect with nearby public zones in the Poblacion District. This process entails recognizing underused or abandoned urban voids and strategically converting them into vibrant spaces, thereby fostering community engagement and reestablishing connections with neighboring public areas. Embracing and rejuvenating these vacant spots empowers cities to create inviting environments that attract people, encourage social interactions, and enhance the overall urban landscape.

Figure 10**:** Derelict urban voids in Quirino Avenue envisioned as activity generators for food park, activity plaza, and multi-purpose public open space

Figure 11**:** An infrastructural void located under Bangkerohan Bridge proposed as passive and active park

The concept of reconnecting nearby public spaces is crucial as it integrates revitalised void spaces into the broader urban landscape. This fosters a cohesive network of accessible public areas, enhancing the quality of life, community identity, and the overall urban environment. Essentially, it transforms neglected spaces into vibrant, active components, thereby boosting the CBD's and the urban inhabitants' well-being and vitality. Furthermore, these efforts attract businesses, residents, and visitors fostering economic activity and community engagement at the same time preventing urban blight. Renewed void spaces enhance the district's appeal, preserving its heritage and cultural significance. This not only safeguards historical assets but also creates a more attractive environment that attracts investment, ensuring the long-term sustainability and vitality of Davao City's CBD or Poblacion District.

4. Conclusion and recommendation

In conclusion, it is imperative to recognize the latent potential within underutilised urban spaces as they stand as a pivotal catalyst for urban development. The revitalisation and reimagining of these areas have the power to enhance the quality of life for residents of cities like Davao City. Simultaneously, this approach can preserve the historical and cultural significance of the Poblacion District, while effectively combating urban blight and decay. To realise this vision, it is crucial for urban planners and policymakers to fully grasp the profound importance of these spaces and their transformative impact on the urban landscape. This understanding will empower them to make well-informed decisions regarding the optimal use of these spaces, thus ensuring the sustainable growth of the city.

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Weaving as Lo-TEK architectural solutions; a transition towards perishable architecture

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Abstract: In the realm of built environment disciplines, focus often gravitates towards high-tech solutions to address architectural challenges. Consequently, softer approaches can remain underexplored. Local traditional ecological knowledge (Lo-TEK) is an approach looking to indigenous peoples and climate-resilient infrastructures to develop unique techniques and methods. Focused on the pressing issue of rental housing quality in Aotearoa New Zealand, this study examines the potential of Māori weaving techniques as Lo-TEK interventions to address subpar living conditions. The research delves into the cultural significance of weaving, emphasising its potential to be applied architecturally. Māori weaving practices and techniques were evaluated, with acknowledgements to the tikanga (Māori customs and values) surrounding the practice. From there, two preliminary studies involving weaved interventions were conducted, utilising Māori weaving techniques. An analysis of these initial studies was conducted using thermal imaging and occupant observations looking into the effectiveness of different weaving techniques in improving temperature control and comfort. Findings indicate promising improvements, establishing a foundation for further research. Discussion highlights the need for larger scale testing to confirm preliminary findings and observations. The paper also acknowledges the departure from traditional harakeke (Māori flax)-based weaving in favour of more readily accessible waste materials, emphasising the potential for future research in collaborating with local iwi (Māori tribe) to explore harakeke-based interventions. This study contributes to development of culturally sensitive and environmentally conscious architectural solutions which are also sustainable, highlighting Lo-TEK's potential to reshape the built environment. As research continues, these findings could pave the way for more.

Keywords: Lo-TEK; sustainable architecture; weaving; indigenous knowledge.

1. Introduction

In the pursuit of sustainable solutions to contemporary challenges, there has been a growing recognition of the significance of local traditional ecological knowledge (Lo-TEK) as a valuable source for innovative approaches. This paper addresses the imperative of incorporating Lo-TEK and similar locally focused approaches to tackle pressing challenges, particularly in the realm of rental housing quality. Within Aotearoa New Zealand, there exists a rental housing quality crisis, with a significant proportion of homes being affected by issues of dampness and cold (Dale *et al*., 2014). These subpar living conditions disproportionately affect marginalized communities, deepening cycles of poverty.

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Weaving, a Lo-TEK approach, stands out as a promising avenue for bridging traditional practices with contemporary architectural solutions. Weaving not only has historical significance as an essential craft but also holds potential as a means to improve housing quality. In this context, this paper explores the weaving practices within the Māori culture of Aotearoa New Zealand, leveraging Māori weaving techniques as a Lo-TEK intervention to address poor housing quality. Through an exploration of Māori weaving practices and their application in architectural contexts, this paper advocates for a more holistic and culturally sensitive approach to addressing housing quality issues. This paper documents two preliminary studies drawing from different Māori weaving techniques to create weaved interventions in the home, and critically reflect on the performance of these prototypes, looking at any improvements that could be made in terms of thermal performance through simple DIY methods. These prototypes were installed and assessed through observational techniques and thermal imaging. Due to this being a preliminary study, it is scoping and establishing what might work, and this paper reports on these early findings. Further research is needed to refine findings, confirm preliminary insights, and establish stronger connections within the space of Mātauranga Māori (Māori way of being and engaging with the world). Thus, this paper is part of a larger study to better evaluate the efficacy of weaved Lo-TEK interventions.

2. Background

2.1. Local traditional ecological knowledge

Local traditional ecological knowledge (Lo-TEK) is defined as a movement, coined by Julia Watson, that investigates lesser-known local technologies and counters the idea that these methods are primitive and secondary to western methods of design (Watson and Davis, 2019). The core assumption is that modern frameworks centre the Western voice, tending to ignore and overlook indigenous methods as simple, primitive, and unsophisticated. In reality, these methods offer a rich understanding of local climate, promoting technologies that live harmoniously with the environment and promoting climate resilient infrastructures.

For many Indigenous cultures, a complex and interconnected relationship with the land and its resources forms the basis of its knowledge system. In Aotearoa New Zealand, this knowledge basis is known as Mātauranga Māori and gives expression to "Māori ways of doing things, aspects of Māori knowledge and the Māori world view" (Royal, 2012, pp. 30). Many traditional methods have been developed to address local concerns unique to specific environmental contexts such as the floating homes of the Ma'dan peoples (Ghisleni, 2020). As argued by Watson *et al*. (2021, pp. 58) there is an increasing need to recognise overlooked indigenous knowledge that can contribute to climatic solutions, and work with and alongside indigenous communities.

Lo-TEK as a movement looks to a design framework that enhances our understanding of indigenous philosophy and vernacular architecture, while highlighting existing indigenous technologies as solutions. The Lo-TEK movement proposes bringing indigenous technologies to the forefront of the building industry, reinforcing the idea that traditional knowledge and methods needs to play a prominent role in architectural practice. Similarly, this paper takes the position that as part of contemporary search for more sustainable approaches, Lo-TEK and similar local- and indigenous-focused approaches should be more actively used as a source of inspiration for potential solutions, especially when considering rental housing. Lo-TEK approaches propose accessible alternative solutions, leading to more obtainable and equitable outcomes for disadvantaged groups.

2.2. Rental housing quality crisis in Aotearoa

Within the context of a relative disconnect from the local and indigenous traditions, research shows that improving housing quality not only improves physical health but also improves engagement with school and work (Howden-Chapman et al., 2018; Ministry of Social Development, 2021). It is estimated 300,000 homes in Aotearoa are considered damp, mouldy, and cold which disproportionately affects people living on low incomes (Dale *et al*., 2014). Often renters, particularly those of a lower socio-economic demographic, are not in the position to make impactful changes to the quality of their homes and are therefore restricted by a system that reinforces the cycle of poverty.

Current responses focus on industrial level changes that are enacted from a top-down perspective, such as the recently introduced standards for landlords to maintain rental properties (NZMBIE, 2018). These, however, are often governed by policy changes within established systems, failing to consider other methods of knowledge. There is a clear need to look at alternative solutions and challenge the status quo approach, particularly around solutions which are more accessible, driven by the people they will most benefit. Browne (2015) states increased autonomy, choice, and agency, all lead to greater outcomes of well-being and empowerment. Solutions that provide a sense of autonomy and choice to those who are disadvantaged can help to generate incremental change in a bottom-up approach, with Lo-TEK solutions providing a potential avenue to do this. Importantly, these might also provide opportunities for the indigenous cultural voice in a way that is enriching on more than one level.

2.3. Durability paradox

There appears to be a paradox within the built environment, of pushing towards the new and improved while also creating long-lasting and permanent structures. Hi-tech architectural solutions strive towards durability and permanence, with the rise of 'starchitects' monopolising monumentality in architecture (Armada, 2012). As stated by Chabrowe (1974, pp.385) "architecture by definition is meant to be permanent, to serve a practical and also aesthetic purpose over an indefinite period of time." Additionally, durability is seen as a key goal regarding sustainability. By reducing the need to replace or rebuild our built environment and moving to longer-lasting outcomes, we are limiting further material and resource consumption (Ragheb et al. 2016).

Consumerist culture pushes the narrative of the latest and greatest, driving accelerating trends and encouraging instant gratification and disposability over long term use (Armada, 2012; Vandevyvere and Heynen, 2014). Brand coined the idea of change within the built environment as "layers of longevity" ordered into site, structure, skin, services, space plan, and stuff (Brand, 1997; Swift et al. 2015). This theory divides the building up into components, attributing each to their frequency of change. As materials become more durable, the lifespans of these products outlast their use in the built environment, particularly when considering the layers of "space plan" and "stuff". A contradiction thus exists where durable design is seen as the status quo, and we are seeing rapid acceleration in changing trends. There is the need to embrace both longevity and adaptability within our built environment, recognising the space perishability can serve. Lo-TEK methods serve as a possible pathway to do this, drawing knowledge from cultures who learnt how to live softly, adapting to what was needed.

3. Weaving in architecture

Weaving is one Lo-TEK approach that has roots in many cultures around the world. The exact origins of weaving and textiles are difficult to determine due to many artefacts deteriorating, however, continued discovery of items from many different cultures suggests a long history with weaving and fibre for creating garments and tools (Barber, 1991; Wilson, 2021).

Weaving as an architectural material is also not a new concept. Semper (1851, pp. 247) states “the beginning of the building coincides with the beginning of textiles”, with notions of weaving exceeding this in the use of protection and defence. Fabric structures are thought to be the oldest form of human constructed shelters. Harvie (2015) discusses how remains of simple structures, constructed of animal skins draped over sticks, have been found, dating back to over 40,000 years. Animal skins progressed to simple weaved textiles with Nomadic peoples utilising loosely woven fabric tents for easily transportable and moveable shelters (Harvie, 2022).

In other cultures, textiles were used to create a visible boundary of space. Semper (1851) argues the wall is one of the four fundamental elements of architecture. The need to define and divide space was done through hanging of weaved mats and carpets, with the structure supporting these irrelevant to the spatial arrangement. Linguistic connections show this concept further through the Germanic words for wall (wand) and dressing (gewand), thus highlighting the idea of woven material becoming the wall (Ingold, 2013). For Māori, weaving of harakeke (flax) with sticks was used to create marked defences around pās (Māori villages) (Semper, 1851). Weaving of tukutuku (wall panels) and whāriki (mats) have also traditionally been used in structures to mark and adorn the space (Puketapu-Hetet, 1989). As the need for more permanent, durable structures progressed, the textiles transformed into wall dressings, in the form of tapestries and decorative panels. Despite no longer being used as a main architectural element, textiles and weaved products are still used around the world to adorn, soften, and warm a space, providing an opportunity for further architectural applications to be considered.

4. Weaving in Aotearoa

Weaving is one of the ancient practices that presents opportunities to deeply connect the Indigenous with the contemporary, and this is even more pronounced in a country like Aotearoa New Zealand. This research looks specifically to Māori weaving and practice techniques as an opportunity for what a Lo-TEK approach can offer.

For many cultures, weaving has been a social labour that has grown from a functional need within the community. For Māori, the act of weaving is much more than just creating a required product, but instead a drawing together of “customs, traditions, history, music, oratory, legends, and the needs of iwi, hapū, and whānau (Tamati-Quennell, 1993, pp. 6). Taonga Māori states these elements “are all drawn together within an individual who becomes a weaver, who creates weaves not for herself alone, but for the mana of the people (cited in Tamati-Quennell, 1993, pp. 6). These aspects can be also employed in the contemporary interventions to empower and enrich those who engage with the making.

It is known that the act of making has positive effects on wellbeing, with Kenning (2015) finding that textile activities create communities of belonging as well as providing a sense of achievement for the maker. Locally, Tamaki Makaurau (Auckland) based group, Pupukemoana, utilises weaving with harakeke as a sensory modulation tool in their work with youth mental health (Kirkwood, 2015). By applying Western ideology of sensory modulation through self-regulation and incorporating Mātauranga Māori, Pupukemoana seek to uplift participants, providing a safe and therapeutic experience for sharing and connection. Seligman (2011) has also identified that engaging with the practice of creating art contributes to improved overall wellbeing by creating the opportunity for authentic connections, absorbing the participant in the craft, and allowing the participant to feel they are contributing to a particular purpose.

Lo-TEK solutions, such as weaved interventions, offer a way to connect more with local communities, grounding participants in their place and environment.

4.1. Weaving and harakeke tikanga

Tikanga, or Māori customary practices or principles, grounds many of the decisions and actions in weaving practice (Aotea 2023). Within weaving, tikanga serves to understand the deeper meaning of the craft, allowing us to form greater connections to nature and the place weaving holds within Te Ao Māori (the Māori world) (Puketapu-Hetet, 1989). Māori weaving practice is grounded in sustainability. Many weaving principles focus on honouring Papatūānuku (Earth Mother), protecting both the weaver as well as the places and environment they are interacting with (Puektapu-Hetet, 1989). As Brown (1993, pp. 27) states one “cannot be a weaver without being a conservationist… if you are not you end up with having nothing… no materials to work with”. Young weavers are not expressly taught the practice and its tikanga but learn through watching and observation from elders (Tamati-Quennell, 1993). Here the weaving acts as a link to the past, with new weavers taking over as custodians of the artform, passing on both the technique and tikanga of the practice.

Pacific ancestors used tapa (barkcloth), produced from the bark of aute (paper mulberry tree), for many purposes before migrating to New Zealand, however found that the cooler climate limited its cultivation (Tamarapa *et al.*, 2021). Instead, early explorers looked to harakeke, which is found abundantly around the country. Harakeke is still the most used plant for weaving in Aotearoa due to its stiffer leaves and ability to grow in diverse conditions (Puketapu-Hetet, 1999).

The harakeke bush represents the whānau or family unit as shown in Figure 46. The centre growth is known as rito and represents the child in the family structure. The leaves either side of the rito are the parent leaves and called matua or awhi rito. The outer layers of leaves are known as the tūpuna and are the only leaves that can be harvested. This not only ensures the lifecycle of the plant but reinforces the connection between the plant and the people (Puketapu-Hetet, 1989). After the weaving has been completed, any unused material is returned to the pā harakeke (plantation area), not only enriching the soil, and feeding new growth, but also acknowledging the connection to Papatūānuku.

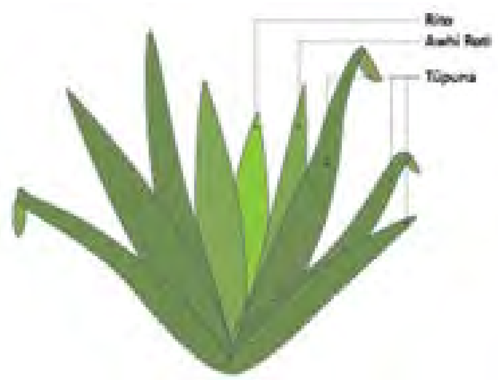

Figure 46 Pā Harakeke. (Source: Author’s own image, 2023)

4.2. Weaving techniques

Pueketapu-Hetet (1989) states that raranga is considered, of all the Māori weaving techniques, to have best survived colonisation and has the strongest links with Pacific Island methods. Raranga is a plaiting technique, involving weaving strips diagonally and was used to produce rourou (food baskets) and kete (bags) among other items (Te Kanawa, 2014). Traditionally the plaiting is done away from the body, and with large items such as mats the weaver needs to sit on the completed sections to reach the working row. Ornamentation is created through variations in the weave along with the combination of both dyed and undyed strands, with iwi producing their own unique patterns (Tamarapa *et al.*, 2021).

Tāniko is the name for both the weaving technique and the designs and patterns constructed through the weave. It is believed that the method developed from single pair twining which was used in the construction of eel traps and common to other areas of Polynesia, however the exact origin of the technique is unknown (Mead, 1999). The weaving technique produces a stiff fabric so was often used as a decorative border around items such as cloaks. The complex technique involves twining multiple strands of coloured aho in order to produce the desired effect (Tamarapa *et al.*, 2021). The designs themselves convey different meanings, ideas, and histories, and have been translated into applications beyond weaving such as carved decorative panels (Mead, 1999).

From this brief review it is possible to conclude that the practice of weaving in Aotearoa presents a dynamic bridge between indigenous heritage and contemporary aspirations. Weaving's profound connections to customs, communal history, and well-being make it a rich conduit for empowerment and therapeutic enrichment within the modern context, highlighting its potential as a Lo-TEK approach. The enduring legacy of harakeke as a weaving resource echoes the deep bond between nature and culture. However, it is important for people engaging with weaving to understand the tikanga and honour the role it plays in the practice.

5. Research proposition

This research contributes to a wider move towards simple interventions drawn from Lo-TEK principles, that could work for a wide range of parameters, adapting to suit specific needs and uses. While this paper focuses on improving thermal performance around windows, Lo-TEK approaches have the potential to address a vast range of issues, such as sun glare, draft, and dampness. This research serves as the basis for an exploration into the possibilities of simple self-made interventions that are made in response to different situations and draw inspiration from existing Indigenous bodies of knowledge.

6. Methods

In order to explore how Lo-Tek can be brought into the contemporary context to alleviate some of the existing housing issues, two preliminary studies on differing weaving techniques were conducted to analyse the potential in developing Lo-TEK interventions that are accessible for occupants to make. The research methods for analysing Lo-TEK weaving approaches are comprised of thermal image testing and reported occupant observations.

Fabric sourced from local second-hand stores was chosen to make the weaving process more accessible for those who are not able to engage with the tikanga around the harvesting of harakeke in the appropriate manner. By utilising recycled fabric and materials readily available in local second-hand stores, this research seeks to circumvent those challenges. This deliberate choice not only facilitates a more inclusive engagement with the weaving process but aligns with the fundamental principles of tikanga by honouring sustainability and the environment. Consequently, this approach widens the scope of community participation, making these preliminary studies accessible to a larger demographic. Through this innovative use of recycled waste materials, the study taps into the essence of weaving as a sustainable practice while empowering individuals to partake in the creation of weaved interventions.

Thermal images and observations were taken of weaved intervention prototypes in two stages. Study 1 comprised of three weaved panels involving different weaving techniques: tāniko (Panel 1), raranga (Panel 2), and hand knitting (Panel 3) as shown in Figure 47. Weaved interventions were fixed to a window and monitored over five days, with thermal images taken of the interventions at 7am each day. Occupant observations were recorded throughout this period as noted when engaging and interacting with the intervention.

Figure 47 Weaved panels from left to right; Panel 1, Panel 2, Panel 3. (Source: Author's own image, 2023)

Study 2 incorporated cardboard into the weaving to test how this would affect the thermal performance as well as the structural integrity (see

Figure 48). This cardboard was obtained from recycled boxes, again making use of alternative waste streams. The same method was followed as for Stage 1 when recording the thermal images and occupant observations.

Figure 48 Study 2 weaved panel. (Source: Author's own image. 2023).

6.1. Thermal imaging

Thermal imaging testing is a tool in evaluating the thermal performance and energy efficiency of building materials and with the range of applications growing, has the potential to be utilised in testing the efficacy of Lo-TEK interventions (Lucchi, 2018; Volmer, 2021). By capturing and visualising infrared radiation emitted by surfaces, thermal imaging provides insights into heat distribution, potential thermal bridges, and areas of insulation deficiency within structures. This technique can help identify areas where heat loss or gain occurs, offering valuable data for improving building energy efficiency, occupant comfort, and indoor environmental quality. In the context of this research, the use of thermal imaging through infrared cameras provides the opportunity to evaluate the success of Lo-TEK interventions in addressing housing quality issues.

Highs and low temperatures for each day were recorded for both Stage 1 and 2, in order to be analysed against recorded panel temperatures. High and low temperatures were taken from airport data and did not consider the ambient temperature for the window, where window temperature averages were estimated based on the thermal imaging data. These preliminary studies also did not take note of indoor temperature fluctuations as well as specific weather conditions when recording. Such conditions should be taken into account when moving forward with future testing.

7. Preliminary results

Preliminary studies of Lo-TEK weaving approaches using a thermal imaging camera and direct observations have shown an improvement in both temperature and thermal comfort in the spaces tested. As this is a preliminary analysis into Lo-TEK approaches the main researcher was the sole observer for occupant findings. This preliminary stage is part of a larger study, with majority of the analysis focusing on reporting the initial findings and establishing what has worked, to use for future studies at a larger scope.

7.1. Thermal Images

Study 1 thermal images, see Figure 49, show that all three panels were approximately 11.6 degrees averaged across the 5 days. This remained consistent despite varying outdoor temperatures and recorded window temperatures as show in Table 20.

Figure 49 Study 1 of thermal imaging tests. (Source: Author's own image, 2023)

Table 20: Study 1 thermal image testing

	29 June	1 July	3 July
Daily High	13	10	11
Daily Low	6	-1	0
Window Temp Average	6.8	5.2	3.4
Panel Temp Average	12	11.3	11.5

When looking at the breakdown across each individual panel, Panel 1 with the tāniko technique appeared to perform the best, this was followed closely by the hand knitting and then the raranga techniques. Despite being more tightly woven than the hand knitting, Panel 2 performed the worst overall, with almost a degree cooler on average (Figure 50). This may have been due to the flatness of the weave; the raranga technique produced a flatter pane which lay directly against the glass. This not only would have created a thermal bridge for heat to escape, but the flatter weave would have reduced any air pockets through which heat gains could be trapped. The tāniko technique (Panel 1) involved the tightest and most dense weave which allowed more heat to be trapped compared to the other panels.

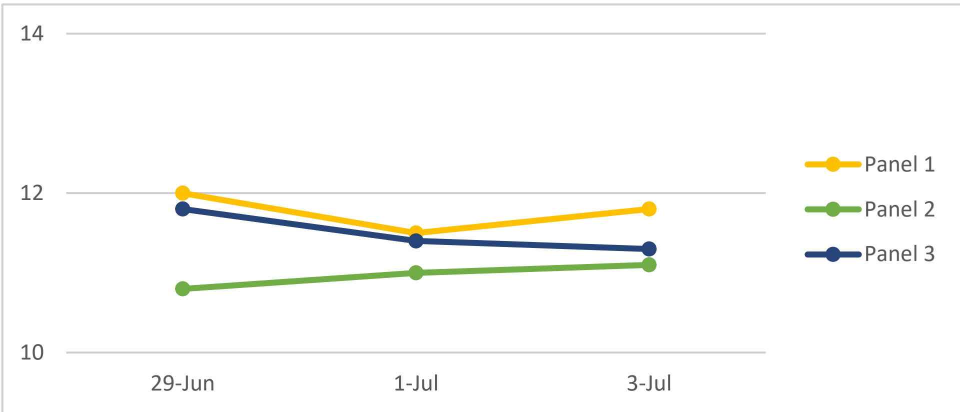

Figure 50 Study 1 Individual panel temperature averages. (Source: Author's own image, 2023)

Study 2 testing was conducted with only one panel comprising of the tāniko technique from Stage 1 and combining it with cardboard strips. Tāniko was chosen due to its performance during stage 1 testing, and the opportunity to incorporate additional materials into the weaving technique. The cardboard not only acted as reinforcement to the fabric, put also provided an additional thermal barrier. This allowed the panel more rigidity to sit flatly within the window and create a better seal with the frame itself.

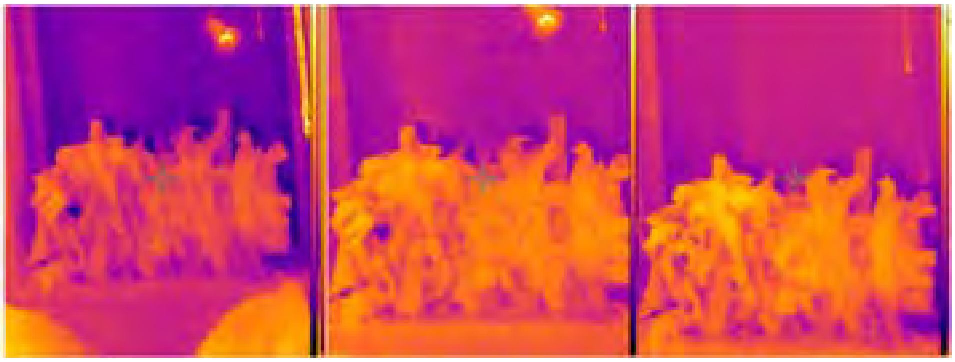

Figure 51 Study 2 of thermal imaging tests. (Source: Author's own image, 2023)

Table 21: Study 2 thermal image testing

	8-Aug	10-Aug	12-Aug
Daily High	8	10	12
Daily Low	5	4	3
Window Temp Average	9.1	9.6	9.2
Panel Temp Average	10	10.3	10.2

Across both stages it is important to acknowledge the limitations of this preliminary analysis, with occupant habits needing to be accounted for when interpreting results. On cooler days more indoor heating was used which would affect the heat gains from the internal panel face. This means there was the potential for the panel to read warmer than if no artificial heating had been applied. As stage 2 was conducted in milder conditions less artificial heating was required when compared to stage 1. The position in the windowpane would also affect the thermal image testing. Panels laying flatter against the glass may have appeared colder due to the thermal bridge created.

7.2. Occupant observations

During Study 1, observations were not observed individually for each panel, but rather the intervention as a whole. As the interventions did not cover the whole window results were minimal unless directly in front of the panel. Despite this, a small difference in temperature and draft could be felt in front of the panels when compared to exposed glass.

Study 2 produced more distinct observations when compared to Stage 1. Less draft was felt when the panel was installed as well as noticeable increases in temperature when compared with the uncovered glass. This may have been due to the addition of cardboard, creating a more insulative layer. The stage 2 panel was also larger than the Stage 1 tests, covering the lower half of the windowpane and more effectively creating an air seal.

Both preliminary studies reduced the amount of condensation forming on the glass overall. This may have been due to the fabric absorbing the moisture instead of the panel reducing the amount of warm air hitting the cool glass. This presents potential for later issues with mould growth occurring and so future studies should look to see if this occurs and address how to mitigate this.

The initial findings from the preliminary studies on Lo-TEK weaving techniques show promising improvements in thermal comfort. These early insights lay the groundwork for further exploration, emphasising the potential of these interventions to bridge traditional practices with contemporary housing challenges. Further research aims to validate and enhance these initial positive outcomes on a larger scale, as well as confirm some of the initial finding and observations within a larger sample pool.

8. Discussion

Preliminary testing of weaving as a Lo-TEK intervention has showed promising results when applied to the home. Stage 1 showed that the denser and tighter the weave, the better the panel retained heat in the thermal image tests, if only marginally better. The addition of carboard for Stage 2 provided better structural rigidity and was more successful at creating a wind block than only using fabric. Both stages were limited in their testing by only testing part of a windowpane, as opposed to the entire window. This limited the data that could be collected from occupant observations as any differences were felt in close proximity to the panels. Future tests should address working at a larger scale to better assess the efficacy of the Lo-TEK intervention and building the weaving up in layers to increase potential air pockets. Experimentations with different materials would also establish whether certain fabric types would be more successful than others.

In a deliberate choice to enhance accessibility, the weaving techniques explored in this study were crafted from repurposed garments and materials sourced from local second-hand stores. This approach sought to bridge the gap between traditional weaving practices and contemporary communities, especially those who may not be familiar with or able to engage in the tikanga associated with harvesting harakeke. By using recycled fabrics, the weaving process becomes inclusive, enabling a wider range of individuals to participate and benefit from the weaved interventions. It's important to acknowledge that while this approach increases accessibility, it represents a departure from the customary use of harakeke, a cornerstone material in Māori weaving. The potential for future experimentation with harakeke looms as a promising avenue, albeit one that necessitates a careful collaboration with local iwi to ensure cultural protocols and tikanga are honoured throughout the process. Balancing innovation and cultural reverence in such endeavours underscores the importance of working in harmony with Indigenous communities.

9. Conclusions and future research

This preliminary research has demonstrated the potential for weaved interventions to be deployed as Lo-TEK solutions within our built environment. Advances in architecture and the built environment have historically looked to new high-tech, durable, and regulated solutions to solve problems. Modern design thinking favours the latest and greatest technology, often centring Western frameworks. These solutions are often at odds with our natural environment, with a focus on taking from the land to create what is perceived as bigger, better, and generally more durable. This research offers an alternative approach which reflects on past architectural and environmental practices and focuses on creating a more personable, ephemeral and softer method.

Temporal approaches to architecture also offer an alternative to more durable materials that are difficult to dispose of when no longer needed. As we strive towards more sustainable built environments, pushes towards improved durability of materials has left us with products that harder to dispose of when unwanted and unneeded. This research proposes the idea of creating temporary solutions to serve our needs, pushing back against the notion of durable always equating to sustainable. Valuing perishability in certain contexts allows room to adapt to changing situations and climates. Lo-TEK solutions such as the ones tested, pose as a path away from architectural permanence and explore the notion of temporality as a way forward.

These interventions draw on Indigenous knowledge surrounding weaving and weaving practices, providing an opportunity to teach a new generation about indigenous craft. In an effort to curb mass consumerism and the effects of climate change people are looking for solutions that draw on natural materials, practices and ways of life (Tamarapa *et al.*, 2021). Interventions, such as those explored, offer an alternative approach to how we can think about retrofitting and improving the thermal performance of our homes. There is an opportunity to draw from local knowledge and existing low-tech when looking for design outcomes. Lo-TEK interventions, pulling from local methods that are more aligned with our environment and connected with community, could serve as a valuable complement to our existing design practices. By intertwining Indigenous knowledge, innovative design, and modern challenges, this study contributes to the discourse on sustainable architecture and housing, shedding light on the potential of Lo-TEK interventions in reshaping the built environment.

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Whole-of-life carbon comparison of retrofit strategies for Aotearoa New Zealand’s existing housing stock

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Abstract: Residential retrofit is essential for Aotearoa New Zealand to achieve carbon neutrality by 2050, given the current detached housing stock exceeds our allocated carbon budget. This paper presents the findings of a research project that examines the life-cycle carbon performance of various retrofit strategies. The aim is to improve the thermal performance of an existing detached house, bringing it closer to Aotearoa’s carbon budget. The paper presents a systematic overview of fabric-first approaches to retrofitting. To achieve this, a range of material retrofit packages are developed and tested on a single case study. These strategies are informed by a review of literature and case studies. The evaluation process considers the whole-of-life carbon of each retrofit package. Quantitative analysis, utilising energy modelling and Life Cycle Assessment, will be employed to assess the case studies’ outcomes. Building from existing research, this study advances the understanding of the carbon performance of different material residential retrofits.

Keywords: Residential retrofit; carbon neutrality; energy efficiency; life-cycle assessment.

1. Introduction

There is a need to improve the condition of New Zealand’s existing housing, to improve health and wellbeing outcomes of New Zealanders. A significant portion of New Zealand's existing detached housing is considered damp and studies have suggested that 53% of New Zealand houses would benefit from retrofit (White and Jones, 2017). Additionally, research has indicated the existing detached housing stock exceeds New Zealand’s allocated carbon budget by a factor of five (Chandrakumar *et al.*, 2020). Retrofitting has been identified as an effective strategy to reduce the operational carbon of existing housing, while also providing health and wellbeing impacts (Howden-Chapman *et al.*, 2011, 2012; Leardini and Manfredini, 2015). Previous retrofit interventions in New Zealand typically focus on the installation of mechanical heating systems, and insulation is often limited to ceiling and underfloor. Basic retrofits can result in health and wellbeing improvements, and research shows the Warmer Kiwi Homes programme had a 4.66:1 benefit-to-cost ratio (Grimes and Preval, 2020). However, achieving New Zealand's carbon goals requires more comprehensive retrofits (Leardini and Manfredini, 2015). Fabric-first approaches should be prioritised, which include upgrading the house’s thermal envelope, such as upgrading insulation and glazing. This study aims to review potential retrofit strategies for an existing detached house located

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in Wellington from a whole-of-life carbon perspective. The goal is to align the existing house more closely with the carbon budget set to limit global warming to 2°C.

2. Background

2.1. New Zealand's existing housing stock

The state of New Zealand's existing housing is leading to adverse health and well-being outcomes. The Building Research Association of New Zealand (BRANZ) 2015 House Condition Survey offers insights into the state of existing housing. White and Jones (2017) found 31% of rental properties felt damp, and 11% of owner-occupied. Furthermore, almost half of the properties surveyed in the study (49%) had signs of visible mould in the house. The study also highlights the number of properties that would benefit from retrofit, from assessing the level of insulation. 47% of houses surveyed had suboptimal roof insulation (<120mm) (White and Jones, 2017). Of the houses with subfloor cavities, approximately one-fifth of houses had less than 80% coverage of floor insulation (White and Jones, 2017).

Further studies also demonstrate the level of deterioration of exterior cladding. Houses that require wall and roof cladding replacement offer simultaneous opportunities to retrofit the house externally. In 11% of houses surveyed in 2020, the roof condition was considered poor, suggesting immediate repair was needed (Stats NZ, 2020). External wall cladding was in poor condition for 1/5 houses surveyed (Stats NZ, 2020). The condition of wall and roof cladding on renter-occupied houses was in worse condition than owner-occupied, indicating a need for home maintenance and upgrades within the private rental market (Stats NZ, 2020).

A study by Business and Economic Research Limited used data from the 2018 Census to categorise housing of each typology that would be suitable for a retrofit. The data was organised by deprivation area to understand which properties were likely impacted by more adverse outcomes such as energy poverty (Parsons *et al.*, 2023). For the Bungalow typology, 31% of total households within the Deprivation index 7 – 10 are considered damp and/or mouldy (Parsons *et al.*, 2023). For the rest of the deprivation index, 21% of Bungalow households are considered damp and/or mouldy (Parsons *et al.*, 2023). This demonstrates an alignment of poorer condition housing with occupiers in more deprived situations. This only highlights the need to accelerate the uptake of thermal retrofits to minimise health, well-being, and energy poverty impacts, but also that certain older house types are more likely to be in urgent need of improvements. As such, the case study used in this study is a Bungalow.

2.2. Carbon in the residential sector

Residential retrofit is essential for Aotearoa to achieve carbon neutrality by 2050, as existing detached housing currently exceeds the carbon budget by five times (Chandrakumar *et al.*, 2020). The primary source of carbon emissions from these houses is operational energy use, accounting for 62% of the total impact (Chandrakumar *et al.*, 2020). A study by Stats NZ indicates that household energy consumption is predominantly influenced by plug loads and interior lighting (Stats NZ, 2020). However, seasonal peaks in heating demand from Aotearoa’s residential sector align with the national electricity peak demand (Jack *et al.*, 2021). During seasonal and daily peaks, the electricity grid relies on a higher proportion of non-renewable sources. Therefore, addressing the seasonal supply-demand mismatch by reducing the heating demand of existing dwellings would support Aotearoa’s transition to 100% renewable electricity. It is fundamental that retrofit strategies are considered from a whole-of-life perspective, to ensure the operational carbon reduction is not negated by the embodied carbon of any materials added or any demolition and waste that occurs because of the retrofit.

2.3. Top-down carbon benchmarks

Top-down approaches to carbon benchmarking include taking the global carbon budget in line with the Paris Agreement and allocating the relevant portion to a sector or in this case, building. The benchmarks are based on a 1.5°C or 2°C pathway, which defines the maximum amount of greenhouse gas (GHG) emissions that can be emitted and still limit global warming to 1.5°C or 2°C above pre-industrial levels. In New Zealand, studies have used the grandfathering principle to present top-down benchmarks for the residential sector in the form of a target value across stages of the house's life cycle (Chandrakumar *et al.*, 2020). The study referenced in this paper uses 2°C as the global carbon target. This paper was selected as it provided a breakdown of the carbon target per gross floor area and for each life cycle module. Table 22 presents the carbon targets for each life cycle module of a detached New Zealand House.

Table 22: Carbon target of detached houses New Zealand

Lifecycle Stage	Carbon target per unit gross floor area ($kgCO2eq/ m^2$)
A1 – A3	34
A4 – A5	7.4
B2 & B4	0.4 (per yr)
B6	1.9 (per yr)
B7	0.27 (per yr)
C1 – C4	10

This study aims to align an existing case study house closer to the 2°C carbon benchmarks presented in Table 1. The LCA will consider modules B2 (maintenance) and B4 (replacement), B6 (operational energy use), B7 (operational water use) and C1-C2 (end-of-life stage). The A1-A5 (product and construction process) emissions of the existing house are considered to already be emitted and are not included in the LCA for this study. The A1-A5 emissions arising from each retrofit package will be attributed to Module B4 (replacement).

3. New Zealand retrofit practice

3.1. Current and historical retrofit programmes

Despite evidence of the poor quality of New Zealand's housing, retrofit practice is limited and primarily focuses on ceiling and underfloor insulation, and the installation of more efficient heating, like heat pumps. Besen and Boarin (2020) found that wall insulation, window upgrades, and airtightness improvements are less common in New Zealand. Historically, several retrofit programmes across New Zealand have been implemented, aiming to support the uptake of retrofits through financial support and incentives, including Warm Up New Zealand; National Energy Efficiency and Conservation Strategy; Auckland Council Retrofit Your Home Programme; Energywise home loans (Parker, 2008; Grimes *et al.*, 2012; Leardini and Manfredini, 2015; Auckland Council, no date). The main programme in operation in 2023 is the Warmer Kiwi Homes Programme, however, eligibility is limited to lower-income owner-occupiers. Warmer Kiwi Homes offer grants for up to 80% of approved insulation and heaters (EECA, 2023). Kāinga Ora runs a retrofit programme for state-owned properties. Kāinga Ora retrofits include full insulation, double glazing, improved airtightness, ventilation, and heating (Kāinga Ora, 2021). For rental properties, there is limited incentive or funding for retrofit application. The Healthy Homes Standard came into law in 2019 and sets minimum standards for heating, insulation, ventilation, moisture ingress and drainage, and draught stopping in rental properties (Tenancy Services, 2023). The Healthy Homes Standard requires landlords to make house improvements to meet these regulations, however, to date, there is limited evidence to suggest the outcome of this standard.

3.2. Review of retrofit strategies

In New Zealand, there are limited studies into retrofit methods or packages beyond ceiling and underfloor insulation, and limited data to understand the potential thermal and carbon improvements from more extensive interventions. Due to New Zealand's difference in housing typologies and heating behaviour, successful retrofit packages implemented overseas may not have the same effect here. Leardini and Manfredini (2015) assessed four incremental upgrade packages for 1940-1960 state houses, focusing on the thermal performance and airtightness upgrades, supplemented by mechanical systems. Findings demonstrated a significant heating reduction compared to the baseline and evidenced the effectiveness of wall insulation and airtightness strategies (Leardini and Manfredini, 2015). A 2012 study applied an eco-retrofit package to a case study in Auckland. This upgrade included a full thermal envelope retrofit, with insulation added to the walls, ceiling, and underfloor, window upgrades to double glazing, and a humidity-variable vapour check to provide a continuous airtightness layer (Leardini and Gronert, 2012). The upgrade achieved a HomeStar rating of 8, demonstrating comprehensive retrofit strategies can achieve significant improvements in health, comfort, and energy efficiency. A study by Bussiness and Economic Research Limited, released in 2023 defined medium and deep retrofit packages for each housing typology in New Zealand and included roof, floor, and wall improvements (Parsons *et al.,* 2023).

Based on the existing literature, a summary of potential retrofit strategies was developed and is presented in this paper. Table 23 presents retrofit strategies summarised into internal retrofits, cavity retrofits and external retrofits. Cavity retrofit includes additional insulation installed in wall, ceiling, and underfloor cavities. Internal retrofit includes adding insulated linings to the interior of the house. External retrofit is a common strategy used overseas, although there has been limited study or application of this strategy in New Zealand. For this study, a cavity retrofit, internal retrofit and external retrofit are tested.

Table 23: Summary of retrofit strategies

Strategy	Ceiling	Floor	Walls	Window
Internally fixed to envelope	Insulated ceiling lining	Insulating floor linings	Insulated wall lining Strap and line internal walls	Acrylic layer stick on
Within the envelope (cavity)	Blown in ceiling insulation Ceiling insulation	Underfloor insulation (Blanket, semi-rigid, rigid insulation)	Remove & replace wall linings and add insulation Blown in wall insulation	Double glazing retrofit into existing frames
Externally fixed to envelope	Warm roof & replace roof cladding	-	Insulated cladding boards Exterior wall insulation & replace cladding	Full window replacement

3.3. Barriers to uptake

Despite research evidencing the health and cost benefits of retrofitting New Zealand's existing housing stock, uptake has been slow (Grimes and Preval, 2020). Several studies have highlighted key barriers to uptake include financial, lack of knowledge or misinformation, and a prioritisation of cosmetic interventions (Ambrose, 2015; Leardini and Manfredini, 2015; Besen and Boarin, 2020; Parsons *et al.*, 2023). Leardini and Manfredini (2015) highlight that capital gain is the primary driver for house renovations, and energy efficient or thermal renovations don't have the same market value improvement that cosmetic or spatial renovations deliver. Knowledge deficit is a key barrier found by many studies, and Besen and Boarin (2020) highlight the need for more examples and case studies.

4. Methodology

This paper presents the findings of a study that examines the whole-of-life carbon performance of various retrofit strategies for a detached Bungalow house in Wellington, New Zealand because it was a key housing type identified in Section 2.2 in need of improvement. This study proposes and tests three retrofit packages and compares them to the baseline, and the carbon target outlined in Section 2.2. The methodology comprises four key stages; (1) Developing a baseline; (2) Developing retrofit packages; (3) Energy modelling; (4) Whole of life carbon modelling.

4.1. Development of the baseline

To develop a baseline, drawings and specifications of an existing detached house were collected from Wellington City Council (WCC) Archives. WCC Archives also provided details of previous alterations and upgrades to the house. The existing house was modelled digitally to put together the overall construction and sizing of the baseline. The operational energy of the baseline was energy modelled using the software Speckel (Carroll and O'Dea, 2023). Assumptions were made about the level of insulation in the walls, ceiling, and underfloor, based on typical levels of insulation in 1920 houses (BRANZ, no date). The existing house was assumed to have no wall insulation, <110mm ceiling insulation, and reflective foil retrofitted to the underfloor. Using these assumptions, R-Values were calculated using Design Navigator (Design Navigator Limited, no date).

4.2. Retrofit packages

Three retrofit strategies were applied to the baseline. The first package is a cavity retrofit with wall cavity insulation, ceiling insulation, and underfloor insulation, bringing the house closer to the New Zealand Building Code (Table 24). The internal retrofit uses insulated plasterboard that are applied to ceiling and walls. These two packages include retrofitting a second glazing into the existing timber frame. The external retrofit package applies PIR-insulated panels to externally retrofit the roof and walls. The external retrofit package also includes a double glazed, thermally-broken aluminum window replacement.

Table 24: Description of retrofit packages

Package	Element	Description
Baseline	Walls	90mm timber framing, no insulation
	Ceiling	R1.8 ceiling insulation
	Underfloor	Reflective foil underfloor
	Windows	Single glazed timber frame windows
Cavity retrofit	Walls	R2.8 90mm glass wool insulation in walls
	Ceiling	R2.6 140mm glass wool insulation in ceiling
	Underfloor	R2.6 110mm underfloor glass wool insulation
	Windows	Retrofit second glazing into existing timber frame
Internal retrofit	Walls	60mm R2.35 insulated plasterboard lining
	Ceiling	90mm R4.2 insulated ceiling plasterboard
	Underfloor	R2.6 110mm underfloor glass wool insulation
	Windows	Retrofit second glazing into existing timber frame
External retrofit	Walls	95mm PIR insulated panel on walls
	Ceiling	155mm PIR insulated panel on roof
	Underfloor	110mm R2.6 underfloor glass wool
	Windows	Aluminum double-glazed unit replacement

The presented retrofit packages enable comparative quantitative evaluation to understand most effective retrofitting strategy for this case study based on carbon impacts.

4.3. Energy modelling methodology

Energy modelling is carried out on the software Speckel. Energy Modelling follows the H1/VM1 energy efficiency methodology (Ministry of Business, Innovation and Employment, 2022b). H1/VM1 is a verification method issued under the New Zealand Building Code and outlines the modelling method for calculating the energy use of houses. Energy modelling requires inputs for the analysed houses' thermal envelope, orientation and geometry, space conditioning, and internal loads. To calculate the R-values of the thermal envelope of each retrofit package, Design Navigator has been used (Table 25). This considers thermal bridging caused by timber framing. The R-value of glazing systems has been taken from H1 and the Building Research Association of New Zealand (Villard, 2018; Ministry of Business, Innovation and Employment, 2022a). Default values from the software for heat capacity and density have been used.

Table 25: R-values of retrofit packages

Strategy	Ceiling m2·K/W	Floor m2·K/W	Walls m2·K/W	Window m2·K/W	Infiltration ACH
Baseline	2.4	1.1	0.3	0.19	0.9
Cavity retrofit	4.55	2.48	2.25	0.36	0.9
Internal retrofit	6.16	2.48	2.62	0.36	0.9
External retrofit	6.36	2.48	3.45	0.5	0.5

The energy use was modelled so that an internal temperature between 18 and 25 was maintained, as per H1/VM1. Natural ventilation modelled at a set point of 24°C, as per H1/VM1. Infiltration was modelled at 0.9, based on research indicating the airtightness of houses pre-1960 (BRANZ, 2020). The infiltration rate has been kept consistent for the cavity and internal retrofit packages, given there are limited improvements to airtightness. An infiltration rate of 0.5 has been modelled for the external package, assuming some improvement to the airtightness due to the window replacement. The infiltration rates are likely a conservative assumption, and there is a degree of uncertainty here given the actual infiltration rate cannot be tested. It is acknowledged that lower infiltration rates can be challenging to achieve in older housing stock due to construction and preservation issues (Leardini and Manfredini, 2015).

The energy use also accounted for lighting, occupant and equipment loads. Occupant and equipment loads were modelled in line with H1/VM1. Lighting plug loads followed the HomeStar methodology as H1 does not require lighting to be accounted for. HomeStar is a green building rating system for residential typologies, administered by the New Zealand Green Building Council ('Homestar v4 Technical Manual', 2020). Assumptions for the energy use for lighting, plug loads and hot water were taken from the Electronic Supplementary Material within the same study used to set the carbon target (Chandrakumar *et al.*, 2020). The energy demand was kept consistent across each package, as no improvement to these are proposed in the retrofit packages investigated in this study. Therefore, any reductions in the B6 module are a result of thermal improvements.

4.4. Life cycle assessment methodology

Life Cycle Assessment (LCA) is a tool to quantify the environmental impacts of a building through all stages of its life. The Life Cycle Assessment used to compare retrofit options for this study covers Modules A-C (D is excluded to align with carbon targets set by Chandrakumar *et al.* (2020) and aligns with EN 15978. The software One Click LCA was used for this study. The functional unit was defined as the occupation of a detached house over its reference service life. For this study an estimated service life of 90 years was taken, to align with previous studies (Chandrakumar *et al.*, 2020). Although the case study house was built in 1926 and has already exceeded its 90-year lifespan, it is assumed the proposed retrofits will extend the useful life, and this assumption ensures a consistent methodology.

4.4.1. LCI (life cycle inventory)

For the product stage, the A1-A5 emissions of the existing house are considered to already be emitted and are not included in the LCA. The A1-A5 emissions of each retrofit package are considered part of the replacement module so are attributed to Module B4. The materials used in A1-A3 for each retrofit package include insulation, gypsum plasterboard, external cladding, glazing, and window frames. For the construction process stage (A4), emissions associated with the transport of building materials to the site are included based on distances from manufacturers to the site in a diesel truck. An average construction site scenario is included for the A5 module, although it is acknowledged due to the nature of the renovation work this may be an overestimation of emissions. The assumption will be consistent for each option, so does not impact the comparative exercise. The total emissions from A1-A5 of each retrofit package are assigned to the B4 replacement module.

For the maintenance module (B2), emissions associated with water and energy use during maintenance are included. This accounts for vacuuming for an hour weekly, and water blasting the exterior of the house once annually. Repainting has been omitted, although it would be considered typical maintenance practice in New Zealand. However, impacts from B2 are generally minimal compared to other modules, so this exclusion is not expected to impact the ability to compare results. Replacement of materials (B4) is based on assumptions of typical house maintenance practices in New Zealand. In the baseline, despite the case study being 97 years old, it is assumed that framing, insulation, and internal linings will not be replaced in the further 90-year lifecycle. Flooring, cladding, and glazing are assumed to be replaced once within the lifecycle. In the cavity and internal retrofit package, it is assumed the existing cladding and flooring will be replaced once in the retrofitted house's life. For the external retrofit package, it is assumed flooring will be replaced once, but no more upgrades to the external fabric will be made following the retrofit.

The operational energy use stage includes emissions associated with energy consumption (heating, cooling, hotwater, lighting and equipment loads). For this study, the operational use stage was assumed to be entirely electricity, however in reality the house in the study may also use gas. The electricity emission factor uses a New Zealand One Click datapoint (0.12 kg CO_2e/kWh). This emission factor does not consider a decarbonising grid projected for 2050, and thus the results for Module B6 are likely to be a conservative measure of the operational energy use. The scope of the retrofit packages does not include upgrades to any water fixtures, and thus operational water use (B7) is taken as a consistent assumption across each retrofit package, based on a report by the Building Research Association of New Zealand (Pollard, 2022).

Demolition (C1) is based on studies of the demolition of timber frame buildings and includes machine operation, spent hydraulic and machine oils, and diesel (One Click LCA Ltd, 2015). End-of-life data (C2-C4) is based on market-based end-of-life scenarios that are tied to material subtypes; in this study, this is namely timber, insulation, glazing, and cladding. For this study, interior fittings such as furniture, kitchen cabinetry, and appliances are excluded. Sanitary fixtures are included. To generate the end-of-life scenarios, the baseline house is modelled in One Click LCA software and the end-of-life impacts are manually added to each of the retrofit results.

Data for the Life Cycle inventory was sourced from original drawings and specifications. Quantities of materials (A1-A3) added for each of the retrofit packages were sourced from the digital models of each package. It is acknowledged that these quantities may vary from reality as digital models may have a level of inaccuracy, however this does not impact the ability to compare results. Data sources have used Environmental Product Declarations (EPD) where available to represent contemporary construction processes in New Zealand. Where EPDs are not available, data sources have been selected with a high level of temporal and geographic relevancy.

5. Results and discussion

Figure 52: Comparison of Global Warming Potential impact of retrofit optionsFigure 52 presents the whole-of-life Global Warming Potential (GWP) of the analysed existing house, and the carbon impact of each retrofit package, compared to the carbon target. All impacts are recorded as $kgCO_2e/m^2$/year to provide a consistent comparison. Results demonstrate the existing house currently exceeds the whole-of-life carbon target by a factor of 8.29. Each of the retrofit packages reduces the carbon impact of the existing house, with the external retrofit having the largest reduction. However, results demonstrate that none of the tested retrofit packages successfully brings the existing house close to the carbon target.

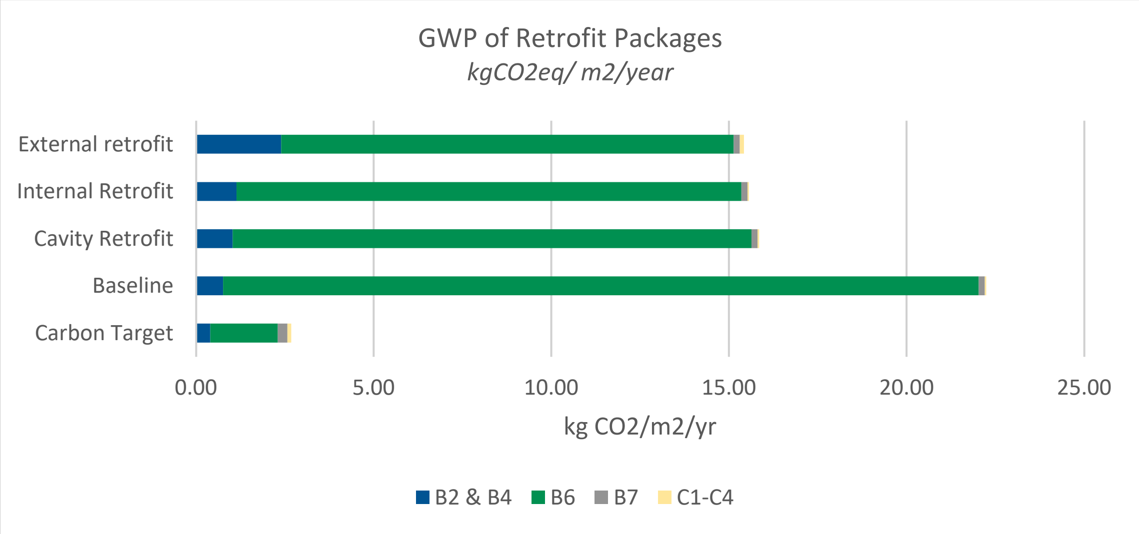

Figure 52: Comparison of Global Warming Potential impact of retrofit options

In the baseline, impacts from B6 (operational energy use) exceed the carbon target by a factor of 11.19. Results demonstrate that a cavity retrofit can reduce this impact by 31%, from 21.27 $kgCO_2e/m^2$/year to 14.6 $kgCO_2eq/m^2$/year. Each of the packages demonstrate similar reductions in the B6 Module, with the external retrofit having the greatest reduction of 40%. Impacts from B6 dominate the total carbon impact of the existing house and each of the retrofit packages.

Figure 53 presents the results excluding B6 to demonstrate the impact arising from the other modules for each package. These results show that for modules B2 & B4 (maintenance and replacement), each of the retrofit packages exceed the carbon target. This is largely due to the upfront carbon emissions of the retrofits being attributed to the replacement module. The existing house (baseline) also exceeds the carbon target for Modules B2 & B4, due to the need to replace materials in the house that pass their useful service life. However, it is acknowledged that often this is not the case, and materials such as cladding are not replaced as they should be.

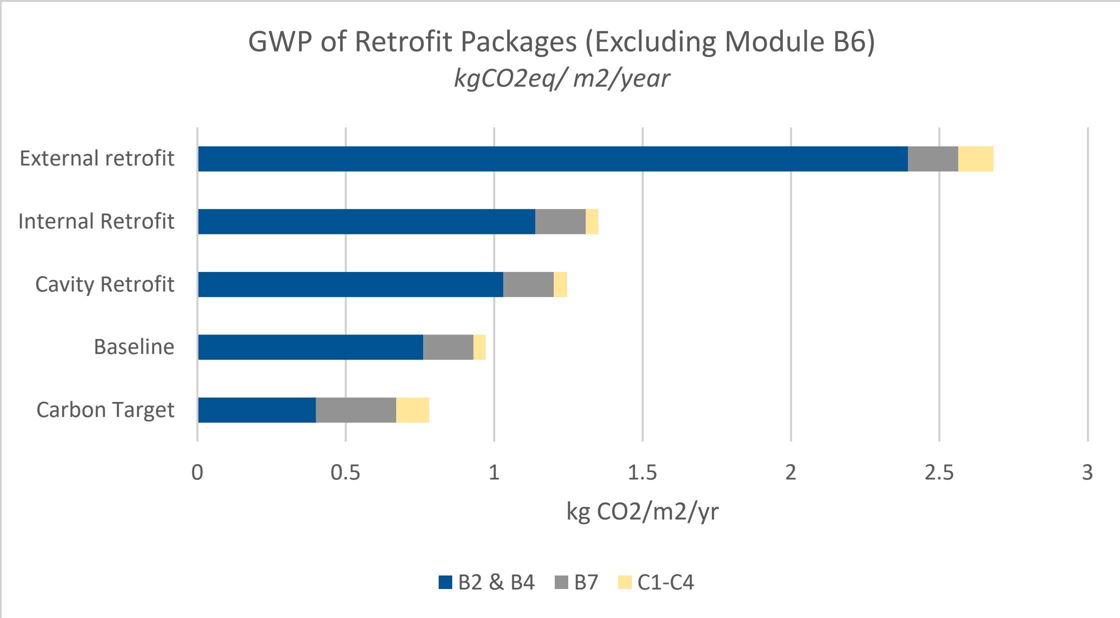

Figure 53: Comparison of Global Potential Warming of retrofit options, excluding Module B6

Given New Zealand's electricity grid is expected to be decarbonised by 2050, and each retrofit package demonstrates similar operational carbon reduction, the carbon emissions arising from material use becomes increasingly significant. Figure 2 demonstrates that the external retrofit is significantly higher in embodied carbon, due to the materials used in the proprietary panel systems (PIR insulation and steel). The cavity retrofit displays the lowest embodied carbon, as the package uses the least materials, and the insulation material (mineral wool) has a lower carbon impact. These results highlight the importance of selecting lower carbon materials when retrofitting existing housing.

Impacts from B7 (water use) are consistent across each retrofit package, as the packages do not include any upgrades to water efficiency. These impacts are within the carbon target. Impacts from end-of-life (C1-C4) for the cavity and internal retrofit are aligned with the carbon target of 0.11 $kgCO_2e/ m^2/year$. The external retrofit end-of-life impacts is 0.12 $kgCO_2eq/ m^2/year$, just exceeding the carbon target.

Table 26: Results of whole-of-life GWP of retrofit packages

Module	Carbon Target *$kgCO_2e$/ m^2/year*	Baseline *$kgCO_2e$/ m^2/year*	Cavity Retrofit *$kgCO_2e$/ m^2/year*	Internal Retrofit	External Retrofit *$kgCO_2e$/ m^2/year*
A1-A5	-	-	-	-	-
B2 & B4	0.4	0.76	1.03	1.14	2.39
B6	**1.9**	**21.27**	**14.6**	**14.21**	**12.74**
B7	0.27	0.17	0.17	0.17	0.17
C1-C4	0.11	0.04	0.04	0.04	0.12
Total	2.68	22.24	15.85	15.56	15.42

The goal of this study was to investigate different retrofit packages to bring an existing stand-alone dwelling closer in line with a carbon target in line with a 2°C pathway. None of the retrofit packages were successful in bringing the existing house in line with the carbon target. Overall, these results highlight the significant impact from the operational energy module and indicate a need for more comprehensive retrofit efforts to achieve more significant operational carbon reductions. For example, retrofitting to the EnerPHIT standard, which sets a maximum heating demand of 20kWh/(m^2a) (Passive House, 2023). However, even with greater reductions in heating demand, energy demand from lighting, hot water and plug loads will still comprise a significant portion of the operational carbon impact. This highlights the need for retrofitting to also include a focus on improving energy efficiency for these other aspects.

Module B2 and B4 (maintenance and replacement) have the next largest impact, due to the upfront emissions of each retrofit package being attributed to this module. These impacts emphasise the importance of ensuring any retrofit measures are low-carbon options, to reduce the climate impact associated with B4. There is opportunity for further research into how more comprehensive retrofits can be achieved without compromising the upfront impacts of the package. For example, this may include higher performing windows, or a larger focus on airtightness improvements. Given that impacts from B4 already exceed the carbon target with typical maintenance and replacement in the baseline, this further highlights the opportunity for low-carbon thermal retrofits. For example, as cladding is likely to be replaced during the existing house's lifetime, this may be a potential opportunity to externally retrofit the dwelling at the same time, to create operational carbon savings without significant additional embodied carbon.

5.1. Software limitations

There are several limitations to this study. Operational emissions for the baseline and each retrofit package are calculated using modelling software, and assumptions on energy use habits, rather than data from energy bills. Operational energy use is largely dependent on occupant's behaviour, and this will vary from household to household. There is also an assumption that the house will be constantly heated to 18°C, which often isn't the case. Secondly, the operational emissions assume the household uses only electricity, rather than a mixture of gas and electricity, or solid fuel and electricity. The electricity data point used does not account for a decarbonising grid, so Module B6 is likely a conservative measure. Thirdly, quantities for materials of the existing house and each of the retrofit packages are taken from a digital model and use assumptions for the ratio of timber and insulation. These quantities may vary in construction. Despite these limitations, assumptions remain consistent across each of the presented packages, so the study presents effective results for the comparison of strategies. Furthermore, there is a lack of data for LCAs in New Zealand. New Zealand specific EPDs have been selected where available, and these include insulation, aluminum windows, plasterboard, and cladding. Where EPDs are not available European datapoints or average datapoints have been selected, and this has the potential to impact the validity of the results. This also highlights the need for more data availability in New Zealand to increase the uptake of accurate studies of this nature.

6. Conclusion

Residential construction must be aligned with a 2^{o}C pathway, or better, a 1.5 ^{O}C carbon target, to ensure our residential sector does not exceed planetary climate limits. This research has compared an existing house to a carbon target for detached dwellings and highlights the need for existing housing to be improved to reduce the carbon impact of operational emissions. This study has presented three retrofit packages, including a cavity retrofit, internal retrofit and external retrofit option, to bring the existing house closer to the carbon target. The study demonstrates none of the presented retrofit options are successful at aligning the existing house with the carbon target. The assessed retrofit packages reduce the emissions associated with operational energy use by up to 40%, demonstrating the importance of thermal retrofits for mitigating operational carbon emissions. This research demonstrates that further refinement and research into retrofit packages is needed to align existing houses with carbon targets, and a focus on lighting, plug loads and hot water alongside thermal upgrades. The study also discussed the limitation of studies of this nature, and demonstrated the possibility that a lack of data might be contributing to limited uptake of retrofitting strategies to reduce carbon impacts.

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Why standards and perceptions are discouraging sustainable access of low-density timber for flooring?

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Abstract: The anecdotal circumstances observed in the timber flooring industry make the introduction of new timber resources and products to the consumers challenging. This study explores the challenges of introducing new timber resources and products to the consumers when standards reflect resources that are informed/based on the availability of high-density, mature timbers. Extensive research exists to determine the timber properties specified in standards as important for flooring applications. However, the lack of consensus in methodologies and boundary conditions employed to differentiate end-user performance requirements restrict the comparison of these studies and standards. This is further complicated by end consumers selecting traditionally accepted species with divergent properties; species used in flooring defies the standards and are informed by aesthetics and cultural attachment. This paper evaluates the commonly used standard tests used for timber flooring and compares them with the feedback received from interviews conducted with several Australian timber industry stakeholders, architects/interior designers, and experts in the field, with the view of designing and developing new flooring products from plantation hardwood timber – a resource that is constrained by the standards that are widely used yet is growing in popularity because of its natural aesthetics and performance as a flooring alternative.

Keywords: Sustainable flooring; standards; product development; performance requirements.

1. Introduction

The global consumption of primary processed wood products is anticipated to increase by 37% in 2050 in comparison to 2020 (FAO, 2020). As cited by Sepliarsky *et al.* (2022), a growth rate of 5% is expected within the next five years in the world timber flooring market with veneer flooring experiencing the highest growth. Although there is still a significant demand for traditional solid hardwood timber flooring, consumer preferences show a gradual shift towards engineered multilayer products, especially in Europe, North America and China due to reduction in cost, increase in stability and competitiveness caused by cost and volume (Acuña *et al.*, 2020; Grześkiewicz *et al.*, 2020). Despite the increase in demand, only a few conventionally used timber species still dominate the global flooring market such as European oak (*Quercus robur* L.) and Ashwood (*Fraxinus excelsior* L.) (Acuña *et al.*, 2020; Grześkiewicz *et al.*, 2020). For

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many timber products, the reason for using a certain species is generally inexplicable or non-quantifiable usually governed by tradition incorporated with local availability, price, trends and superficial knowledge (Neyses and Sandberg, 2015). This can lead to overconsumption of certain species, and underutilisation of lesser-known species. Consequently, with the increasing demand for supply and depletion and restricted access to high-density native timber species with changing environmental policies, it is advantageous to consider alternative plantation species as a resource for the flooring market (Millaniyage *et al.*, 2022; Sepliarsky *et al.*, 2022).

Sustainability in this paper refers to the importance of identifying alternative material sources for the continuation of the timber industry as well-managed plantations can help mitigate the shortage of timber supply and protect the remaining natural forests (Paquette and Messier, 2010). With the increasing demand and timber being promoted as an environmentally friendly construction material, the pressure on global forests to deliver economic, social, and environmental services has reached unsustainable levels (Freer-Smith *et al.*, 2019). For instance, the predictions on timber supply in Australia shows that the access to native species such as Tasmanian Oak is rapidly decreasing (Sustainable Timber Tasmania, 2022) similar to observations made in Europe for Oak. Australia has high volumes of plantation Eucalypts which could generate reasonable quantities of timber flooring products if identified as suitable for appearance flooring applications. Most of these short rotation plantations are managed for pulpwood production and therefore, the sawn wood consists of many natural features such as knots and generally do not comply with the Australian standards for appearance grading. Most of the engineered timber flooring products in Australia are imported and the market still prefers solid timber flooring products. With the supply of high-density, native timber species becoming quickly restricted, increased requirement for sustainable certifications and the implications to supply chains because of Covid-19 pandemic and war in Ukraine, more interest has been generated into the use and opportunity of plantation species for higher value applications in buildings.

This study forms part of a National Institute for Forest Products Innovation (NIFPI) project in Tasmania, Australia conducted with the view of introducing low-density plantation *Eucalyptus nitens* into an engineered flooring application. The preliminary literature review informed the non-existence of an Australian standard for plantation timber for appearance applications. In addition, the lack of consensus and context specific approaches for solid or engineered timber flooring standards commonly used by other developed countries limits the comparison of timber property studies. Density and hardness are the typical criteria used in selecting a timber species for flooring in Australia. The general conception is that the high-density species will last longer than species with lower density due to hardness. It is also common practice that higher prices are afforded to species with higher densities. But this rationale based on standards is challenged by species such as Tasmanian Oak (Janka hardness: 4.9 kN) which is a widely used flooring species for over a century in Australia although it has lower density and hardness values in comparison with some of the common flooring species. Another global example is the use of Baltic Pine (Janka hardness: 3.2 kN) and European Oak (Janka hardness: 4.9 kN).

Since timber flooring is used in a wide variety of end user applications (domestic/commercial), understanding the performance requirements is important to validate a product as fit-for purpose which is not comprehensively reflected in the standards. The authors observed the explicit requirement to understand what the end users require from a timber floor if new engineered products are yet to be developed. Furthermore, most standards used by the flooring industry were written over 50 years ago and the resources, properties and building codes have changed significantly since then. Therefore, in an attempt to better understand the acceptance of lower density species into the flooring market, which was an early concern among timber processors, the following research method was employed. Structured interviews were conducted with 17 participants. Six Australian architects/interior designers familiar with specifying Tasmanian timbers, seven Tasmanian plantation/timber industry participants and four experts in timber specifications took part to identify the consumer preferences, manufacturing capabilities and the significance of standards towards their decision making. This paper presents a review of the commonly referenced standards and tests in literature for determining the suitability of a timber species for flooring application and the feedback received from interviewees. A comparison is made between what the standards specify against the preferences of the end users.

2. Evaluation of commonly referenced timber flooring standards for species selection

European (EN), British (BS) and American (ASTM) timber flooring standards are commonly referred in published studies testing species properties for flooring. In total 10 key standards are referenced in this study. Europe has the highest number of standards compared to Australia. Density, static hardness and dimensional stability are considered important for timber flooring, irrespective of which part of the world the standards originated from (Figure 1).

Figure 1: Comparison of origin of standards referred in the present study

The most used properties to select a species for flooring are density and hardness. Apart from them, there are other attributes that also need to be considered such as aesthetics, wear resistance, dimensional stability, and strength parameters, all of which are relevant in different end-use applications and of importance if non-conventional timbers are to be introduced to the flooring market. Although the aesthetic attributes highly influence the acceptance of species for flooring, it is subjective on the preference of the designer, specifier and/or consumers. A major challenge faced by flooring industry globally is adapting to the diverse and changing consumer preferences (Roos and Hugosson, 2008). Furthermore, there are multi-factors impacting the appearance selection such as colour, natural features, general character, width of boards and the finish applied (ATFA, 2009). In Australia, there are standards that relate to grading and manufacturing process of timber flooring and the market has a general perception of an acceptable level of a finished flooring. AS 2796 (*Timber – Hardwood – Sawn and milled products, Part 2: Grade description*), provides guidance for visual grading of timber flooring based on the size and number of features present in the element. The floorboards are classified into three grades: select, standard and high feature. It was noted that most timber flooring studies available in literature address density, hardness, abrasion resistance and dimensional stability, and this paper evaluates the standards used in those studies, due to the focus of the larger project to determine the suitability of plantation *E. nitens* for a flooring application. Table 1 provides a summary of the key standards identified. There are other standards on relevant properties to timber floors (machinability, finishes, grading, installation, and aesthetic attributes) which are beyond the scope of this review.

However, most of these tests and methods either compare a species with another species with known performance or is based on information obtained from studies conducted over 50 years ago, which presents data from traditional species with high-density. This hinders new timber flooring products and species from entering the market as plantation timber resources are not a direct substitute for high-density, native timbers due to the distinctions of species, forest silviculture and management. It is important to identify applications where the plantation resource base could be a better fit so that consumers could confidently accept these products in their households allowing the greater use of a renewable resource and less carbon intensive emissions to produce.

Table 1: Summary of key standards discussed in the study

Standard	**Specified testing material/ property**	**Density**	**Static hardness**	**Dynamic hardness**	**Abrasion resistance**	**Dimensional stability**	**Thickness swelling**	**End use categories**	**Remarks**
ASTM D143	Small clear specimens of timber	×	×			×			Includes methodology for Janka test
ASTM D2394	Simulated service testing of timber and timber-based finish flooring		×[1]	×	×		×[2]		[1]different test methodologies for impacts from concentrated loading and small area loads provided [2] methodology to test surface wetting included
ASTM D1037	Timber based fibre and particle panels material	×	×	×	×	×	×		Abrasion resistance using navy wear tester, accelerated aging cycles for dimensional stability
AS 1720.2	Timber properties for structure design	×	×			×			Provides properties including Janka hardness and tangential shrinkage for commonly used timber in Australia
BS 8201	Timber and timber-based flooring	×			×	×		×	Species classification for different end user applications provided
BS/EN 13329	Laminate floor covering with amino plastic thermosetting resin surface layers	×[3]			×	×	×	×	Provides classification for different end user levels, [3] uses tests specified to determine effect of a castor chair and furniture leg in classification
EN 1534	Timber flooring and parquet	×							Methodology for Brinell test
EN 14354	timber veneer floor coverings		×		×	×	×	×	Threshold values for different end user applications provided
EN 318	Timber based panels					×			Humidity cycling method
EN 1910	Timber flooring, paneling, and cladding					×			Humidity cycling method

2.1 Hardness and density

Density is considered important when selecting a species for flooring because dense timber provides more resistant floors to denting (Costa *et al.*, 2021). Density is a reliable indicator of many solid timber properties including hardness, strength and stiffness (NAFI, 2004). Therefore, some guidelines such as BS 8201 (2011) titled *Code of practice for installation of flooring of wood and wood-based panels* and the book *Construction timbers in Queensland* (Hopewell, 2018) use density to classify timber species for different flooring applications. Mohmod and Tahir (1990) state that the density values are used to classify Malaysian timbers for flooring in different levels of traffic (650 kg/m^3 for medium traffic and 800 kg/m$^{3)}$ for heavy traffic). Although density might have a close correlation with solid timber flooring hardness, engineered flooring panels with composite structure will have its hardness properties vary based on the overall structure and the testing method used to determine the hardness (Grześkiewicz *et al.*, 2020; Millaniyage *et al.*, 2022). Barbuta (2012) states that low density timber species are suitable to produce composite materials such as oriental strand board (OSB) used as a backing layer for engineered flooring as the composites made from low-density timber will have superior mechanical properties and lesser variations of density than if manufactured from high-density timber. Another study (Grześkiewicz *et al.*, 2020) found that the influence of the bottom layer density on overall product hardness was governed by the thickness of each layer. Similar observations were reported by Millaniyage *et al.* (2022) in a previous study on *E. nitens* engineered flooring prototypes with different layer configurations.

In a timber flooring context, hardness is more widely used to evaluate the surface properties of flooring materials (Meyer *et al.*, 2011; Oliveira *et al.*, 2019; Acuña *et al.*, 2020). Timber floors get subjected to indentations generated by both static and dynamic loads. Especially with respect to industrial flooring, the dynamic impacts play an important role, caused by people walking over the floors or the falling of tools and materials in places such as workshops and industrial facilities (Meyer *et al.*, 2011). However, most tests on timber flooring are based on static hardness. Both the Janka and Brinell hardness tests are commonly applied using round indenters. These are preferred in timber testing as they cause minimal cracking on the timber (Sydor *et al.*, 2022). Brinell hardness (EN 1534, 2020) is conducted in most European countries to determine the hardness of timber while Janka hardness (ASTM D 143, 2000) is used in countries including America and Australia for the same purpose. Recent studies on timber flooring have also identified dynamic hardness tests as important and conducted testing on different species by determining the impact caused by a steel ball on the timber surface when dropped from a specific height (ASTM D 1037, 1999; ASTM D 2394, 2017).

Janka test as specified in ASTM D 143 is the primary methodology used to determine the suitability of timber species for flooring in United States and Canada (Wiemann and Green, 2007). Australian standard AS 1720.2 (2006) lists Janka hardness values for Australian timber determined according to the methodology specified by Mack (1979). When applying the Janka hardness values published in literature, it should be noted that the standard size samples used for the test is 50 mm in thickness in ASTM D 143, and the flooring boards will rarely be of this thickness in application. In contrast, a solid flooring board in Australia is typically 19 mm thick for structural applications and 12 mm thick for non-structural overlay. For instance, ASTM Standard D 1037 on evaluating the properties of wood-base fiber and particle panel materials specify the Janka test to be conducted on 25 mm thick samples and further suggests that since most panels are manufactured in thicknesses of less than 25 mm, the specimen for test shall be made by bonding together several layers of the panels to obtain the required thickness. Janka values are also reported in different ways in industry leading to confusions, especially if the measuring unit is not specified. For instance, the United States usually reports in pounds-force (lbf), Australia in Newtons (N) or Kilonewtons (kN) and in Sweden as kilograms-force (kgf). When considering the technical aspects of the test, the Janka test produces a deep indentation on the specimen generating a considerable level of side-stresses on the steel ball when it reaches maximum penetration. This causes wood failure, and some dense timbers tend to split before the ball reaches the expected penetration. Many of these factors have limited the possibility of comparing different species against each other using the available literature data. A limitation in Brinell test is that the small contact area provides much variability in results when testing wide grained timber species and the difficulty in taking accurate measurements of the indentation (Doyle and Walker, 1985). It should be noted that due to the relatively deep penetration caused by the steel ball used in the Janka hardness test, a gross hardness value is obtained, which does not replicate a reliable measure of the actual hardness of the wearing surface especially in engineered flooring with multiple layers with varying thicknesses (Millaniyage *et al.*, 2022). Static hardness standards such as Janka test are developed to compare timber species properties and not to test the final flooring product. For instance, 50 mm thick sample size in ASTM D 143 is for the feedstock.

Although static indentation may not accurately replicate in-service conditions faced by timber flooring, many studies (Blanchet *et al.*, 2008; Berti *et al.*, 2018; Borysiuk *et al.*, 2019) conducted on deciding a species' suitability of flooring have used these tests to quantify and compare the hardness of timber. Recent studies have also identified dynamic hardness tests as useful for industrial flooring since they may better simulate timber flooring performance in service than static load test (Oliveira *et al.*, 2019; Acuña *et al.*, 2020).

2.2 Abrasion resistance

The ability of timber to resist abrasion is a contributary factor for the performance of timber flooring. Resistance to abrasion is not easy to replicate in laboratory tests since there are many variables such as foot traffic conditions. There are three different tests found in the literature that have informed timber's resistance to abrasion. The earliest evidence of a laboratory testing approach to determine the abrasion properties was reported in 1948. Youngquist and Munthe (1948) reports conducting abrasion resistance testing on timber using US Navy wear test machine which is the origin of the method specified in American standard ASTM D 2394 (2017). ASTM D 2394 also specifies to compare the values obtained in a test with the values published in Youngquist and Munthe (1948). Armstrong (1957) used a planning machine originally designed to test metal to determine quantitative mass loss of timber due to abrasion as well as in-service trials for qualitative assessment of surface abrasion due to traffic exposure. Armstrong (1957) reports categorising timber species based on qualitative and quantitative approaches and provides a list of species as suitable for different end use applications. British standard BS 8201 (2011) has used the lists by Armstrong (1957) in the specification to categorise the timber species for different end user applications. Therefore, the current standards rely on early literature data to determine the abrasion resistance properties of timber. Forestry silviculture and management have changed significantly meaning reported properties are less reliable on reflecting the current materials sold.

Despite early existence for abrasion testing of timber in literature from 1940's and 1950's, a standardised method for testing the abrasion resistance of solid timber is still unavailable (Brischke *et al.*, 2019). Another test described in the literature to determine the abrasion resistance was Taber abraser method. This was originally developed to test the abrasion resistance of high-pressure laminated papers/ coated veneer floor coverings (Militz *et al.*, 2013). The resistance to abrasion is determined as a percentage of thickness loss or mass loss due to abrasive action. These existing standards: EN 438-2 (2005); EN 13329 (2006); EN 14354 (2017), which are related to wear resistance of finishing layers might not provide accurate results when applied to solid timber due to the differences in abrasive materials and the method of abrasion application. For instance, the loads applied by Taber Abraser method based on the action of rotating sandpaper under grinding pressure might not replicate the exposure conditions of an outdoor exposed flooring (Brischke *et al.*, 2019). Although in-service abrasion testing of flooring might provide more reliable observations for an expected end use application if closely replicated with the actual circumstances, this requires considerable time frames and have many uncontrollable variables such as the nature of foot traffic and environmental conditions. Most of these types of in-service trials are conducted by product manufacturers in commercial confidence and are usually not published.

2.3 Dimensional stability

Dimensional changes occurring in timber due to variations in moisture content result in observable shrinkage or swelling in timber boards. This causes deterioration and excessive gaps between floorboards (Knapic *et al.*, 2012). The long-term performance of a timber floor is usually evaluated by studying the distortions observed when subjected to humidity and temperature cycles using a relative humidity chamber method (Németh *et al.*, 2014). Water soaking tests are also conducted to determine the thickness changes of timber when it comes to direct contact with water. Humidity-cycling tests take much longer time to produce results when compared with the water soaking tests. However, in most of the end-uses, the timber floors do not routinely come in direct contact with liquids. Therefore, the humidity-cycling tests are considered as an important predictor of the timber's in-service behaviour. Even though the dimensional stability tests provide important information on how the timber might behave in-service, there is little consensus on appropriate test methods to be used (Sargent, 2019). This study reviews the two tests commonly used in timber flooring industry: humidity cycling and thickness swelling tests are discussed.

2.3.1. Humidity Cycling Tests

Humidity cycling tests are commonly used to determine dimensional stability and the standards, usually follow the procedure of exposing samples to several high and low humidity environments until reaching equilibrium and measuring the resulting dimension at the end of each humidity condition (Sargent, 2019). The observations acquired from dimensional stability from humidity-cycling tests can be used to compare the behaviour of different timber species, as well as to compare modified timber against its unmodified counterpart (Sargent, 2019). Some of the standards commonly used for the purpose are EN 1910 (2000): *Wood and parquet flooring and wood panelling and cladding-determination of dimensional stability* and EN 318 (2002): *Wood based panels-determination of dimensional changes associated with changes in relative humidity*. Due to different temperature and humidity conditions applied in reported studies (Blanchet *et al.*, 2002; Knapic *et al.*, 2012; Németh *et al.*, 2014; Berti *et al.*, 2018), most of the results are unable to be directly compared.

2.3.2. Water Soaking Tests

Both solid and engineered timber flooring products usually behave poorly when they come into direct contact with liquids, such as during an accidental water leakage or flooding. If an engineered timber flooring panel gets exposed to a moist environment or to liquids, the deterioration of the glue lines generates irreversible release of compressive stresses in the composite. Direct contact with liquids also causes swelling of timber. Two major factors impacting the thickness swelling of timber-based materials are the swelling of timber itself and the spring back effect. Spring back effect can be termed as the ability of a material to reinstate into its original form partially or completely after the release of the stress reducing force which caused the dimensional change (Sanne *et al.*, 2020). Width swelling is also important in timber flooring, as high width swelling can result in severe floor distortions (Blanchet and Barbuta, 2011). Water saturation tests are generally easy to perform and produce quick results. EN 13329 (2006) and ASTM 1037-06a are common standards for the purpose in studies (Blanchet and Barbuta, 2011; Barbuta, 2012; Knapic *et al.*, 2012). These tests are mostly used in literature to compare the results which quantify the improvements in dimensional stability due to timber modifications or surface treatments of the same species. Although dimensional stability is of high importance to timber flooring, it is not considered as important as density or hardness in the market.

2.4 Species selection guidelines for different performance requirements

It was observed that most of the standards specifying testing methodologies for timber flooring do not provide threshold values to differentiate a species' suitability in an anticipated end use application. Decisions on the suitability of timber species for various flooring applications is based on the known performance of the wood species (Armstrong, 1957; BS 8201, 2011). British Standard BS 8201 provides lists of species categorised into different end user applications. The species names are listed under various exposure conditions and is suggested to be used as an initial reference considered together with other performance factors listed in the same standard. Although, the species lists also consist of density and movement classifications, it is stated in the standard that the species selection was derived from Armstrong (1957). The categorisation by Armstrong (1957) is based on the testing and evaluation described in section 2.2, whereas the timber classification was based on the relationship between anatomical structure, surface wear and breakdown. Therefore, the classification in BS 8201 is mainly based on the abrasion properties of the species while densities and movement classifications are provided for general reference. Another standard commonly referred to compare end user specifications for timber flooring is EN 14354 (2017): *Wood-based panels - Wood veneer floor coverings*. Brinell hardness, thickness swelling, and wear resistance are some of the criteria used for the classification in EN 14354.

3. Interview feedback for new engineered flooring product development

In the view of developing design concepts for engineered flooring prototypes using Tasmanian plantation *E. nitens* it was important to understand the expectations of major stakeholders, identify capabilities and drivers in specifying a flooring product in practice. Interviews were conducted with industry practitioners to extract tacit knowledge to inform the processes of product design and development. Seventeen participants were involved in 14 interviews belonging to three clusters 1. industry participants, 2. architects/interior designers, and 3. specifiers/researchers. All the participants had experience in specifying/processing or research in Tasmanian timbers including Tasmanian Oak. Most participants had close to or more than a decade of practical involvement in the timber industry. Each interview lasted 30-minutes, conducted either face-to-face or online using structured questionnaires designed for each cluster. Key findings obtained from each cluster are summarised below.

3.1 Industry participants

Industry participants indicated that use of engineered flooring is still novel to the Australian market, solid boards and overlay are the common choices. There is a preference in selecting timber for flooring among the states of Australia governed by tradition and availability. States with access to native, high-density timber are reluctant to use solid 12 mm thick overlay. In Tasmania and Victoria, around 70% of the demand is for overlay and 30% for solid 19 mm thick boards. In Western Australia, New South Wales and Queensland, 90% of the demand is for 19 mm thick boards and 10% for overlay products. They perceive that with the current boom in construction industry, it is opportune to introduce plantation species for flooring but require more understanding of properties, economics and product differentiation. Industry participants are interested in a premium engineered flooring product with a plywood backing and a reasonable wear layer on top (4-6 mm) and wanted to check the possibility of using sliced veneers as a top layer to suit in-state capabilities.

3.2 Architects/interior designers

All participants declared that timber is commonly specified by them for flooring due to aesthetics, comfort, and sustainability. Other than one participant who is exclusively specifying solid floors (due to the high traffic exposure of educational/institutional floors) all others have specified both solid and engineered flooring for their projects. They indicated that previously mostly solid floors were specified but due to lower availability and rising costs, they have moved towards engineered flooring. All participants in the group expressed that high priority is given to specifying local timber due to sustainability, investment duration and capability for replacement of product during service but are constrained by costs, unavailability of locally manufactured engineered products, lack of clear information on chain of custody/ carbon stewardship. The participants unanimously agreed to the requirement of a product sourced and manufactured 100% in Australia and suggested that provision of technical data, good examples of installed areas and a pleasing narrative of the product life cycle is important in gaining consumer confidence. They further suggested that lighter colours with natural finishes, wider boards, prefinished products, and environmentally conscious products are currently important factors in decision making. Thicker top layers in engineered flooring products with the knowledge of possibility to re-sand provided them confidence in specifying a product. Unlike imported American/European Oak products, local products lack comprehensive data sheets such as available thicknesses/ widths, stewardship, installation descriptions and support in finding the right aesthetics which were the challenges faced by them when specifying a new product.

3.3 Specifiers/researchers

The participants acknowledged that Australian standards need to be updated to address the current resource base including plantation timbers and clarifications are needed in areas like hardness testing. They agreed that the standards should reflect reality and no dedicated standard exists for engineered flooring in Australia. There are publications that provide guidance to industry and consumers and some websites are commonly used to refer to timber species properties. They commented that plantation timbers have concerns which need consideration in existing and new standards as well as the consumer market. These include the presence of large knots, lower hardness but the increase of restricted access to native high-density timbers and global drive towards sustainability will support timber flooring from plantation timbers.

3.4 Hardness as a key indication of flooring performance

In terms of the use of Janka hardness as a selection criterion for flooring species, all three groups had different aspects of focus. Industry partners stated that Tasmanian Oak is regularly marked down against high density species such as Blackbutt and Spotted Gum. They identified that the nonexistence of a method to comprehensively guide the consumer to select timber for specific flooring applications hinders the introduction of novel plantation species to the flooring market. The requirement of a novel method to assess the performance of timber flooring species as fit-for-the purpose of a specific end use application was noted as important instead of the principal reliance on Janka hardness. Architects/interior designers focusing on domestic market did not generally have hardness consideration on Tasmanian Oak as it has known performance whereas commercial prospects required hardness considerations if high traffic exposure is expected. In common practice, architects/interior designers did not conduct direct reference to standards but referred to product and manufacturing specifications, and the compliance to Australian building codes. Timber technical data is obtained from websites providing information on state timbers (woodsolutions.com.au / tasmaniantimber.com.au/ timberqueensland.com.au). Even though past specification manuals refer to Janka hardness, specifiers and processors expressed that Janka test can be used to compare the hardness property of timbers and were aware that the published values might not represent the current resource base.

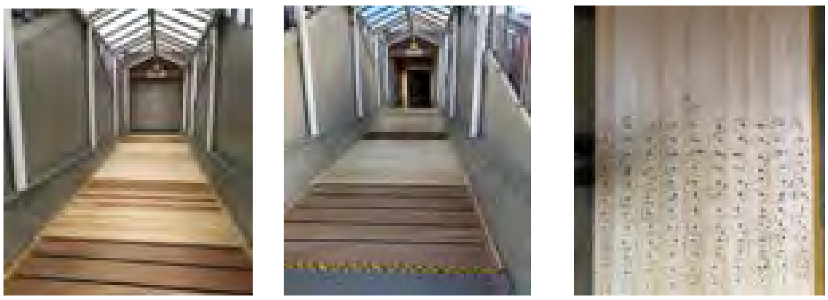
4. Discussion

The review of commonly referenced standards revealed the non-existence of an inclusive standard to determine the suitability of a timber for an expected end-use performance. The standards instead provide guidelines to methodologies in testing specific properties of timber such as hardness or dimensional stability. Therefore, the published studies have usually compared the results obtained for solid timber against the benchmark values provided in standards for wood veneer floor coverings with finished surfaces or have conducted the same test procedure for a commonly used flooring species as a control to assess the performance of a lesser-known species. It was further noted that different tests are conducted to suit the market; tests conducted in Europe are different to tests conducted in Australia. For instance, in Australia, Janka hardness is the main consideration in marketing a species for flooring applications, whereas in Europe, the most used flooring species is European Oak with moderate hardness, same as Tasmanian Oak in Australia. However, the hardness factor does not seem to affect the marketing of European Oak. Unlike Australian flooring market, which is still novel to engineered flooring products, the European market is more acceptable of engineered flooring products which governs majority of the flooring market share. In addition, there is greater expectations/standards in Europe to facilitate the provision of comprehensive technical data sheets.

However, with the decrease of native high-density timber and the drive for more renewable resources in construction will undoubtedly support changes in consumers and the use of plantation timber worldwide in value-added flooring applications. There is a significant shift in Tasmania where the present study is conducted, towards plantation timber, due to the predicted lower supply of native timber including Tasmanian Oak in near future. The interview process informed the authors of the expectations of the specifiers and processors if new engineered flooring products are to be developed from low-density plantation species, which were not comprehensively reflected by the standards. Based on this information, six prototypes of engineered flooring products with plantation *E nitens* top layers were developed and subjected to further testing (Figure 02).

Figure 2: Cross sections of the developed flooring prototypes (a-c: 6 mm plantation *E. nitens* on marine plywood substrates, d: solid densified *E. nitens*, e: 1.2 mm *E nitens* veneer on marine plywood, F: 1.2 mm *E. nitens* veneer on *E. nitens* plywood)

Other than laboratory testing of the prototypes following the guidelines from relevant standards, the prototypes were subjected to a long-term in-service trial installed at a high school premise in Tasmania exposed to moderate traffic conditions, and environment with high fluctuations of temperature and relative humidity with exposure to sunlight (Figure 3). The observations from in-service trial proved that the potential of using low-density plantation timber in domestic/light commercial engineered flooring applications in comparison to Tasmanian Oak, although the Janka hardness ratings were in the lower range (sawlog *E. nitens* Janka hardness: 3.7 kN).



(a) (b) (c)

Figure 3: In-service trials and testing of flooring prototypes ((a) solid flooring trial, (b) engineered flooring trial, (c) dynamic hardness test conducted on an engineered flooring prototype)

The evaluation of standards and information from interviews showed that there is a difference between what the standards specify and the market requirement. Although, the standard test methodologies can be used to determine the properties, a numerical basis such as Janka hardness value used to assess the suitability for a flooring application is somewhat misleading as it does not consider all factors important in performance and is also not suitable for engineered flooring composites. These types of quantitative analysis can be used to compare the characteristics of species for academic interest but may not be a reliable indicator for general service conditions. If the floors remain acceptable for the end use application, a comparatively large indentation or abrasion loss seems to be relatively unimportant, especially in domestic applications. Furthermore, in Australia comparatively lower density timber such as Tasmanian Oak, Baltic Pine and Hoop Pine have been used for many years as flooring species, based on known performance or general acceptance for common use. The flooring markets are commonly influenced by aesthetics, cost, and traditional knowledge. This makes the introduction of novel timber species and manufacture of engineered flooring products a market challenge, especially when there are ample solid and engineered imports available.

There is need in the Australian marketplace for new standards to be developed that incorporates the increased use and availability of engineered floors and new plantation resources. Furthermore, there is a general need to update standards and guidelines for timber species and timber flooring applications as the values used for standards are based on studies from 50 years ago where the age of the trees fell was much older. The authors identify the requirement to develop a generalised standard guideline for timber flooring species selection to assess the use of flooring to different end user applications and support the introduction of low-density plantation timber into domestic and light commercial applications.

5. Acknowledgements

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Wrapping it up: managing the successful hygrothermal supply and storage of timber boards.

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Abstract: For the last three decades Architects and Engineers have used one and two dimensional hygrothermal simulation tools to better understand the flow of heat and moisture through building envelopes. These tools have provided significant guidance regarding risks of moisture accumulation and mould growth. Many of the algorithms used in these tools have been established around the physical properties of solid wood products. Recent research has identified significant concerns from the design and construction professions regarding the moisture content of kiln dried solid wood products at construction sites. Changes in timber moisture content are inevitable as it progresses from end of production, through to storage, transportation and installation. Using WUFI® 2D modelling, this research utilises recorded under-wrap temperature and humidity data to investigate the likely change in timber moisture content that occurs due to the use of impermeable membranes for timber packaging. Packaging used for timber is typically impermeable and comes in a variety of colours and translucency. Previous research has proven that timber protected from the elements by impermeable plastic wrap can experience significant moisture content change from 11% to >30%, dependent on climate and storage practices. Such changes in moisture content are likely to promote mould growth and early stages of decay, rendering the timber unsatisfactory for building applications. This research seeks to prove that digital modelling can be used to reliably predict changes in timber moisture content prior to dispatch and improve management practices including the wrap membrane (thickness, colour and translucency) to mitigate supply claims and material loss.

Keywords: Timber; Moisture Content; Modelling.

1. Introduction

1.1. Timber supply and storage.

Timber is a product that has had higher and higher performance demands placed upon it as the world shifts towards more renewable building materials, and as a result, new products and treatments for those products are constantly being developed. Building materials are increasingly coming from larger single sources that produce larger volumes of product and thus often have further distance to travel to their

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final installation location. However, common to all wood products, timber may develop stain, mold, dimensional changes, splitting or decay when it is exposed to prolonged periods of heat and excessive moisture. According to AS 2796 (2006) and AS 2858 (2008) at installation, most timber is intended to be at or around an equilibrium moisture content (EMC) of 9-14% as this is appropriate to conditions found at most locations where the timber will be likely to be installed. EMC is the moisture content where timber neither gains nor loses moisture from the surrounding atmosphere. Installation of timber at an inappropriate moisture content can result in the deformation or partial destruction of the timber as it equilibrates to its environment and can potentially lead to loss of serviceability by swelling, shrinking or warping.

During transport, timber is usually packed using plastic (polyethene 100um) sheeting that is impermeable to air and moisture, with the aim being to maintain the moisture content of the timber as it leaves the timber mill, however, as well as protecting the timber, this packing can be detrimental to the timber depending on the mode and duration of transport, and storage conditions and duration at the destination as it can result in unequal amounts of moisture distributed throughout the packed timber, which occurs as “sweating” near the outer layers of the product, resulting in moisture induced defects such as visual defects, mould, and dimensional change. This is primarily driven by;

- The storage conditions and climate at the storage site,
- The level of additional protection given by any enclosure (if any) that the timber is stored in and
- Immediate environmental protection such as other objects surrounding the timber.

Past studies into the transportation of timber focus on export shipping to global markets and the EMC changes (Hopewell, 2004; Simpson, 2001; Simpson and Ward, 1991). Hopewell (2004) found that it was period prior and post shipping where timber EMC could reach up to 20% and temperatures up to 50 ˚C (p. 96, 94). The study recommends that appropriate packaging materials are used and refers to the need to insulate or regulate the transport conditions for high-value timber products. It mentioned that limited research existed to support industry with these decisions. Mould and condensation were only mentioned once or twice. Difficulty was experienced to find any followed up research or guidelines after 2004, until a recent study of the effects of different plastic wrappings on the temperature and on the humidity in transported timber (Kotlarewski and Nolan, 2022). Private communications with members of the timber industry suggest that the mould is planed off, discarded, or perhaps even used where it cannot be seen.

Today the type of material used to wrap timber in Australia varies according to the purpose of the timber being wrapped. Clear plastic is an emerging style of timber protection in the Australian supply chain as it allows for quick and easy identification of goods on a construction site. Other reasons that the wrapping of timber is currently being examined relate to avoiding single use plastic (Naylor Love, 2021).

1.2 Hygrothermal modelling.

If it is known that packs of timber cannot be stored under ideal conditions, it needs to be protected appropriately, and part of that may include planning for additional shelter or wrapping the timber appropriately. To understand how this may be planned better, Hygrothermal modelling might be used. Hygrothermal modelling consists of the computational calculation of the movement of moisture driven by temperature through a building material. There are multiple hygrothermal modelling packages which are currently on the market which can perform hygrothermal analysis but not all of them are capable of two dimensional transient/dynamic state hygrothermal simulation. WUFI® 2D (2023) was selected for use in this case as it has been previously used. WUFI® 2D (2023) is capable of simulating hygrothermal conditions and providing resultant information in several ways. Three-dimensional graphs in video format, one frame per hour of calculated results for four data types: moisture content, temperature, humidity, and vapour pressure. In addition to two-dimensional graphs showing time series data for single location calculated data or a two- dimensional area of material.

WUFI® 2D allows us to display an isopleth simulation for individual packs as well as locations within each two- dimensional simulation. An isopleth is a boundary that defines all combinations of temperature and relative humidity that permit a particular mould growth rate(Viitanen *et al.*, 2010). This gives us the ability to show the potential for mould growth during the simulated storage period.

2. Method

This experiment was conducted in two parts. The first part took place under a National Institute of Forestry and Product Innovation grant NT045, which consisted of testing of wrapped packs in different scenarios and wrapping formats (Kotlarewski and Nolan, 2022). The original experiment included three different types of plastic wrap, however for the purpose of this preliminary modelling research only the data from the clear plastic wrap timber packs was used. The second part was hygrothermal simulation attempting to replicate the results obtained in the first part.

2.1. Storage of wrapped timber

This research trial began by comparing primary data from the use of clear plastic wrap to protect timber in two climate zones; Tasmania (climate zone 7 – CZ7), and Queensland (climate zone 2 – CZ2) as defined by the National Construction Code (NCC, 2022). There were other wraps examined however for the purpose of this paper we are examining the in-service trials with the WUFI® 2D (2023) software. Four packs of E. *nitens* timber were dispatched for monitoring the change in timber MC over the summer of 2021-2022. These packs were 600 x 600 x 1200 mm. The packs were irregular in length to a ‘typical’ pack as they were cut in half to compare like timber in an external and internal setting. This smaller pack size also allowed for 300mm to be cut off from each end of the ‘typical’ pack material. Each pack consisted of random width boards dressed 25 mm thick. They incorporated temperature and humidity sensors for monitoring environmental conditions at the top of the pack, underneath the wrap (Figure 1). Additional sensors were placed on the exterior of the pack for comparative data. The type of sensor used was a Minnow-1.0TH. In addition, the packs also consisted of five sample boards to determine the change in MC prior and post the monitoring period. The sample boards provided the initial MC conditions of the timber in the assembled pack and were used to determine the change in MC at the trial’s end. These were marked with paint at each end and positioned on the top layer middle, centre layer east and west side, middle of the pack, and bottom layer middle (Figure 1).

Figure 1. Five sample boards positioned in the timber pack.

All plastic wrap was supplied by Industry who frequently use the plastic to protect their product during transit to the customer. The plastic wrap was brand new, the packs were wrapped on the base and over the top to exclude water pooling with overlapping wrap on the ends and both sides and tapped at each end to prevent water penetration. This follows industry practice in Tasmania (Figure 2).

Figure 2. Clear and Opaque wrapped timber in-situ

2.1.1. Packs, their location, protection, and condition monitoring

For the duration of the data collection the clear packs were stored at an industry facility at Mowbray, a northern suburb of Launceston in CZ7, Koppen Climate zone Cfb (Oceanic) and at the Queensland Department of Agriculture and Fisheries (QDAF) facility at Salisbury, Brisbane in CZ2, Koppen Climate zone Cfa (Humid subtropical). Each site included an internal storage area and an exterior yard, which were largely open to ambient conditions. For each site, one pack was placed in the exterior yard and oriented north-south and the other pack was stored in the interior area. The Queensland packs were dispatched from CSAW's Newnham workshop on December 7, 2021, and arrived at QDAF on January 5, 2022. Additional sensors were installed to the dispatched packs (exterior to the wrapping) to monitor the environmental conditions during transit.

The packs were exposed on each site from 14/12/21 in Mowbray, Tasmania, and 5/01/22 at Salisbury, Queensland, and remained exposed to 9/05/22 and 5/05/22 respectively (Figure 3). The Tasmanian packs were then broken down at CSAW's Newnham workshop, while QDAF recovered and processed the sample boards at the Salisbury workshop. All MC assessment was done using the oven dry method according to AS/NZS 1080.1:2012. In addition, all sensors form the Queensland packs were returned via return mail to CSAW and the data was recovered from the sensors and assessed.

Figure 3 - Pack storage locations, Tasmania (left column) and Queensland (right column) storage sites

2.2. Hygrothermal simulation of wrapped timber

Existing data on E.nitens was used to populate materials data, any missing datapoints were substituted from species with similar properties.

3. Results

3.1. Storage of wrapped timber

Three wrapping techniques were trialled within the experiment however only the results for the packs of timber wrapped in clear plastic will be considered for the purposes of this paper. Two primary results were obtained from the study, temperature and relative humidity within the packs, and MC of individual boards at predetermined locations within the packs.

3.1.1. Tasmanian site results

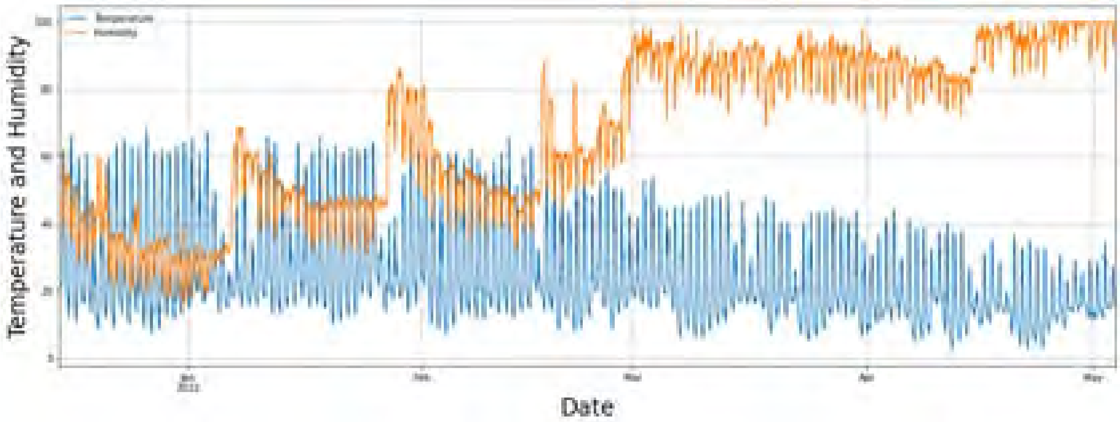

Figure 4 - Temperature and humidity, clear wrapped pack stored externally, Tasmanian site

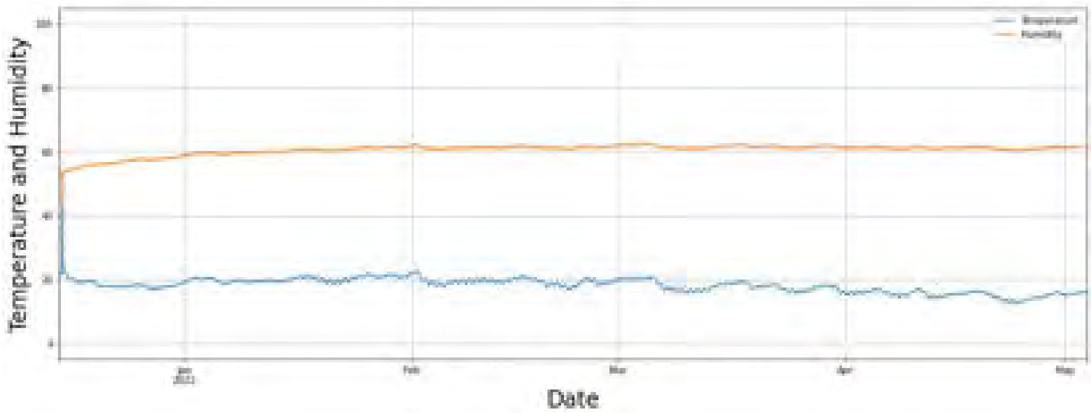

Figure 5 - Temperature and humidity, clear wrapped pack stored internally, Tasmanian site

Table 27 - Board MC change within clear wrapped timber pack, stored outside at Launceston, Tasmania

Sample board position	Change in exterior stored timber MC for each sample post-trial	Change in interior stored timber MC for each sample post-trial
Initial average MC %	(11.6)	(11.5)
Top Middle	+20.6	-0.1
West	-0.7	-0.4
Centre	0.0	-0.2
East	-0.5	-0.7
Bottom middle	0.1	0.0
Final average MC %	(15.5)	(11.3)
Change in average MC for five sample boards before and after trail	(+3.9)	(-0.3)

3.1.2. Queensland site

In the case of the pack of timber in Queensland stored externally, the datalogger failed after 14 days after installation so data is only indicative of that initial period. This is not shown in a graph here however, Figure 6 shows the result of the internally stored timber pack.

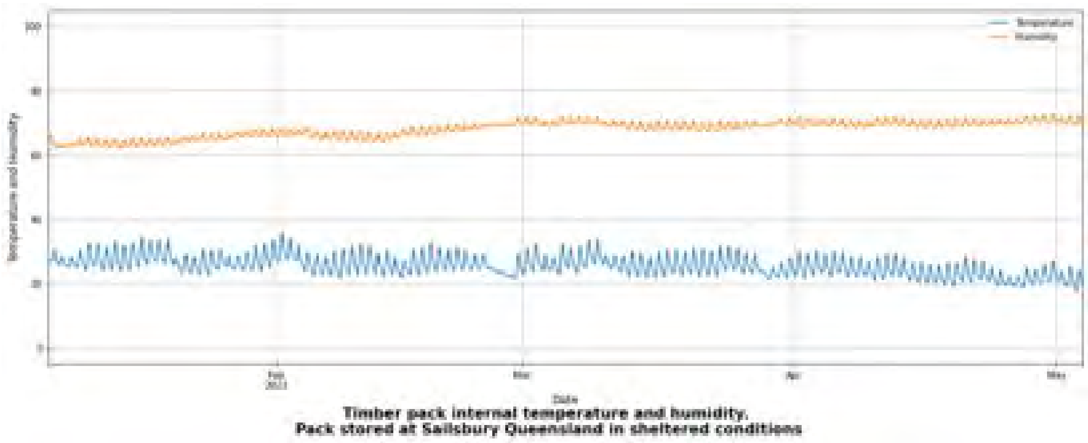

Figure 6 - Temperature and humidity, clear wrapped pack stored internally, Queensland site

Table 28 – Board MC % change within clear wrapped timber pack, stored outside at Sailsbury, Queensland.

Sample board position	Change in exterior stored timber MC for each sample post-trial	Change in interior stored timber MC for each sample post-trial
Initial average MC %	(11.7)	(11.0)
Top Middle	+27.7	-0.3
West	+8.3	+0.3
Centre	+9.4	+0.2
East	+4.4	+0.3
Bottom middle	+4.5	+0.6
Final average MC %	(22.5)	(11.2)
Change in average MC for five sample boards before and after trail	(+10.9)	(+0.2)

3.2. Hygrothermal Modelling

Environmental data for the simulation was obtained from sensors placed on the outside of the pack. Simulations were run for the same scenario with one separate variable – impermeable wrap and permeable wrap. Figure 7 shows three dimensional graphs showing moisture within a short orientation cross-section of the clear-wrapped timber pack at the end of three months simulated exposure. Moisture is shown on the vertical axis, with the bottom of the pack shown at bottom left side of the graph.

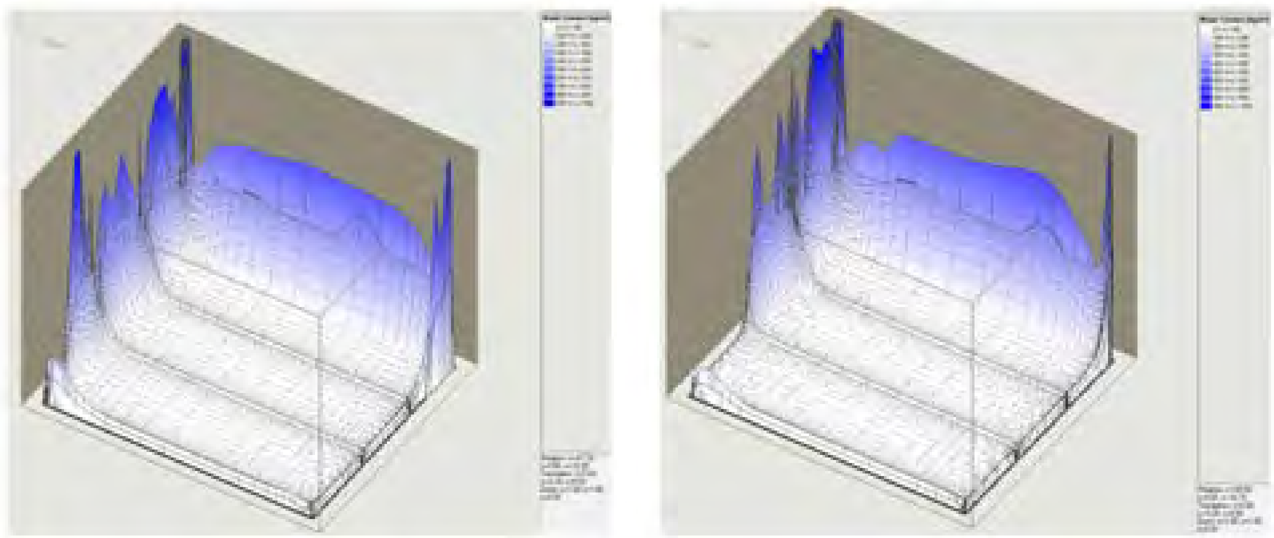

Figure 7 – Modelled MC at end of exposure trial – exterior stored timber rack, impermeable (left) and permeable (right) wrap, Launceston

Table 29 - Results for Experimental exposed pack, simulated impermeable and permeable wrap, Launceston

Sample board position	Change in exterior stored timber MC for each sample post-trial	Change in exterior stored timber MC for simulated pack – Impermeable wrap	Change in exterior stored timber MC for simulated sample locations – permeable wrap
Initial average MC %	(11.6)	(11.3)	(11.3)
Top Middle	+20.6	+39.3	+41.2
West	-0.7	+8	+6.8
Centre	0.0	0.0	0.0
East	-0.5	0.1	0.1
Bottom middle	0.1	0.6	3.9
Final average MC %	(15.5)	(15.4)	(15.2)
Change in average MC for five sample boards before and after trail	(+3.9)	+4.1	+3.8

In Figure 54, Temperature is graphed against Relative Humidity %. Throughout the simulation, both these figures are calculated and are shown as point on the graph in a colour range from dark green to light yellow to represent the passage of time. The two lines in each graph represent isopleth limits that represent the lower limits favourable to mould growth. If a point representing simulated conditions is above the isopleth lines, mould growth will be likely to occur at that point.

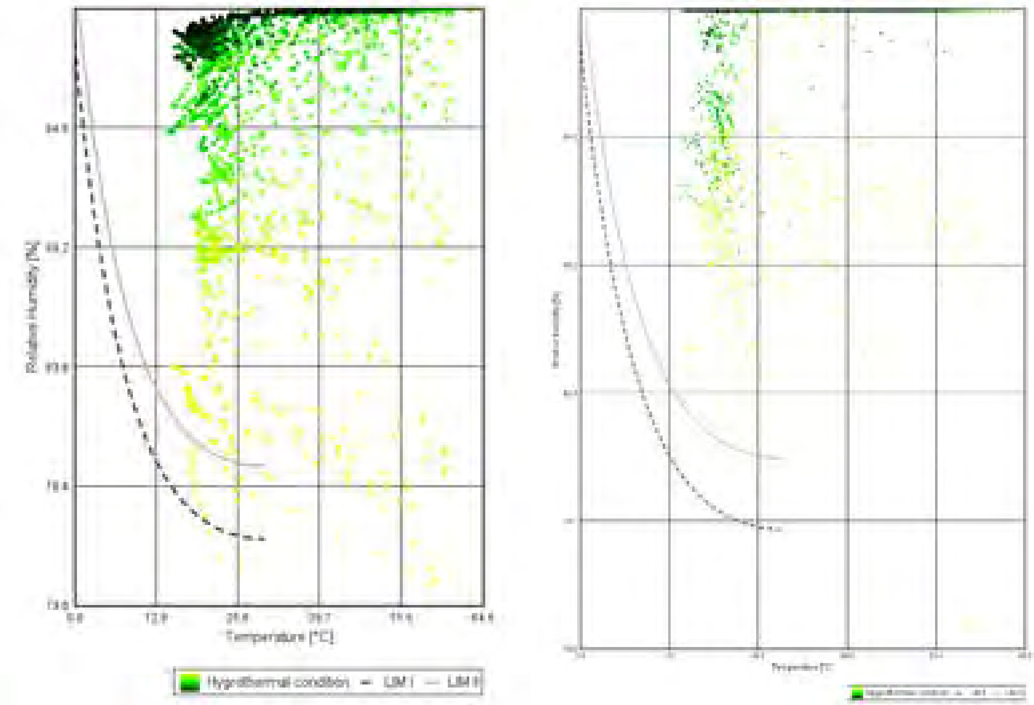

Figure 54 – Isopleth diagram for top centre board in simulated pack with impermeable (left) and permeable (right) membrane.

4. Discussion

4.1. Timber wrapping trials

Figure and Figure 55 show both the monitored temperature and humidity from each site as well as daily rainfall. Daily solar input was also considered but it’s impact on microclimatic conditions inside the pack was much less obvious than that of daily rainfall.

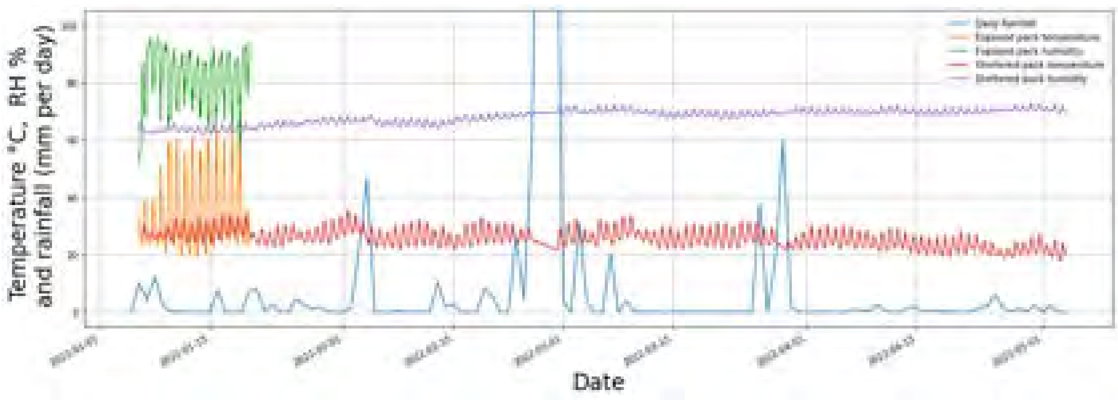

Figure 9 - Temperature and humidity, Internal and externally stored packs, Queensland site

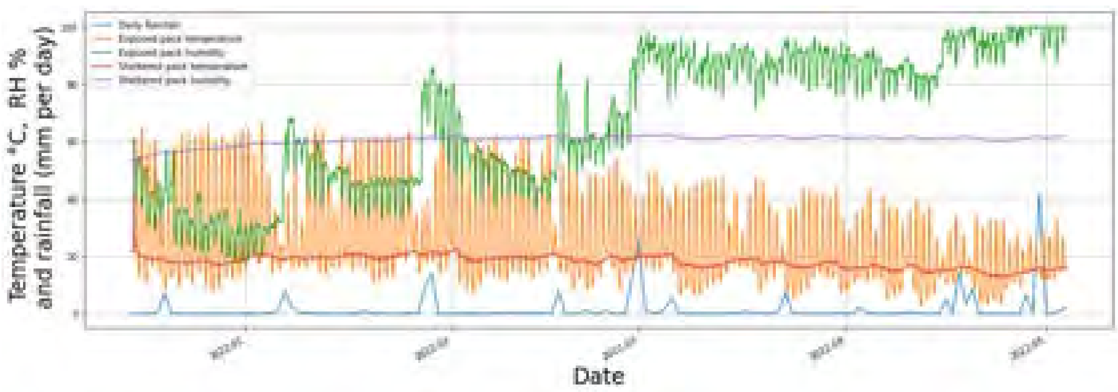

Figure 55 - Temperature and humidity, Internal and externally stored packs, Tasmania site

Little information can be gained from the datalogger that failed inside the pack stored outside at the Queensland site other than the initial conditions within the pack.

Timber stored at the Tasmanian site shows significant correlation between rainfall events and increases in humidity inside the pack, potentially indicating that there was significantly more airflow through the pack than originally assumed, as moisture ingress should not be possible through the impermeable wrap.

Relative humidity within all four packs is above 60% relative humidity by the end of the trial and in some cases is above 70% at the start of the trial. Mould growth on building materials occurs within a range of favourable moisture and temperature conditions (Viitanen and Ojanen, 2007), and the timber within each of the packs stored in exterior environments had unacceptable levels of mould growth, particularly on the top layers of timber where condensation had occurred. Mould growth was both observed on the timber stationed in Queensland and in Tasmania.

4.2. Hygrothermal simulation

These initial simulated and experimental conditions appear to be broadly comparable (Table 3), indicating moisture accumulation in the top and side layers of timber where solar radiation induces condensation the most.

Moisture content comparison between the simulations with non-permeable and permeable membranes displayed some reduction in moisture in the simulation with the permeable membrane wrapping but did not completely eliminate the problem. Reasons for this might be that permeable materials are not sufficient to eliminate the condensation issue or it might be that some of the values applied in the simulation were not appropriate.

The Isopleth diagrams shown in Figure 54 show mould growth risk throughout the simulated period. In both the non-permeable and permeable wrapped packs of timber, the mould index was well above the upper isopleths representing risk of mould growth.

5. Conclusion

Visible decay in the form of mould and fungus that is present within building materials is a good sign that those building materials may not be suitable for their intended use, and if a wrapped pack of materials has been stored for sufficient time for fruiting bodies to appear, the remainder of the pack may well be inoculated by airborne spores from the initial decay outbreak which might contribute to increased decay rates in the completed structure when conditions become favourable.

Some fungal species produce mycotoxins that cannot be detected without laboratory equipment and as with food, even when contaminated material is removed, toxins can still be present (Kasza *et al.*, 2022). Furthermore, surface planing of timber can leave fungal hyphae that penetrate deeper into the timber than planing but are invisible without microscopic examination (Pernilla *et al.*, 2013). Given these factors, removal of mouldy timber from affected packs does not represent an ideal solution. Prevention of the problem by utilizing proper storage is preferable. Currently, Australia is having some significant issues with toxic moulds and fungi (Dewsbury *et al.*, 2021), with several of the most toxic moulds (*Aspergillus spp*) also being found within decaying timber at varying rates.

The results of the hygrothermal simulation for this trial produced results that are comparable to those shown by the physical trials, however it is likely that more specific data that was used in this case will be required to make the simulations more meaningful. Recommendations for further investigations includes updating WUFI specific timber species data, air change rates in the timber packs, more experimental data, different wrap properties and a mould species survey. In addition, examining the difference of impregnated timber is to non-treated timber. This study has shown that the issue of storing and transporting timber and the possible problems that may being caused with both visible and invisible mould on timber used potentially in construction can be reliably modelled to assist in the management and use of new wrap materials for timber packs.

6. Acknowledgments:

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Future of work: positioning home offices in the work landscape

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Abstract: The COVID-19 (coronavirus disease) pandemic shook the world by storm and affected human living in various ways and at multiple levels, politically, socially, and economically. The changes emerging from workplaces of new working habits could be considered one of the most significant transformations. Although working from home has become the new norm globally, more knowledge is needed about the impact of working from home. There is a significant amount of literature on the effects of working from home on productivity and health/well-being. In contrast, the physical and environmental implications of remote work require further research. This paper begins by examining the historical context of working from home and its current position in the modern work landscape. It then sets out a proposed study to investigate the physical aspects of home working, such as space design, adaptation and user experience of home workspaces, in order to understand whether fully or partly working from home has benefits in both personal and environmental terms, focusing on Wellington, New Zealand, as the context. This study will be exploratory and inductive. Ultimately, the proposed study aims to develop guidelines for optimising home office workspaces and environments.

Keywords: COVID-19, Home Offices, Space Design, Adaptation, User Experiences, Sustainability

1. Introduction

The concept of working from home or remote work has a long history, dating back to ancient civilisations, where people ran their businesses from their homes. Before the Industrial Revolution, skilled workers like weavers and spinners operated from home-based workshops, which led to this way of working being named 'cottage industries' (Mansson, 2022). While the Industrial Revolution led to a shift towards centralised workplaces in factories, certain occupations like tailoring and farming continued to be practised from home. In the late 19th and early 20th centuries, telecommunications technologies like the telephone and telegraph enabled some professionals to work remotely to a limited extent (Gillen & Dantsiou, 2019). However, with advancements in computing and internet technologies in the late 20th century, remote work became more widespread and accessible (Cunliffe & Raymond, 1997). In order to understand the future of the home office, it is essential to understand the history of working from home when it comes to the modern home workplace.

This paper begins by examining the historical context of working from home and its current position in the modern work landscape. It then sets out a proposed study to investigate the physical aspects of home working, such as space design, adaptation and user experience of home workspaces, in order to understand whether fully or partly working from home has benefits in both personal and environmental terms, focusing on Wellington, New Zealand, as the context.

1.1. History of workspace

Throughout history, how people work has evolved from ancient civilisations to the current era of hybrid work, where employees partially work from home and partially in a traditional or active base office. Work has always been essential to human life, from hunter-gatherer societies to complex civilisations. There are various types of modern work arrangements, and office work is one of the most common and well-discussed forms of work, especially when transitioning to remote work.

The idea of offices can be traced back to ancient times, as Roman towns had forums composed of various establishments, including offices (Kranzberg & Hannan, 2023). Still, during the pre-industrial era, this was an exception rather than the norm, as homes were commonly used for domestic and work purposes. In the 18th century, purpose-built office buildings emerged in Britain, such as the Old Admiralty Office (1726) and East India House (1729) (Kranzberg & Hannan, 2023).

Throughout history, the design of office buildings has undergone numerous transformations to cater to the changing needs of employees. As a result of the Industrial Revolution, the rise of office workers led to the development of "white-collar factories," heavily influenced by Frederick Taylor's principles of promoting efficient work (Meel, 2000). In the 1920s, American skyscrapers emerged with impressive glass and steel structures celebrating engineering excellence. Office design during this period was characterised by large open floor spaces with desks facing in the same direction (Meel, 2000).

In the 1960s, the Bürolandschaft concept was introduced, emphasising employee comfort by providing various work environments. This era also saw the emergence of "Action Furniture," offering privacy and opportunities for interaction (Herman Miller, 2023). However, the 1970s saw the rise of cubicles, prioritising productivity and cost-efficiency over employee well-being (Meel, 2000). Some architects and clients sought to create more human-centred open-plan spaces, deviating from traditional cubicle interiors. By the 1990s, technological advancements, such as mobile phones and laptops, allowed for greater location and working hours flexibility, leading to innovative ideas about the perfect office environment (Gripenstraw & Saini, 2020).

The 2000s saw a shift towards open-floor office plans and the rise of coworking spaces. During this period, the term "coworking" was coined, referring to shared workspaces that gained popularity. This trend allowed employees to work in alternative spaces outside traditional offices, like coffee shops and shared spaces, further diversifying the work environment. In the 2010s, the focus was on integrating technology into workspaces and emphasising the relationship between employees and their work environments. Hot-desking and flexible desk spaces became increasingly popular, catering to the growing trend for remote working (Gillen & Dantsiou, 2019).

However, these trends were significantly impacted by the COVID-19 pandemic, which caused significant disruptions in many aspects of life. At the beginning of 2020, governments implemented lockdown restrictions and safety measures to control the spread of the virus. As a result, millions worldwide shifted from working in traditional office environments to working remotely from home. Once considered niche, this practice has become the new norm for many industries and professions (Cuerdo-Vilches, et al., 2021). Together with home-schooling, which was also commonly required during the lockdowns, office-type activities entered homes at an unprecedented rate. The question is, how much of this post-lockdown heritage will be retained in the years to come?

According to Forbes Advisor (Haan & Main, 2023), the computer and IT sectors have emerged as the leading industry for remote work in 2023. Other industries like marketing, accounting and finance, and project management have adopted remote work using digital tools and platforms to ensure seamless operations. The medical and health industry has also moved towards remote work, largely due to the increasing popularity of telehealth services and the digitisation of health records.

The development of workspaces has been shaped by factors such as societal changes, technological advancements, and a focus on employee well-being and productivity. This journey through history has significantly impacted the current and future state of the workplace.

1.2. Working from home and the future of the workplace

Workspaces have changed, reflecting more significant societal and technological shifts. The COVID-19 pandemic is a clear example of how external factors can impact our work. Before the pandemic, shifts and trends were already occurring in how people approached their work and how businesses organised their operations.

According to a survey conducted by GetApp in November 2019 (before COVID-19), out of 912 respondents who reported full-time employment in the United States (Capers, 2020), 78% worked remotely occasionally, 58% worked remotely at least once a month, and 36% worked remotely at least once a week. Trends noted by the survey included increased interest in remote work, the rise of co-working spaces, technological advancements, work-life balance discussions, and exploring alternative work arrangements. The pandemic has forced many people to switch to working from home, accelerating trends such as co-working and remote work that were already emerging. (Oygür, et al., 2022).

According to WFHResearch in a study done in August 2023 (Barrero, et al., 2023), 12.2% of full-time employees in the USA worked from home, indicating a significant increase in remote work environments. Additionally, 29.3% of USA employees have adopted a hybrid work model, which combines working from home and the office. The survey concluded that this model provides flexibility while ensuring a physical presence in the workplace.

In the future, workplaces are expected to adopt a hybrid model that combines remote work with office spaces in different locations. The pandemic has shown the benefits of remote work, including reduced commute time and the environmental impact of commuting, more flexibility, better work-life balance and access to a broader pool of talent where employers can tap into a wider talent pool by hiring remote workers from different geographic locations. However, it has also highlighted some challenges, such as loneliness, unclear boundaries between work and personal life, and the importance of socialising. It is predicted that companies will embrace a more adaptable work model, where staff can work remotely while having the chance to meet in person and build teamwork in the office. This mixture of approaches demands a thoughtful design of homework areas that prioritises establishing versatile environments that facilitate remote and in-person work (Cuerdo-Vilches et al., 2021).

2. Study of home office spaces based on current research

Since 2020, studies have been conducted to investigate the future of remote work. This paper analyses existing research and identifies areas that require further examination.

Between mid-2021 and early 2022, a Global Survey of Working Arrangements (G-SWA) was conducted in 27 countries, including New Zealand and Australia (Aksoy, et al., 2022). The survey collected individual-level data on demographics, earnings, current work-from-home (WFH) arrangements, employer plans, and worker preferences regarding WFH after the pandemic. The survey was carried out in two stages. The first was in late July/early August 2021, and the second was in late January/early February 2022.

The survey found that individuals prefer to work from home for 1.1 to 2.3 days per week (Aksoy, et al., 2022). When employees who currently worked from home for one or more days a week were asked how they would react if their employer required them to return to the worksite full-time, some of them expressed their intention to resign or search for a job that would allow them to work from home one or two days a week. Remote work saves time on commuting. Commute times vary by country, with the USA and Serbia having the shortest at 48 minutes and India and China having the longest at 93 and 96 minutes, respectively (Aksoy, et al., 2022). Based on the data, it appears that women generally value the ability to work from home more than men “except in a few countries” (Aksoy, et al., 2022). This trend is also seen among individuals with higher levels of education. Additionally, both men and women who have children under 14 tend to prioritize the option to work from home when possible.

The Microsoft New Future of Work Report 2022 (Teevan, et al., 2022) provides a comprehensive overview of recent research on hybrid work. It brings attention to key themes that have emerged in the past year and brings older research back into relevance. This report includes a vast number of researchers from Microsoft, LinkedIn, and GitHub. The collaboration has established the New Future of Work Initiative, the most extensive research undertaking in the history of Microsoft.

One research article in the Microsoft New Future of Work Report 2022 (Subramanian & Gilbert, 2021), “Returning to the office will be Hard”, states that 47% of American workers prefer to work in a hybrid model, 21% want to return to the office full-time, and 32% want to stay fully remote (Mizen, et al., 2021). Another research study in the same report shows that compared to white men, people of colour and women are slightly more in favour of remote work.

The Microsoft New Future of Work Report 2022 also examines the analysis done by Deloitte Insights (Evans-Greenwood, et al., 2021). This found that in the era of hybrid work, the most important relationships are between digital technologies and physical space. There are three possible ways that digital and spatial technologies can interact. According to the article, these are;

- The digital workplace – the digital overlay that enables the physical work experience.
- Working digitally – work for which physical space or place is unnecessary, as it is done digitally.
- The virtual office – the technologies (tools and media) that allow people to work individually and as a team anywhere, anytime, anyhow.

In 2020, PwC researched the effectiveness of remote work by surveying 120 US executives and 1200 US office workers (PwC, 2021). Before the COVID-19 pandemic, only 39% of these employees wanted to work from home. However, 77% of workers reported enjoying remote work during the pandemic. After the pandemic, this number dropped to 55%, still much higher than the original 39%, suggesting some people are finding home working comfortably. This indicates that a considerable number of people found the experience of working from home offered certain benefits. In this survey, individuals with 0-5 years of professional experience preferred working in the office more frequently. Of this group, 30% would prefer to work remotely no more than one day a week, whereas only 20% of all respondents shared this preference. Additionally, those with less experience felt less productive when working remotely, with 34% reporting this sentiment compared to 23% of more experienced workers. They also valued meeting with managers and participating in company training programs (PwC, 2021).

The article “Working from home can save energy and reduce emissions. But how much?” by the International Energy Agency (Crow & Millot, 2020) emphasized that the shift towards remote work could impact sustainability and the environment in several ways, both positively and negatively. Reduced carbon emissions, less traffic congestion, energy savings, and reduced office space demand could be considered positive impacts, and increased residential energy use, the digital carbon footprint, and e-waste generation could be considered negative impacts. According to their analysis, individuals who drive to work can decrease their carbon dioxide (CO_2) footprint by working from home if their commute is longer than 6 kilometres. However, if their commute is short or they use public transportation, working from home may increase CO_2 emissions due to additional home energy usage (Crow & Millot, 2020).

Although there is extensive research on the advantages of remote work, there has been limited focus on studying home office spaces, their design, adaptation, and user experience. Yet, the future of how home offices will integrate into homes will influence many aspects of both the future and sustainability of the increase in working from home.

2.1. Space design

A well-designed home office space is crucial for productivity and well-being while working remotely. Research shows that a well-lit, ergonomic workspace with comfortable furniture positively impacts task performance and cognitive function (Clements-Croome, 2006). Incorporating biophilic design elements like plants and natural materials enhances creativity, reduces stress, and increases job satisfaction. A flexible layout allows for customisation and adaptation to individual preferences, maintaining motivation and focus (Browning & Cooper, 2015).

During the lockdown period in 2020, a study was conducted in Spain using a mixed-method approach (Cuerdo-Vilches, et al., 2021). The study's primary objective was to assess the characteristics of home working spaces. In addition to the questionnaires, participants also provided photographs and narratives. The study gathered 1800 responses, over 200 images, and texts related to home office environments. There are very few comprehensive studies that document the spatial analysis of working from home during the early lockdown period like this one.

According to participant ratings, the most essential aspects of their remote workspaces were having good daylighting (53%), a spacious room (48.8%), and a comfortable room temperature (46.1%). Other factors like furniture (33.8%), surface finishes (33.5%), and external views (31.6%) were also considered important. Furthermore, the participants found the quality of windows, including their solar control devices (28%) and noise insulation (27%), satisfactory.

These findings prompt further discussion about the most satisfactory work environment for remote work and the design of the home office space. Moreover, they give a further opening to discuss the features that need any improvements and additions. Continuous dialogue and adaptation are crucial for maintaining this new work model and ensuring its long-term impact on the working landscape by aligning with the evolving needs of employees and companies.

2.2. Space adaptations

The same study (Cuerdo-Vilches, et al., 2021) showed that many participants had to work from home and turn their living spaces into functional offices due to the pandemic. Before the lockdown, 42.2% of the respondents had no designated workspace in their homes. As a result, remote workers had to either find a space at home for work during the lockdown (33.7%) or to work temporarily in various areas of the home based on their household circumstances or spatial arrangements. This required some adjustments, such as creating temporary workstations and investing in ergonomic furniture. However, according to this study, having a separate home office space has improved many people's job satisfaction and work-life balance.

A survey conducted at the University of Cincinnati in late 2020 (Davis, et al., 2020) revealed that most of the faculty (n = 4,200) and staff (n = 4,300) had used some form of office chair (58%), although not necessarily a good one. Others used dining chairs (27%) or non-chair options like a bed or couch (15%). Most workers (88%) sat at a desk, while a small portion (7%) sat at a table, such as a dining table. Out of those who worked at a desk, four people had a standing workstation, and one had a treadmill workstation. The researchers concluded that home offices must prioritize ergonomic principles to safeguard the well-being of employees in the long run. As remote work continues to be a viable option for a significant number of workers, companies need to offer suitable provisions to ensure the comfort and safety of their employees.

2.3. User experience

The experience of working from home after the COVID-19 pandemic varies greatly depending on personal preferences, job roles, and individual circumstances. While some people have found remote work to be a positive and convenient change, others have faced challenges and made adjustments. According to the results of the New Zealand National Survey (O'Kane, et al., 2020): Initial Report July 2020 about Remote Working during COVID-19, the main difficulty faced by those surveyed was the inability to disconnect from work (35%). Additionally, one-third of respondents found communicating and collaborating with their colleagues challenging. Some also reported struggling with motivation and being distracted by home responsibilities, such as caring for children. This research indicated that participants noted that working from home eliminated the need for daily commuting, resulting in cost savings. They also appreciated the freedom to manage their own time and found that they were more productive.

It is essential for companies to thoughtfully design and implement remote work policies based on these findings. Customised and flexible approaches are necessary to accommodate the various needs and difficulties that remote workers might encounter. Offering support for establishing boundaries, keeping in touch, avoiding distractions, and promoting mental well-being can help foster a more favourable remote work environment for staff.

3. Anecdotal information

The anecdotes gathered in the initial stages of this research suggest that the combination of a view of a natural environment and a dedicated workspace can influence individual preferences to work from home in the future. The presence of nature and a designated work area might also affect overall satisfaction and productivity, leading to the continuation of remote working. However, it seems that this does not apply to all. Some people who lack suitable workspaces appear to choose and prefer to work from home, while others with comfortable workspaces seem not to enjoy these. This suggests that aside from the physical workspace, other aspects (perhaps personality or stage of life) might also affect personal inclination towards remote work.

4. Discussion

The literature review showed that many people have continued to work from home, underscoring the importance of home office spaces. The anecdotes gathered in the initial stages of this research suggest that physical space can influence individual preferences for working from home both now and in the future. Despite their growing popularity, there needs to be more worldwide understanding of home office spaces, including their arrangement, layout, furniture, overall environment, and the sustainability aspects of having home office spaces. The proposed study of home office spaces in New Zealand will be conducted under three stages: the first stage will identify the research gap, the second stage will be data collection and data analysis, and the final stage will be the conclusion and reporting.

The proposed study is exploratory and inductive, with the goal of understanding how remote work affects physical spaces in the post-pandemic era. It will use an ethnographic approach to collect data at a single point in time, employing a non-probability sampling strategy. The study will use qualitative methods, such as semi-structured interviews and photographic evidence, along with quantitative data analysis to determine the sustainability impact of remote work. This cross-sectional study aims to provide new insights into how remote work has transformed physical spaces, considering both personal experiences and objective changes to home workspaces.

When evaluating a home office, there are numerous factors to consider. As part of the research, semi-structured interviews will be conducted to gather information about the physical workspace of a home office. The aim is to gain a general understanding of what a home office space looks like, as there is limited secondary data available in both the global and New Zealand contexts. During the interviews, participants will be asked about their experiences, changes made to their workspace, lighting, acoustics, privacy, furniture, equipment, productivity, and their opinions on the future of work. Photographic evidence of the home office will also be collected and analysed to gain further insight.

To properly assess the impact of remote work on sustainability, it is important to take a comprehensive approach that considers both hybrid and full-time office work. This assessment should consider various factors, such as energy, transportation, waste, and technology. The focus of this study is to examine the energy consumption and commuting associated with remote work. During the interviews, data will be collected for each life cycle stage. After that, energy and commute consumption will be quantified, emissions will be calculated, and the data will be normalised into CO_2 equivalents. The overall environmental impact will then be assessed. Finally, a comparison will be made between the home's emissions usage and that of a typical office setting.

In the discussion and reporting stage, guidelines will be developed for optimising home office workspaces and environments. In the third stage, the physical characteristics of home office spaces will be classified to identify similar patterns, unique situations, and commonalities among different home office spaces. The Life Cycle Energy Assessment (LCEA) will evaluate the positive and negative effects of remote work on sustainability. The findings will guide future sustainable practices in remote work. Based on these findings, guidelines will be developed for optimising home office workspaces and environments in Wellington, New Zealand.

There are some limitations and assumptions regarding the proposed research study. Firstly, there is a concern about sample bias, as the data collected may only partially represent a part of the workforce, given that participation was voluntary. Secondly, due to the scope of this study, it may not be possible to conduct an in-depth analysis of specific aspects of remote work. Finally, it is important to note that the findings of this study may only apply to certain industries or geographical regions, as the research will be conducted in Wellington, New Zealand.

5. Conclusion

In conclusion, the COVID–19 pandemic changed various aspects of human life and society, and how people work experienced a significant transformation. Working from home/remote work became the new norm of society. This paper examines existing research on home office space design, adaptation, and user experiences in the pre- and post-pandemic landscape.

As examined in the paper, throughout history, the workspace has evolved with social/ political changes, technological advancements and to address employee well-being and productivity. Workplaces have undergone significant changes from ancient civilizations to the modern era of hybrid work. Since 2000, there has been a trend towards remote work due to technological advancements. The COVID-19 pandemic has further solidified this trend, making remote work a more permanent solution for many companies.

Remote work arrangements have impacted home office experiences, affecting autonomy, lifestyle sustainability, and flexibility. While reduced commutes and better work-life balance are advantages, virtual social connections and isolation pose challenges. Optimizing home office space is crucial for employee well-being and productivity in the new hybrid work model.

While there have been many studies conducted on working from home, this paper summarizes the findings of these and proposes a new analysis of workspace design, adaptation, and user experiences. One area to explore is the impact of available workspace in the home on the preference for remote working and whether personality factors also play a role. Additionally, it is important to take a comprehensive approach when assessing the sustainability impact of remote work, considering both hybrid and full-time office work.

It is important to conduct longitudinal and comparative studies on home office spaces to improve remote work environments after the pandemic. These studies should explore design changes, psychological and social factors, management practices, sustainability, and technological advancements. The proposed investigation of home-office spaces in Wellington, New Zealand, is a first step towards this goal.

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