ASA 2022 Proceedings

Architectural Science and User Experience: How can Design Enhance the Quality of Life

55th International Conference of the
Architectural Science Association (ANZAScA)
1-2 December 2022, Perth, Australia

Editors
Dr. Parisa Izadpanahi
Dr. Francesca Perugia

The Architectural Science Association and Curtin University

Edited by
Dr. Parisa Izadpanahi and Dr. Francesca Perugia

Published by
The Architectural Science Association (ANZAScA)

Hosted by
School of Design and Built Environment, Curtin University, Perth, Australia

Printed in Perth, Western Australia, Australia
Designer: Jin Zang and Francesca Perugia

Please cite papers from these proceedings as follows

Lastname, A. (2022) Example Title of ASA 2018, in P Izadpanahi and F. Perugia (eds), Architectural Science and User Experience: How can Design Enhance the Quality of Life, 55th International Conference of the Architectural Science Association 2022, pp. XX-XX, 1-2 December 2022, Curtin University, Perth, Australia.

ISBN 978-0-9923835-8-9

Forward

The Architectural Science Association (ASA), formerly known as the Australian and New Zealand Architectural Science Association (ANZAScA), is an international organisation, the objective of which is to promote architectural science, theory and practice primarily about teaching and research in institutions of higher education.

In the context of climate emergency, global pandemic and greater striving for clean and renewable energy resources, the 55th International Conference of the Architectural Science Association (ANZAScA) explores how design can enhance the quality of life. The emphasis is on the intersections of architecture, building science, urban design, health and wellbeing to increase the sustainable quality of life and user experience to make cities more liveable.

Architectural science is pivotal in informing innovative sustainable, resilient outcomes. Current technology development and trends in architectural education show an increasing interest in highly efficient solutions that closely integrate users' needs and quality of life as an intrinsic part of the design equation. This approach goes beyond building physics and shows how health, social and environmental science shape architectural responses. The themes explored in ASA 2022 at Curtin University include:

Environmental Performance

Urban Environments

Building Science Principles

Big Data

Architectural Education

Life Cycle Analysis

Beyond Building Physics

Researchers, academics, doctoral students, and practitioners have been invited to submit research papers and critical essays and to attend the Conference to widen our discussion about engaging architectural science and its future trajectories. The presentation happened in hybrid modes—face-to-face and online. This publication presents 60 accepted papers presented at the Conference hosted by the School of Design and The Built Environment, Curtin University, Perth, Western Australia, 1-2 December 2022.

The conference website is accessible at:

https://www.asaconference2022.com/

Papers in this proceedings are archived at the ASA website:

www.anzasca.net

Each of the submitted papers was reviewed by two members of our International Scientific Committee, made up of 50 experts.

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 2022 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.

We are grateful to our sponsors: the Chartered Institute of Architectural Technologists (CIAT), the Western Australian Planning Commission, the Western Australia Department of Land and Heritage, the Western Australia Office of the Government Architect, the School do design and Built Environment and Curtin University. We extend our appreciation to those who have been working diligently behind the scenes to make this Conference happen Steven Feast, Hursh Ramcharitur, and Jin Zhang.

Dr. Parisa Izadpanahi and Dr. Francesca Perugia
Perth 2022

Committees

INTERNATIONAL SCIENTIFIC COMMITTEE

Dr.TahminaAhsan, Curtin Universit, Australia
Ms Zahra Amrollahi Biyouki, Curtin University, Australia
Dr. Mary Myla Andamon, RMIT University, Australia
Dr. Courtney Babb, Curtin University, Australia
Prof. George Baird, Victoria University of Wellington, New Zeland
Dr. Aleksa Bijelovic, Curtin University, Australia
Dr.Christhina Candido, The University of Melbourne Australia
Dr. Heap-Yih Chong, Curtin University, Australia
Prof. Robert H. Crawford, The University of Melbourne, Australia
Prof.Sambit Datta, Curtin University, Australia
Dr. Mark Andrew Dewsbury, University of Tasmania, Australia
Dr. Ruwini Edrisinghe, RMIT University, Australia
Mr Steve Feast, Curtin University, Australia
Dr. Tanja Glusac,Curtin University, Australia
Prof. Carolyn Susan Hayles, Cardiff Metropolitan University, United Kingdom
Dr. Petra Helmholz, Curtin University, Australia
Dr. Dominique Hes, City of Melbourne, Australia
Prof. Richard Hyde, The University of Sydney, Australia
Dr. Parisa Izadpanahi, Curtin University, Australia
Dr. Andrea Jia, The University of Melbourne, Australia
Prof. Chunlu Liu, Deakin University, Australia
Prof. Francesco Mancini, Curtin University, Australia
Prof. Dora Marinova, Curtin University, Australia
Prof. Paola Marrone, University of Roma Tre Italy
Terrance McMinn, Curtin University, Australia
Dr. Vanessa Menadue, Bond University, Australia
Dr. Roberto Minunno, Curtin University, Australia
Dr. Shohreh Nematollahi, Curtin University, Australia

Dr. Boon Ong, Curtin University, Australia
Dr. Ehsan Pashajavid, Curtin University, Australia
Dr. Linda Pearce, University of South Australia, Australia
Dr. Francesca Perugia, Curtin University, Australia
Prof. Priyadarsini Rajagopalan, RMIT University Australia
Dr. Alessandro Sanches Pereira, Curtin University, Australia
Dr. Rebecca Louise Scherini, Curtin University, Australia
Dr. Ramisa Shafqat, Curtin University Australia
Dr. Salman Shooshtarian, RMIT University, Australia
Prof. Veronica Soebarto, University of Adelaide, Australia
Dr. Yongze Song, Curtin University, Australia
Dr. Vittoria Strazzeri, Curtin University, Australia
Dr. Mohammad Swapan, Curtin University, Australia
Dr. Raquel Tardin-Coelho, Curtin University, Australia
Dr. Ruffina Thilakaratne, Chu Hai College of Higher Education, Hong Kong
Dr. Graham Thompson, Curtin University, Australia
Dr. Nicola Willand, RMIT University, Australia
Dr. James PC Wong, RMIT University, Australia
Dr. Jin Woo, RMIT University, Australia
Dr. Rebecca Yang, RMIT University, Australia
Dr. Atiq Zaman, Curtin University, Australia
Dr. Junxiang Zhu, Curtin University, Australia

EXECUTIVE SCIENTIFIC COMMITTEE

Dr. Parisa Izadpanahi, Curtin University (Co-Chair and Convener)
Dr. Francesca Perugia, Curtin University (Co-Chair)

CONFERENCE ORGANISING COMMITTEE

Associate Professor Tanja Glusac, Curtin University (Co-Chair)
Dr. Parisa Izadpanahi, Curtin University (Convener)
Professor Francesco Mancini, Curtin University (Co-Chair)

ADMINISTRATIVE SUPPORT

Steven Feast

Hursh Ramcharitur

Jin Zang

PROUDLY SPONSORED BY

Table of Contents

A Case Study for future re-use of buildings to reduce carbon

Llewelyn Griffiths[1], Emily Newmarch[2] and Fritha Powell[3]

[1,3]Warren and Mahoney Architects, Wellington, New Zealand
Llewelyn.griffiths@warrenandmahoney.com[1]
[2] Victoria University, Wellington, New Zealand

Abstract: The reduction of embodied carbon in buildings has been increasingly recognised as a high priority for the building and construction industry globally. Among the many strategies that can be implemented, adaptive reuse is frequently cited as being one of the most promising options due to extending the building's life, reducing waste and the need for large quantities of materials to rebuild the structure. However, the reuse of a structure in a seismically active country, like New Zealand, isn't as simple as stripping away the shell and adding a new one. There is a significant amount of work that is required to ensure the structure will be strong enough to meet updated building codes and last for another life cycle. To reflect on the impact of sustainable initiatives through the case study of a building reuse, this paper seeks to understand the carbon emissions from both embodied and operational contributions. The intent is to understand, what elements are key to decarbonise adaptive reuse buildings and how the design process could better accommodate carbon reduction strategies. The results are compared against international carbon targets to understand the embodied and operational carbon implementation of adaptative reuse for office buildings. These indicators can be used for the strategy of adaptive building re-use when an existing building is not designed for re-use or intended purpose. This paper is a collaboration between industry and academia to test a real-world project.

Keywords: Adaptive, re-use, LCA, Design.

1. Introduction

The construction industry accounts for a substantial portion of global carbon emissions and reduction is critical to limit global warming to below 1.5 degrees Celsius. Buildings are reported to account for 36% of global final energy use and 39% of energy and process-related CO2 emissions. Consequently, the building sector has a key role in reducing global greenhouse (GHG) emissions to a level compatible with global climate goals (BRANZ et al., 2021). Much of the literature on carbon within the construction industry relates to new builds. However, it is commonly accepted that the best strategy to reduce carbon is to "refurbish, reduce, replace, reuse, and require (low carbon)" (One Click LCA, 2021c). This study explores the carbon emissions across embodied and operational use of refurbishment within a New Zealand context and any potential limitations.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 1–11.*

2. Background

2.1. Carbon savings when reusing over building new

It has been globally acknowledged that the 'greenest building is the one that already exists.' (Adam, 2019) There are several strategies in construction to reduce carbon such as substituting low carbon materials, building lighter, building less and reuse to extend the life of existing buildings and materials (Lewis et al. 2021). By reusing the existing structure, embodied carbon can be reduced by lowering material quantity and reducing demolition emissions and waste required for a new build. If this is achievable, this can be a head start in intensive emission savings.

2.2. New Zealand design context

In New Zealand we sit between two large tectonic plates, resulting in a significant amount of seismic activity in most of our densely built environments and populated cities. Therefore, safety is paramount when considering the reuse of an existing structure. Regular earthquakes and seismic events of varying scale means our built environment needs to not only withstand but perform to a high standard and reflect the relative IL (Importance Level). A substantial proportion of building reuse therefore results in seismic strengthening and upgrading of the existing structure to reflect the building code. During seismic upgrading a large amount of embodied carbon is emitted as steel strengthening is applied to the existing structures. For this reason, the reuse of a building is not always the best-case scenario for embodied carbon within seismic zones.

2.3. Embodied Carbon Benchmarks in New Zealand

In both New Zealand and Australia, the industry is waiting for carbon limits to be established. However, many organizations are forming their own targets to reduce carbon. A limit is developed at a national level, or globally with a budget. A target is something more aspirational and typically used as a pathway to achieve net zero carbon by 2050. Warren and Mahoney Architects have a target that by 2030 all new projects will be net-zero carbon in operation, be 50% more energy efficient and have 40% less embodied carbon (Warren and Mahoney, 2022). The top-down scenario is occurring with government initiatives and companies now setting carbon targets and driving emphasis on carbon reduction. BRANZ (2021) has released carbon research as we move to our 2050 zero carbon goal and defined the following for New Zealand's carbon budgets: 208 kgCO2/m^2 (base case) and 280 kgCO2/m^2 (1.5-degree high overshoot). Office buildings have been targeted as a case study for carbon consumption as they make up a substantial proportion of our building stock. The refitting of existing structures into offices will be an increasingly used strategy for lowering carbon emissions in construction.

2.4. Operational Carbon Benchmarks in New Zealand

Research from Department of the Built Environment et al. (2022) outlines that refurbished building operating emissions is between 30-50kgCO2e/m2 per year and could be further reduced through insulation heating, cooling systems, and minimising structural changes. This case study required increased services embodied carbon and operation costs to account for the low existing R-value for the building. New Zealand typically has had lower insulation requirements compared to similar temperate countries across the western world. However, the R-value requirements have now been increased by MBIE (Ministry of Business & Innovation) to a level comparable to international standards and will be mandatory by 1 May 2023 (MBIE, 2021). The R-value of the envelope greatly affects the operational carbon requirements to heat or cool a building. Therefore, reuse buildings built prior to 2023 in New Zealand will typically have large operational carbon emissions unless the R-Values are increased. Currently, there is no requirement to upgrade the R-value in commercial reuse projects unless changes or alternations are proposed to the envelope.

3. Method

3.1. Strategy for identifying sustainable methods

An architect will typically rely on supplier presentations, events, online research, or available technical documentation to make informed decisions on sustainable design and material selections. However, without quantifying and comparing this information with similar projects it is difficult to know if they are achieving the set targets or maximising the potential carbon reduction. To analyse the research used in this case study, we used One Click LCA to calculate life cycle carbon and confirm the carbon savings the sustainable design decisions made after the completion of the design phase.

3.2. Life Cycle Assessment

The life cycle carbon was calculated through 'One Click LCA' and split between reporting categories of embodied and operational carbon to compare against a Business-as-usual (BAU) estimates. This study follows a typical LCA scope and method, while exploring the carbon impacts of the design and material selections. The life cycle assessment for the case study was completed using One Click LCA, a web-based application to generate whole of Life Cycle Assessments in line with the EN (European Norm) 15978 standard (One Click LCA, 2021b). The tool used within One Click LCA was the Life Cycle Carbon Global Tool, this allows access to both CML (Centrum voor Millikunde Leiden) and TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) data and reports on the Global Warming Potential (GWP), biogenic carbon storage and the social cost of carbon as the environmental indicators (One Click LCA, 2021c). The Life Cycle Carbon Global Tool was chosen as it allowed access to the BRANZ (Building Research Association of New Zealand) Construct material database, which has relevant generic data on substitute materials without EPD's in New Zealand.

3.2.1. Revit to LCA

We utilized the Revit to One Click LCA workflow and data conversion for the Life Cycle Analysis for the project. We exported quantitative data from the Revit file (3D design model) and mapped this within the One Click tool. The methodology utilized was to split the architectural, services and structural data out from Revit and map these as separate entities within One Click to allow maximum data control. The Revit model data was modelled at LOD 300 (Level of Development) to ISO (International Organization for Standardization) 19650 standard.

3.2.1 What was measured.

Table 01 outlines the elements included within the LCA calculations. The elements excluded were furniture, fixtures & equipment (FF&E) and other soft-fit out item (rugs, curtains, office accessories).

Table 1: Measured elements by design discipline

Discipline	**Elements included**	**Elements excluded**
Architecture	Stairs, walls, glazing, ceilings, doors, floor finishes, blinds, acoustic panels, architectural finishes, roof lining	FF&E, Soft fit-out
Structures	Seismic upgrade steel, infill flooring, service flooring & structure, secondary steel	
Services	Fan coil units, diffusers, insulation, ducting, cable trays, lighting, communication/data/electrical devices, sprinkler heads, sprinkler pipes, water pipes (galvanized), wastewater (PVC), plant equipment, cabling (data & power).	Seismic bracing, cabling, secondary plant equipment, transformer

3.3. Case Study Overview

The selected case study is an existing 5-level library repurposed into an office building. The building was originally built in 1980 and the refurbishment project is programmed for completion in 2023. The GFA of the building is approximately 2600m^2 and will include open plan office spaces, meeting rooms, focus rooms, café, a library, and various well-being spaces. The case study has completed the design phases and is in the construction phase. This is beneficial as the material selections have been agreed, documented and are being procured by the contractor. This enables this research to have a level confidence of the embodied carbon calculated.

3.3.1. Operational carbon

The operational carbon figures were supplied by the Project Service Engineers. The Energy Use figures were generated through energy modelling. The hot water generation was excluded from this modelling and was estimated to be 16,700kWh. The water usage was calculated assuming 14L/D per person based on typical office consumption. However, it is expected that the actual usage could be lower with modern fixtures. The energy emissions profile used is ‘Electricity New Zealand Disruptive 2023’ which assumes a 0.14 kg CO2e / kWh.

3.3.2 Services design

The embodied carbon of the services design was calculated using the information provided within Revit and design specifications. However, it wasn’t possible to measure the embodied carbon of these elements in the same way as the architectural and structural models. Instead, the size or length of the main service elements, refer table 1, were extracted from the model and calculated with generic material information to support the discussion. The embodied carbon for the services is expected to be larger than outlined due to various elements being unable to be calculated. For this reason, the services embodied carbon is approximate only and could vary significantly.

3.4. Sustainable Design Options – BAU vs Proposed

To calculate the potential carbon savings of the architectural material selections a separate LCA was created (Architectural – High Carbon). The selected materials, refer to table 3, were updated to estimate a high carbon option. The BAU material EPDs were selected on the average New Zealand EPD's available within One Click. Many of the available EPDs had large kgCO2e ranges so an average EPD was selected to compare against.

4. Limitations

4.1. Available carbon data

When completing the LCA we were limited to our knowledge of the materials specified in the project and the information available in the One Click LCA database. In addition to this the available data provided through BIM or design specifications can affect its validity. This project utilised data from Revit and assumes correct descriptive element naming, accurate modelling and no discipline model overlaps which could all impact the data generated. Some elements within the engineer's documentation were specified as a performance requirement and excluded material or sustainable requirements. Where required we have made educated assumptions to determine material EPDs and measurements. A static grid factor of 0.14 CO2e / kWh based on BRANZ 2023 energy data available in One Click was used. An alternative way to calculate energy is to accounts for the grids projected shift to more sustainable forms of energy production i.e., hydro. At each year over the lifecycle energy this method accounts for progressively cleaner energy. However, this information could not be utilised for this paper, so a static grid factor has been assumed. This will produce a conservative energy use figure.

4.2. Software limitations

One Click calculates profiles base on a cubic meter rate. For aluminium joinery this is not appropriate as these are folded metal resulting in incorrect carbon outputs. To avoid this, we calculated the total length of the aluminium joinery and used the 'Aluminium Mullion based on a Ullrich 75mm product' at 1.477kg/m and a factor of 10.68kgCO2/kg to calculate the embodied carbon. Where possible we have tried to alter data to produce more accurate results. However, the calculation methods in the programme are limiting and have the potential to reduce the validity of the results.

5. Results

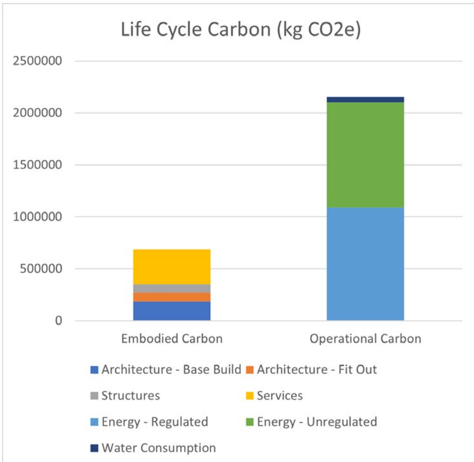


Figure 1: Life Cycle Carbon

Table 2: Life-cycle carbon by group

Group (50 years)	Carbon (kgCO2e)	Carbon (kgCO2e/m^2)
Architecture – Base Build	185,450	71
Architecture – Fit Out	83,800	32
Structures	83,170	32
Services	335,840	129
Operational Carbon	2,153,270	828
Total	**2,841,530**	**1,092**

The life cycle carbon of the building is calculated to be 2,841,530 kgCO2e over a 50-year service life, refer to table 2. This equates to a combined embodied carbon of 688,264 kgCO2e or 264.4 kgCO2e/m^2.

5.1. Operational vs embodied carbon

As highlighted in figure 2, the operational carbon accounts for 76% of the building's life cycle carbon. The building energy use spilt between regulated and unregulated (kWh) shown in figure 3 highlights that 48% is unregulated.

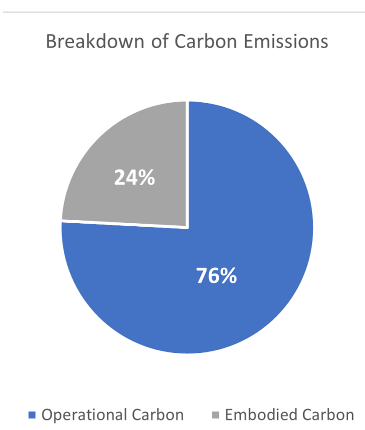


Figure 2: Carbon Emissions Results

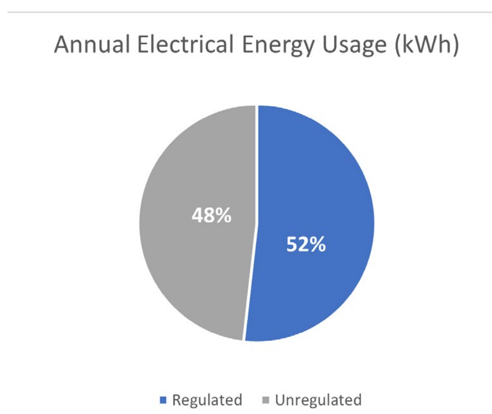


Figure 3: Regulated vs unregulated energy use

5.2. Embodied carbon reduction in reuse & material selection

Figure 4 highlights significant reduction in embodied carbon between the BAU and Case study, refer to Table 2 for the material selections comparison. It total, the material selections saved 156,000 Kg CO2e of carbon compared to the BAU material selections. These selections were primarily part of the Fit-Out design, which accounts for 31% of the architectural embodied carbon, refer to figure 5. This is approximately a 53% reduction in embodied carbon in the fit-out design.

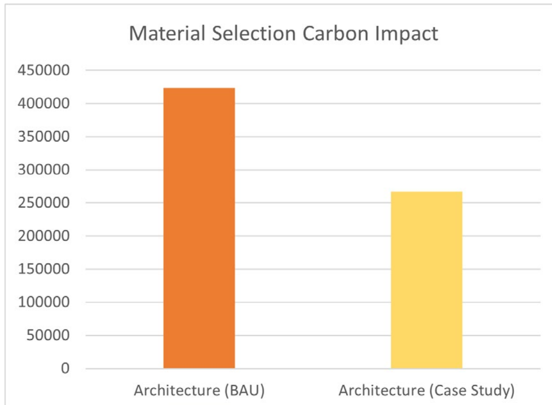


Figure 4: Architectural embodied carbon material selection

Table 3: Architectural Material Selection Initiatives

Type	High Carbon (baseline)	Low Carbon (selected)
Internal Walls	Steel stud plasterboard	X-frame
Acoustic Panels	polyester	Recycled wood wool
Wall Linings	Plasterboard	Saveboard
Flooring	Standard Carpet & backing (12.3kg CO2e / m^2)	Low carbon carpet & Carbon Negative Carpet backings (2.2kg CO2e /m^2)
Flooring	Full Carpet Tile (1591m2)	Reduced carpet scope (910m2) - exposed concrete
Flooring	Vinyl	recycled rubber

5.3. Building embodied carbon

The base-build accounts for 69% of the architectural embodied carbon. As described in section 5.4. the material selections focused on low carbon options. Assuming the selected baseline assumptions the fit-out had the potential to include an additional 156,700 kgCOe2. This would result with the fit-out design accounting for 56% of the architectural embodied carbon. As shown in figure 6, the buildings Base-Build embodied carbon (Architecture Base-Build + Structure) was calculated as 103kgCO2e/m^2.

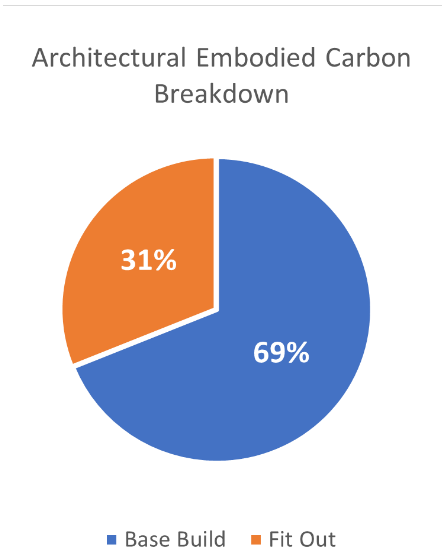


Figure 5: Embodied carbon comparison

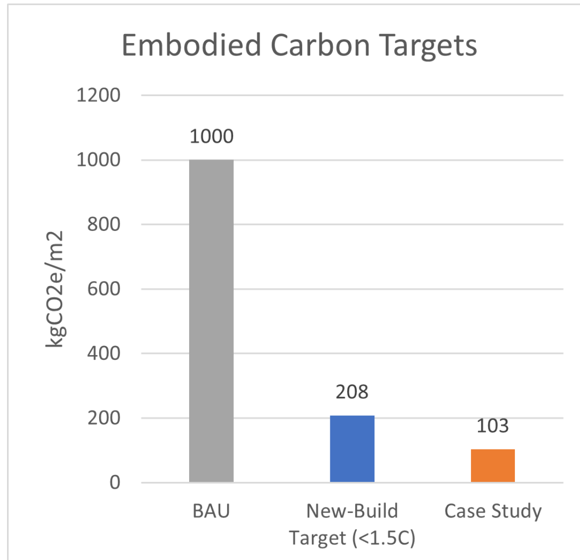


Figure 6: Embodied carbon target comparison

6. Discussion

As a reference BAU new build project we have used 1000kgCO2e/m^2 for the architectural and structural elements of a building (2021b). The case study achieved 103 kgCO2e/m^2 which validates reusing structure as a method to reduce embodied carbon. One issue that needs to be considered in New Zealand is earthquakes. In New Zealand there are strict requirements to meet NBS standards which can require significant input into an existing building to bring it up to standard and have large carbon requirements. For this case study we were able to avoid replacing the full façade and remediate as required, which enabled a significant carbon saving. BRANZ outlines a reduction Targets 2025-2030 of 208kgCO2e/m2 for new build office buildings to meet a GWP of <1.5C (BRANZ et al., 2021). As shown in figure 6, the case study surpasses the 2030 target. This highlights that building reuse, even with New Zealand's seismic upgrades requirements, is a viable method to reduce buildings embodied carbon to meet the targets for 1.5 degrees warming.

6.1. Embodied carbon reduction in reuse

As shown in figure 1 the structural embodied carbon is significantly less than a comparable new build project, only accounting for 3% of the life cycle carbon and 12% of the embodied carbon. This highlights one of the benefits of reusing a building and extending its life for another 50 years. LETI found in their research that an office fit-out should focus on reducing products/materials (A1-A3) and maintenance / replacement (B1-B5) to best reduce embodied carbon (LETI, 2020). Following this strategy, we were able to greatly reduce the embodied carbon for this project. However, much of this relies on the design intent and the condition or construction of the existing building. This project utilised and expressed the existing concrete and double-tee floor structure which reduced the materials requiring architectural finishing. While this strategy was achievable on this case study it is specific to the building can't be assumed or expected on all reuse projects.

6.2. Material selections impact on embodied carbon

As shown in figure 4, there was a significant reduction in embodied carbon through the sustainable material selection of the architectural design. For a building reuse project, the architect typically has the most control over architectural materials and can greatly influence the projects sustainability with these choices. The design intent from the onset was to have honest materials which express the original building. This was sensitive to the existing design but also an opportunity to reduce the projects embodied carbon. Expressing the existing concrete structure and not using unnecessary materials to cover it greatly reduced the projects embodied carbon. The methods to reduce carbon should start with 'reduce' where possible. In addition to this strategy, sustainable materials were utilised as noted in table 3. However, this had a far less impact than expected. The key areas for carbon reduction, as expected, are the materials with the most volume in the project. While the cost of these selections has not been calculated a 2021 report from RMI found that case studies that had embodied carbon savings of 24–46% incurred at cost premium of less than 1% (Lewis et al., 2021).

While materials are selected and specified during the design phase many changes can occur once it is ordered and built on site. During the Tender, Procurement and VE (value engineering) phases the contractor will provide cost estimates and outline a construction programme. This information is then reviewed against the project costs and timelines and if not aligned the client will typically request the design team investigate alternate solutions. Material & general upfront costs, lead times, available stock, and the contractors' experiences will greatly influence the actual materials used on site and when there is a cost saving this can be appealing to the client. This has been especially true during the COVID era where supply chain issues, material shortages and labour constraints greatly affected the industry. Therefore, it isn't as simple as specifying materials, there needs to be leadership and confidence behind the decisions being made to ensure they are achieved. This was especially true for this project which had specified circular construction materials like X-Frame system. While this was an upfront cost to the client the benefit will be far greater through the duration of the building's life.

6.3. Operational versus embodied carbon

While embodied carbon is typically less for refurbished buildings, the energy use may be higher due to the quality of existing materials retained. For this case study the retained window frames, double glazing, wall external insulation build-ups, and insulation achieve lower R-Values compared to new building minimum requirements. To accommodate the lower insulation levels the mechanical (heating & cooling) requirements were larger resulting in higher operational carbon. This project was calculated to use 307,265 kWh/y or 118KwH/m^2/y. The RIBA 2030 Climate Challenge (RIBA, 2019) outlines sustainable target metrics of kWh/m^2/y for BAU, 2025 targets, 2030 targets, to be 130, <75, <55 respectively. Assuming this project could achieve the RIBA 2030 targets the energy use would be 143,000KwH/y. This equates to 1,100,270 kgCO2e/50 years which is 46.5% the case studies operational carbon or a reduction of 1,152,000 kgCO2e/50 years. This highlights a significant reduction in carbon compared to the potential savings in embodied carbon and suggests that reuse buildings should focus on reducing operational carbon to maximise potential carbon savings.

To reduce the operation carbon the project could have revised the services & energy strategies, i.e., passive ventilation, or re-insulate the building to a higher R-Value (limited by façade cavity depth). However, these options have large cost implications and were not feasible for this project. Another opportunity could be to focus on reducing unregulated energy use, which accounted for 48%, refer figure 3. Architects do typically have the most impact in this area, after the client, and by encouraging the use of low energy computers, IT equipment, dishwashers, fridges, and design to encourage low energy user interactions, a significant reduction in carbon could be achieved. The next steps of the study are to calculate the potential embodied carbon of a new façade and whether this outweighs the potential operational carbon savings.

6.4. Knowledge in the industry

As discussed in 4.1.2., education within the industry is crucial to the validity and uptake of LCAs. One area that would greatly benefit the process is to ensure that where elements are specified by performance requirements that sustainability requirements are also set. This would ensure that contractors are procuring materials not only selected by cost and lead-times but also embodied and operation carbon impact.

7. Conclusion

A high priority for the building and construction industry, globally, is to reduce embodied carbon. While the reduction of embodied carbon is more easily achieved with building reuse compared to a new build, the context and existing materials impact the potential benefit. An integrated approach is required, considering both the operational and embodied carbon to ensure the sustainability initiatives have the desired impact. From the perspective of a practitioner, the key to achieving this is to connect the design and sustainability initiatives by comparing operational and embodied outcomes in parallel. This will highlight when to invest carbon to benefit the whole project. Material selections at the end of the design phase may reduce the overall embodied carbon however this is not sufficient for the industry to meet the carbon targets. While the case study was able to significantly reduce the embodied carbon within the architectural scope, this was outweighed by the high operational carbon. For sustainable action to have a significant impact sustainability needs to be considered at the start of the project. This requires input from the engineers, an engaged client and leadership from the architect or designer. The next steps of this research are to utilise One Click LCA earlier in the design process and analyse and compare the outcomes of carbon reduction alongside cost comparisons to inform decisions. Lifecycle costing was not considered in this case study however removing the facade from scope made the initial project cheaper and achievable for the client. However, as shown this impacted the projects ongoing operational carbon expenditure. Expanding the available case studies to compare against will further help the industry identify effective areas for embodied and operational carbon reductions to ensure the industry lowers emissions to limit global warming to 1.5 degrees.

References

Adam, Robert. (2019). *The Greenest Building is the one that already exists*. Architects Journal. https://www.architectsjournal.co.uk/news/opinion/the-greenest-building-is-the-one-that-already-exists'.

BRANZ, Bullen, L. B., McLaren, S. M., & Dowdell, D. D. (2021). Carbon Budget of New Zealand Buildings: A Sensitivity Assessment. BRANZ.

Department of the built Environment, Röck, M. R., & Sørensen, A. S. (2022, March). *Towards embodied carbon benchmarks for buildings in Europe*. Ramboll.

London Energy Transformation Initiative. (2020). LETI Climate Emergency Design Guide. https://www.leti.london/cedg

Meghan Lewis, Monica Huang, Stephanie Carisle, Kate Simeon. (2021). *Strategies for Reducing Embodied Carbon*. Carbon Leadership Forum. https://carbonleadershipforum.org/toolkit-3-strategies/

MBIE (2021). *Outcome of consultation Building Code update 2021. https://www.building.govt.nz/building-code-compliance/annual-building-code-updates/2021-building-code-update/*

One Click LCA. (2021a). *Building According to EN 15978*. One Click LCA. https://oneclicklca.zendesk.com/hc/en-us/articles/360014967540

One Click LCA. (2021b). *Life Cycle Carbon Global*. One Click LCA. https://oneclicklca.zendesk.com/hc/en-us/articles/360016978800-Life-Cycle-Carbon-Global

One Click LCA. (2021c). *Low Carbon Refurbishment: 10 ways to reduce embodied carbon emissions*. One Click LCA. https://oneclicklca.zendesk.com/hc/en-us/articles/360016978800-Life-Cycle-Carbon-Global

RIBA, (2019). 2030 Climate Challenge https://www.architecture.com/about/policy/climate-action/2030-climate-challenge

RPS. (2021). *Embodied Carbon: What it is and how to tackle it*. RPS Group. https://www.rpsgroup.com/services/environment/sustainability-and-climate-resilience/expertise/what-is- embodied-carbon/

Warren and Mahoney’s 2020 Sustainability Commitment. (*n.d.). Warren & Mahoney. Retrieved October 28, 2022, from https://warrenandmahoney.com/articles/warren-and-mahoneys-2020-sustainability-commitment*

A comparative study between urban and rural play of Bhopal, India; to identify stimulating play environments

Ar. Richa Raje [1], Ar. Saurabh Ojha [2], Ar. Akshaya Saravanan[3], Ar. Priyanka Agarwal[4] and Ar. Ajit Kumbhar[5]

[1, 3, 4, 5] *School of Planning & Architecture, Bhopal, India*
richa.raje@spabhopal.ac.in[1], akshaya.saravanan125@gmail.com[3], prianca0603@gmail.com[4], akitsmeajit@gmail.com[5], ORCID-0000-0003-2929-6100[1]
[2,] *Indian Institute of Technology Roorkee, India*
skishoreojha@ar.iitr.ac.in[2], ORCID-0000-0001-6565-2673[2]

Abstract: Play seems to be simple and a fundamental activity. When children play, they learn – develop their physical capabilities, explore and experiment materials around them. It contributes to their physical, cognitive, social, cultural and emotional strengths and development. The purpose of this study is to examine the difference in the utilization of the current play environment between urban and rural play areas—specifically by examining children play satisfaction levels, interaction with natural elements and their frequency, analyse the relationship between the spatial features by studying the degree of affordance of the children to its immediate environment. The age group considered ranges between 6 to 12 years and data collection through playfield audit, on-site visits, survey and activities. The study suggests that children have affinity towards nature, however rural play environment offers a higher degree of affordance than urban play. The rural play builds curiosity and encourages them to invent newer opportunities with natural elements. Ironically, urban playscape senses a deficiency in creativity, which leads to a lesser connectedness towards nature. This study can become basis for designers to identify the landscape features in outdoor play areas that can create challenging, stimulating and meaningful play environments for the overall development of children.

Keywords: Affordance, Child development, Rural play, Urban play environment.

1. Introduction

Play is the first and foremost step of getting acquainted with one's own environment. An environment where children can enjoy, be passionate, spontaneous, self driven and purposeless (Piaget, 2007).It is an engagement where the outcome is not important but the activity itself is as it triggers physical, social and cognitive abilities in children (Kellert, 2005). Presently, India has 472 million children (0-18 years), making it home to the largest number of children in the world. Of this, nearly 128.5 million children (nearly 34% of the urban population) live in urban areas. Although cities provide additional facilities to learn, improved

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 12–21.*

life but the mundane, unsafe and neglected open areas have negative impact on children and has contributed to a rise in passive modes of recreation such as digital games, watching television, etc. This kind of disconnect between children with natural environment can give rise to *Nature Deficit Disorder* (Louv, 2006).

Studies on Indian outdoor play exposure are fragmented, but these independent studies help to understand play scenario. A survey conducted in 2016 by Edelman Intelligence found that 56% of Indian parents felt that their children have lesser opportunities to play in comparison to their childhood. Furthermore, according to the 2018 India Report Card on Physical Activity for Children and Youth, C- grade (nearly 40-46%) was awarded on the criteria of active play i.e. proportion of children and youth who report being outdoors for more than 2 hours per day (Bhawra, 2018). Other reasons behind the decline of play in urban areas are restriction on park accessibility especially for children, reduced time limit, lack of maintenance of the children play areas for e.g. damaged equipment results many cases of child injury. These studies indicate sedentary lifestyle of children, inadequate availability of play areas and uninspiring play environments for their holistic development especially in the urban areas. There are no guidelines on play in India and not enough information on how play spaces should be designed and built to accommodate a child’s needs & behaviour. This study tries to probe about child’s responses w.r.t. environmental qualities between urbanised and non urbanised i.e. rural play areas.

2. Literature

Typically the available playgrounds available to children are designed by adults with little idea about their requirements and therefore are underutilized and ineffective to their development needs (Arlinkasari, 2018). Playgrounds are spaces identified by children to play while playgrounds are places for children given by adults (Rasmussen, 2004) (Said, 2015). Therefore, there is need to understand children environment relationship and play preferences.

2.1. Theory of Affordance

Gibson developed the concept of affordance which refers to the action possibilities the environment offers an individual. Accordingly, he is both affected by his environment and affects his environment with his activities (Gibson, 1979). Therefore, the environment and behavior are interrelated and the physical environment affects behaviour and learning with different affordances that it has (Gibson, 1979). Affordance can be subdivided into two levels i.e. Potential and actualised affordance (Kyttä, 2003). The potential affordance refers to the countless possibilities based on individual perception of the quality and quantity in the environment; and the actualised affordances refer to ones that children have experienced through movement (Heft, 1988) (Kyttä, 2003). The actualised affordance can be categorised into three types of activities i.e. performatory, exploratory and productive (Chawla, 2001).

- **Performatory activity**: actions directed towards some objects or individual within a setting for an intended purpose for e.g.; jumping into water, rolling on ground etc
- **Exploratory activity**: Actions directed towards discovering new properties in the environment. E.g. Spraying mud to create dust storm, skimming stones in water etc.
- **Productive activity**: Actions transforming into new environment structures. E.g. Sculpting mud to make toys, or banging object to create music etc.

2.2. Factors influencing environmental preference

The factors that influence varied environmental preferences are as coherence of information and legibility, complexity and mysteriousness (Kaplan & Kaplan, 1989) (Ulrich, 1983) (Min-JinLi, 2012). The attractive environments which can challenge the abilities of children have greater affordance; while the one that lacks complexity and opportunities to manipulate or explore has lesser affordance.

- **Coherence of information and legibility:** Can be created using composition of elements, forming focal points to trigger movement and action.
- **Complexity:** Varied and rich environmental features encourage exploration.
- **Mysteriousness:** Sense of mystery triggers exploratory behaviours and interest to enhance satisfaction.

2.3. Children behaviour and development

Erikson's fourth stage of psychosocial development is industry vs inferiority occurring during middle childhood i.e. 6-12 years (Erikson, 1950). Erikson suggested that children are exposed to leaders and followers, and understand the norms of their environment and the expectations of their peers. This stage indicates the ecological connection between the individual and the environment (Bishop, 2013).

- **Industry characteristics**: The child exhibits personal power and competence; is ready to learn skills and win recognition; can complete tasks by steady attention and diligence; the child learns to adjust to circumstances and surroundings
- **Inferiority characteristics**: Loosing hope of industrious association leads to isolation; sense of inadequacy and inferiority; feeling doomed to mediocrity

Table 1: Childhood developmental stages and the supportive environmental features (adapted from (Moore, 1974) (Loebach, 2004) (Newman, 1979) (Katherine Masiulanis, 2017)(Arlinkasari, 2018)

Developmental Stage	**Developmental tasks**	**Activity/Experience**
Middle childhood (6-12 years) Psychosocial crisis: Industry vs inferiority	Friendship Concrete operations Skill learning Self-evaluation	Performatory: Purposive social interaction & Team play Exploratory: Educational activity & Risk taking physical activity Productive: Educational activity, Restorative experience for emotion regulation

Children perceive landscape not as forms or background but as functions or opportunities; which is a key to create successful play environments (Sebba, 1991). The functional taxonomy given by Kytta is used to evaluate actualized affordance on a scale (Kyttä, 2003). The aim of this research is to compare the stimulating play environments in rural and urban context. The objectives are firstly to identify the relationship between nature and play possibilities (i.e. affordance); and secondly to relate affordances with child's development.

3. Methodology

The nature of this study is to identify various stimulating play environments in urban as well as rural context. Therefore, two live case examples were studied i.e. an urban park for children and a village open space. The data collection was carried out through photographs, video recordings and perceptual interview of children. The participants were between the age of 6-12 years, as they can relate to outdoor environments and communicate their ideas easily. This is useful because it helps us to understand outdoor physical environment through their perspective. Both qualitative as well as quantitative assessments were performed to understand their play activities. For qualitative assessment, affordance and behavioural maps were made as per the field survey; and quantitative assessment was based on the questionnaire using Likert scale.

The study was carried out twice; i.e. in the month of October 2021 and July 2022, as the weather was neither very hot nor very cold and the data was gathered for continuous 3 days. The rural study was conducted from lunch hour i.e. 1pm onwards till sunset i.e. 7pm. The urban park was studied from 4pm onwards as the children played during evening hours after their school and extra classes or tuition.

3.1. Perceptual Interview

A total of 62 respondents i.e. 30 nos. urban kids and 32 nos. rural kids were interviewed after seeking permission from their guardian about their play activities and experience of the space. The questionnaire as shown in Figure1 was framed about their frequency, usage of space, physical capacity and social bonding, and their interaction with natural materials available to them in outdoor context.

Name: .... **Gender : M/F** **Age:** ......

1) Do you play outside every day?

○ Never ○ Rarely ○ Sometimes ○ Often ○ Always

2) Do you play with your parents around?

○ Never ○ Rarely ○ Sometimes ○ Often ○ Always

3) Do you like to play in large group of friends?

○ Strongly disagree ○ Disagree ○ Neither ○ Agree ○ Strongly agree

4) Do you get hurt while playing outdoors?

○ None ○ Very mild ○ Mild ○ Moderate ○ Severe

5) Do you like to play alone outside?

○ Strongly disagree ○ Disagree ○ Neither ○ Agree ○ Strongly agree

6) Have you ever climbed a tree?

○ Never ○ Rarely ○ Sometimes ○ Often ○ Always

7) Have you ever jumped in water?

○ Never ○ Rarely ○ Sometimes ○ Often ○ Always

8) Do you play with mud / rocks outside?

○ Never ○ Rarely ○ Sometimes ○ Often ○ Always

9) Do you feel comfortable to play outside with animals?

○ Never ○ Rarely ○ Sometimes ○ Often ○ Always

Figure 2: Questionnaire for urban and rural children about their play environment

3.2. Rural play environment

The rural villages capture true essence of India, modest people and rustic landscape. These villages are surrounded by agricultural fields, water bodies, forests, mud and brick houses, unpaved roads and are seldom touched by modernity. This adds struggle to their life and hard work to sustain their livelihood; however, they are abundant in space, fresh air, cattle, trees and plants etc. Therefore the children living in rural areas get an atmosphere to interact with natural world.

3.2.1. About site context

Neelbad village is located in the outskirts of Bhopal city (central India). This village settlement is spread across 25 acres and has approximately 70-80 households, surrounded by agricultural lands and one primary school, and a departmental store. The majority people over here are farmers and cattle grazers and nearly 50% of the population living over here are children. The houses are organically spread out providing ample open space to each house where children play. There is no dedicated play area for children, but the primary school along with surrounding open areas provides children to play freely.

3.2.2. Behaviour mapping of Neelbad village

Nearly 32 nos. children were studied; their distribution and behaviour was mapped based on the activities carried out at various locations. They were engaged in unstructured play, which seldom requires any play equipment and were able to find play opportunities from elements around them like sand, soil, water, trees, sticks , tyres and pebbles etc as shown in Figure 2. They played in large groups and engaged in imaginative play, invent new fun games, traditional rule games like hide & seek, *gulli danda*, kabaddi, cricket, etc. Rural environment affords various opportunities to interact with their spatial components as shown in the Table 2.

Figure 3: Rural village behavior mapping for 6-12 years age group. (Source: Author)

Table 2: Relationship between space component, environmental quality and affordances in rural context

S. No	Space Component	Environment Quality	Affordances associated with the activities
1	Pool, Running Water, Rain	Water	Affords swimming; affords jumping; affords fishing; affords sitting; affords playing in rain, affords throwing stone in water, affords splashing water.
2	Road, Pathway, Ground, Lawn	Flat surface	Affords playing with toys; affords sitting; affords chasing and running; affords wrestling; affords lifting; affords flipping; affords somersault learning; affords digging; affords cycling; affords skipping rope
3	Ramp, Mound, Rocky Edge	Sloped surface	Affords hanging from ramp handle; affords balancing to walk on handle; affords sitting on slope; affords sliding; affords rolling

4	Objects: Stones/Tire/ Ball/ Sticks etc.	Graspable detached objects	Affords lifting young ones; rolling tyres with sticks; affords collecting flowers; affords making toys; affords stick fight
5	Branches, ropes, pipes, swings etc	Non-rigid attached objects	Affords swinging from branches; affords feeding animals; affords swinging from ropes, affords siting, affords climbing
6	Tree, wall, stairs, mound, shelter	Climbable object/ shelter	Affords jumping from wall; affords resting; affords climbing auto; affords climbing trees; affords lifting one another; affords dancing; affords tapping and making music; affords hiding; affords plucking fruits; affords pole climbing
7	Mud, puddle, sand, leaves, stones, flowers, soil etc.	Mouldable material	Affords rolling on ground; affords drawing with sticks; affords skidding on street; affords throwing mud; affords collecting stones; affords building house; affords games with stones; affords sculpting toys from mud; affords game with marbles; affords game with ball and stones (pithu); affords game with stick and ball (gully-danda), playing hopscotch
8	Stage, firm, ground, shade, amphitheatre,	Sociality (being noisy; team games, role play)	Affords chasing game; affords cricket; affords football; affords group discussions; affords hand games; affords hide & seek; affords kabbadi; affords colour games; affords dumb charades; affords ring-a-ring o'roses ; affords singing and dancing, affords playing treasure hunt

3.3. Urban play environment

Most Indian cities are densely populated therefore urban parks are the refuge areas for its residents to break away from the dense built fabric and relax with nature. These open areas include play fields for children, neighbourhood greens, pocket parks, and system of interconnected walkways and squares.

3.3.1. About site context

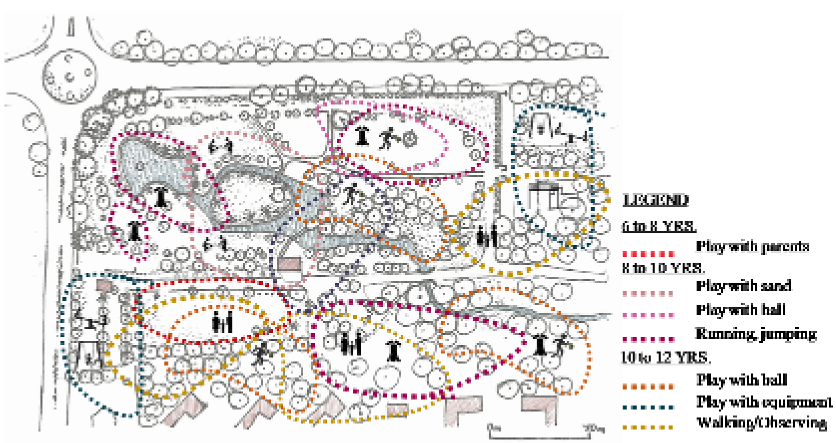


Figure 3: Urban Park behavior mapping for 6-12 years age group. (Source: Author)

The city of Bhopal houses an exclusive recreational space for children which lie in the BHEL township. The Kamla Nehru park that is spreads across 17.05 acres and is open to all the public between 4pm-8pm and the behavior mapping is shown in the Figure3. It is a large park, with play equipment and spread out usable green areas for children and adults can enjoy playing, relaxing, walking or jogging. Urban park environment affords various opportunities to interact with spatial components as shown in the Table 3 .

Table 3: Relationship between space component, environment and affordances in urban context

S. No	Space Component	Environment Quality	Affordances associated with the activities
1	Pool, Rain	Water	Affords sitting, affords playing in rain, affords taking pictures
2	Road, Pathway, Ground, Lawn	Flat surface	Affords chasing and running, affords cycling, affords playing with toys, Affords sitting, affords lifting, affords taking pictures
3	Ramp, Mound,	Sloped surface	Affords sitting, affords balancing, affords sliding
4	Objects: Stones, Ball, Sticks, toys etc.	Graspable detached objects	Affords collecting flowers and leaves, affords throwing
5	Branches, swings & equipment	Non-rigid attached objects	Affords hanging to branches, affords plucking leaves and flowers, affords swinging, affords climbing, affords balancing, affords sitting,
6	Tree, wall, stairs, mound, shelter	Climbable object/ shelter	Affords climbing, Affords hanging, Affords balancing, Affords walking on a height, Affords jumping from height, keeping ball on branches
7	Mud puddle, sand, leaves, flowers, etc.	Mouldable material	Affords collecting flowers and leaves, affords running on mud.
8	Stage, firm, ground, shade, amphitheatre,	Sociality (being noisy; team games, role play)	Affords chasing game, affords playing cricket, affords football, affords hide and seek, affords playing badminton, affords playing Frisbee, affords sitting

4. Observations

4.1. Rural play observations

The spatial organisation of a place affords various activities depending on how the user perceives them. It is then based on user's abilities and movement that of many perceived affordances, which one gets actualised on ground. The nature of these affordances determines the mental, physical and social state of these children. Some of the actualised affordances can be categorised into:

- **Performatory**: These majorly include physical exertion like chasing, jumping, lifting, wrestling, hanging, contesting etc. These activities improve their motor skills, physical capabilities; strengthen social connection and builds team spirit.
- **Exploratory:** The environment qualities spark curiosity in the children towards self directed exploration. Children were found exploring the fluid nature of water by splashing it, skimming stones in them; skidding and spraying mud to create dust storm; the soft mud cushions them to do headstands and somersault etc. The fruit laden trees compel them to climb and pluck fruits, flowers and share with each other. The inquisitiveness drives towards multisensory development, risk taking and experience based learning.
- **Productive:** The children were creative to translate their interactions and exposure into skills like swimming in the well, fishing in pond; sculpting from clay and drawing on mud; building toys and

doll houses; composing music on metal box with hand and sticks etc. They acquired skills from practicing and their experiences, and learned about decision making etc.

Following observations were based on behaviour mapping and perceptual interview:

- The rural respondents when enquired about their frequency of play, it was found that nearly all of them played outside on a regular basis for 6hours average. The children were found to play during the daylight hours except for morning school duration.
- Most respondents (i.e. 80% approx.) mentioned that were not accompanied by their parents during play; also they were free to venture everywhere within the village premises to play. It is also because the villages have a very close knit neighbourhood, low population and strong community. The children were familiar with the entire village to play comfortably on their own.
- Nearly 70 % of the respondents agreed to play in large groups ranging from 5-7 nos. (min.) and up to 25-30 nos.(max.). While playing, there were spectator children around them, who wait, run commentary and fill in when required. They disliked (nearly 83%) the idea of playing alone.
- Their groups were inclusive i.e. comprised of all age children from toddlers to early teens & not necessarily of similar age. They would make the game rules flexible or give easier tasks to accommodate everyone. This helps them to learn from each other & the older kids safeguarded the younger ones especially from tripping and getting hurt. However for some activities the groups were gender specific, for e.g. doll house play, climbing trees, jumping in water etc.
- These respondents were often engaged in adventurous and risk taking activities, which makes them prone to getting hurt. Since the village has lesser built and more of natural surroundings, they would get mild hurt, but these events tripping, falling, slipping, etc. didn’t stop their game.
- The respondents when asked if they attempted climbing a tree; most male respondents knew how to climb, while the female respondents had not attempted. Similarly, majority of the male respondents jumped in water and learned to swim from each other. This is also because of the societal restrictions on the female child to perform such strenuous tasks.
- Most respondents played with mud and rocks; they moulded the soil to make toys, houses and sculptures etc. They would spray mud, roll in them, perform headstands as its soft enough to take their fall.
- The children often ventured inside small woodland which is quiet, shaded, and peaceful and away from their usual playground. This woodland became their private place to relax and passive play (talk, imaginative play, build houses, collect leaves and berries etc.).
- These respondents bonded with animals very well, fed them, played with them and cared.

4.2. Urban play observations

Following observations were based on behavior mapping and perceptual interview:

- The respondents when enquired about their frequency of play, it was found that nearly all of them played on a regular basis but only 1 - 2 hours.

- Majority of the respondents were accompanied by their parents during play; who constantly monitored them when the mingled with others around. This had led to their preference(nearly 60%) to play in small groups or alone. The selection of play activities mostly was around equipment in the park.
- Groups were formed of maximum 5 nos. mostly of similar aged children. Most of them were only playing with their elder or younger siblings. Some children were found playing with their parents or by themselves.
- Most respondents refused about attempting to climb trees as they were afraid of falling down. They also disliked playing with mud or water as they would get dirty and soil their clothes. The respondents were continuously monitored therefore no risk taking/adventurous activities were performed by the children of either gender.
- Most respondents never played around animals as they were scared of getting hurt, however some children did play with puppies.

4.3. Comparing rural and urban play

Based on functional taxonomy given by Kytta, Figure 4 line graph shows a distinct variation in rural and urban affordances due to its environmental qualities. This suggests that the rural context provided more opportunities to play as compared to urban parks. It is important to note that the rural play grounds had neither designated zone for children nor equipment to facilitate actions. The urban park showed higher affordance in non rigid attached objects due to the presence of play equipment for play.

The bar chart on the right indicates the level of affordances on the basis of performatory, exploratory and productive activities. It was found that the rural play offers greater level of affordance in comparison to the urban parks. Urban play observed a drop in the exploratory activities and complete absence of productive activities which indicates that the children were less curious about their environment and did not prefer to transform or shape elements around them. As per Erikson's development stage children have innate ability to learn new skills, contest and complete tasks to win recognition from others; however the absence of such activities makes them vulnerable to inferiority. Freedom of circulation/movement, flexible duration of outdoor play, presence of natural elements like trees, plants, water, animals, soft ground and uninterrupted play gives the rural children an immersive experience where they can explore, experiment, meet their goals and are satisfied.

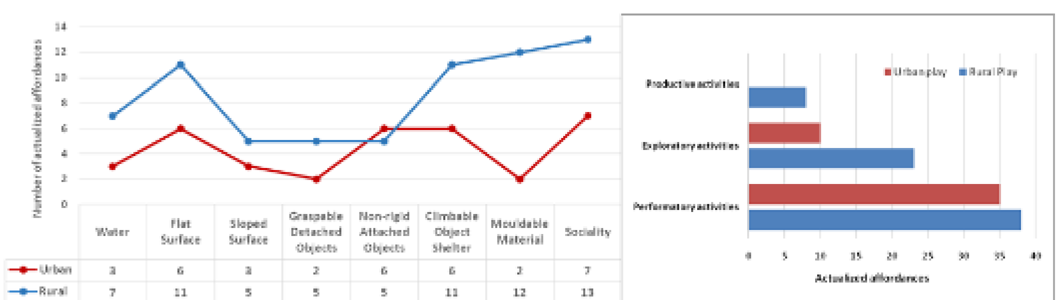


Figure 4: Comparative variation in environmental qualities and level of affordance in rural & urban play

5. Conclusion

Such studies explicitly reveal that free play requires no gadgets, equipment or surveillance. It proves that child needs possibility to choose their activities and create their 'play' ground as Moore mentioned in his book *Childhood's Domain.* The design of stimulating play areas is incomplete without understanding the environmental connection and developmental stage of children. These innocent interactions with nature, is getting diminished and more importantly taken over by object play. Children needs are ever-changing as they overcome each goal, seek newer opportunities and our aim as designer is to strengthen this fragile connection, so that they become aware, sensitive and responsible adults.

References

Arlinkasari, F. a. (2018). Developmental-Affordances An Approach to Designing Child-friendly Environment. *Annual Conference on Social Sciences and Humanities.* Malang.

Bhawra, J. a. (2018). Results from India's 2018 Report Card on Physical Activity for Children and Youth. *Journal of Physical Activity and Health* , S373-S374.

Bishop, C. L. (2013). Psychosocial Stages of Development. *The Encyclopedia of Cross-Cultural Psychology* .

Chawla, L. (2001). *Growing Up in an Urbanizing World.* London: Routledge.

Erikson, E. (1950). *Childhood and society.* NewYork: Norton .

Gibson, J. J. (1979). *"The Theory of Affordances" The Ecological Approach to Visual Perception. .* Boston: Houghton Mifflin: Hillsdale.

Heft, H. (1988). Affordances of children's environments: A functional approach to environmental description. *Children's Environments Quarterly* , 29-37.

Kaplan, R., & Kaplan, S. (1989). *The experience of nature : a psychological perspective.* Cambridge: New York : Cambridge University Press.

Katherine Masiulanis, E. C. (2017). *How to Grow a Playspace: Development and Design.* London: Routledge.

Kellert, S. (2005). Building for Life: Designing and Understanding the Human-Nature Connection. *Bibliovault OAI Repository, the University of Chicago Press* , 63-89.

Kyttä, M. (2003). *Children in Outdoor Contex Affordances and Independent Mobility in the Assessment of Environmental Child Friendliness.* Helsinki University of Technology.

Loebach, J. (2004). *Designing Learning Environments for Children [microform] : an Affordance-based Approach to Providing Developmentally Appropriate Settings.* Thesis (M.E.D.S.)--Dalhousie University.

Louv, R. (2006). *Last child in the woods: Saving our children from nature-deficit disorder.* Chapel Hill: Aloquin Books.

Min-JinLi, H. Z. (2012). Environmental Characteristics for Children's Activities in the Neighborhood. *ASIA Pacific International Conference on Environment-Behaviour Studies (AicE-Bs). 38*, pp. 23-30. Elsevier.

Moore, R. C. (1974). Patterns of activity in time and space: The ecology of a neighborhood playground. *Psychology and the built environment* .

Newman, B. M. (1979). *Development Through Life: A Psychosocial Approach.* Stamford.

Piaget, J. (2007). *The Child's Conception of the World.* Rowman & Littlefield.

Rasmussen, K. (2004). Places for Children – Children's Places. *Childhood , 11* (2), 155-173.

Said, N. F. (2015). Affordances., Outdoor Environments as Children's Play Spaces: Playground. (B. H. Evans, Ed.) *Recreation, Health and Well Being. Geographies of Children and Young People , 9*.

Sebba, R. (1991). The Landscapes of Childhood: The Reflection of Childhood's Environment in Adult Memories and in Children's Attitudes. *Environment and Behavior , 23* (4), 395–422.

Ulrich, R. (1983). Aesthetic and Affective Response to Natural Environment. *Human Behavior & Environment: Advances in Theory & Research , 6*, 85-125.

A critical review of Biophilic design and its design framework

Archie Patel[1], Dr. Akari Nakai Kidd[2], Dr. Astrid Roetzel[3] and Mark DeKay[4]

[1, 2, 3] Deakin University, Geelong, Australia
{patelar[1], akari.nakaikidd[2], astrid.roetzel[3]}@deakin.edu.au, ORCID-0000-0002-5161-8236[1], ORCID-0000-0002-1456-294X[2], ORCID-0000-0003-3243-7744[3]
[4] University of Tennessee, Knoxville, TN, USA
mdekay@utk.edu[4], ORCID-0000-0003-4779-9510[4]

Abstract: Since the publication of Rachel Carson's Silent Spring in the 1960s, the architecture realm has witnessed a surge in sustainable design approaches. These have primarily focused on developing solutions that reduce negative environmental impacts. A growing body of research has identified that merely reducing the destructive impacts may not suffice to fight the global environmental crisis. In response, a number of architectural design approaches, such as biophilic design, restorative design and emotion-based nature-oriented architecture, have been developed to not only overcome the destructive environmental impacts of design and planning but also to improve human-nature interactions in the built environment. This paper critically reviews one of the most recognized approaches in the literature among the three: biophilic design. It discusses its relation to sustainability and the strengths and potentials for fostering pro-environmental behaviour. An in-depth analysis of biophilic design's emerging design frameworks follows, explicitly considering their applicability in informing the process of designing nature experiences in architecture. The paper concludes with two main shortcomings of biophilic design and outlines an area for future research.

Keywords: architecture design, biophilic design, Nature experiences, spatial Nature experiences.

1. Introduction

Rachel Carson (1962) 's *Silent Spring* is recognized for advocating the ill effects of pesticides on the environment. At its most influential, the book stirred up the first major American environmental movement (Ndubisi, 2014). Since its publication, the architecture realm has witnessed a surge in the growth of sustainable design approaches. (Dias, 2015) These sustainable design approaches have primarily focused on developing solutions that reduce the negative impacts on nature, mainly caused by how we design our built environments. Yet, a growing body of research (See O'Neill *et al.*, 2001; IPCC's Fifth Assessment Report by Lucon O. and Liphoto, 2014; Dias, 2015) considers that given the pace at which

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 22–31.*

the human population is multiplying merely diminishing the destructive impacts may not suffice to fight the current global environmental crisis.

Addressing such concerns in the sustainable architecture design context, social ecologist Stephen Kellert (2005b, p. 123) argued that the existing design knowledge must go beyond the limited objective of reducing modern development's adverse effects. Following such arguments, sustainable design scholar Chrisna Du Plessis (2012, p. 3) identified the need for design strategies that nurture a more harmonious and cooperative bond between humans and nature. Recent environmental psychology scholarship by Steg *et al.* (2012) concluded that human-nature connections fostered through experiencing nature promote pro-environmental behaviour. This view is further confirmed by Martin *et al.* (2020) through an empirical study that investigated the relationship between types of nature contact and pro-environmental behaviour. The results showed that nature connectedness was positively related to pro-environmental behaviour. Furthermore, a meta-analysis by Mackay and Schmitt (2019) analysed many such empirical studies to deduce that connecting people with nature could encourage positive behaviour and actions in protecting the environment.

Collectively, these arguments highlight how the positive behavioural changes resulting from connections fostered through nature experiences encourage concerns about the environment, promote sensitivity towards the environment and contribute toward sustainability. The following section assesses how nature experience has been addressed in architecture design.

1.1 Nature experiences and architectural design approaches

Conscious design of nature experiences within the built environment can potentially facilitate meaningful interactions with nature (Wielenga, 2021) and restore human connections with the natural world (Miller, 2005). In line with such views, three distinct architectural design approaches have been developed in the last two decades to purposefully design nature experiences within the buildings and landscape. These approaches stemmed from concerns about human detachment from nature and were intended to harmonize the human-nature relationship. The approaches are Biophilic design (Kellert, 2005b), Restorative Environmental Design (Kellert, 2005b) and an Emotion-based approach to Nature-oriented architecture (Joye, 2012). According to Kellert (2005b, p. 124), the primary intention of biophilic design is "…to elicit a positive, valued experience of nature in the human-built environment". Restorative Environmental Design (RED) integrates biophilic design principles with a low-impact ecological strategy to minimize and mitigate environmental impacts (Kellert, 2005b, p. 124). And an emotion-based approach to nature-oriented architecture aims to infuse and transpose object-oriented emotions such as awe, wonder, fascination, and delight that nature triggers (Joye, 2012).

Upon a preliminary review of the literature on all these three design approaches (See Kellert and Wilson, 1993; Kellert, 2005b; 2005a; Cramer and Browning, 2008; Heerwagen and Gregory, 2008; Kellert, 2008; Kellert and Heerwagen, 2008; Joye, 2012; Browning *et al.*, 2014; Kellert and Calabrese, 2015) it was found that Biophilic design offers several design frameworks. These frameworks are specifically intended to assist design professionals in fostering positive interactions between people and nature in designed settings and are recognized as "the largely missing link" in prevailing approaches to sustainable design by Kellert and Heerwagen (2008, p. viii). Berkebile *et al.* (2008) acknowledged that Biophilic design literature, in particular, the publication of *Biophilic design: the theory, science and practice of bringing buildings to life,* had provided a new language of architecture by suggesting strategies that designers could weave into building design to transform contemporary building practices.

Following such arguments, this paper critically reviews Biophilic design and its emerging frameworks. It first traces the various stages of the evolution of Biophilic design as a design concept. This is followed, and second, by a more in-depth analysis of theoretical underpinnings to distinctively highlight the potential of such an approach in fostering pro-environmental behaviour and its relation to sustainability. Third, it maps out the existing frameworks to conclude that there are three distinct lineages (as seen in Figure 1) among their evolution. Lastly, the paper concludes on the limitations of such frameworks, explicitly considering their applicability to inform design processes in fostering nature experiences and the importance of addressing such shortcomings in the architectural design context.

2. Methodology

A critical literature review was determined as the most appropriate method for this study. A critical review illustrates that the researcher has extensively studied the literature and critically evaluated its quality. (Grant and Booth, 2009) Furthermore, an effective critical review analyses materials from diverse sources and synthesis an existing school of thought (p. 93). Aligning with the objectives of this paper, the critical review of the literature on Biophilic Design was conducted in the following steps: The first step involved searching the extant literature with an emphasis on primary works that had been central and pivotal in shaping the concept of 'Biophilic Design'. The second step extracted relevant data that focused on: 1) How Biophilic Design developed as a design approach and 2) What are the different frameworks intended to assist in realizing the practical application of Biophilic design in the built environment? The final step collated, organized and mapped data to offer a new perspective on what is missing, identify the knowledge gap and distinguish other research areas (Grant and Booth, 2009).

3. Evolution of Biophilic Design

3.1 Defining Biophilic Design

The earliest use of the word "Biophilic" can be traced back to 1993. With an intention to separate the positive responses from the negative responses, architectural scholar Roger Ulrich (1993), in *The Biophilia Hypothesis* (Kellert and Wilson, 1993), defines biophilic as "positive responses" to certain natural stimuli and configurations (1993, p. 75). It was not until 2005 that such a positive association with nature was translated into a design approach and was formally introduced and defined by Kellert (2005b) as "Biophilic design" in the publication *Building for life: Designing and understanding the human-nature connection* (Kellert, 2005a). According to Kellert (2005b), the fundamental objective of biophilic design is to create a positive, valued experience of nature in the man-made built environment. As an architectural design approach, Biophilic design is based on the hypothesis that biophilic affinities for nature are innate (Wilson, 1984; Kellert and Wilson, 1993) and are vital to people's long-term physical, mental, and spiritual well-being by promoting positive interactions between people and nature in the built environment (Kellert, 2005b). Rendering the importance of such an approach, Kellert and Heerwagen (2008, p. viii) recognize Biophilic design as an integral approach to sustainable design.

In 2006, Kellert brought together a diverse group of researchers and industry representatives who shared a common interest in increasing nature connection opportunities at a three-day meeting in rural Rhode Island, USA. The shared intent of the participants was "…to assist designers and developers in pursuing the practical application of Biophilic design in the built environment" (Kellert and Heerwagen, 2008, p. 5; Browning *et al.*, 2014, p. 21). As an outcome of this gathering, *Biophilic design: the theory, science and practice of bringing buildings to life* (Kellert et al., 2008) was published in 2008. This work specifically clarifies Biophilic design as a theory, outlines its significance, and discusses design insight and guidance considering the architectural expression of biophilic design (Kellert and Heerwagen, 2008). A handful of these design insights such as: 'Characteristics of Biophilic buildings' (Heerwagen and Gregory, 2008), 'Dimensions, Elements and Attributes of Biophilic design' (Kellert, 2008) and 'Categories that define Biophilic buildings' (Cramer and Browning, 2008), were then recognized, revised, and combined into multiple frameworks to further expand the use of Biophilic design into practice. Before proceeding to the analysis of such frameworks, the following section firstly discusses the potential of Biophilic design in fostering pro-environmental behaviour and its relation to sustainability.

3.2 Theoretical underpinning: Biophilia, Biophilic Design and Sustainability

According to Kellert (2005b; 2008), Biophilic design as a design approach is the manifestation of an inherent need for affiliation with nature which is known as Biophilia. Biophilia is "the idea that humans possess a biological inclination to affiliate with natural systems and processes instrumental in their health and productivity" (Kellert and Heerwagen, 2008, p. viii). In other words, Biophilia is an inborn affinity and an innate desire to connect with nature (Wilson, 1984; 1993) and is a vital basis for human physical and mental wellbeing (Kellert, 2005b). However, in modern times, humans have destructed and degraded the natural environment because they failed to develop a non-destructive relationship with nature (Fromm, 1973, p. 389). As per Fromm (1973, p. 389), by fostering and perfecting the biological capability of Biophilia, humans could redevelop this non-destructive relationship with the environment. Nurturing Biophilia, as Gunderson (2014, p. 7) argues, is vital for "harmonizing society's relation with the Biosphere".

Similar to Fromm (1973) and Gunderson (2014), Wilson (1993)'s account of Biophilia also acknowledges the importance of affiliating with nature in enhancing nature's value to humans. These enhanced values, in turn, as per Kellert (2005b), promote pro-environmental behaviour. Such claims are further empirically supported by Pereira and Forster (2015, p. 1), who concluded that "connectedness to nature and biospheric values were positively related to pro-environmental behaviours". Furthermore, in a scholarly commentary, Berto and Barbiero (2017) suggested that exposure to nature "determines positive attitudes toward the environment and works as a motivator for pro-environmental behaviour." According to Kellert (2005b), such positive behavioural/attitudinal changes are beneficial to the degrading ecological conditions. Investigating further these positive effects of pro-environmental behavioural changes, Masud *et al.* (2015) argued that people who exhibit pro-environmental behaviour are willing to behave in a more environmentally friendly way to lessen the impact of climate change. Furthermore, in an EU-based case-specific study, van de Ven *et al.* (2018) confirmed that modest to rigorous levels of such behavioural change could reduce per-capita footprint emissions by 6 to 16 per cent. The arguments and studies presented above evince how fostering Biophilia could contribute to addressing the current global environmental crises.

As Biophilic design develops on the foundations of Biophilia, Biophilic design can potentially foster pro-environmental behaviour. As argued by Steg and Vlek (2009), such a positive change in building occupants' behaviour has the potential to help manage environmental problems, such as global warming, urban air pollution, water shortages, and loss of biodiversity. The following section further discusses the capacity of incorporating the existing Biophilic Design frameworks into practice.

3.3 Biophilic Design Frameworks

Over two decades, the Biophilic Design literature offered nine different Biophilic design frameworks. Such frameworks were developed with the intent to assist designers in pursuing the practical application of Biophilic design. Appraising these frameworks, a critic of biophilic design, Söderlund (2019) calls them 'the beginning of the tool kit' for design professionals to foster nature experiences in architecture. In the current study, the review of the existing literature revealed that these existing nine design frameworks underwent a 'change in its structure and content' (Pickett *et al.*, 2010). The critical mapping of these transformations follows three distinct lineages. (See Figure 1)

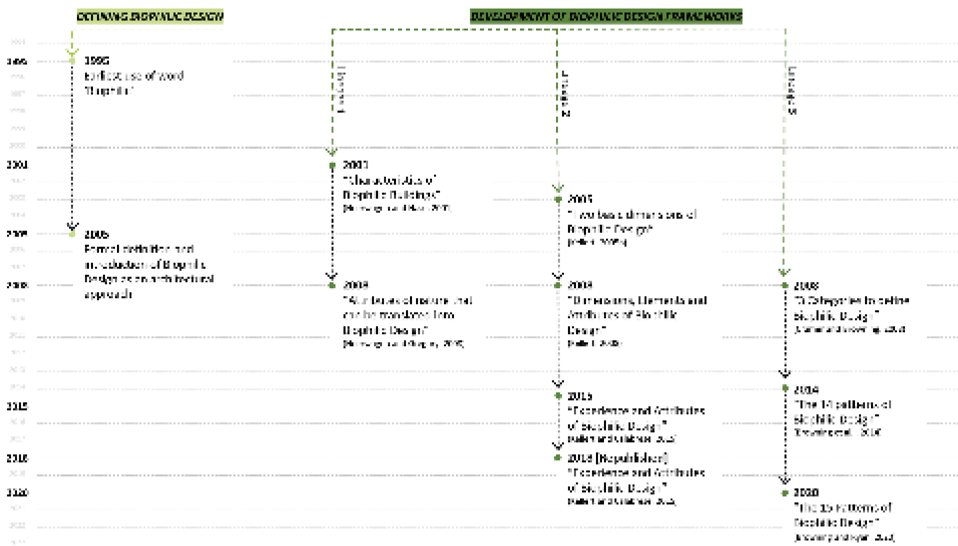


Figure 3 : A Timeline - Evolution of Biophilic Design as a concept (Source: Authors)

Although the formal definition of Biophilic design was introduced in 2005, the earliest known framework that notably defined what makes a building Biophilic was unveiled by Heerwagen and Hase (2001) in 2001. Heerwagen and Hase's work outlined "Characteristics of Biophilic Building", which consists of seven key features of a biophilic building and corresponding specific design attributes and qualities associated with each feature. This framework was successively revised and reintroduced by Heerwagen and Gregory (2008) as "Attributes of nature that can be translated into biophilic design" in the book *Biophilic design: the theory, science and practice of bringing buildings to life* (Kellert et al., 2008). Through this revised framework, Heerwagen and Gregory (2008, p. x) focused on 'how Biophilia can be expressed in building design'. It outlined seven Biophilic attributes or qualities of nature that could be translated into architecture with the use of light, air, materials, colours, spatial definition, movement patterns, openings and enclosers and connections to the outdoors (Heerwagen and Gregory, 2008, p. x). These seven qualities/attributes include: 'Sensory richness, Motion, Serendipity, Variations on a theme, Resilience, Sense of freeness, Prospect and refuge.' These two frameworks constitute the first lineage of Biophilic design frameworks. (See Lineage 1: Figure 1)

Parallel to the development of Heerwagen, Hase and Gregory's frameworks, in 2005, to deepen the understanding of Biophilic design, Kellert (2005b) introduced "two basic dimensions of Biophilic design": an organic (or naturalistic) design and vernacular (or place-based) design. Kellert (2008, p. 6) expanded these two dimensions into six elements: Environmental features, Natural shapes and forms, Natural patterns and processes, Light and space, Place-based relationships and Evolved human-nature relationships into a new set of strategies and named it - "dimensions, elements and attributes of Biophilic design". These elements were further expanded into a newer framework that consisted of seventy design attributes. Kellert and Calabrese (2015) later revised and simplified these seventy design attributes and condensed the list into a subsequent framework that offered twenty-four attributes. These attributes were then reorganized into the corresponding nature experiences it satisfies and classified under: direct experience of nature, the indirect experience of nature, and or the experience of space and place. They defined this newer listing as "experience and attributes of biophilic design". In recent times, in 2018, Kellert and Calabrese's framework was then refined into three basic elements and twenty-five associated attributes and presented in the book - *Nature by design: The practice of Biophilic design (Kellert, 2018)*. These four frameworks collectively compose the second lineage of Biophilic Design frameworks. (See Lineage 2: Figure 1)

Alongside the above two parallel lineages of Biophilic design frameworks, the third and the last lineage consists of two frameworks. Among the two, Cramer and Browning (2008) presented the first framework that consisted of "three categories that define Biophilic buildings": 'Nature in the Space, Natural Analogues and Nature of the Space'. The intent of this framework, according to Cramer and Browning (2008) was to transform practice to integrate better the theory of biologic design and its elements into man-made environments. Later, in 2014, Browning (2014) critiqued and questioned the capacity of most of the existing frameworks to provide "the guidance for implementation". To help close this gap, positioning biophilic design in the context of architectural practices, Browning *et al.* (2014) outlined "[T]he 14 patterns of Biophilic design". These patterns were an expansion of Cramer and Browning (2008) in their earlier framework. In the most recent publication by Browning and Ryan (2020) a 15th pattern was added to this list, offering a total of 15 patterns of Biophilic design. (See Lineage 3: Figure 1)

This section has outlined how the frameworks originated and transformed across three lineages. What follows presents a critical analysis of the diverse "design strategies" (Kellert *et al.*, 2008) and "design considerations" (Browning *et al.*, 2014) that these Biophilic Design frameworks offer, specifically considering their applicability to architectural practise.

4. Results:

As discussed in the previous section, Biophilic design offers nine design frameworks developed through three distinct lineages. This present paper has conducted a comparative analysis of the design strategies that these frameworks offer. This analysis revealed five different themes among these strategies: (i) Spectrum of nature experiences, (ii) Sensory interaction with nature, (iii) Characteristics and qualities found in nature, (iv) Symbolic forms of nature and (v) Nature elements.

The first theme (See Figure 2) identified among strategies the biophilic frameworks from Lineage 1 and 2 offers is 'a range of nature experiences' that has the potential to be designed to enhance the experiences of nature (Theme one). For example, the strategy – "Direct experience of nature" involves actual contact with nature, whereas "indirect experience of nature" involves experiencing the metaphorical forms of nature (Kellert and Calabrese, 2015; Kellert, 2018).

The second theme derived from the analysis is a set of strategies that do not specify the essence of nature experiences they aim to foster but rather outlines 'a range of sensory interaction' with nature that is around or within the built environment (Theme two), such as "visual, non-visual and non-rhythmic"

(Browning *et al.*, 2014). Such multi-sensory interactions with nature are significant as a design strategy, because, according to Kaplan and Kaplan (1989), they are interpreted on an emotional, physical, spiritual, or intellectual level; and are crucial in shaping an experience of nature.

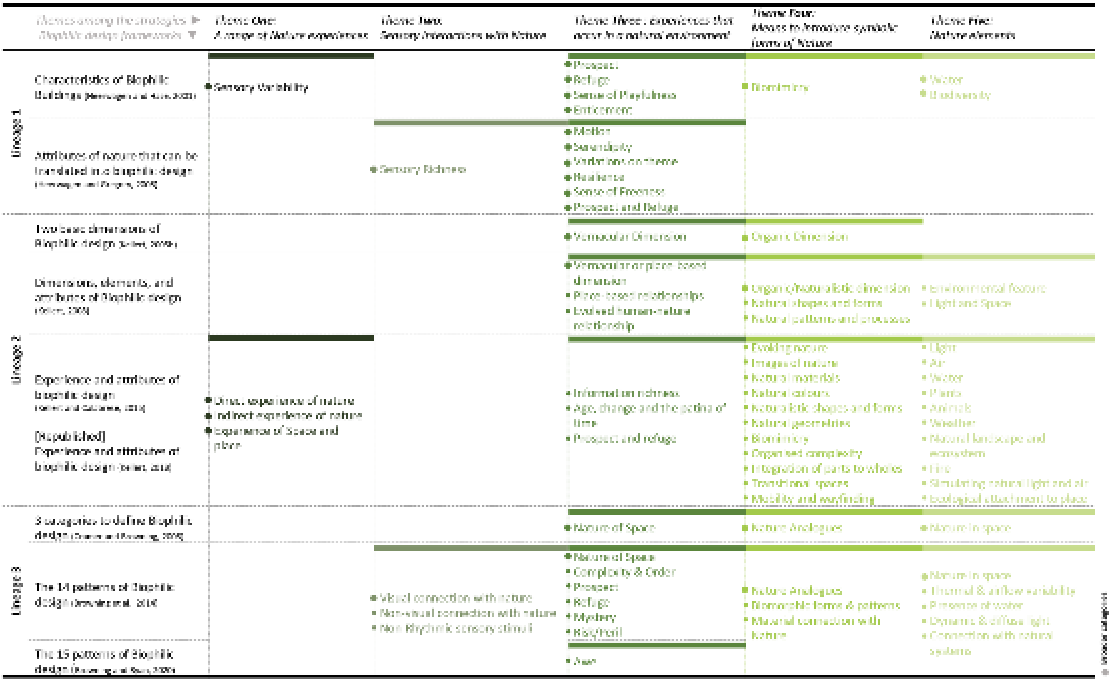


Figure 4 : Themes among the Biophilic strategies (Source: Authors)

The analysis also revealed that several design strategies collectively outlined experiences that occur in a natural environment (Theme three). An example of such experiences includes: Enticement, Refuge, Prospect, Mystery etc. (Heerwagen and Hase, 2001; Heerwagen and Gregory, 2008; Browning *et al.*, 2014). Referred to as *qualities or attributes*, these experiences are considered "fundamental aspects of the inherent human relationship to nature" by Kellert (2008, p. 13). These qualities, as Kaplan and Kaplan (1989) argue, coincide with the qualities of therapeutic environments; and, as per Browning *et al.* (2014), can be spatially configured in architectural design to induce an experience similar to the one experienced in nature. Furthermore, rendering the significance of these, Joye (2012) argued that such spatial qualities serve as an inspiration - that are easily applicable to induce nature experiences in the absence of biotic elements such as urban spaces.

Following this, a number of design strategies, such as "natural shapes and forms, natural colours, organized complexity" (Kellert *et al.*, 2008; Browning *et al.*, 2014; Kellert and Calabrese, 2015; Kellert, 2018), outlined means to introduce symbolic forms of nature (Theme four) into the built environment. According to Kellert (2008), these symbolic forms, when integrated into building design, can induce experiences of nature in the absence of natural elements in their natural form. Expanding further on the importance of symbolic representation of nature, Jeon *et al.* (2018) stated that indirect nature experience fostered by mimicking nature provides positive psychological and physiological effects similar to direct nature experiences.

Lastly, the comparative analysis revealed a collection of design strategies outlined by the majority of frameworks, namely "water, light, air, animals, plants", were merely listing of different natural elements that contribute to fostering nature experiences (Theme five). These Biotic and Abiotic components, when integrated into the design, as per Beery *et al.* (2017), hold the potential to foster 'direct, intentional experiences of nature in the built environment'.

5. Discussion and future recommendations:

The aim of this paper was to highlight the potential of biophilic design in fostering pro-environmental behaviour and its relation to sustainability; and to review its emerging design strategies, explicitly considering their applicability in informing the design process. The themes identified in the above comparative analysis revealed that the existing literature on Biophilic Design offers a range of strategies to design nature experiences. Despite these developments, offering a critique of Biophilic frameworks, Parsaee *et al.* (2019, p. 19) argued that "the existing [strategies] have offered no systemic framework by which designers can actively and consciously utilize biophilic recommendations in their design". In line with such arguments, this review identifies two main shortcomings of Biophilic design and its frameworks:

While Biophilic design as a design approach aims to restore and enhance the Nature experiences within the built environment, the first limitation that this paper has identified is how the existing extant literature on Biophilic Design does not offer a detailed and comprehensive definition of 'nature' in the phrase -'experience of nature'. While Browning *et al.* (2014, p. 10), one of the contributors to the third lineage of Biophilic design frameworks, defined nature as "…as living organisms and non-living components of an ecosystem – inclusive of everything from the sun and moon and seasonal arroyos, to managed forests and urban rain gardens, to Nemo's fishbowl habitat", the remaining literature on Biophilic Design and its design strategies do not offer what Bratman et al. (2012) and Gaston and Soga (2020, p. 2) define as – a clear and an explicit clarification on what constitutes nature in the nature experiences. Although nature is a broad term and is difficult to define, such clarification is crucial as 'it will affect what may or may not constitute nature [experience]' (Gaston and Soga, 2020, p. 2) in the built environment. As per Browning *et al.* (2014), a comprehensive and detailed articulation of what the term 'nature' means will help give context to practitioners in designing nature experiences in architecture. In particular, according to DeKay (2011), it will assist architects in translating the corresponding meanings/perceptions of nature into the 'designing experience of nature in architecture.

Furthermore, in realizing the practical applications of Biophilic design, although the existing frameworks offer design guidelines that are referred to as 'strategies', *they are limited in providing clear design recommendations on how different architectural elements can be configured to induce spatial experiences that enhance nature awareness.* For instance, the design strategy – 'Presence of water' (Browning *et al.*, 2014) suggests that having a water element in and around the building can foster a range of multi-sensory nature experiences; however, it does not specify in what ways architectural elements can be composed to better integrate a water element within the design. One possible explanation for this, as per Joye (2012, p. 213), is that all these existing frameworks and arguments were launched by "scholars who do not have architectural background". Therefore, the translation of the frameworks into applicable design strategies has been challenging. Nevertheless, addressing this lack of applicable Biophilic design strategies is important as such an attempt could potentially assist architects in curating spatial experiences in the built environment through design. Such purposefully designed nature interactions and experiences deepen our connection with nature, trigger pro-environmental behaviour, and contribute to the deteriorating conditions of nature. Based on this, further research is necessary to propose a more systematic and pragmatic design framework that offers visual-spatial patterns for designing transformational spatial experiences that induce a more profound and holistic connection with nature.

References

Beery, T. H., Raymond, C. M., Kyttä, M., Olafsson, A. S., Plieninger, T., Sandberg, M., Stenseke, M., Tengö, M. and Jönsson, K. I. (2017) Fostering incidental experiences of nature through green infrastructure planning, *Ambio*, 46(7), 717-730.

Berkebile, B., Fox, B. and and Hartley, A. (2008) Chapter 23 Reflections on Implementing

Biophilic Design, in S. R. Kellert, J. Heerwagen and M. Mador (eds.), *Biophilic design: the theory, science and practice of bringing buildings to life*, John Wiley & Sons.

Berto, R. and Barbiero, G. (2017) How the psychological benefits associated with exposure to nature can affect pro-environmental behavior, *Ann. Cogn. Sci*, 1(336), 10.36959.

Bratman, G. N., Hamilton, J. P. and Daily, G. C. (2012) The impacts of nature experience on human cognitive function and mental health, *Annals of the New York academy of sciences*, 1249(1), 118-136.

Browning, W. D. and Ryan, C. O. (2020) *Nature inside: a biophilic design guide*, ed., Routledge.

Browning, W. D., Ryan, C. O. and Clancy, J. O. (2014) 14 Patterns of Biophilic Design : Improving Health & Well-Being in the Built Environment.

Carson, R. (1962) *Silent spring*, Fortieth Anniversary Edition ed., Houghton Mifflin Harcourt.

Cramer, J. S. and Browning, W. D. (2008) Chapter 22 Transforming Building Practices

Through Biophilic Design, in S. R. Kellert, J. Heerwagen and M. Mador (eds.), *Biophilic design: the theory, science and practice of bringing buildings to life*, John Wiley & Sons.

DeKay, M. (2011) *Integral sustainable design: Transformative perspectives*, ed., Routledge.

Dias, B. D. (2015) Beyond sustainability–biophilic and regenerative design in architecture, *European Scientific Journal*, 11(9), 147-158.

Du Plessis, C. (2012) Towards a regenerative paradigm for the built environment, *Building Research & Information*, 40(1), 7-22.

Fromm, E. (1973) 12. Malignant Aggression: Necrophilia, in E. Fromm (ed.), *The anatomy of human destructiveness*

Macmillan.

Gaston, K. J. and Soga, M. (2020) Extinction of experience: The need to be more specific, *People and Nature*, 2(3), 575-581.

Grant, M. J. and Booth, A. (2009) A typology of reviews: an analysis of 14 review types and associated methodologies, *Health information & libraries journal*, 26(2), 91-108.

Gunderson, R. (2014) Erich Fromm's ecological messianism: The first biophilia hypothesis as humanistic social theory, *Humanity & Society*, 38(2), 182-204.

Heerwagen, J. and Gregory, B. (2008) Chapter 13 Biophilia and sensory aesthetics, in S. R. Kellert, J. Heerwagen and M. Mador (eds.), *Biophilic Design: The theory, science, and practice of bringing buildings to life. New Jersey: John Wiley & Sons*, John Wiley & Sons, 227-241.

Heerwagen, J. and Hase, B. (2001) Building biophilia: Connecting people to nature in building design, *Environmental Design and Construction*, 3, 30-36.

Jeon, J. Y., Yeon, P. S. and Shin, W. S. (2018) The influence of indirect nature experience on human system, *Forest science and technology*, 14(1), 29-32.

Joye, Y. (2012) Can architecture become second nature? An emotion-based approach to nature-oriented architecture, *Ecopsychology: Science, totems, and the technological species*, 195-217.

Kaplan, R. and Kaplan, S. (1989) *The experience of nature: A psychological perspective*, ed., CUP Archive.

Kellert, S. (2008) Chapter 1 Dimensions, Elements, and Attributes of Biophilic Design, in S. R. Kellert, J. Heerwagen and M. Mador (eds.), *Biophilic design: the theory, science and practice of bringing buildings to life*, John Wiley & Sons.

Kellert, S. and Calabrese, E. (2015) The practice of biophilic design, *London: Terrapin Bright LLC*.

Kellert, S. and Heerwagen, J. (2008) Preface, in S. R. Kellert, J. Heerwagen and M. Mador (eds.), *Biophilic design: the theory, science and practice of bringing buildings to life*, John Wiley & Sons.

Kellert, S. R. (2005a) *Building for life: Designing and understanding the human-nature connection*, ed., Island press.

Kellert, S. R. (2005b) Chapter 5 Biophilic Design, in S. R. Kellert (ed.), *Building for life: Designing and understanding the human-nature connection*, Island press.

Kellert, S. R. (2018) *Nature by design: The practice of biophilic design*, ed., Yale University Press.

Kellert, S. R., Heerwagen, J. and Mador, M. (2008) *Biophilic design: the theory, science and practice of bringing buildings to life*, ed., John Wiley & Sons.

Kellert, S. R. and Wilson, E. O. (1993) *The biophilia hypothesis*, ed., Island Press.

Lucon O., D. Ü.-V., A. Zain Ahmed, H. Akbari, P. Bertoldi, L.F. Cabeza, N. Eyre, A. Gadgil, L.D.D. Harvey, Y. Jiang, E. and Liphoto, S. M., S. Murakami, J. Parikh, C. Pyke, and M.V. Vilariño (2014) *Buildings*, in O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. and P. E. Brunner, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.),Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kingdom and New York, NY, USA.

Mackay, C. M. and Schmitt, M. T. (2019) Do people who feel connected to nature do more to protect it? A meta-analysis, *Journal of environmental psychology*, 65, 101323.

Martin, L., White, M. P., Hunt, A., Richardson, M., Pahl, S. and Burt, J. (2020) Nature contact, nature connectedness and associations with health, wellbeing and pro-environmental behaviours, *Journal of environmental psychology*, 68, 101389.

Masud, M. M., Akhtar, R., Afroz, R., Al-Amin, A. Q. and Kari, F. B. (2015) Pro-environmental behavior and public understanding of climate change, *Mitigation and Adaptation Strategies for Global Change*, 20(4), 591-600.

Miller, J. R. (2005) Biodiversity conservation and the extinction of experience, *Trends in ecology & evolution*, 20(8), 430-434.

Ndubisi, F. O. (2014) *The ecological design and planning reader*, ed., Springer.

O'Neill, B. C., MacKellar, F. L. and Lutz, W. (2001) Population and climate change, *ENVIRONMENTAL CHANGE & SECURITY PROJECT REPORT*, 137.

Parsaee, M., Demers, C. M., Hébert, M., Lalonde, J.-F. and Potvin, A. (2019) A photobiological approach to biophilic design in extreme climates, *Building and Environment*, 154, 211-226.

Pereira, M. and Forster, P. (2015) The relationship between connectedness to nature, environmental values, and pro-environmental behaviours, *Reinvention: An international journal of undergraduate research*, 8(2).

Pickett, S. T., Kolasa, J. and Jones, C. G. (2010) *Ecological understanding: the nature of theory and the theory of nature*, ed., Elsevier.

Söderlund, J. (2019) *The emergence of Biophilic design*, ed., Springer.

Steg, L. and Vlek, C. (2009) Encouraging pro-environmental behaviour: An integrative review and research agenda, *Journal of environmental psychology*, 29(3), 309-317.

Steg, L. E., Van Den Berg, A. E. and De Groot, J. I. (2012) *Environmental psychology: An introduction*, ed., BPS Blackwell.

Ulrich, R. S. (1993) Chapter 3 : Biophilia, biophobia, and natural landscapes, in E. O. Wilson and S. Kellert (eds.), *The biophilia hypothesis*, 73-137.

van de Ven, D.-J., González-Eguino, M. and Arto, I. (2018) The potential of behavioural change for climate change mitigation: a case study for the European Union, *Mitigation and Adaptation Strategies for Global Change*, 23(6), 853-886.

Wielenga, B. (2021) New experiences in nature areas: architecture as a tool to stimulate transformative experiences among visitors in nature areas?, *Journal of Tourism Futures*.

Wilson, E. O. (1984) *Biophilia*, ed., Harvard University Press, Cambridge, UNITED STATES.

Wilson, E. O. (1993) Chapter 1 : Biophilia & the conservation ethics, in S. R. Kellert and E. O. Wilson (eds.), *The biophilia hypothesis*, Island Press.

A hygrothermal analysis of 6 Star envelope systems used in code compliant homes in Victoria

Mark Dewsbury[1], Freya Su[2], Toba Olaoye[3] and Hartwig Kuenzel[4]

[1,2,3] University of Tasmania, Launceston, Australia
mark.dewsbury@utas.edu.au[1], ORCID-0000-0002-3607-3637[1]
[4] Fraunhofer Institute of Building Physics, Holzkirchen, Germany
hartwig.kuenzel@ibp.fraunhofer.de[4], ORCID-0000-0001-8305-0262[4]

Abstract: The correlation between energy efficient buildings and the increased risk of condensation and mould inside homes and within the built fabric of homes has been internationally recognised for more than nine decades. In the northern hemisphere, regulations and standards have been in use for more than five decades. However, the regulatory development in Australia has been tardy. Researchers at the University of Tasmania have been completing steady state, hybrid steady state and transient hygrothermal calculations and simulations for the last decade and much of this data has performed the back-bone for the “Condensation in Buildings –Tasmanian Designers’ Guide” which is referenced with the National Construction Code for Tasmania and the Australian Capital Territory. The guide is also used in Victoria. Recent research that has been exploring risks of moisture, moisture accumulation and mould growth in ‘code compliant’ 6 Star homes in Victoria. To gain an understanding of current problems in new housing and to plan recommendations for 7 Star housing, the Victorian Building Authority contracted the University of Tasmania to complete a series of hygrothermal research tasks. The first part of the research explored eleven external wall common external wall types used in external walls of Class 1 and Class 2 buildings, within NatHERS climates for Victoria. This paper reports the results of the hygrothermal analysis for the six of the simulated wall systems, demonstrated significant durability and human health risks in current construction practices.

Keywords: Condensation, Mould, Hygrothermal, Energy Efficiency.

1. Introduction

The purpose of this research is to establish if new homes in Victoria are susceptible to moisture accumulation (condensation) or mould growth, within external wall systems that are built in compliance with current regulations. The National Construction Code (NCC) describes minimum methods and systems to meet regulatory compliance. Internationally, and in Australia, the correlation between buildings that create a significantly different conditions (temperature and humidity), between the interior and exterior environments are more susceptible to moisture on building surfaces, interstitial condensation, and mould

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 32–43.*

growth has been known for quite some time (Rogers, 1938). This introduction firstly provides a brief history of the application of energy efficient envelope requirements for Class 1 and Class 2 buildings. This is followed by an introduction to conditions for moisture on and in the built fabric, mould growth, reasons why the requirements are within the Health & Amenity section of the NCC, and methods that can be used to ascertain risks for the built fabric and building occupants. As a point of reflection, it has been estimated that the leaky building syndrome in New Zealand has cost their economy more than NZD$46B (Dyer, 2019; 2021). Whilst, recent research within the United Kingdom has identified that up to £1 billion per annum of the National Health Service budget can be attributed to the medical treatment of people living within ‘wet’ buildings (Rickaby, 2021).

Prior to 2002, in Australia there were no national requirements for a measurable thermal performance of the building envelope and its impact on heating or cooling energy use. However, the Nationwide House Energy Rating Scheme (NatHERS) was established in 1993 as a mechanism to quantify energy that may be used to heat and cool Australian homes (Ballinger and Cassell, 1995; Delsante, 1996). Research using the NatHERS simulation method established that most new housing had a NatHERS Star rating between 1 Star and 3 Stars (Drogemuller, 1999). After the acceptance of climate change and the need to reduce greenhouse gas emissions, the improvement of building envelopes was identified as a ‘low hanging fruit' in terms of the economic cost and the national benefit (Australian Greenhouse Office, 1998; 2002). In 2003, the first set of building regulations, within the Building Code of Australia (BCA), were introduced requiring envelope insulation, building sealing and glazing performance were implemented (ABCB, 2003). In 2004, the NatHERS star rating system was applied to BCA 2004, where a compliant home generally had a Star rating score of 4 Stars (ABCB, 2004). In 2006, the minimum performance requirement within the BCA was increased to 5 Stars (ABCB, 2006), followed by a 6 Star requirement in 2010 (ABCB, 2010). It is anticipated that the NCC will include a minimum 7 Star requirement for new Class 1 and Class 2 buildings in 2022/2023. During each of these steps there has been a reduction in the simulation-based energy needs for household heating and cooling.

Nath (Nath *et al.*, 2019) noted the general changes in simulated household interior temperatures between pre-2003 housing (1 to 3 Star housing) and modern 6 Star housing. Whereas pre 2003 housing had a spread of room temperatures from 6°C to 36°C, more recent housing has a spread between 10°C to 36°C, but with a strong concentration of data between 16°C and 22°C. The concentration of room temperatures, from one perspective, reflects a better building envelope for human thermal comfort, but from another perspective, it indicates that the air within the home may be containing a lot more water vapour. Air with a temperature of 12°C and a relative humidity of 55%, contains five grams of water per kilogram of air. Air with a temperature of 21°C and a relative humidity of 70%, which is a common condition in many Australian homes, contains eleven grams of water per kilogram of air. By making the home more thermally comfortable, we have more than doubled the amount of water vapour contained within the air in the home. Additionally, many materials used to construct and furnish a home adsorb water vapour, and in some cases are referred to as seasonal hygrothermal buffers (Di Giuseppe and D'Orazio, 2014; Slimani *et al.*, 2015). The combination of an increased amount of water vapour in the air and an increased adsorption of water vapour by the building and its contents creates a moister interior environment. Understanding the temperature and relative humidity in new homes is critical to understand what may be happening to the durability of the built fabric and/or the interior air quality.

For several centuries, we have been aware of how water in the air may condense and form moisture on building surfaces and/or interstitially within envelope elements (floors, walls and roof spaces). A simplified equation to calculate the dew point temperature for different conditions is:

$$Td = T - \left(\frac{100 - RH}{5}\right)$$

Table 3, below, shows some dew point temperatures for different interior conditions. What this data shows, for example, is that when a room is conditioned to 21°C and the relative humidity is 75%, any surface that is thermally bridged (glass, window frame, structural framing, gaps insulation, air leakage, etc) and has a temperature of 16°C, will have moisture condense out of the air onto thermally bridged interior surface. This is commonly observed on single glazing windows during winter. In the context of Victoria, the outdoor temperature is often 15°C or less.

Table 3: Examples of dewpoint temperature for conditioned interiors

Temperature (T°C)	**Relative Humidity (RH%)**	**Dew point (T°C)**
21	55	12
21	65	14
21	75	16
21	80	17
24	65	17
24	75	19

Since the early 2000s, very little research has been done in Australia on the impact of excessive moisture on building structures and material durability. There was some limited Australian research regarding the impact of excessive moisture on nail plate mechanical fixings in timber trusses (Paevere *et al.*, 2009), but very little research on these matters has progressed. This contrasts with international research (Viitanen and Ritschkoff, 1991; Siagian, 2008; Krus *et al.*, 2010; Zhang *et al.*, 2011; Cederlund and Josefsson, 2015; Roslan *et al.*, 2015; Harriman *et al.*, 2016; Kuenzel and Dewsbury, 2022) and the recent findings from the nationwide condensation survey commissioned by the Australian Building Codes Board (Dewsbury *et al.*, 2016), which identified that up to 40% of all new Class 1 and Class 2 dwellings constructed in the decade from 2006 to 2016, in all jurisdictions, had a concerning amount of condensation identified by the responding building design or construction professionals.

Innovations, like the advent of European cavity brick construction in the late 19th century was an attempt to disconnect the moist and cold outer brick from the dry and warm inner brick. This method of construction also demonstrated benefits in hot climates, where the hot outer brick was disconnected from the cool inner brick. When brick veneer construction commenced in the late 1920's, the same principle was adopted. These innovations occurred well before any insulation was added to external floors, walls of roof spaces of homes and sadly, many other styles of external wall system construction haven't adopted these principles.

One of the less visible, equally destructive, and significantly impacting human health effects from moisture in housing is mould growth and mould spores within habitable spaces. Observed and simulated temperature and relative humidity conditions within Australian homes between 2010 and 2018 has shown a propensity to create ideal conditions for mould growth (Ambrose and Syme, 2015; Dewsbury and Law, 2016; Nath *et al.*, 2018). Figure 5 below shows the temperature, relative humidity and nutrient conditions that mould needs for effective growth. The greyed in section highlights the typical interior conditions for relative humidity and air temperature for human comfort. This shows how the temperature and relative humidity conditions within modern Australian homes may be providing ideal mould supporting temperature and humidity conditions. The nutrient component within homes is provided by the dust that is created by human occupation and building infiltration. Within the interstitial spaces, materials like timber and construction dust also provide nutrients for mould growth. Most mould growth calculation methods require the selection of a construction system, which then allocates value for available nutrients for mould growth.

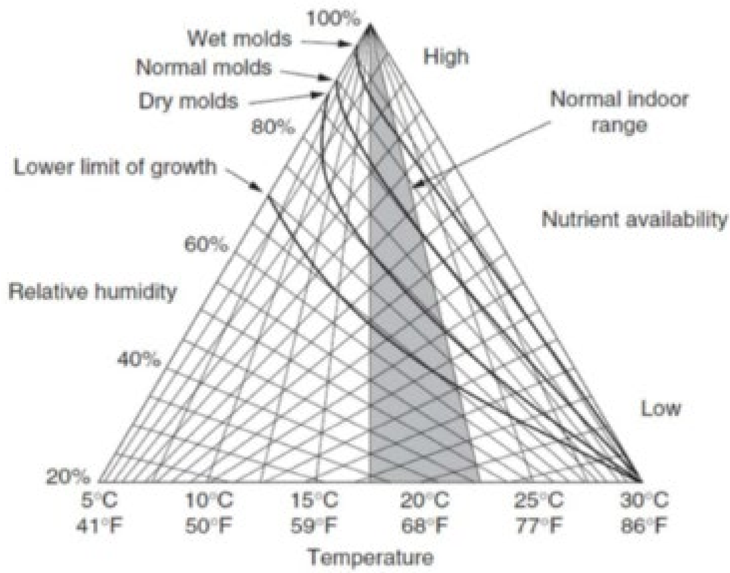


Figure 5: Conditions that support mould growth (Clarke *et al.*, 1999)

It is important to note that, subject to the amount of interior air movement and the comprehensiveness of the ventilation, the amount of ventilation required to remove excess water vapour and the environment needed for mould to grow can change. Research presented at the 1st International Conference on Moisture in Buildings (ICMB2021), at University College London, and the 2021 annual InnoRenew conference included research that documented mould growth within fully air-conditioned and ventilated museum buildings when the relative humidity was set at 60% (Bastholm *et al.*, 2021; Vcelak, 2021). What this research identified were the differences between areas of good air movement and areas where there was good mechanical ventilation but some areas where the air was quite still. In many respects, this is not too different to many homes, where furnishings and methods of fresh air supply and exhaust will allow for some areas within a room to be well ventilated, and other areas that may include very still air spaces. This may suggest that relative humidity control in homes may need to be kept below 60%RH.

The critical issue surrounding mould growth and its impact on building occupants is internationally recognised. Mould spores within buildings are attributable to several short-term and life-long medical conditions (WHO, 2009b; 2009a; Braubach *et al.*, 2011). Nath identified that Australia has twice the OECD average for Asthma rates per head of capita (Nath *et al.*, 2019). In 2009, the international recognition of the significant impact that mould within buildings has on human health led the World Health Organisation, to state that no building should have a visible presence of mould growth.

Within the Australian regulatory context, there have been no regulatory requirements for condensation of mould until NCC 2019 (ABCB, 2019). The initial performance requirement and acceptable construction methods only applied to Class 1 and Class 2 buildings in NCC climate zones 6, 7 and 8. By comparison to other developed nations, this may be up to 50 years too late, as many homes built prior to the introduction of energy efficiency regulations in 2003, and homes constructed between 2003 and 2019 have condensation and mould problems. It could be argued that the acceptable construction requirements introduced in 2019 may be inadequate.

2. Method

In this research, the method adopted uses a hygrothermal (heat and moisture) and bio-hygrothermal (mould growth) simulation programs, that have been developed by a government funded research organisation, (Fraunhofer Institute of Building Physics, Germany), and has been empirically validated and improved over more than 25 years (Schwab, 2021). The WUFI Pro software was used for hygrothermal simulation and the WUFI VTT add-on was used for bio-hygrothermal simulation. Research by Nath, in collaboration with researchers from the Fraunhofer Institute of Building Physics, established the most appropriate methodology for hygrothermal and bio-hygrothermal simulations in Australia (Nath and Dewsbury, 2019; Nath *et al.*, 2020). More recently, the Australian Institute of Refrigeration, Air-conditioning and Heating (AIRAH) has entered a data sharing arrangement with the American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) and published DA-07- Criteria for moisture control in buildings (AIRAH, 2020), which is very similar to ASHRAE standard 160 of the same name (ASHRAE, 2016). In this research several factors for the methodology needed to be considered within the context of Class 1 and Class 2 6 Star buildings in Victoria, being external envelope types, external and internal climates, house design and construction material physical properties.

2.1 External envelope types

The research was guided by a Project Steering Committee that included members from the four contributing organisations, namely:

- Victorian Building Authority (VBA)
- Master Builders Association of Victoria (MBAV)
- CSIRO, and
- Forest and Wood Products Australia.

After reviewing the eight external wall types described within the Energy Efficiency section of the NCC (3.12.1.1), it was identified that some of these external wall types were extremely uncommon and that some external wall types needed to be added. This led to the selection of the nine external wall types, as shown in Table 4. In each case, the external wall system composition was informed by data provided by the CSIRO, VBA and MBAV.

Table 4: External wall systems that were selected

	Description	Rationale for selections	Described within NCC
1	Weatherboard cladding with insulated timber frame	This wall type comprises 20% of the Victorian Class 1 and Class 2 market.	Yes
2	Compressed fibre cement sheet cladding with insulated timber frame	This wall type comprises 9% of the Victorian Class 1 and Class 2 market.	Yes
3	Clay masonry veneer with insulated timber frame	This wall type comprises 61% of the Victorian Class 1 and Class 2 market.	Yes
4	Concrete blockwork masonry with interior insulation	This wall type comprises 0.5% of the Victorian Class 1 and Class 2 market.	Yes
5	Externally insulated clay masonry (reverse clay masonry veneer) with insulated timber frame	This wall type is very rare, but due to its use to provide thermal mass in many award-winning eco-designer homes, this wall type be retained.	Yes
6	Extruded polystyrene (XPS) cladding with insulated timber frame	This wall type was common but current data uncertain.	No
7	Expanded polystyrene (EPS) cladding with insulated timber frame	This wall type was common but current data uncertain.	No
8	Autoclaved aerated concrete masonry cladding with insulated timber frame	This wall type comprises 6% of the Victorian Class 1 and Class 2 market.	No
9	Flat metal cladding with insulated timber frame	This wall type comprises 2% of the Victorian Class 1 and Class 2 market. This can include products like sheet metal and thin composite steel and aluminium cladding systems.	No

2.2 External climate data

The selection of climates and climate data needed to consider both the climate zones within the NCC and the climate zones within NatHERS. The ABCB NCC climate map for Victoria includes four 4 climate types, namely; climate zone 4, climate zone 6, climate zone 7 and climate zone 8. The NCC climate zones inform the minimum thermal resistance values for the external envelope. The minimum thermal resistance values establish how much insulation is needed within the selected external wall systems.

The second layer of climate data was the NatHERS climates. The NatHERS climate data is allocated by postcode. In Victoria, there are 1558 distinct localities with postcodes that are (mostly) sorted into 13 NatHERS climate zones. There is a slight anomaly where six of these postcodes, are in areas of low housing density and are not assigned a NatHERS climate zone. These were eliminated for this this stage in the research. Some localities straddle more than one NCC climate zone. These areas were replicated to compile a longer list cross referencing Victorian localities and their corresponding postcodes with NatHERS and NCC climate zones, bringing the count to 1726 localities. A cross analysis between postcodes, areas of development and population centres established eight NatHERS climate zones, representing 1682 postcode-based localities. These included NatHERS Climate zones 21, 22, 27, 60, 61, 63, 64, and 66. Compatible climate files for these NatHERS climate zones were obtained in *.epw format from US Energy Plus website. These files form part of the Australian government provided files for building energy simulation.

2.3 Interior Climate

The interior climates selected in this research adopted many of the principles outlined in ASHRAE Standard 160. Key parameters which were applied included:

- An Air Change Rate @n50 of 10, as per the verification method in the NCC 2019. This is significantly different to the ACR5@n50 within ASHRAE 160, where airtightness measures have been required for some time.
- A 70% relative humidity cap as per international guidelines (Deutsches Institut Fur Normung E.V. (German National Standard), 2020)
- Heating thermostat setting of 20.0°C (NatHERS Administrator, 2019)
- Building volume - a house plan that has been used for several building thermal performance and hygrothermal analysis projects was used. The house plan floor area (not including the garage) is 152.5m^2, with an interior volume of 366m^3.

2.4 Hygrothermal and bio-hygrothermal simulation

In this research, adopting the principles of ASHRAE Standard 160 and the most recent version of the German Standard DIN-4108, hygrothermal simulations were completed for a ten-year period. Internationally, the minimum of a ten-year simulation period is increasingly being required due to the expected long-term performance of buildings (Nath *et al.*, 2020). The results from the ten-year hygrothermal simulations were then post processed by the WUFI VTT mould growth software. It should be noted that these two international standards provided regulatory verification in North America and Europe.

3. Results

The section summarises the hygrothermal and bio-hygrothermal simulation of 940 external wall systems within eight NatHERS climates of Victoria. The nine external wall systems comprised contemporary materials and materials that were compliant with the requirements of the National Construction Code (2019) for 6 Star housing. The simulations included 532 with an ACR of 10 and 408 with an ACR of 5. An ACR of 10 is the maximum allowed for a 6 Star home, as specified in the verification method for building sealing.

The hygrothermal simulation of most wall systems showed no moisture accumulation. Where moisture accumulation was simulated, it was within the boundary of exterior cladding and acrylic render systems.

Of the 532 bio-hygrothermal simulations with an ACR of 10:

- 299 showed a MI of NIL or less than 1.0

- 119 showed a MI greater than 1.0 and less than 3.0, indicating these wall systems require further investigation, and
- 114 showed a MI of 3.0 or more, indicating that these methods of construction are climatically inappropriate.

Of the 408 bio-hygrothermal simulations with an ACR of 5:

- 21 showed a MI of NIL or less than 1.0
- 63 showed a MI greater than 1.0 and less than 3.0, indicating these wall systems require further investigation, and
- 324 showed a MI of 3.0 or more, indicating that these methods of construction are climatically inappropriate.

The results of the bio-hygrothermal simulations of the nine external wall systems in 14 to 15 NatHERS climate and built fabric variables, with an ACR of 10 and an ACR of 5, as shown in Table 5 documented:

- Except for the polystyrene clad wall systems, the other seven wall systems were not constructed in a climatically appropriate method in many climate types.
- All external wall systems had an unacceptable mould growth index when the ACR of 5 was applied.

Table 5: Number of climates where all four orientations had an acceptable mould growth index (MI <3.0)

Wall system	**ACR10**	**ACR5**
Timber clad external wall system	1	Not assessed
Compressed fibre cement sheet clad external wall system	Nil	Not assessed
Clay masonry veneer external wall system	5	Nil
Concrete block, internally insulated, external wall system	3	Nil
Externally insulated clay masonry external wall system	2	Nil
Extruded polystyrene clad external wall system	15	Nil
Expanded polystyrene clad external wall system	15	Nil
Autoclaved aerated concrete cladding external wall system	4	Nil
Flat pan metal cladding external wall system	Nil	Nil

4. Discussion

From these simulations some pertinent matters are evident with regard orientation and shading, cladding insulation properties, wall system hygrothermal buffering properties, water vapour diffusion resistivity properties and building airtightness.

Due to the radiation influenced drying potential, the northern orientation for many scenarios showed a NIL mould growth index, whilst other orientations of the same wall system ranged from requiring further analysis to an unacceptable mould growth index. The NCC does not differentiate construction methods based on orientation. Within this context, it should be demonstrated to relevant parties that the southern (non-equatorial) orientation has an acceptable MI prior to construction approval. This demonstrates that at this stage the aspect of wall orientation and its corresponding impact on moisture and mould is not addressed adequately within the NCC. Furthermore, if an eastern, northern or western external wall system is shaded by a nearby structure, verandah, eaves, or landscaping, its hygrothermal performance will be closer to that of the southern orientation, rather than its actual orientation.

Only three of the eight wall types described with Section 3.12 of NCC 2019 require a vented cavity. Within this research, the only external walls that included a vented cavity space were the clay masonry veneer, the externally insulated clay masonry, and the autoclaved aerated concrete wall systems. In this report, these three wall systems performed better than others due to their inclusion of a vented vapour cavity. Internationally, cavities are required for many external wall systems. In Australia, this aspect needs more analysis and should be the focus of further analysis and development, to reduce the risk of unacceptable levels of mould growth in external wall systems.

NCC 2019, only required the pliable membranes for a 6 Star Class 1 or Class 2 building to be of a AS4200 Class 3 in NCC climate zones 6, 7 and 8. The NCC 2019, had no vapour permeability requirement for pliable membranes for a 6 Star Class 1 or Class 2 building located in NCC climate zone 4. The ability of a wall system to allow the water vapour to leave the built fabric is a critical component to promote wall drying capacity and reduce the risk of mould growth.

Materials that provided insulation on the exterior of the insulated timber frame, like extruded polystyrene, expanded polystyrene and autoclaved aerated concrete performed well, as they allowed the timber frame to stay above dewpoint and mould growth conditions for longer periods of time. However, even these systems failed when the ACR was reduced to 5.

Materials like concrete, clay brick and autoclaved aerated concrete allow for daily seasonal adsorption and release of moisture. The externally insulated clay masonry (reverse brick veneer) wall system had a better performance than the timber, compressed fibre cement sheet and flat metal clad external wall systems due to their ability to act as a hygrothermal buffer. Cross laminated, mass-timber and concrete elements are known for their hygrothermal buffering properties.

The NCC 2019 has a performance requirement that a new 6 Star home have an airtightness value not greater than ACR 10. This value has been used as a baseline for all simulations. However, governments, practitioners and homeowners have spent the last two decades exploring how to improve the airtightness of homes. As a result, many new homes have an ACR significantly less than 10.0. When the ACR was 10, 43% of the external wall systems simulated had a MI that required further investigation or an MI greater than 3.0. When the ACR was further modified to 5, 94% showed the need for a more detailed analysis or an unacceptable mould growth index greater than 3.0. As buildings increase in thermal performance the careful selection and installation of pliable building membranes on the interior and exterior of the external wall system becomes increasingly significant. This is to manage the rate and amount of water vapour diffusing through the external wall.

As buildings become more air-tight, and we accept that many building occupants may not open windows and doors, due to many reasons, but not limited to noise, security, the external air temperature, the external wind speed and periods when home. In the simulations completed in this research, the interior relative humidity has been capped at 80% due to the international nature of the software. However, except for the operable window requirement, there is no requirement to manage water vapour and relative humidity in Australian Class 1 and Class 2 buildings. As other nations have made their buildings more air-tight and acknowledged occupant limitations, there has been an increased use of enthalpy recovery ventilation systems to ensure the interior air quality and relative humidity are appropriately managed.

5. Conclusion

In all scenarios, the southern orientated external wall systems showed the greatest mould growth index values. Due to the solar radiation induced drying potential, the northern facing walls often performed much better, with a nil or lower mould growth index value. However, if one considers external wall shading from nearby buildings, eaves or landscaping, the minimum performance requirement should use the material arrangements such that the southern wall has a nil, or acceptable mould growth index.

Each of the 6 Star wall systems needs to be modified such that the southern orientation shows either a nil, or an acceptable long-term mould growth index (MI of Nil or <2.9). This would include the specification of pliable building membrane water vapour diffusion resistance properties and the inclusion of a vented cavity for most external wall systems. The next stage of the research includes 7 Star wall systems. It is anticipated that many Australian state governments will adopt the 7 Star thermal performance requirements in 2022/2023. When compared to a 6 Star home, a 7 Star home will have a NatHERS simulation based 25% reduction in energy needed to heat or cool the habitable rooms. This will further increase the challenges of water vapour diffusion through the built fabric. The findings from the hygrothermal and bio-hygrothermal simulations of the 6 Star wall systems will need to be applied to the 7 Star wall systems. A significant education program needs to be undertaken to inform design and construction professions of the risks evident in the simulation results. Since 2014, the Tasmanian government has actively engaged with the design and construction professions via training activities and two editions of the Tasmanian condensation design guide. Further research must consider various aspects of airtightness and the climatically appropriate envelope elements to control water vapour diffusion such that concerning amounts of, or unacceptable amounts of mould growth do not occur. There needs to be a coordinated approach by the ABCB, NatHERS Administrator, appropriate researchers, and industry-based representatives, for the co-development of energy efficiency and hygrothermal regulations. Finally, this research is limited to the wall systems and inputs, as shown and discussed. Changes to these inputs will change the results.

Acknowledgements

This research was supported by the Victorian Building Authority through a research grant in association with financial and project advisory committee support from CSIRO, Master Builders Association of Victoria, Forest and Wood Products Australia, Fraunhofer Institute for Building Physics.

References

ABCB (2003) The building Code of Australia: 1996 Amendment 13, in A. B. C. Board (ed.).

ABCB (2004) The Building Code of Australia, Australian Building Codes Board, Section 3.12.

ABCB (2006) The Building Code of Australia, Australian Building Code Board.

ABCB (2010) The Building Code of Australia, Australian Building Codes Board.

ABCB (2019) The National Construction Code: Volume 2, in A. B. C. Board (ed.), Canberra.

AIRAH (2020) DA-07 Criteria for moisture control in buildings, Australian Institute of Refigeration, Air-conditioning and Heating, Melbourne.

Ambrose, M. and Syme, M. (2015) House energy efficiency inspections project: final report, CSIRO, Canberra.

ASHRAE (2016) Standard 160-2016 - Criteria for Moisture-Control Design Analysis in Buildings (ANSI Approved), Atlanta.

Australian Greenhouse Office (1998) The national greenhouse strategy: strategic response for advancing Australia's greenhouse response.

Australian Greenhouse Office (2002) AGO-CSIRO Greenhouse Efficient Design, in Australian Greenhouse Office Department of the Environment Water Heritage and the Arts (ed.).

Ballinger, J. and Cassell, D. (1995) Solar Efficient Housing and NatHERS: An Important Marketing Tool, Fuel and Energy Abstracts, 36(4), 237.

Bastholm, C., Madsen, A., Frisvad, J. and Richter, J. (2021) Whate defines "moisture in buildings"? Growth of xerophilic fungi in museum repositries challenges the perception of humid buildings and the preservation of cultural heritage., 1st international conference on moisture in buildings, University Collge london, 28-29 June, 2021.

Braubach, M., Jacobs, D. and Ormandy, D. (2011) Environmental burden of disease associated with inadequate housing : a method guide to the quanti cation of health effects of selected housing risks in the WHO European Region, World Health Organisation.

Cederlund, O. and Josefsson, F. (2015) An evaluation of two well insulated structures, Faculty of Engineering, Lund University.

Clarke, J., Johnstone, C., Kelly, N., McLean, R., Anderson, J., Rowan, N. and Smith, J. (1999) A technique for the prediction of the conditions leading to mould growth in buildings, Building and Environment, 34(4), 515-521.

Delsante, A. (1996) The Australian Nationwide House Energy Rating Scheme, IBPSA NEWS, 8(1), 17-20.

Deutsches Institut Fur Normung E.V. (German National Standard) (2020) DIN 4108-4: Thermal insulation and energy economy in buildings - Part 4: Hygrothermal design values, Germany.

Dewsbury, M. and Law, T. (2016) Recent increases in the occurrence of condensation and mould within new Tasmanian housing,50th International Conference of the Architectural Science Association 2016, Adelaide, 715-724.

Dewsbury, M., Law, T., Fitz-Gerald, D., McComish, B., Potgieter, J., Chandler, T. and Soudan, A. (2016) Scoping study of condensation in residential buildings: final report, Australian Building Codes Board.

Di Giuseppe, E. and D'Orazio, M. (2014) Moisture buffering "active" devices for indoor humidity control: preliminary experimental evaluations, in R. J. Howlett (ed.), 6th International Conference on Sustainability in Energy and Buildings, 42-51.

Drogemuller, R. D., A; Moller, S; Sharpe, R; Blackmore, J; Oakes, S; (1999) Scoping study of minimum energy performance requirements for incorporation into the building Code of Australia, in CSIRO (ed.), Australian Greenhouse Office.

Dyer, P. (2019) The story of New Zealand's leaky buildings disaster, ed., David Bateman Limited.

Dyer, P. (2021) Something rotten in the state…. Architecture New Zealand.

Harriman, L., Grimes, C., Hart, K., Hodgson, M., Thi, L., Offerman, F. and Rose, W. B. (2016) ASHRAE position document on limiting indoor mold and dampness in buildings, ASHRAE, Altanta, Georgia.

Krus, M., Seidler, M. and Sedlbauer, K. (2010) Comparative evaluation of the predictions of two established mould growth models, ASHRAE Transactions, 116.

Kuenzel, H. and Dewsbury, M. (2022) Moisture control design has to respond to all relevant hygrothermal loads, UCL Open: Environment.

Nath, S. and Dewsbury, M. (2019) The use of an innovative hygrothermal simulation method to develop built fabric recommendations for southern Australia, in A. A. a. R. Gupta (ed.),Revisiting the role of Architecture for 'Surviving' Development: 53rd International Conference of the Architectural Science Association 2019., Architectural Science Association (ANZAScA), IIT Roorkee, India, 373–382.

Nath, S., Dewsbury, M. and Douwes, J. (2019) Has a singular focus of building regulations created unhealthy homes?, Architectural Science Review.

Nath, S., Dewsbury, M. and Orr, K. (2018) Is new housing a health hazard?, in P. R. a. M. M. Andamon (ed.),Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association, The Architectural Science Association and RMIT University, RMIT University, 71-78.

Nath, S., Dewsbury, M., Watson, P., Lovell, H. and Kunzel, H. (2020) A bio-hygrothermal mould growth analysis of typical Australian residential wall systems, The 54th International Conference of the Architectural Science Association (ANZAScA) 2020, edited by A. G. Ali Ghaffarian oseini, and Nicola Naismith, School of Future Environments, Built Environment Engineering, Auckland University of Technology, Auckland, NewZealand, 1-10.

NatHERS Administrator (2019) Nationwide House Energy Rating Scheme Software Accreditation Protocol, |Canberra.

Paevere, P., Nguyen, M., Syme, M., Leicester, R. and Ho, K. (2009) Mechano-sorptive nailplate backout in nailplated timber trusses, Forest and Wood Products Australia, Melbourne.

Rickaby, P. (2021) The long road to quality assured, moisture-safe retrofit in the UK, International conference on moisture in buildings 2021, University College London, 28-29 June 2021.

Rogers, T. (1938) Preventing condensation in insulated structures, Architectural Record, March 1938, 109-119.

Roslan, Q., Ibrahim, S., Affandi, R., Nawi, M. and Baharun, A. (2015) A literaturere view on the improvement strategies of passive design for the roofing system of the modern house in a hot and humid climate region, Frontiers of Architectural Research, (5), 126-133.

Schwab, R. (2021) 25 years of the WUFI® program family, Fraunhofer Institute for Building Physics IBP., Holzkirchen.

Siagian, I. (2008) Mould growth in HDB environment, Singapore, Department of Building Science, National University of Singapore.

Slimani, Z., Trabelsi, A., Virgone, J., Belarbi, R. and Djedjig, R. (2015) Use of the buffering capacity of the building envelope for the reduction of the rate of air exchange, 6th International Building Physics Conference (Ibpc 2015), 78, 1531-1536.

Vcelak, J. (2021) Prevention of mold formation based on continuous condition monitoring of timber constructions, InnoRenew CoE International Conference 2021: Healthy and Sustainable Renovation with Renewable Materials, 10 June 2021.

Viitanen, H. and Ritschkoff, A. (1991) Mould growth in pine and spruce sapwood in relation to air humidity and temperature, The Swedish University of Agricultural Scienses, Department of Forest Products., Uppsala.

WHO (2009a) Damp and mould: health risks, prevention and remedial actions, WHO Regional Office for Europe.

WHO (2009b) Guidelines for Indoor Air Quality: Dampness and Mould, in R. O. f. Europe (ed.), World Health Organization, Denmark.

Zhang, J., Pezoulas, L. and Karagiozis, K. (2011) Environmental weather loads for hygrothermal analysis and design of buildings, ASHRAE, Atlanta.

A novel method established to convert Australian climate data for hygrothermal simulation

Shruti Nath[1], Mark Dewsbury[2], Freya Su[3], and Hartwig Kuenzel[4]

[1, 2,3] University of Tasmania, Launceston, Australia
mark.dewsbury@utas.edu.au[2], ORCID-0000-0002-3607-3637[1]
[4] Fraunhofer Institute of Building Physics, Holzkirchen, Germany
hartwig.kuenzel@ibp.fraunhofer.de[4], ORCID-0000-0001-8305-0262[4]

Abstract: The correlation between energy efficient buildings and the increased risk of condensation and mould inside residential and non-residential buildings has been known for some time. Since the 1990's transient calculation methods have been developed to initially calculate the flow of heat and moisture. These tools were then improved to calculate risks associated with mould growth, which causes building decay and affects human health. Internationally, frameworks, standards and guidelines are being developed establishing boundaries and requirements to limit too much user interaction with input and output variables. Key input variables include the exterior and interior climates and the physical attributes of construction materials. In 2018, collaborative research between the Germany and Australia identified a lack of suitably formatted Australian climate data for hygrothermal simulation. Parallel research was also exploring matters regarding water vapour diffusion resistivity properties of Australian construction materials and the development of more appropriate interior climate parameters. This article focusses on the development of a novel method, developed in 2019, to convert Australian government sanctioned climate data into a suitable format for transient hygrothermal simulation. The tool became known as AusHygro 1 and included options for including rain data and hourly interior temperature and relative humidity conditions.

Keywords: Condensation, Mould, Hygrothermal simulation, Climate data.

1. Introduction

The process of designing and making buildings that use less energy for heating and cooling, has required greater amounts of insulation and air control within external envelope systems. This process has made the outside skin much cooler in cool climates and much warmer on hot and humid climates. This act has then created significant differences between the interior and exterior skins of conditioned buildings leading to increased occurrences of condensation and mould in Australian buildings. Sadly, this correlation

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 44–54.*

has been known for more than a century (ASHVE, 1937; Teesdale, 1937; Rogers, 1938; Babbitt, 1939; CSIRO, 1962; 1970). As it was proven that the design and construction professions did not address this structural and human health affecting matter, many developed nations commenced instigating building regulations since the 1960's (British Standards, 2002; International Organization for Standardization, 2012; Shrubsole *et al.*, 2014; Dewsbury *et al.*, 2016). Whether it be the southern hemisphere being a bit slower, a more temperate climate, or a lessor expectation regarding the presence of mould in buildings, New Zealand and Australia have been slow to implement change (Dewsbury and Law, 2016; Bulic *et al.*, 2019; Nath *et al.*, 2019; Brambilla and Sangiorgio, 2020). The 'leaky buildings' crisis, which includes moisture ingress, and moisture and mould resulting from hygrothermal processes, has by recent estimates, cost the New Zealand economy NZ$46 billion (Howden-Chapman *et al.*, 2005; Moll and van Raamsdonk, 2011; Buckett, 2013; Overton, 2016; Walls, 2016; Dyer, 2019; 2021). The response on New Zealand has been the inclusion of condensation and mould related building regulations since 2006. In Australia, the first regulations, which only applied to Class 1 and Class 2 residential buildings located within National Construction Code climate zones 6, 7 and 8, were introduced in 2019 (ABCB, 2019).

Since 2008, researchers from the University of Tasmania have been expecting similar events to occur in Australia, and have been liaising and discussing hygrothermal, condensation and mould matters with State, Federal government agencies and industry-based research collaborators. In 2013, this included international relationships with UK condensation risk software developers JPA (JPA TL Ltd, 2016). Between 2013 and 2018, the JPA non-transient software had been used to assess condensation risk within Australian floor, external wall and roof systems in the climates of Darwin, Brisbane, Sydney, Melbourne, Launceston, Hobart, Oatlands and Cradle Mountain. This research was performed based on requests from Government and industry-based collaborators. By 2017, it was acknowledged that the non-transient software that had been used for much of this research, was in common regulatory use in the UK, and which met the requirements of ISO13788 (International Organization for Standardization, 2012), was not the best starting point for broader hygrothermal research in Australia. At this time, informal discussions with the developers of the WUFI transient hygrothermal simulation software, the Fraunhofer Institute of Building Physics increased, leading to a long-term collaborative relationship.

The climatic data for the non-transient JPA software only required twelve monthly inputs for temperature and relative humidity. Research conducted in 2015 for the Insulation Council of Australia and New Zealand explored the impacts of selecting twelve monthly mean climatic values, twelve hot year values and twelve cold year values. This variety of input was selected, to obtain a broader condensation risk response for the wall and roof systems analysed in hot and humid, temperate and cool temperate climates. This highlighted the impact that climate data could have on simulation results.

The 2018 shift to the use of the WUFI Pro transient hygrothermal simulation software required the re-examination of climate data and its critical role in hygrothermal simulation. Whereas the non-transient software only required a monthly value for temperature and relative humidity, the transient software required a more comprehensive data set that included hourly values for a full calendar year, namely:

- air temperature
- relative humidity
- barometric pressure
- wind speed

- Wind direction
- Global solar radiation, and
- Diffuse solar radiation.

The research team drew strong analogies between the international development of transient building energy rating (BER) programs and hygrothermal simulation programs. Both originated in the 1950's with simplistic, non-transient, calculation methods that were enhanced progressively until the broad adoption of desktop computers in the 1990's (Frank B. Rowley, 1941; Muncey, 1966; 1969; Ahmad, 1993; Delsante, 1997; Salonvaara *et al.*, 1998; Künzel and Holm, 2000; Crawley *et al.*, 2005; Delsante, 2006). The sudden availability and calculation capacity of desktop computers allowed for single annual mean values, to become monthly mean values and by the late 1990's hourly values for a month, which were soon replaced by hourly values for a calendar year. This change in calculation capacity, not only provided significant simulation results, for both BER and hygrothermal programs, that could be used to inform design but also required much higher quality inputs in terms of climate data, construction material physical properties and internal loads.

It is interesting to consider the development of climate data within the Australian regulatory framework. The Nationwide House Energy Rating Scheme (NatHERS) was established in 1993 (Ballinger and Cassell, 1995). It became an accepted simulation based method to prove attainment of house design heating and cooling energy use in 2003 (ABCB, 2003). This demonstrates there was a ten-year period where the simulation method, climate data, material physical properties and internal loads were debated and refined within the Australian architectural science and government policy spaces. Whereas the National construction Code had eight climate zones, by 2006, NatHERS had 69 nationally agreed climate zones (ABCB, 2006a; 2006b).

This development of the climate data sets for NatHERS highlights the mix of public servants, architectural scientists, engineers, and CSIRO scientists that were engaged to review international methods for climate data selection and the adoption of the best methods of the day, to establish the 69 climate data sets for NatHERS. Data sets that included a full year of hourly values as listed above. Back in 2018, discussions with peers in the North America, United Kingdom and Europe all agreed that the first step forward for Australian hygrothermal research should be the use of the government sanctioned Building Energy rating climate files. This highlighted a few challenges that were resulting from Australia's slow adoption of hygrothermal aspects to the national building regulations. The first, which is still an issue in 2022, is that there are no government sanctioned files for hygrothermal simulation. Secondly, the government sanctioned files for building energy rating, do not include precipitation data, an issue that is not exclusive to Australia. Thirdly, is the use of a building energy rating data set the best method for hygrothermal simulation. Some of these matters, like precipitation data, if data exists, could be added to existing data sets. However, the greater question regarding the suitability of Australian building energy rating climate data sets and what data should be used for hygrothermal simulation requires a deeper exploration of data collection and data selection. These matters aside, there was a need to establish whether Australian external envelope systems were promoting surface and interstitial mould growth, condensation and moisture accumulation. This position was also supported by leading international researchers, who based on their own experiences in North America and Europe, found that building energy rating climate data sets often provided a 'conservative' answer, as the first step down a nation's hygrothermal research journey.

2.1. Establishing climate data parameters

To quantify what climate data was required and what climate data was available initially required an analysis of the data sets available. The two government sanctioned climate data sets that were available in 2018 included the TMY data that was used for Nationwide House Energy Rating Scheme (NatHERS) simulations and the EPW files that had been provided by the Australian Greenhouse Office (AGO) to the United States government for use with the EnergyPlus building energy rating software. The data included within these two data sets is shown in Table 1. This table shows that the EPW files can include many more types of data than the NatHERS TMY files. There are also some notable differences in the values for some data items, like atmospheric pressure which is measured in hPa for TMY and mb for EPW. Table 1 also shows the much smaller data selection that is required for the hygrothermal software's WAC format. It should be noted that the hygrothermal simulation software used in this research (WUFI Pro), could read an EPW climate data input. However, the AGO provided EPW formatted climate data, did not include any precipitation data. Additionally, a preliminary analysis found differences in the values for temperature and solar radiation between the NatHERS TMY and AGO EPW climate data sets. Based on these differences, the next stage of the research was to develop a software tool that could convert and amalgamate the needed data from the NatHERS TMY data format into a WAC formatted climate data file.

2.2. The development of a software tool to extract and reformat data (AusHygro1)

To establish a suitable WAC climate data set required the development of a new software. This was made possible through a Work Integrated Learning program for final year Information and Communication Technology students. The first stage of the research was to consider both informed and less informed capabilities of the likely software users. This required the establishment of various forms of front-end user interfaces and testing these BETA application versions with likely users (house energy rating professionals and academic researchers). This established some significant differences in user skills and knowledge of the House Energy Rating software input libraries, SCRATCH file and output data-sets for zone temperature and energy use. Based on these differences, two climate data selection pathways were established, namely:

- Selection of SCRATCH file – once a SCRATCH was selected, the software selected the appropriate NatHERS TMY file from the software's weather file library, or
- Section of climate file – where the software identified where the NatHERS TMY weather files were, and the user selected the appropriate climate number.

Table 6: Climate data included in TMY, EPW and WAC formats

	TMY (NatHERS) (Delsante, 2006)	EPW (AGO)	WAC (WUFI)
Location	Yes	Header	Header
Year	Yes	Yes	Not applicable
Month	Yes	Yes	Yes
Day	Yes	Yes	Yes
Hour (0-23)	Yes	Yes	Yes
Minute (0-60)	Not applicable	Yes	Not applicable
Flags re data quality	Not applicable	Yes	Not applicable
Air temperature (0.1°C)	Yes	Yes	Yes
Dew point temperature (0.1°C)	Not applicable	Yes	Not applicable
Absolute moisture content (0.1 g/kg)	Yes	Not applicable	Not applicable
Relative humidity (0.0 to 1.0)	Not applicable	Yes	Yes
Atmospheric pressure	Yes (hPa)	Yes (mb)	Yes (hPa)
Extraterrestrial horizontal radiation (Wh/m^2)	Not applicable	Yes	Not applicable
Extraterrestrial direct normal radiation (Wh/m^2)	Not applicable	Yes	Not applicable
Horizontal infrared radiation from sky (Wh/m^2)	Not applicable	Yes	Not applicable
Wind Speed (0.1m/s)	Yes	Yes	Yes
Wind Direction	Yes (0-16; 0 = calm, 1 = NNE, 16 = N	Yes (Degrees)	Yes
Total cloud cover (oktas, 0 - 8)	Yes	Yes	Not applicable
Flags re data quality	Yes	Not applicable	Not applicable
Global solar radiation on a horizontal plane (Wh/m^2)	Yes	Yes	Not applicable
Diffuse solar radiation on a horizontal plane (Wh/m^2)	Yes	Yes	Not applicable
Normal direct solar radiation on a plane normal to the beam (Wh/m^2)	Yes	Yes	Yes
Global horizontal illuminance (Lux)	Not applicable	Yes	Not applicable
Direct normal illuminance (Lux)	Not applicable	Yes	Not applicable
Diffuse horizontal illuminance (Lux)	Not applicable	Yes	Not applicable
Zenith Luminance (Cd/m^2)	Not applicable	Yes	Not applicable
Solar Altitude (0 to 90)	Yes	Data in header	Not applicable
Solar Azimuth (0 to 360)	Yes	Data in header	Not applicable
Flags re data quality	Yes	Yes	Not applicable
Year data (19, 20)	Yes	Not applicable	Not applicable
Blank	Yes	Not applicable	Not applicable
Opaque sky cover	Not applicable	Yes	Not applicable
Visibility	Not applicable	Yes	Not applicable
Ceiling height	Not applicable	Yes	Not applicable
Present weather observation	Not applicable	Yes	Not applicable
Present weather codes	Not applicable	Yes	Not applicable
Precipitable Water (mm)	Not applicable	Yes	Yes (Ltr/m^{2}h)
Aerosol Optical Depth (0.001)	Not applicable	Yes	Not applicable
Snow Depth (cm)	Not applicable	Yes	Not applicable
Days since last snowfall	Not applicable	Yes	Not applicable

This first stage then converted the Month, Day, Hour, Air temperature, Atmospheric pressure, wind speed, wind direction and Normal direct solar radiation into columns data suitable as a WAC file. The data for absolute moisture content was required to be converted to relative humidity for the WAC file. A formula was provided by the CSIRO. A selection of data was converted. A selection of the converted relative humidity data was provided to the CSIRO and Fraunhofer Institute of Building Physics researchers who confirmed the quality of the converted data. This conversion method was then included in the overall data reformatting process. This allowed for the climate data from the NatHERS TMY file to provide all the data required, except for precipitation data.

Precipitation data was obtained from the Bureau of Meteorology (BOM). In many cases this data may have been a single value for a twenty-four-hour period. This required the team to average the rain data based on cloud cover and relative humidity. The cloud cover data in the NatHERS TMY file identified when the sky had 100% cloud cover. At time like this, rain could occur. This was then cross matched with relative humidity data. Periods of correlating 100% cloud cover with relative humidity conditions above 90% were selected as the likely times of precipitation. Corresponding precipitation data from BOM was then averaged over these occurrences. The combination of these three processes established a WAC file for the Hygrothermal simulation using the WUFI Pro Software.

2.3. Hygrothermal simulations using EPW, NatHERS TMY and NatHERS TMY + Precipitation

To establish if there was any discernable difference in hygrothermal and bio-hygrothermal simulation results a series of residential external wall system simulations were completed using the WUFI Pro and WUFI VTT software. The WUFI Pro software was used for the hygrothermal simulation, which would calculate the flow of heat and moisture through the external wall system (Schwab, 2021). This would provide hourly temperature and moisture conditions through the wall system for a period of ten years. The WUFI VTT software uses the hourly hygrothermal simulation results to calculate mould growth risk (Viitanen *et al.*, 2015). The mould growth risk simulation applies the mould growth index (MI) developed by Hukka & Viitanen (1999). Internationally, a mould index of 3.0 or more is regarded as undesirable on surfaces or interstitially in external envelope systems (ASHRAE, 2016; AIRAH, 2020; Deutsches Institut Fur Normung E.V. (German National Standard), 2020). This undesirability is based on the international medical acceptance that any presence of visible mould will affect human health (WHO Regional Office for Europe, 2009; Nath *et al.*, 2019). A mould index of nil or 1.0 generally indicates a wall system is safe to construct. A mould index of 1.0 to <3.0 refers to microscopic mould growth, and normally indicates that the wall system should be further investigated, as small differences between the simulation inputs and the wall construction may lead to significant mould growth problems. A mould index of 3.0 of more refers to optically visible mould, and this type of wall should not be constructed.

3. Results

The results discussed here focus on some challenges regarding the establishment of the WAC climate data sets and the results from the hygrothermal and bio-hygrothermal simulations.

3.1. EPW and WAC Climate data

As discussed in the method section, differences were identified in the temperature and other data categories between what was in the NatHERS TMY data and the EPW climate data sets for the same locations. These differences would and did provide different hygrothermal simulation results. For time reasons and the need to focus on the conversion of the NatHERS TMY data, the effect of these differences was not pursued further. Future research must evaluate these differences. Both the NatHERS TMY and AGO EPW climate data sets do not include precipitation data. The method described above to 'average' the precipitation data does not consider rain intensity. This may be a critical matter, as research has identified the need to critically understand wind driven rain and its impact on inward and outward moisture flows within external wall systems (Overton, 2016; Ge *et al.*, 2021; Kuenzel and Dewsbury, 2022). This aspect requires further refinement but may be significantly challenged by data available from the Australian Bureau of Meteorology.

3.2. Hygrothermal and bio-hygrothermal simulations

Figure 1 below shows an example of the hygrothermal and bio-hygrothermal simulation results for the outer portion of the insulation layer in a 7 Star brick veneer wall system in a western orientation. The top graph shows the temperature (red), relative humidity (green) and moisture (blue). The bottom graph shows the mould growth index. In this scenario, the MI is greater than 3.0 in the second year, indicating that this wall is likely to promote mould growth and should not be constructed in this manner within the simulated climate. This simulation was completed using the AGO EPW climate data.

Figure 2 below shows an example of the hygrothermal and bio-hygrothermal simulation results for the outer portion of the insulation layer in a 7 Star brick veneer wall system in a western orientation. The top graph shows the temperature (red), relative humidity (green0 and moisture (blue). The bottom graph shows the mould growth index. In this scenario, the MI may exceed 3.0 in the eleventh year, indicating that this wall requires further investigation. This simulation was completed using the NatHERS TMY data converted to a WUFI WAC file with precipitation data added.

In this wall system, bio-hygrothermally simulated using the AGO EPW climate data showed a mould growth index of 3.0 or more on the interior surface of the clay brick, interior and exterior surfaces of the pliable building membrane and in the outer layer of the wall batt insulation. However, this same wall system, bio-hygrothermally simulated using the converted NatHERS TMY climate data showed a mould growth index of <3.0 in only the outer layer of the wall batt insulation.

Figure 6: Hygrothermal and bio-hygrothermal results of 7 Star brick veneer wall with a western orientation (AGO EPW data)

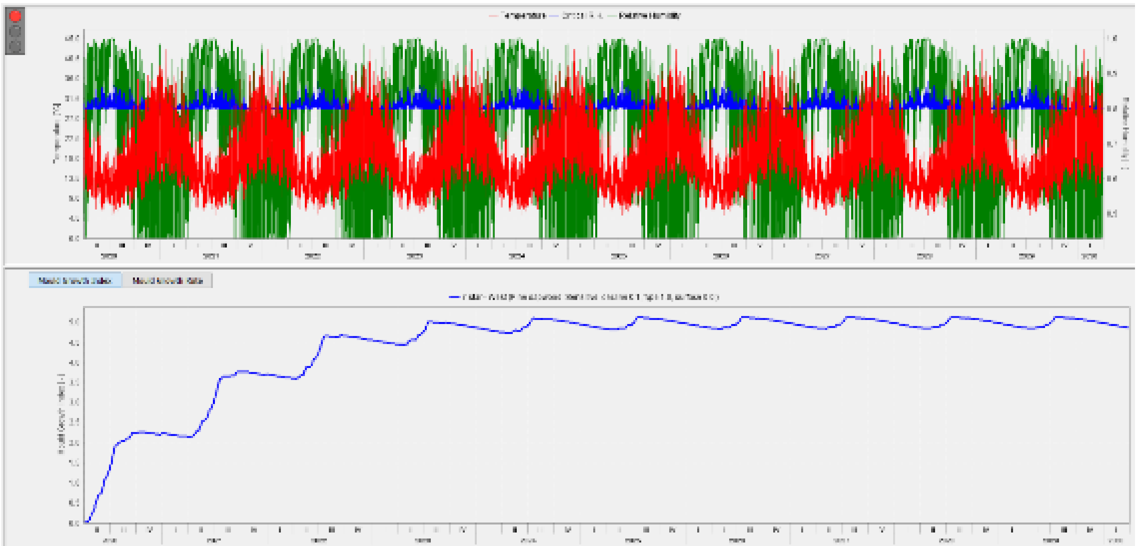
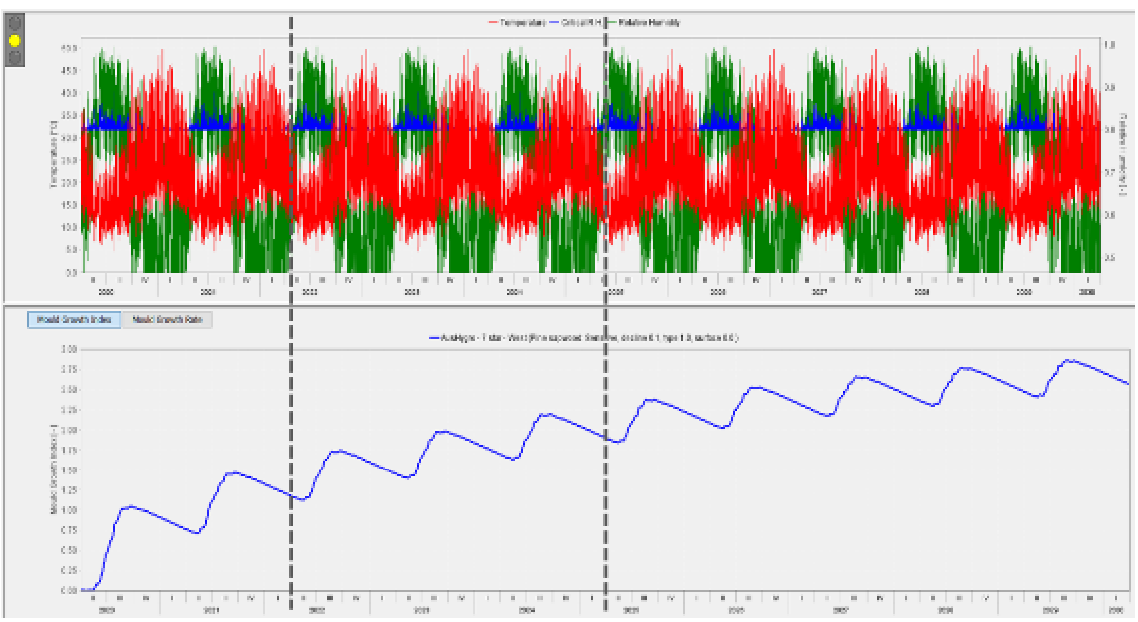


Figure 7: Hygrothermal and bio-hygrothermal results of 7 Star brick veneer wall with a western orientation (NatHERS TMY converted file, with rain data)



4. Discussion

The research involved the development of a computer program, (AusHygro1), which was used to convert NatHERS TMY data into a WAC climate data format for use in by the WUFI suite of hygrothermal simulation programs. The process also included adding precipitation data, which is not present in either the NatHERS TMY or the AGO EPW climate data sets. The aspect of climate data selection plays a critical role in hygrothermal simulation. This research has identified differences in climate data sets provided by the Australian government for use in Building Energy Rating simulations and how these differences provide significantly different results from a hygrothermal and bio-hygrothermal simulation. The differences are significant, as the simulation results shown in Figure 1, would deem this construction system climatically unsuitable, whilst the climate data used for the simulation results shown in Figure 2, might allow for this wall system to be constructed. The differences identified in this research are from two government sanctioned forms of climate data. At this stage, there is no regulation or government-based guidance regarding the selection of climate data for hygrothermal simulation purposes. Based on the experiences of this research, one could ask, what climate data are hygrothermal simulation professionals using to provide guidance to the design and construction professions. Anecdotal evidence from discussions with design professionals using hygrothermal simulation tools includes the use of the last calendar year of data and EPW data from a range of web-based sources. In the case of using data from the last calendar year, a bias would be achieved based on the climatic conditions from that year. The average data sets available in EPW format would remove the bias provided by a single year, but the variety of data sets available would ensure a variety of hygrothermal and bio-hygrothermal simulation results.

Furthermore, recent research by Su (Su *et al.*, 2022) has identified potential risks in the use of climate data sets that have been developed for building energy rating purposes, due to an over-emphasis on air temperature and solar radiation in the data selection process. This process has not recognised the importance of moisture and precipitation and its impact on the wetting and drying processes of external wall systems. Su is exploring this issue as a key component of her doctoral studies.

5. Conclusion

In 2018, this research started to ask the question about what climate data should be used for hygrothermal simulation purposes in Australia. Initial advice from North America and Europe recommended the use of existing government sanctioned Building Energy Rating climate data sets. This research identified differences in the data contained in the NatHERS TMY and AGO EPW climate data sets that are used for Building Energy Rating purposes. These differences led to significant differences in hygrothermal and bio-hygrothermal simulation results. The software developed in this research, AusHygro1, is about to undergo some improvements based on the updated NatHERS climate data that will be released in 2022. This new climate data for simulation purposes will provide yet another version of results. Finally, there is no government- based guidance in Australia regarding which climate data, from which source should be used for hygrothermal simulation purposes. This highlights the need for two very important research and policy actions. There is an urgent need to understand and develop appropriate Australian climate data sets that recognise recent international experiences for hygrothermal simulation purposes. To protect the design and construction professions and building occupants, the building regulators need to specify what data sets a certified design professional should use for hygrothermal and bio-hygrothermal simulation.

Acknowledgements

This research was enabled through the engagement of graduating Information Communication and Technology students undertaking a University of Tasmania Work Integrated Learning (WIL) activity in 2019. The students were Brad Smedley, Caryn Tanuwijaya, Harry Wall, Jack Dowl and Louis Brown. This research was further assisted via a 2019 University of Tasmania funded Visiting Fellowship for Professor Hartwig Kuenzel. Dr Dong Chen from the CSIRO, was a collaborator in this research.

References

ABCB (2003) The building Code of Australia: 1996 Amendment 13, in A. B. C. Board (ed.).

ABCB (2006a) The Building Code of Australia, Australian Building Code Board.

ABCB (2006b) Protocol For House Energy Rating Software V2006.1, Australian Building Codes Board.

ABCB (2019) The National Construction Code: Volume 2, in A. B. C. Board (ed.), Canberra.

Ahmad, Q. S., SV; (1993) Thermal Design Tools in Australia: A Comparative Study of TEMPER, CHEETAH, ARCHIPAK and QUICK,BS1993, IBPSA, Adelaide, Australia, 351-357.

AIRAH (2020) DA-07 Criteria for moisture control in buildings, Australian Institute of Refigeration, Air-conditioning and Heating, Melbourne.

ASHRAE (2016) Standard 160-2016 - Criteria for Moisture-Control Design Analysis in Buildings (ANSI Approved), Atlanta.

ASHVE (1937) Proceedings of the 43rd annual meeting, 23.

Babbitt, J. (1939) The diffusion of water vapour through various building materials, Canadian Journal of Research, (February 1939).

Ballinger, J. and Cassell, D. (1995) Solar Efficient Housing and NatHERS: An Important Marketing Tool, Fuel and Energy Abstracts, 36(4), 237.

Brambilla, A. and Sangiorgio, A. (2020) Mould growth in energy efficient buildings: Causes, health implications and strategies to mitigate the risk, Renewable and Sustainable Energy Reviews, 132.

British Standards (2002) BS5250 - Code of Practise for condensation in buildings, British Standards, London.

Buckett, N. (2013) Building better: advanced residential construction techniques for New Zealand, New Zealand.

Bulic, T., Cole, V. and Erbas, B. (2019) Review of the effects of condensation in low-rise residential buildings, 43rd Australasian Universities Building Education Association Conference, Noosa.

Crawley, D., Hand, J., Kummert, M. and Griffith, B. (2005) Contrasting the Capabilities of Building Performance Simulation Programs, United States Department of Energy, University of Strathclyde, and University of Wisconsin, 56.

CSIRO (1962) Some common oversights in building, in, Notes on the science of building, Experimental Building Station: Department of Housing and Construction, Marrickville.

CSIRO (1970) Note 61: Condensation in Dwellings, in, Notes on the science of building, CSIRO, Rydalmere.

Delsante, A. (1997) The development of an hourly thermal simulation program for use in Australian Nationwide house energy rating scheme, CSIRO Division of Building Constriction and Engineering, Victoria.

Delsante, A. (2006) Description of Input Data File for the AccuRate Simulation Engine V2.13, CSIRO.

Deutsches Institut Fur Normung E.V. (German National Standard) (2020) DIN 4108-4: Thermal insulation and energy economy in buildings - Part 4: Hygrothermal design values, Germany.

Dewsbury, M. and Law, T. (2016) Temperate climates, warmer houses and built fabric challenges,International High-Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016, Procedia Engineering, Sydney.

Dewsbury, M., Law, T., Fitz-Gerald, D., McComish, B., Potgieter, J., Chandler, T. and Soudan, A. (2016) Scoping study of condensation in residential buildings: final report, Australian Building Codes Board.

Dyer, P. (2019) The story of New Zealand's leaky buildings disaster, ed., David Bateman Limited.

Dyer, P. (2021) Something rotten in the state…. Architecture New Zealand.

Frank B. Rowley, A. B. A., Clarence E. Lund (1941) Condensation of moisture and its relation to building construction and operation, Bulletin of the University of Minnesota, 56, 74.

Ge, X., Taylor, J., Pelsmakers, S. and Castaño, R. (2021) Modelling mould growth risk in English social housing,1st International Conference on Moisture in Buildings (ICMB21), ScienceOpen, London.

Howden-Chapman, P., Crane, J., Matheson, A., Viggers, H., Cunningham, M., Blakely, T., O'Dea, D., Cunningham, C., Woodward, A., Saville-Smith, K., Baker, M. and Waipara, N. (2005) Retrofitting houses with insulation to reduce health inequalities: aims and methods of a clustered, randomised community-based trial, Social Science & Medicine, 61, 2600-2610.

Hukka, A. and Viitanen, H. A. (1999) A mathematical model of mould growth on wooden material, Wood Science and Technology, 33, 475-485.

International Organization for Standardization (2012) ISO 13788:2012 - Hygrothermal performance of building components and building elements -- Internal surface temperature to avoid critical surface humidity and interstitial condensation -- Calculation methods, Geneva.

JPA TL Ltd (2016) JPA Designer: SAP 9.92 module • U-value modules & Condensation Risk (Version 6.03a1 and above) User Manual, JPA TL Ltd., Newcastle upon Tyne.

Kuenzel, H. and Dewsbury, M. (2022) Moisture control design has to respond to all relevant hygrothermal loads, UCL Open: Environment.

Künzel, H. and Holm, A. (2000) Non-isotherm moisture transfer in porous building materials,Materials week 2000, Munich.

Moll, L. and van Raamsdonk, T. (2011) A new Zealand based study on airtightness and moisture management, Pro Clima, New Zealand.

Muncey, R. S., J (1966) Calculation of non-steady heat flow: considerations of radiation within the room, Journal of the Institution of Heating and Ventilation Engineers, 34(01), 35-38.

Muncey, R. S., J (1969) Calculation of Temperatures in Buildings by the Matrix Method: Some Particular Cases, Building Science, 3, 227-229.

Nath, S., Dewsbury, M. and Douwes, J. (2019) Has a singular focus of building regulations created unhealthy homes?, Architectural Science Review.

Overton, G. (2016) Vapour control in New Zealand walls, Porirua, New Zealand.

Rogers, T. (1938) Preventing condensation in insulated structures, Architectural Record, 109-119.

Salonvaara, M. H., Ojanen, T. T., Kokko, E. and Karagiozis, A. N. (1998) Drying capabilities of wood frame walls with wood siding, Thermal Performance of the Exterior Envelopes of Buildings Vii, Conference Proceedings, ed.

Schwab, R. (2021) 25 years of the WUFI® program family, Fraunhofer Institute for Building Physics IBP., Holzkirchen.

Shrubsole, C., Macmillan, A., Davies, M. and May, N. (2014) 100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock, Indoor and Built Environment, 23(3), 340-352.

Su, F., Dewsbury, M., Burnham, R. and Fay, R. (2022) The incorporation of precipitation into climate data and its impacts on hygrothermal simulations, Australasian Building Simulation Conference 2022, Brisbane.

Teesdale (1937) Condensation in walls and attics, in US Forest Products Laboratory (ed.), Madison (WI).

Viitanen, H., Krus, M., Ojanen, T., Eitner, V. and Zirkelbach, D. (2015) Mold risk classification based on comparative evaluation of two established growth models,6th International Building Physics Conference, IBPC 2015, Elsevier, Energy Procedia, 1425-1430.

Walls, K. (2016) Ensuring adaptation to climate change does not increase health risks from the built environment, Journal of Environmental Engineering & Ecological Science, 5.

WHO Regional Office for Europe (2009) WHO guidelines for indoor air quality: dampness and mould, ed., World Health Organisation, Germany.

A parametric approach to defining archetypes for an integrated material stocks and flows analysis and life cycle assessment of built stocks

Katarina Slavkovic[1], André Stephan[2] and Gildas Mulders[3]

[1, 2, 3]Université Catholique de Louvain, Louvain-la-Neuve, Belgium
katarina.slavkovic@uclouvain.be[1], andre.stephan@uclouvain.be[2], gildas.mulders@uclouvain.be[3]
ORCID-0000-0002-5563-1016[1], ORCID-0000-0001-9538-3830[2], ORCID-0000-0001-5060-269X[3]

Abstract: Archetyping is a method for developing representative models of groups of buildings or infrastructure assets that share similar attributes. They typically focus on buildings and often support a single assessment method, such as urban building energy modelling, regardless of other significant flows (e.g. materials). Simplifications in developing archetypes and the inability to represent the distribution of flows across scales of the built environment reduce the precision of a model, which is critical in conducting a robust assessment that yields useful results. This paper aims to present an archetyping approach that supports an integrated life cycle assessment and material flow analysis of stock assets. As such, developed archetypes represent buildings, infrastructure, vegetation and soils. Built assets are defined as nested sets of assemblies, elements and materials. To improve reliability, we couple material compositions with geometrical data through the use of geographic information systems. We present the procedure for defining archetypes, and apply it to a building and transport infrastructure asset. The high resolution of the proposed archetyping approach enables a very high data granularity. This granularity enables a more detailed modelling of different scenarios, as well as dynamic life cycle assessment, and provides a high spatial resolution.

Keywords: Digital twin; buildings; infrastructure; GIS.

1. Introduction

Cities are major contributors to climate change. Globally, cities are responsible for 78% of energy use, more than 60% of greenhouse gas (GHG) emissions (UN, 2018) and over 75% of resource use (UNEP, 2018). The reported environmental impacts of climate change (IPCC, 2018) and the urgency of achieving the 1.5 – 2.0 °C Paris Agreement targets (UN, 2015), have prompted city governments to set and commit to the achievement of environmental targets. For example, the city of Brussels aims to reduce GHG emissions by at least 40% by 2030, as compared to 1990 (Brussels, 2020). The city of Melbourne aims to achieve carbon neutrality by 2050 (Melbourne, 2018). However, developing and testing the associated strategies require modelling the environmental performance of thousands of buildings and infrastructure

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 55–65.*

assets. It may be argued that it is not possible to model each single asset at the city scale. Such modelling is time-consuming and requires significant computational resources. To overcome these challenges, we often rely on archetypes. Archetyping is a widely recognised method for determining a set of average built assets, that represent clusters of assets with similar attributes (e.g. age).

Studies relying on archetypes typically focus on buildings, not including infrastructure in scope, even though infrastructure assets are mostly publicly owned, which potentially enables a more rapid action to improve their environmental performance. Moreover, archetyping methods for buildings are typically developed for the assessment of energy efficiency in the use phase of buildings (*Tabula Episcope*, 2016). However, we are observing a shift in focus from the building use to the whole life cycle of buildings (Lotteau *et al.*, 2015) and to the material stocks and flows at the urban level (Tanikawa *et al.*, 2015).

Life cycle assessment (LCA) and material stocks and flows analysis (MFA) are methods for modelling environmental and material flows of products (e.g. built assets) or systems (e.g. cities). LCA is a method for the assessment of environmental impacts relating to all the life cycle stages of the product, from the extraction of natural resources until the end-of-life stages (ISO, 2006). MFA is a method for quantifying amounts of resources contained in the system at any given moment in time (i.e. material stocks), as well as all inflows and outflows of resources that occur over a certain period, which is often based on mass balance of resources inputs, outputs and changes in the system. The need for integrating LCA and MFA modelling methods has clearly been emphasised in the scientific studies e.g. (Stephan *et al.*, 2022a).

Archetypes in LCA and MFA modelling need to provide detailed data on material quantities for compiling life cycle inventories. Calculated material quantities are combined with the environmental attributes of each composing material (e.g. embodied energy per unit of structural steel). Life cycle inventories are then used to quantify the overall inputs (e.g. material, energy and water) and outputs (e.g. material waste and GHG emissions) of the assessed asset during its life cycle. As such, archetypes in LCA and MFA modelling are data-intensive and largely influenced by the parametrisation and material compositions of their constructing assemblies.

The geometrical properties of archetypes are often derived from statistical data, based on most common attributes shared by a cluster of assets (e.g. building floor shape or number of floors). This may lead to poor-quality inventories, potentially leading to unreliable modelling results. Another common approach is to use the average material intensities per typical floor area (e.g. per m^2). This enables the quantification of general results, e.g. mass of clay in a city, but an unknown spatial distribution for a given material. The third possibility is to fix the geometry and employ a building-by-building approach (Mastrucci *et al.*, 2017), where the geometry of each asset is modelled individually. This approach can achieve a high level of precision but is hardly applicable at larger built environment scales (e.g. city).

Combining archetypes with a building-by-building approach can achieve a high level of precision, while streamlining the process. This is possible through the integration of geospatial data into archetyping. Detailed spatialised data on larger built environment scales are becoming more widely available with the advance of satellite imagery. Despite this, geographic information systems (GIS) databases, such as Microsoft (2022) and Belmap (GIM, 2022) databases, often contain limited data types, e.g. building footprint and height. As such, we still need to infer data (e.g. material composition) from other data sources. From a material composition perspective, archetypes are associated with a series of issues such as the poor resolution of data and limited number of modelled materials. Moreover, there seems to be a lack of material location data within the archetypes (Tanikawa *et al.*, 2015). Archetypes fail to encompass the links between the smaller scales, such as between element and material. For example, it is important to know if a material (e.g. steel) is located within a specific assembly (e.g. column or pipes) as this could inform later decision-making (e.g. on reuse or recycling).

In light of the above, there is a need to develop a streamlined archetyping approach that combines available GIS data on a building-by-building level, that enable data rich archetypes for LCA and MFA. This paper aims to develop a method to define archetypes for buildings and infrastructure assets, able to support MFA and LCA at the urban scale. The paper focuses on developing the method and provides examples of archetypes applied on two case studies. It does not include method application at city scale.

After the Introduction, Section 2 describes the proposed method and applies it on a building and infrastructure asset case studies. Section 3 presents and illustrates the results for each case study. Section 4 discusses the proposed modelling approach and its limitations, and concludes the paper.

2. Method

2.1. Research approach

The proposed archetyping approach is depicted in Figure 8. First, the stock composition and its scope are defined. Second, typical buildings and infrastructure assets are specified and selected from the established typology of built assets. This database is developed by selecting the built asset types collected from available classification systems, and according to authors' experience. Third, typical construction assemblies are parametrised and selected. To do this, typology of construction assemblies per built asset type is fixed by filtering and documenting assembly types from classification databases and scientific literature. Then, we developed a database of assembly scale archetypes. The aggregated assemblies are attributed to different building geometries through the integration with GIS databases. This leads to the development of digital twins, which represent virtual models that accurately present the analysed stock. The marked (hatched) block of steps is applied on the case studies, which are a single-family residential building and a road with a side walk, located in Melbourne, Australia.

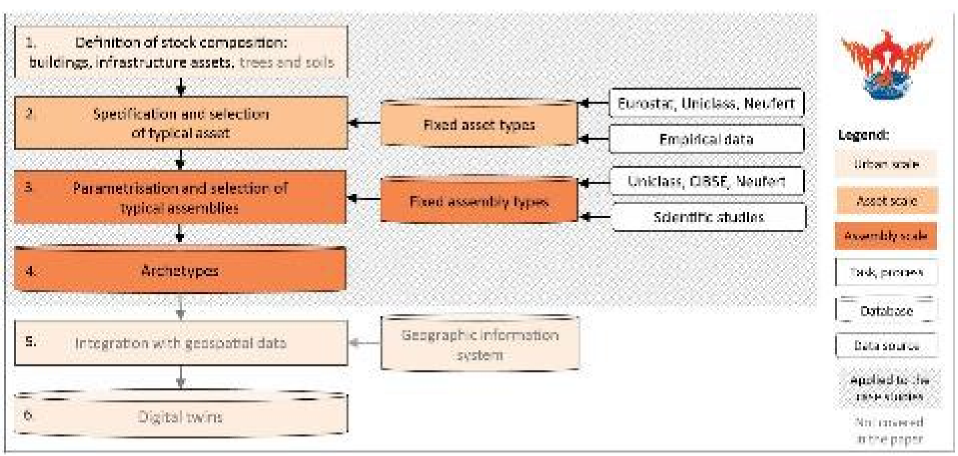


Figure 8: Proposed archetyping approach

2.2. Typologies of built assets

In order to develop archetypes, the types of built assets (e.g. residential building) need to be determined. Building and infrastructure asset typologies are systematically organised and documented in many data sources, including the Eurostat Reference and Management Nomenclature (Eurostat, 1998), the Uniclass classification system for construction industry (NBS, 2022), European Commission regulations systematising terms for transport infrastructure (EC, 2006) and a widely referenced book in building design "Architects' data" (Neufert and Neufert, 2012) which provides extensive spatial descriptions of asset types with references to German standards and regulations. We developed the built asset typologies by selecting asset types based on their prevalence and uniqueness. The building and infrastructure asset typologies comprise more than 20 and more than 15 types, respectively. The less present asset types in the cities (e.g. stadiums) were excluded.

2.3. Typology of assemblies per built asset type

Once the built asset types are fixed, we needed to determine what are the typical construction assembly types contained within each built asset archetype. Construction assemblies are systematised and detailed in several sources, such as the "Architects' data" book (Neufert and Neufert, 2012), and scientific articles (e.g. Stephan and Athanassiadis, 2017; Weththasinghe, 2020). Assemblies relating to the building services (e.g. heating) are well documented in standards compiling manufacturer information, such as CIBSE (2022). The core assembly categories (e.g. structural system or infrastructure utilities) and types (e.g. foundations, columns and beams; or electricity, sewage, water and gas distribution systems) are selected and attributed to built asset types based on prevalence and empirical knowledge. Less common assembly types (e.g. fireplace) are filtered out and excluded from the database.

Specific assemblies in complex building types (e.g. sprinkler system and fire compartments in shopping malls) were investigated to determine their contribution in terms of materials mass and embodied flows. Since they were significant, we decided on their inclusion in the database of assembly types. In addition to the fixed assembly types per built asset type, we allow the definition of custom assembly types. This enables the inclusion of assembly types (e.g. oxygen ducts in hospitals), that may be relevant for specific applications. Typology of construction assemblies is shown in Table 1.

To be able to attribute the construction assembly types to the built asset geometrical data, first we need to parametrise assembly types. Each assembly type comprises one or more elements, which comprise one or more materials. This nesting model was initially developed by and further adapted in . Parametrisation of assemblies in residential buildings was developed by and adapted for non-residential buildings by . Two examples of assembly types are shown in Table 2.

2.4. Deriving the bill of quantities for assemblies, elements and materials

The bill of quantities of assemblies, elements and materials is calculated by linking the parametrised data for each assembly type with the geometric variables derived and processed from the GIS database. Geometric data, such as the shape and size of an asset, height, number of floors, roof shape can be derived from GIS databases e.g. (Microsoft or Belmap). The Nested Phoenix model (Stephan *et al.*, 2022b) leverages these data to infer assembly quantities based on hypotheses, estimations and rules of thumb specific to each asset type. Measured quantities of elements and materials are then multiplied by a wastage coefficient that replicates on-site wastage. Resulting quantities are converted to mass in kg of material, by using densities systematised in the EPiC database (Crawford *et al.*, 2019; 2022). Finally, the integration with GIS enables spatialising the LCA and MFA results, in terms of environmental indicators and material stocks and flows.

2.5. Application of the proposed approach to case studies

The proposed archetyping approach is applied to a detached single-family house, and a suburban road with sidewalk in Melbourne, in the state of Victoria, Australia. The house floorplan is approximated by a rectangle shape, that is 20 m deep and 14.85 m wide, with a usable floor area of 270.8 m^2. The house has one floor that is 3.1 m high, with a window-to-façade ratio of 0.28. The house is timber-framed with brick veneer insulated walls. Figure 2 shows the simplified floorplan (left) and the main façade (right). Two examples of assemblies, their parametrisations, enclosing elements and enclosing materials are presented in Table 2. The second case study is a 5.5 m wide concrete road with 1.5 m wide sidewalks on each side, that is 45 m long. This includes associated infrastructure installations i.e. power lines, water distribution, sewage and gas.

Figure 9: Floor plan and south façade of the case study house in Melbourne, Australia. Image credit: Robert Crawford

3. Results

The results of the development of the proposed archetyping approach comprise the typologies of buildings and infrastructure assets listed in the following paragraph, and the typology of construction assemblies for buildings shown in Table 1. The applied method for the assembly and element parametrisations is demonstrated on the window and road assemblies in Table 2. The associated mass estimations are explained with the results of the method application to the building and infrastructure asset. There is no intention on specific parametrisations of results of each assembly type.

The typology of buildings comprises 10 building categories, namely residential buildings, accommodation, administration, retail, industry, cultural, entertainment, educational, health and parking. Each category comprises one (e.g. office buildings) or more building types (detached, semi-detached, terraced houses, apartment buildings), amounting to more than 20 building types in total. Moreover, the typology of infrastructure assets contains eight asset categories, namely pedestrian and bicycle paths, roads, utilities, railways, squares, parks and accessories, with more than 15 asset types.

Table 7: Typology of construction assemblies for building assets

Assembly categories	**Assembly types**
Structural system	Foundations, columns, beams
Wall, window and barrier systems	External walls, internal walls, windows and balcony doors, doors, fences
Roof, floor and paving systems	Roof, floor slabs, ground floor slab, balconies and terraces, driveways and pathways, ramps for vehicles
Stair and ramp systems	Staircase, lift, shaft, ramp, escalator
Furnishings and equipment	Sink, toilet, shower, bath
Accessories	Kitchen cabinets and tops, office partition walls
Space heating and hot water system	Heat generation, emitters, distribution, hot water storage and distribution
Ventilation and air conditioning	Mechanical ventilation with heat recovery, ventilation ducts, fans
Cooling system	Air conditioning system
Electrical and electronic systems	Plugs, and switches, wires, electrical panel, telecommunication cable, electrical battery, lighting system
Water system	Water delivery, waste water system, sewage system, rainwater drainage systems, rain water collection system, water tank, pumps, pipes
Fire extinguishing system	Pipes, sprinkler heads
Solar thermal system	Solar thermal collectors, mounting system, water tank, pipes, pump, electric system
PV system	PV modules, mounting system, inverter, battery, electric system
Custom	User defined

Note: Boxed assembly types are represented in Figure 3.

Table 8: Parametrisation of the window and road assemblies and their associated elements, and the quantification of the material stock

Assembly	**Element**	**Parametrisation**	**Measured quantity**	**Wastage coefficient**	**Delivered quantity**	**FU**	**Material**	**Mass** [kg]
Aluminium window, double glazed, total area 24 m^2	Flat glass sheet - 4 mm	Window/façade ratio 0.28;	90.75	1.03	93.55	m^2	Glass	1 028
	Aluminium Frame	3 m of frame for each m^2 of window	181.50	1.05	190.58	m	Aluminium	126
	Clay bricks[a]	Height 110 mm	6.66	1.05	6.99	m^2	Clay	440
	Steel Lintel	100 mm x 8mm	0.38	1.02	0.39	t	Steel	153
	Plastics General (PVC)[b]	20 mm x 5 mm,	0.01	1.05	0.01	t	PVC [c]	2.5
Concrete road with asphalt, and sidewalks, total length 45 m	Screenings	2 cm of gravel on sidewalks	2.70	1.3	3.51	m^3	Sand and stone	8 424
	Sand	10 cm under sidewalks	13.50	1.1	14.85	m^3	Sand and stone	23 760
	Rolled asphalt	5 cm thickness	12.38	1.05	13	m^3	Bitumen	13 254
	Concrete 32MPa	15 cm thickness	37.13	1.05	39	m^3	Concrete	93 555
	Steel reinforcement and structural	100 kg of steel per m^3 of road concrete	3.71	1.05	3.9	t	Steel	3 898

Note: FU = Functional unit, [a]Sill, [b]Joints, [c]Rubber assumed as plastic, in Figure 3. grouped to “Other materials”.

Results of the application of the proposed archetyping approach to the single-family house and road with sidewalks case studies are presented in Figure 3. Figure shows the distribution of mass (tons) and its percentage share, across assemblies, nested elements and nested materials, for the house as built after the initial construction, and the same quantities for the road. A sample of the data used to create the diagram is available in Table 2. It provides details on the parametrisation of assemblies and constituting elements, and estimated material stocks expressed in relevant functional units. The case studies demonstrate the strengths and potentials of the proposed archetyping approach.

Figure 3 demonstrates the breakdown of each assembly's mass by element and each element's mass by material, thus illustrating the many-to-many relationships between these scales. This enables understanding the distribution of the stock across different scales. For example, Figure 3 shows that external walls contain five different elements, among which the highest mass (42.8 t) is allocated to the sand, and the lowest (0.3 t) to the category Pipes, wires and others. The plasterboard, on the other hand, is an element that is used within two additional assemblies other than the external walls (2.2 t) i.e. internal walls (12.6 t) and roof (3.7 t). The same graph illustrates that concrete material represents the highest mass (137.8 t) among all material types in total mass of the building (268.1 t). However, only 13 t could be potentially reusable (Vandervaeren *et al.*, 2022), as they belong to the concrete roof tiles and not in foundations (the remaining 124.8 t). Such illustration of the spatial distribution of stocks is significant as it is able to inform the decision-making process.

The high data resolution enables investigation of stocks that may represent a small share of the total. For example, we can read on Figure 3 that windows assembly has among the least contributing mass (3.1 t). However, since the case study house comprises two types of windows, that are single- and double-glazed, the results associated specifically to double-glazed windows are presented in Table 2. Double-glazed windows have a total mass of only 1.75 t and yet are comprised of five elements, three of which constitute a window (1028 kg of glass panes, 126 kg of frame and 2.5 kg of joints) and two its structural support (153 kg lintel and 440 kg sill). This high granularity of data is able to provide valuable information, in terms of stocks and flows e.g. which structural elements will be captured within the asset and will last as long as its life cycle (such as the lintel and sill), or the stock quantities that could become available when replaced (such as 93.5 m^2 of glass panes).

The proposed archetyping approach can be used to explore what-if questions, not only in terms of the implications for the studied material stocks, but also in terms of environmental flows (e.g. embodied greenhouse gas emissions). For example, what if we decide to replace the 5 cm layer of asphalt on the 45-m-long case study road? What if we replace the electricity distribution system alongside it? Answers can be found in Table 2, which shows that the road contains 12.38 m^3 of asphalt, and in Figure 3 which shows that 10.9 t is allocated to the assembly "electricity distribution system", 9.7 t belong to the element "Timber Hardwood (poles)" and the same quantity to the material "Timber products".

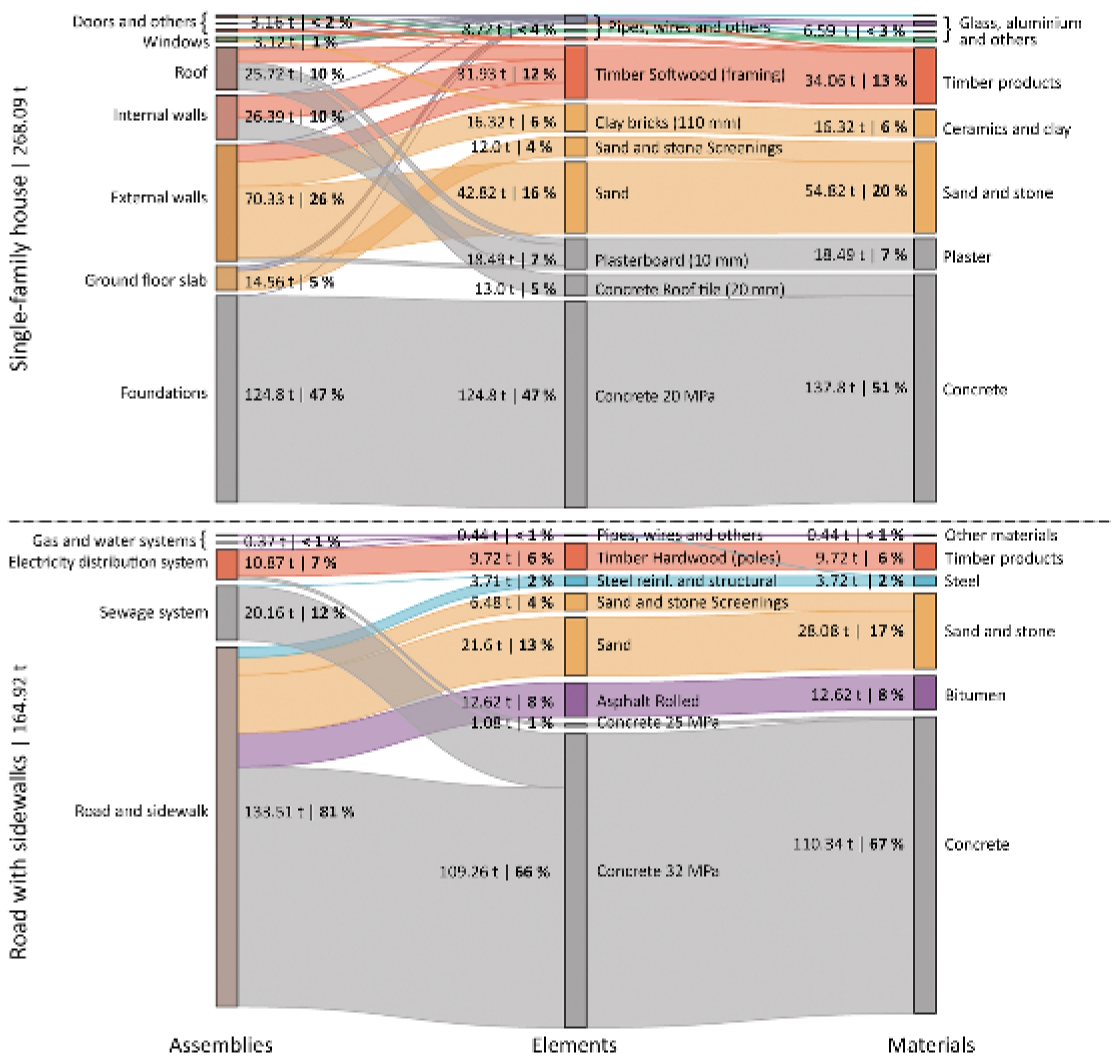


Figure 10: Assembly, element and material stocks of the single-family house and the road with sidewalks

4. Discussion and conclusion

This paper proposes a method for developing building and infrastructure archetypes and demonstrates its application to a single-family house and a road with sidewalks case studies, located in Melbourne, Australia. The contribution of the study is a consistent archetyping approach that supports more robust MFA and LCA stock modelling at high data resolution, and the distribution of flows across the asset, assembly, element and material scales. Moreover, its parametric nature enables upscaling from the asset to neighbourhood, city, regional and national scales. The approach is able to support the decision-making process by answering what-if questions and visualising many-to-many relationships between scales of the built environment.

The typical steps of creating building archetypes for urban building energy modelling can vary across scientific publications, but usually comprise data collection, preparation, classification, segmentation, normalisation, and clustering. When transferring this process to develop archetypes for LCA assessment, the process relies largely on defining significant parameters for the classification of sampled population of assets (Colleto and Gomes, 2021). Demonstrated archetyping approach does not follow this process, but integrates the use of building-by-building approach (Mastrucci *et al.*, 2017), through attribution of groups of parametrised assemblies to the corresponding geospatial data. The proposed archetyping approach is consistent with the published studies modelling the building stocks in cities and visualising the associated spatial distribution of materials (Tanikawa *et al.*, 2015; Kleemann *et al.*, 2017; Lanau and Liu, 2020; Stephan *et al.*, 2022b) while achieving higher resolution of material quantifications.

Yet, the proposed archetyping approach suffers from limitations. The set of building and assembly types should be extended to other uses (e.g. offices), and developed in such a way to allow mixed-use building types (e.g. retail on ground floor of residential building). While there are no theoretical limits on the application at high urban scales (e.g. region or national), computational power and data intensity present challenges in archetype development for LCA and MFA modelling. Data sources may be a limitation, depending on their availability in the given context. To be able to apply the archetyping approach at the urban scale, the following data types are necessary: three-dimensional geospatial data, year of asset construction, asset typology, aggregation of assembly types for each asset cluster (defined by age and use type), local-specific database of embodied flows in the materials and elements, database for simulating operational flows (e.g. meteorological data, building use schedules, thermal properties of materials etc.) and data associated to evolving parameters (e.g. energy mix or construction and demolition rates) as reviewed by Slavkovic et al. (2022b). In case of unavailable GIS data types, it might possible to provide default values or enable manual input of missing data (Stephan *et al.*, 2022b). Such high level of data advances granularity of the proposed approach, simultaneously putting a burden in terms of the required computational power.

Archetyping approaches are most often inadequate because they present a poor level of model detail, they usually focus exclusively on buildings and they report on only one environmental flow. This paper proposes a novel archetyping approach for MFA and LCA assessment that relies on defining and parametrising nested sets of assemblies, elements and materials. Modelling at assembly scale allows an increased level of detail, and linking to GIS databases enables geospatial distribution of findings. This paper tests part of the proposed methodological approach through its application to a single-family house and suburban road located in Melbourne, Victoria, Australia. Assembly, element and material stocks are modelled and the distribution of associated mass is visualised through Sankey diagrams. Findings demonstrate that the archetyping approach has a high potential in providing decision-support for practitioners or policy makers. This will help model the built environment in a more robust manner, enabling a better quantification of environmental performance and addressing the climate emergency.

Acknowledgements

We would like to thank Professor Robert Crawford from the University of Melbourne for providing data on the case study residential building. This research is funded by the Fonds de la Recherche Scientifique - FNRS under Grant n° F.4547.21, titled Nested Phoenix. More information on

Authors contributions

KS: Conceptualisation, Methodology, Investigation, Writing – original draft, Writing – review and editing, Visualisation. AS: Conceptualisation, Methodology, Visualisation, Writing – review and editing, Supervision. GM: Software, Visualisation, Writing – review and editing.

References

Brussels (2020) *Climate Plan City of Brussels*. Available from: City of Brussels <https://climat.bruxelles.be> (accessed June 2022).

CIBSE (2022) *Embodied carbon in building services: residential heating*, in C. B. G. Louise Hamot, Yara Machnouk, Hugh Dugdale (ed.), The Chartered Institution of Building Services Engineers CIBSE, London.

Colleto, G. M. and Gomes, V. (2021) Review of archetype development strategies for energy assessment at urban scale, *IOP Conference Series: Earth and Environmental Science*, 855(1), 012021.

Crawford, R. H., Stephan, A. and Prideaux, F. (2019) *Environmental Performance in Construction (EPiC) database*, ed., The University of Melbourne, Melbourne.

Crawford, R. H., Stephan, A. and Prideaux, F. (2022) The EPiC database: Hybrid embodied environmental flow coefficients for construction materials, *Resources, Conservation and Recycling*, 180, 106058.

EC (2006) *COMMISSION REGULATION (EC) No 851/2006 of 9 June 2006 specifying the items to be included under the various headings in the forms of accounts shown in Annex I to Council Regulation (EEC) No 1108/70*.

Eurostat (1998) *Reference And Management Of Nomenclatures, Classification of Types of Constructions*. Available from: <https://ec.europa.eu/eurostat/ramon/nomenclatures> (accessed June 2022).

GIM (2022) *Belmap*. Available from: Smart Geo Insights <https://www.belmap.be/index.php?l=en> (accessed May 2022).

IPCC (2018) *Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

ISO (2006) *International Standard ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework*, International Organization for Standardization (ISO).

Kleemann, F., Lederer, J., Rechberger, H. and Fellner, J. (2017) GIS-based Analysis of Vienna's Material Stock in Buildings, *Journal of Industrial Ecology*, 21(2), 368-380.

Lanau, M. and Liu, G. (2020) Developing an Urban Resource Cadaster for Circular Economy: A Case of Odense, Denmark, *Environmental Science and Technology*, 54(7), 4675-4685.

Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E. and Sonnemann, G. (2015) Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale, *Building and Environment*, 93, 165-178.

Mastrucci, A., Marvuglia, A., Leopold, U. and Benetto, E. (2017) Life Cycle Assessment of building stocks from urban to transnational scales: A review, *Renewable and Sustainable Energy Reviews*, 74, 316-332.

Melbourne (2018) *Climate change mitigation strategy to 2050: Melbourne together for 1.5°C*.

Microsoft (2022) *Microsoft Planetary Computer*. Available from: Microsoft <https://planetarycomputer.microsoft.com/dataset/ms-buildings> (accessed June 2022).

NBS (2022) *Uniclass*. Available from: National Building Specification <https://uniclass.thenbs.com/> (accessed April 2022).

Neufert, E. and Neufert, P. (2012) *Architects' Data*, ed., Wiley-Blackwell.

Stephan, A. (2013) *Towards a comprehensive energy assessment of residential buildings: a multi-scale life cycle energy analysis framework*, School of Engineering, Université Libre de Bruxelles and Faculty of Architecture, Building and Planning, The University of Melbourne, Brussels.

Stephan, A. and Athanassiadis, A. (2017) Quantifying and mapping embodied environmental requirements of urban building stocks, *Building and Environment*, 114, 187-202.

Stephan, A., Crawford, R. H., Bunster, V., Warren-Myers, G. and Moosavi, S. (2022a) Towards a multiscale framework for modeling and improving the life cycle environmental performance of built stocks, *Journal of Industrial Ecology*.

Stephan, A., Mulders, G. and Slavkovic, K. (2022b) Nested Phoenix: a bottom-up Python model for the life cycle environmental performance of urban built stocks, *Sustainable Built Environment SBE* Helsinki Finland.

Tabula Episcope (2016). Available from: <https://episcope.eu/building-typology/> (accessed June 2022).

Tanikawa, H., Fishman, T., Okuoka, K. and Sugimoto, K. (2015) The Weight of Society Over Time and Space: A Comprehensive Account of the Construction Material Stock of Japan, 1945-2010, *Journal of Industrial Ecology*, 19(5), 778-791.

UN (2015) *Paris Agreement*, United Nations Framework Convention on Climate Change.

UN (2018) *Generating Power - the United Nations*. Available from: United Nations <https://www.un.org/en/climatechange/climate-solutions/> (accessed June 2022).

UNEP (2018) *Resource Efficiency and Green Economy*. Available from: United Nations Environment Programme <https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/resource-efficiency-green-economy> (accessed June 2022).

Vandervaeren, C., Galle, W., Stephan, A. and De Temmerman, N. (2022) More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings, *Resources, Conservation and Recycling*, 177.

Weththasinghe, K. K. (2020) *Assessment of life cycle embodied energy and material cost in Australian shopping centres: Implications for material selection*, Melbourne School of Design. Architecture, Building and Planning, University of Melbourne, Melbourne.

A parametric tool to quantify the life cycle embodied environmental flows of built assets

André Stephan[1], Fabian Prideaux[2] and Robert H. Crawford[3]

[1] *Université Catholique de Louvain institution, Louvain-la-Neuve, Belgium*
Andre.Stephan@uclouvain.be, ORCID-0000-0001-9538-3830[1]
[2, 3] *The University of Melbourne, Melbourne, Australia*
fprideaux, rhcr@unimelb.edu.au[2], ORCID-0000-0002-4959-3615[2], ORCID-0000-0002-0189-3221[3]
[2] *KU Leuven, Leuven, Belgium*

Abstract: The construction and maintenance of buildings and infrastructure assets are the main drivers of raw material extraction and are responsible for significant embodied environmental flows such as energy and water use as well as greenhouse gas emissions. It is critical to empower actors of the built environment with advanced tools to quantify the life cycle environmental performance of different designs to inform design decisions. This paper presents one such parametric tool, EPiC Grasshopper, developed as a plugin for the Rhinoceros 3D and Grasshopper 3D environment. EPiC Grasshopper is a bottom-up parametric tool that operationalises the Environmental Performance in Construction (EPiC) Database of hybrid environmental coefficients for construction materials. The paper presents the architecture of EPiC Grasshopper, verifies its calculations and validates its output by comparing its application to a case study house in Australia to figures from a previous study. Results validate the plugin and show minor variations of the total life cycle embodied energy (-2%) at a whole building level as well as very minor variations in the contribution of each material to the total life cycle embodied energy, as compared to the figures from the previous study (maximum 1.7% of variation). The visualisation of results directly within the Rhinoceros 3D and Grasshopper 3D environment is also showcased. Future research includes demonstrating the parametric aspect of EPiC Grasshopper and developing more advanced functionalities. This will enable actors of the built environment to include life cycle embodied environmental performance directly into their workflows in a streamlined yet advanced manner.

Keywords: EPiC Grasshopper; bottom-up; embodied carbon; model.

1. Introduction

Constructing and maintaining buildings and infrastructure assets is the main driver for raw material extraction, notably of non-metallic minerals (UNEP, 2016). These raw materials need to be processed, manufactured and transported to be incorporated into built assets. Manufacturing processes require

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 66–75. © 2022 and published by the Architectural Science Association (ANZAScA).*

energy and often result in greenhouse gas emissions, due the reliance on fossil fuels. Embodied environmental flows, such as the aforementioned energy and emissions, represent an increasing share of the total life cycle environmental flows of buildings, notably energy (>70%, see Stephan *et al.* (2013)) and greenhouse gas emissions (Röck *et al.*, 2020). As the operational energy efficiency of buildings increases and net zero operational energy buildings emerge, embodied environmental flows can represent up to 100% of the life cycle environmental flows of a building (Stephan and Stephan, 2020).

A range of tools have been developed to quantify the embodied environmental flows of buildings (Hollberg and Ruth, 2016) and to a lesser extent infrastructure assets. These tools vary in terms of scope and functionalities, as reviewed by Hollberg and Ruth (2016). Recently, algorithms to quantify embodied environmental flows have been bundled into plugins for existing 3D software (e.g. Bombyx (Basic *et al.*, 2019), Cardinal LCA (Chen *et al.*, 2021)). This enables designers to capitalise on existing design workflows and parametric approaches while incorporating embodied environmental flows from the onset.

Yet, existing tools tend to be characterised by their reliance on process data which can underestimate embodied environmental flows (energy, water and greenhouse gas emissions) by an average of 50-57% as compared to hybrid figures, and up to 99% for a specific material (Crawford *et al.*, 2021). Furthermore, existing tools do not systematically offer an easy-to-use graphical interface or flexible functionalities. As such, there is a need to develop an open-source, open-access, bottom-up, parametric tool to integrate the quantification of life cycle embodied environmental flows at the early stage of design.

1.1. Aim and scope

The aim of this paper is to introduce EPiC Grasshopper, a parametric plug-in for Grasshopper3D that quantifies the life cycle embodied environmental flows of buildings and infrastructure assets using a hybrid life cycle inventory approach.

This paper focuses solely on describing the functionalities of the tool developed by the authors, its design, verification and its validation using a case study residential building in Melbourne, Australia. EPiC Grasshopper quantifies embodied energy, water and greenhouse gas emissions, the three environmental flows considered in the Environmental Performance in Construction (EPiC) Database, developed by the authors (Crawford *et al.*, 2019b; 2021).

2. Method

2.1. Overall research approach

Figure 11: Overall research approach

Figure 11 depicts the overall research approach followed to develop EPiC Grasshopper. The software functionalities are first determined based on a review of studies on life cycle assessment tools for buildings as well as the scientific literature. These functionalities are implemented into the plugin using the Python programming language. The calculations of the resulting plugin are verified for correctness and the output is validated against manual calculations for a case study house.

2.2. Tool functionalities

In light of existing parametric tools to quantify embodied environmental flows and recommendations from existing literature on the topic, Table 9 presents the core functionalities of EPiC Grasshopper.

Table 9: Core functionalities of EPiC Grasshopper.

Functionality	Objective	Comment
Use of a hybrid life cycle inventory approach in the quantification of embodied environmental flows	Ensure that embodied environmental flows are quantified using comprehensive system boundaries	All existing parametric tools to quantify embodied environmental flows rely on process analysis for their assessment
Simple and intuitive workflow	Enable users to directly and intuitively user EPiC Grasshopper with a mellow learning curve	Existing tools often provided complicated workflows with the need to connect to a database, select materials by layer, or other (e.g. Cardinal LCA).
Simple-to-use user interface with minimum amounts of Grasshopper components	Facilitate user interaction and enable a rapid analysis through a streamline workflow	Most existing tools included multiple components that were hard to differentiate in terms of icons (e.g. Bombyx, Cardinal LCA).
Data visualisation and export from within the tool	Enable a rapid feedback on design decisions and changes to the user and the ability to slice the data in multiple manners	Most existing tools enable basic data visualisation and/or exports with limited capacity for data slicing and detailed exports.
Open-access and open-source database, tool and code	Enable users to access the tool freely and scrutinize its back-end code enabling further development	Only the Bombyx tool is available in open-access and in open-source with an open access database. Yet, the database itself is not transparent in terms of how it was compiled, as compared to the EPiC database.

2.3. Tool design

EPiC Grasshopper is designed around three main principles. Firstly, there is a clear separation of data, back-end code and front-end user interface on Grasshopper3D. The Grasshopper3D components contain the bare minimum of code and act only as input/output components. Each component creates an instance of a class on the back-end, e.g. an EPiC Material Component creates an EPiCMaterial instance. Only EPiCMaterial instances read from the EPiC database (which is a single file) and the data flows from Materials to the Analysis. Secondly, EPiC Grasshopper adopts the nested systems approach described in (Stephan *et al.*, 2022). This helps replicate the physical built environment, with materials nested into construction assemblies, nested into built assets, which are analysed. Thirdly, the code is written as open-access and open-source. The python code of any Grasshopper3D component is accessible by double-clicking on the component on the Grasshopper3D canvas. The back-end python code is also available openly on Github. Finally, all the detail behind the EPiC Database is available on its website, alongside fully transparent hybrid inventories for each main material in the database.

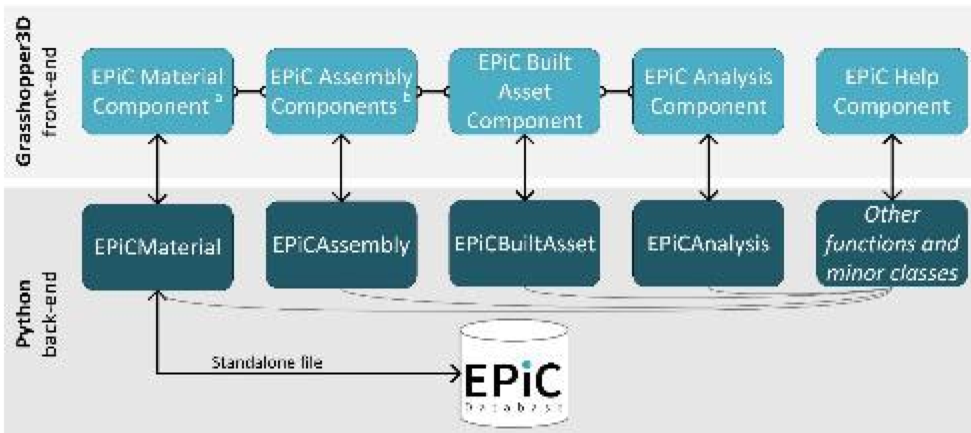


Figure 12: Design of EPiC Grasshopper. Note: [a] EPiC Custom Material enables creating custom materials and is not linked to the EPiC Database. [b] There are four types of Assembly components: EPiC Assembly Unit, EPiC Assembly Linear, EPiC Assembly Surface, and EPiC Assembly Volumetric.

2.4. Quantifying embodied environmental flows

Life cycle embodied environmental flows as quantified as per Equation 1 below. This is done by multiplying the quantity of each material within each assembly by the hybrid coefficient of the material from the EPiC database and by an on-site wastage coefficient. This is repeated for each material replacement, given by dividing the period of analysis by the average service life of material m.

$$LCEF_{an} = \sum_{b=1}^{B}\sum_{a=1}^{A}\sum_{m=1}^{M}\left(Q_{m,a,b,an} \times WC_m \times FC_m\right) + \sum_{b=1}^{B}\sum_{a=1}^{A}\sum_{m=1}^{M}\left[\left[\frac{POA_{an}}{SL_m} - 1\right]\right] \times \left(Q_{m,a,b,an} \times WC_m \times FC_m\right) \quad (1)$$

Where:

$LCEF_{an}$ = Life cycle embodied flow of an analysis *an* (e.g. in GJ for energy); B = Total number of built assets in the analysis; A = Total number of construction assemblies in built asset *b*; M = Total number of materials in an assembly *a*; $Q_{m,a,b,an}$ = Quantity of material *m* in assembly *a* within built asset *b*, in analysis *an* (e.g. m² of double-glazing (m) in windows (a) in a house (b) being analysed within a neighbourhood (an)); *WCm* = On-site wastage coefficient of material *m*, e.g. 1.05 for concrete 25 MPA; FC_m = Hybrid embodied flow coefficient of material *m*, in environmental flow unit (e.g. GJ for energy) per functional unit; POA_{an} = Period of analysis *an*, in years; and SL_m = Service life of material *m*, in years.

2.5. Verification

Verification, as part of a software development, consists of ensuring that the mathematical operations of the algorithm are correct. In this paper, we verify variables related to selected geometries in Rhinoceros3D and Grasshopper3D, calculations of material quantities by assembly, calculations of embodied environmental flows at the assembly, built asset and analysis level, data visualisation correctness and data exports. For each step, we used simple test cases where we measured or calculated manually the result and compared that to the output of EPiC Grasshopper. We imposed a relative difference of maximum 0.01%. In addition, where a variable was obtained by a simple arithmetic operation of two other variables (e.g. c = a × b), we assumed that if a and b are verified, then c is also verified.

Based on the above, we successfully verified all variables and outputs of EPiC Grasshopper. In the process, we identified a few issues (notably related to collecting data from Rhinoceros3D geometries) that we resolved to match the verification benchmark.

2.6. Description of case study for validation

In software development, validation consists of measuring if the model provides a realistic enough approximation of reality. Within the context of EPiC grasshopper, validation consisted of comparing the output of EPiC Grasshopper in terms of life cycle embodied environmental flows for a given house to those of an existing study by the authors. This enables a robust comparison of the outputs of EPiC Grasshopper. As infrastructure assets, e.g. roads, are simpler than a house in terms of material composition and geometry, we did not include a case study infrastructure asset in this paper due to space limitations.

Table 10: Case study characteristics.

Characteristic	Value
Period of analysis	60 years
Areas	135.4 m² net conditioned floor area (NCFA)
	9.8 m² unconditioned utilities (bathroom and laundry)
	38.9 m² unconditioned Garage
	36.68 m² glazing
Roof	Concrete tile attic-type roof with 160 mm fibreglass insulation batts (U-value=0.29 W/(m²·K)) and a 60 mm reflective blanket (U-value=0.77 W/(m²·K))
	Metal deck roof to garage, no insulation
External walls	Brick veneer walls with 90 mm fibreglass insulation batts (U-value=0.5 W/(m²·K)) plus single sided reflective foil
	Single brick walls to garage, no insulation
Internal walls	Plasterboard on stud frame, 90 mm fibreglass insulation batts (U-value=0.5 W/(m²·K)) to unconditioned spaces
Floors	Concrete slab on ground, no insulation, tiles in wet areas, carpet in other living spaces.
	Concrete finish in garage
Windows	Timber framed, clear single glazing

A typical Australian house was chosen for validation because it was previously modelled and studied by the authors (Crawford *et al.*, 2019a) using the EPiC database. This offered a benchmark against which EPiC Grasshopper could be validated. Only embodied energy figures are compared as data for embodied water and greenhouse gas emissions are not available. However, given that the embodied water and greenhouse gas emissions are calculated using the exact same algorithm as embodied energy, and that the hybrid coefficient within the EPiC database are validated, the calculations of embodied water and embodied emissions are also validated. Table 10 presents the main characteristics of the case study house for which Figure 13 depicts the Rhinoceros3D model. It is important to flag that some construction assemblies, such as the driveway, fencing or plumbing were not modelled as part of the validation and are therefore not taken into account.

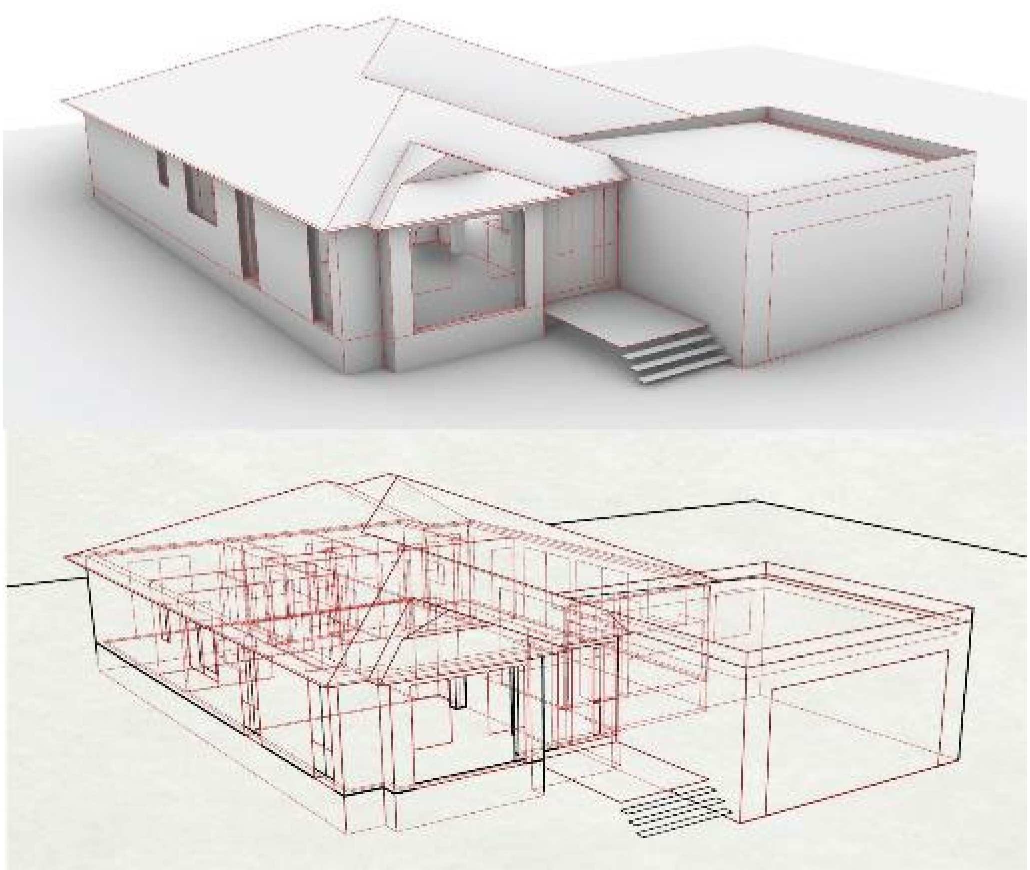


Figure 13: Case study house as modelled in Rhinoceros 3D (top: rendered, bottom: wireframe). Red lines represent geometries selected by EPiC Grasshopper for quantifying embodied environmental flows

3. Results of the validation case study

Results demonstrate insignificant differences in life cycle embodied energy figures at a whole building level with the benchmark case study representing 1,291 GJ and the EPiC Grasshopper results representing 1,267 GJ (-2%). These differences are due to the way geometry is inferred in EPiC Grasshopper, leading to the exclusion of wall intersections, minor approximations in terms of the quantities of finishes, as well as the way materials are modelled per functional unit of construction assembly. This nested modelling approach accumulates approximations, propagates them, and is discussed in Section 4.

Figure 14 compares the percentage contribution of each material to the life cycle embodied energy of the case study house, as calculated with EPiC Grasshopper and manually from Crawford *et al.* (2019a). Results show that the contribution of each material to the total varies slightly between the two models, notably because of the way materials are modelled. For instance, cement mortar is calculated by mass or volume in the bill of quantities but is inferred by the mass of cement per m² of brick wall in EPiC Grasshopper. This mass is in turn modelled based on the thickness of the bricks and the surface ratio of bricks to joints per m². These modelling approximations, and assumptions are behind most shifts in contribution to the total.

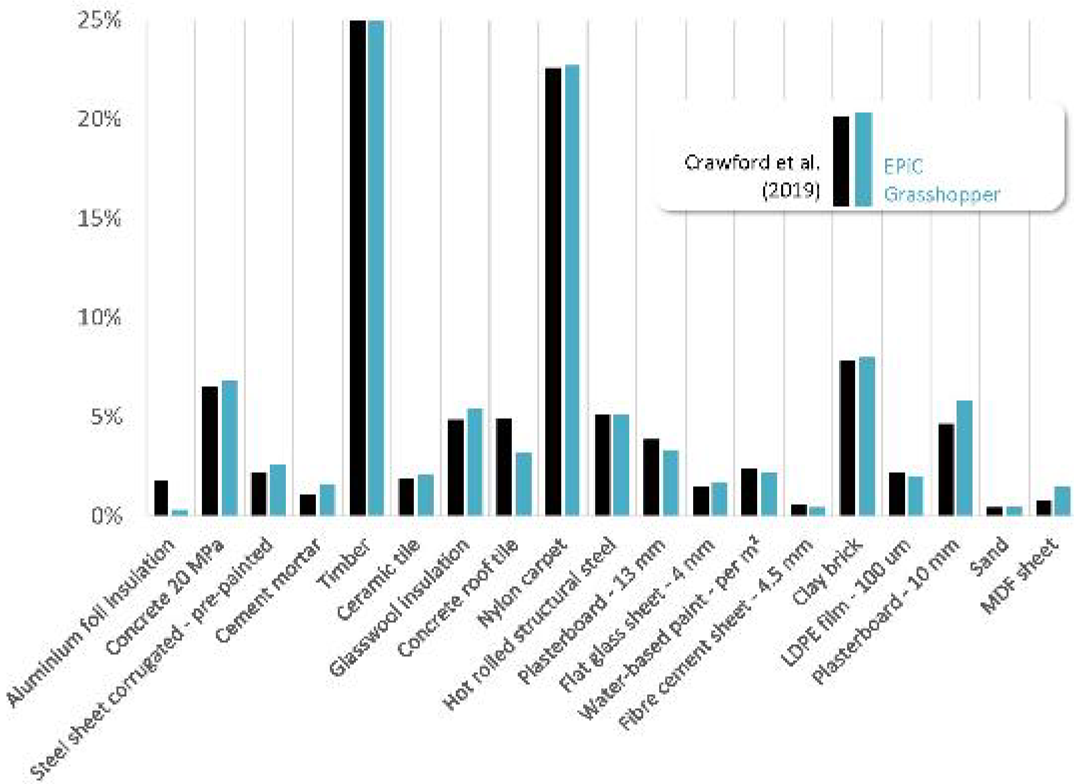


Figure 14: Comparison of the contribution to the life cycle embodied energy of the case study house, by material, using data from Crawford et al. (2019) and EPiC Grasshopper

Overall, variations between the contribution of individual materials to the life cycle embodied energy of the case study house were limited to ±2% (using absolute differences we obtain: mean=0.46%, median=0.24%, standard deviation=0.11%, minimum=0.01%, maximum=1.7%). This validates the outputs of EPiC Grasshopper.

Figure 15 showcases one of the ways results can be visualised directly within Rhinoceros3D, using EPiC Grasshopper. The user can either show results at the whole building level, by assembly, by material and by material within each assembly. This provides the user with powerful means to understand the life cycle embodied environmental flows profile of their designs, to compare them and to improve them.

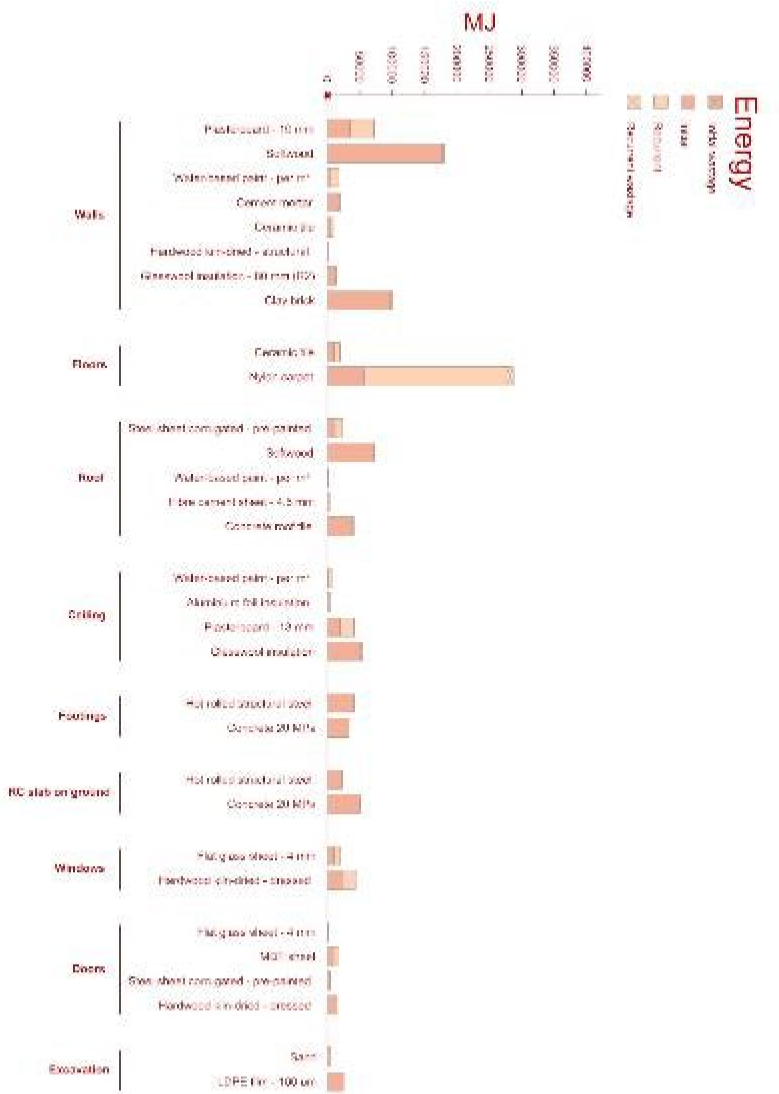


Figure 15: Breakdown of life cycle embodied energy of the case study building directly within Rhinoceros 3D, using EPiC Grasshopper, by material. Note: This figure is a direct screenshot, without any post processing.

4. Discussion and Conclusion

This paper has presented for the first time EPiC Grasshopper, a bottom-up parametric tool, operating within the Rhinoceros 3D and Grasshopper 3D environment, to quantify life cycle embodied environmental flows using the EPiC database. EPiC Grasshopper is the first plugin to operationalise a hybrid life cycle inventory database for construction materials. This study has validated the plugin by comparing its life cycle embodied energy results to those of a benchmark case study, previously studied by the authors. The embodied energy of that case study was calculated manually using the EPiC database. This comparison demonstrates that EPiC Grasshopper produces reliable figures with a minor deviation at a whole building level (-2%) and deviations in the contribution of each material to the total of less than 2% (average of 0.46% variation between the benchmark and the EPiC Grasshopper model).

These slight variations are mostly due to the modelling approach within EPiC Grasshopper. Since EPiC Grasshopper is adopts a nested modelling approach, using construction assemblies that include EPiC Materials to model a building, the total quantities of materials within a building might differ from what is reported in a bill of quantities. This is one of the limitations of this approach. However, at the early stage of design, using assemblies to rapidly compare alternatives for geometry and material compositions significantly streamlines the process of exploring different designs.

On top of relying on the consistent, transparent and complete EPiC database (Crawford *et al.*, 2019b; 2021), EPiC Grasshopper provides advanced features that other existing plugins, such as Bombyx (Basic *et al.*, 2019) and Cardinal LCA (Chen *et al.*, 2021), do not cover. These include built-in visualisation of results (see Figure 15), detailed data exports directly from within Grasshopper by exporting data from panels or by relying on the 'export to csv' function of the EPiC Analysis component.

This paper suffers from limitations, as any scientific inquiry. Its scope is limited to validating the figures obtained with EPiC Grasshopper to those from a benchmark. As such, the parametric features of EPiC Grasshopper are not explored and are part of future research. Furthermore, EPiC Grasshopper itself suffers from limitations. To date, it only covers stages A1-A3 and B4 according to European Standard 15978 (2011) and does not include transport from factory to site, nor the construction process. Importantly, EPiC Grasshopper does not yet include a material selector and forces the user to choose a particular material. A more advanced manner would be to filter materials by attributes and propose different alternatives to a user. While the visualisation already enables a powerful analysis within the Rhinoceros/Grasshopper environment, further refinement is needed, notably enabling graphs of embodied environmental flows per year. These limitations will be addressed in future releases of the plugin.

By developing user-friendly tools that enable a parametric approach to the life cycle assessment of buildings and infrastructure assets, within existing design workflows, we aim to empower actors of the built environment to act on the climate and resource emergency. This will help achieve designs of buildings and infrastructure assets that result in net life cycle environmental performance.

Acknowledgements

This research was funded by a seed funding grant from the Faculty of Architecture, Architectural Engineering and Urban Planning, Université Catholique de Louvain, Belgium and by the Belgian Fund for Scientific Research (F.R.S.-FNRS) *Mandat d'Impulsion Scientifique* grant (F.4547.21).

References

Basic, S., Hollberg, A., Galimshina, A. and Habert, G. (2019) A design integrated parametric tool for real-time Life Cycle Assessment – Bombyx project, *IOP Conference Series: Earth and Environmental Science*, 323(1), 012112.

Chen, J., Kharbanda, K. and Loganathan, H. (2021) *Cardinal LCA v0.0.1*.

Crawford, R. H., Stephan, A. and Prideaux, F. (2019a) A comprehensive database of environmental flow coefficients for construction materials: closing the loop in environmental design, *Revisiting the Role of Architecture for 'Surviving' Development. 53rd International Conference of the Architectural Science Association 2019*, edited by A. Agrawal, Roorkee, India, 28 - 30 November, 353-362.

Crawford, R. H., Stephan, A. and Prideaux, F. (2019b) *Environmental Performance in Construction (EPiC) database*, The University of Melbourne, Melbourne.

Crawford, R. H., Stephan, A. and Prideaux, F. (2021) The EPiC database: Hybrid embodied environmental flow coefficients for construction materials, *Resources, Conservation and Recycling*, 106058.

European Standard 15978 (2011) *Sustainability of construction works -Assessment of environmental performance of buildings - Calculation method*, European Committee for Standardization (CEN), Brussels, 66.

Hollberg, A. and Ruth, J. (2016) LCA in architectural design—a parametric approach, *The International Journal of Life Cycle Assessment*, 21(7), 943-960.

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T. and Passer, A. (2020) Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation, *Applied Energy*, 258, 114107.

Stephan, A., Crawford, R. H., Bunster, V., Warren-Myers, G. and Moosavi, S. (2022) Towards a multiscale framework for modeling and improving the life cycle environmental performance of built stocks, *Journal of Industrial Ecology*, 26(4), 1195-1217.

Stephan, A., Crawford, R. H. and de Myttenaere, K. (2013) A comprehensive assessment of the life cycle energy demand of passive houses, *Applied Energy*, 112, 23-34.

Stephan, A. and Stephan, L. (2020) Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate, *Applied Energy*, 280, 115932.

UNEP (2016) *Global Material Flows and Resource Productivity. An Assessment Study of the UNEP International Resource Panel.*, United Nations Environment Program, Paris.

A rapid relief architecture for primary schools

Kate Poole[1] and Guy Marriage[2]

[1, 2] Victoria University of Wellington, Wellington, New Zealand
katejaqpoole@gmail.com[1], guy.marrige@vuw.ac.nz[2]

Abstract: A natural disaster will inevitably strike New Zealand in the coming years, damaging educational facilities. Delays in building quality replacement facilities will lead to short-term disruption of education and create the risk of long-term inequality for the affected students. The Christchurch earthquake demonstrated the issues arising from a lack of school planning and support. This research proposes a system that can effectively provide rapid, prefabricated primary schools in post-disaster environments to continue education for children in the short term while using construction that is suitable until the total replacement of the given school is completed. The expandable prefabricated architecture meets the strength, time, and transport requirements to become a robust, rapid relief temporary construction adaptable to any area within New Zealand. This design solution supports personal well-being and mitigates the risk of educational gaps, PTSD linked with anxiety and depression, and many other mental health disorders that can impact students and teachers after a natural disaster.

Keywords: Prefabrication, rapid relief, Primary School, New Zealand, permanent.

1. History of disaster relief in New Zealand

New Zealand is very susceptible to earthquakes, tsunamis, and volcanic eruptions (Capability Assessment Report, 2022), the most vulnerable areas being low-lying and close to the coast (Upton, 2015) due to sea level rising/floods, especially those which are unsheltered. The current proposal looks at the Wellington region, which holds 542,000 (Facts & figures, 2022) of the New Zealand population.

Many primary schools lie in the region's suburban coastal areas, which are prone to these natural disasters. Each disaster carries different threats that the New Zealand educational system is not prepared for. Gaps in primary school education shown in the Department of Education and Training statistics showed an extended period of academic impact (Gibbs et al., 2019) presented after infrastructure and facility loss. The Civil Defense disaster relief report shows the gap between our "current and ideal state to meet people's basic needs" (Capability Assessment Report, 2022).

New Zealand does not currently have sufficient capacity to meet this need for rapid infrastructure replacement and provide post-disaster relief of sufficient structural and social quality, particularly in suburban areas. Disaster relief globally is often "informally built without responding to building codes or seeking expert advice and supervision" (Wagemann & Ramage, 2013), creating more exposure if the

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 76–85.*

disaster strikes again. These issues combine to increase the risk of widening the urban-to-rural poverty gap in New Zealand, changing population movement, and increasing social and economic inequalities (Wagemann & Ramage, 2013) due to the facilitation and ability to build schools in denser areas rather than schools in less populated areas. Long-term design strategies need to be implemented into this relief process to expand the building life and create design solution that can aid a range of primary schools, rural or not, that reduces the need for additional materials, construction time, and cost.

1.1. Aim: To rapidly provide a temporary, transitional relief design with progressive design features

- **Strength and response time:** Rapid construction. Strong enough to withstand post disaster shocks and flooding. Transportable able to be delivered by truck.
- **Community and social adaptability:** Modern infrastructure to support students and teachers and their communities to grow in the short to long term to reduce negative economic, social, and cognitive effects of the disaster. Provide a design which is: adaptable to a range of school needs and sizes; is not limited to a singular place; and will aesthetically create pride, all of which will reduce the marginalization that may occur when immediate response plans are provided.
- **Educational requirements:** Areas for physical and social activities that improve student wellbeing. Spaces with good ventilation, heating, and acoustics, with passive strategies to create interior climate control.

1.2. Methodology

The proposed methodology uses research and correlation through qualitative and quantitative research methods supported by physical modeling to verify the construction of the building. Quantitative, evidence-based research will support the study based on previous post-disaster architecture, planning, and the current architecture for primary schools; to compare effective and ineffective systems within time, transport, cost, and accessibility of materials, constraints, within the NZ context. Using quantitative methods helps to understand the full spectrum of the design intent regarding prefabrication methods that can expand on a rapid relief structural frame. Qualitative research regarding the aesthetic, educational, cultural, social, and economic relevance will enhance the overall application of the design.

2. Disaster relief planning

Relief depends on many variables, from the available materials, resources, money, time, environmental conditions, and, most importantly, those in charge of the relief plans and coordination. If NZ cannot assess the total range of variables and consequences regarding economic, social, and environmental inter-dependencies, this will result in inadequate disaster relief (United Nations, 2014). Prior preparation and management of a disaster relief plan can significantly improve the effectiveness of the relief.

A lack of coordination from the government can create stress and discomfort if not performed with effective prior planning and communication between administrative authorities regarding who will take responsibility for new disaster tasks (Raju, E. & Van Niekerk, D., 2013). An example of a poorly organized process was presented after the 7.1 magnitude earthquake in Christchurch 2011 when the decision was made to relocate students whose schools were in the red zone to alternative schools.

In 2015, Carol Mutch provided a report on the impact of the Canterbury earthquakes on schools and school leaders. She found that the co-location of students to non-impacted schools was a workable solution but not an educational idea or suitable long-term (Mutch, 2015). Mutch, drew on a study that assessed the long-term impacts on young people in Thailand who were affected by the 2004 Indian Ocean Boxing Day tsunami, which found that many students still suffered years later from concentration problems, headaches, tiredness, nightmares, and confusion. Problems arose around long travel times, reduced school hours, and lost school cultural values, creating an unnatural learning environment. The effects of loss are reduced through peer support, community programs, a sense of school spirit, religion, and education. Prior planning to provide a place for students to receive this type of support is key to an effective relief process, which is a flaw in our current ability to provide a solid educational plan for disaster situations and mental health management in New Zealand.

2.1. Challenges with transplanting architectural relief

Architectural relief globally has a reputation for transplanting architecture without considering the characteristics of the place (Wagemann & Ramage, 2013). The transplantation of architectural relief is shown in the Oxfam Polyurethane Emergency House, the West German Red Cross polyurethane igloo, and, more recently, the Cardboard Cathedral.

The use of polyurethane in the Oxfam Emergency house and West German Red Cross igloo was donor orientated rather than based on the needs of the survivors. Although the design was easy to transport and assemble, it was socially, culturally, and climatically unsuitable. In contrast, Shigeru Ban's designs, including the Paper Log House designed for survivors of the 1995 Kobe, Japan earthquake, have benefited worldwide. Cardboard was the signature material; his designs are tremor resistant, low cost, able to withstand extreme weather conditions, recyclable, easy to transport, store and to construct (Material District, 2013). The exception was Shigeru Ban's design of the Cardboard Cathedral after the Christchurch earthquake. Due to the profound change in climates compared to his previous designs, challenges arose regarding sourcing and keeping the cardboard dry. The Cathedral used 98 cardboard tubes; each piece weighed around 120kgs (Material District, 2013). Over time, the tubes had to be cut out and replaced. The solution was to cover the Cathedral with a polycarbonate lid and insert steel beams into the tubes and extra laminated timber beams into the main frame to aid structural support (Material District, 2013). Due to the scale of the design and the environment, the paper tubes offered beauty rather than a cost-effective, easily constructed building design, illustrating each country's unique challenges when resourcing and applying materials. For this reason, the case studies that influenced the final design were all applicable to NZs climate, creating relevant consistencies that could positively influence the design process and outcome.

2.2. Temporary to permanent reconstruction

After a significant disaster deeming many buildings unusable, several different types of accommodation are typically used. Disaster relief shelters are categorized as emergency, temporary, transitional, progressive, core shelters/one-room shelters, and permanent housing (Bashawri, Garrity and Moodley, 2014). When a community experiences these trials, sustainable reconstruction can take several years, particularly within urban environments. Providing a long-lasting, durable temporary solution is key to a smooth recovery process.

The research aims to provide a rapid temporary primary school design, adaptable to any primary school, that will support those in need until a permanent building is constructed. Creating a design guide for this architecture will mean all the requirements (including building codes and construction programming) for a range of school sizes are completed in advance, leaving construction as the last step.

The 2011 Christchurch earthquake affected 163 primary and secondary schools. Of those, 24 reported further assessment, and 11 were seriously damaged (Effects of the Canterbury Earthquakes, 2022). It is difficult to directly compare how many schools will be affected by future earthquakes as the intensity of an earthquake is unpredictable. Therefore, the aim will be to create 12 fully prefabricated schools, placing two in each of the six Army camps across NZ. The design will be able to be rapidly deployed by truck or helicopter and entirely constructed within one week.

3. School architecture in New Zealand

A primary focus of this design is to provide a unique, effective school environment that adheres to the New Zealand department and regulatory requirements for schools. School architecture is influenced by political and social movements and new technological advancements. School designs are slowly becoming more holistic, benefiting the masses, to continuously improve previous problems and solutions need to be understood.

3.1. Current problems

New Zealand school designs and systems are built on ideas created in the mid-1900s. In the 1940s, NZ started transitioning fully from the one schoolhouse to the finger plan school design as many students moved inwards toward the city areas. In the 1950s, the baby boom created a sudden demand for primary schools, which was met by mass produced school responses all built with low budgets. The concept of the open-plan school emerged in the 1960s-1970s to improve the standard classroom design. This concept is found commonly in NZ and has its challenges. As explained by Ben Graves, an open-plan environment led the individual to be more innovate, self-assured, intelligent and understanding (Perez, 2017). However, the downside to this approach is that spaces became noisy and visually distracting, making it more difficult to teach students in a structured way. The design challenge was providing an effective medium between chaos and control.

By the 1970s, worsening economic conditions led to educational funding cuts and poorer school design outcomes. Education was made mandatory at this time for students up to fifteen years old, increasing the need for rapid construction with minimal budgets and low-quality designs. The cost and time limitations meant most standard primary school plans in New Zealand derived from the basic dominion plan, where the teacher was the room's focus, and there was a one-size-fits-all approach (Garnock-Jones, 1966). The minimum areas for each classroom were 58m^2 with a max of 74m^2; the size dictated by the given budgets (Garnock-Jones, 1966), consistent with what we still see today. The increase in student numbers over the years means these designs are now overcrowded, leading to an excess of heat in summer and inadequate ventilation due to the higher amounts of air pollution from students and nearby roads.

To date, the solution to overcrowded classes has been to provide basic, rectangular, prefabricated units for schools made of timber and steel, with thin layers of insulation. These structures have poor sound quality due to the limiting shape, which increases reverberation. Due to the low quality of the buildings, the prefabricated units suffer from physical neglect and create an uninspiring, unadaptable learning atmosphere rather than an active learning environment.

3.2. School design problems and their solutions

- **Problem:** Average size classroom is 74m^2, unable to adapt to an increase of students. **Solution:** Increase the average class size to 100m^2 to aid the gradual yearly increase of students.

- **Problem:** Underutilization of passive ventilation through window opening. **Solution:** Including two sets of windows on either side of the class, including clerestory windows with screens to cover excess winds and control exterior noise from the roads.
- **Problem:** Bad acoustics as quality materials and construction are uncommon. **Solution:** Better thermal insulation, warmer roof, and floor designs, and multiple sound absorbers on the ceiling, wall, and floor area as well as portable partitions to move freely around the room.
- **Problem:** Noise pollution in classrooms from roads and nearby buildings. **Solution:** Screens placed around the school to block excess sounds entering the classroom space.
- **Problem:** Strictly teacher-centred environments. **Solution:** Active play zones incorporated into the classrooms, including separate exterior play zones for physical activities.
- **Problem:** The need for playgrounds that push students and layouts that provide a range of private and group spaces. **Solution:** Central courtyard spaces with private and group zones, including an atmosphere that evokes the mind beyond the standard playground design.
- **Problem:** Lack of proper insulation relying on mechanical heating systems. **Solution:** Thick floor, walls, and ceiling insulation above the minimum with double glazed glass.

4. Requirements for designing disaster relief school spaces for New Zealand schools

There are specific legal and Ministry requirements for each school, including those that are necessary for rapid relief design. These requirements create guidelines for appropriate comfort levels and necessary school spaces based on fitness for purpose, constructional asset assessment, and operational efficiency. Some Ministry requirements will be applied later in the construction after the legal and essential rapid relief requirements are in place, for example, a sprinkler system and lifts. The rapid relief primary school architecture meets each of these eight main components to provide an incredibly effective rapid design whose main aims are to create transportation and construction ease, earthquake, and flood protection; adaptability for a range of schools, infrastructure replacement (classrooms, staff spaces, toilets, play zones) and overall, an aesthetic holistic student-centered learning environment. These requirements are:

1	Lighting and visual comfort:	Window ratio, orientation, light zoning, window height and width, reflection, shading, clerestory glazing, task lighting, illuminance levels, and visual contrast.
2	Thermal comfort and control:	R values, double glazing, blind systems, facades, fountains, computer zones and placement of windows.
3	Design for emotional & behavioural and learning difficulties:	Breakout zones, decibel rating, visual learning tools, active spaces, visual cues, noise zoning and airflow.
4	Accessibility:	Priority for ramps, grab handles, visual guides, disability toilets, viewing platforms, flexible furniture, brail, pictographs, and colour blocking.
5	Acoustics:	Sound absorbers, floor coverings, highly rated NRC materials, acoustic panels, door and window placement, room dividers, and room shape.
6	Transport	Flat pack design, transport guidelines in terms of sizing, and weight restrictions.
7	Programming:	School size requirements and limitations, storage, classroom, offices, shared spaces, medical centre, toilets, corridors, reception, and yard space.
8	Indoor air quality:	Carbon dioxide levels, window openings, and position, mechanical heating systems, ceiling fans, room shapes/sizes.

Figure 1: Summarised guidelines and requirements for the final design

5. Case studies

Twenty-six case studies offered relevant design and construction information that was appropriate to the local NZ climate. Panelised, fully modular, and standardised systems were all researched, and each design's advantages and disadvantages influenced the final development of the design. The panelised systems were the most customisable prefabricated designs; this allowed an increased range of spaces and adaptability, but in some circumstances, they were more expensive. The modular relief designs showed a lack of aesthetics and provided minimal spaces restricted by the bulk nature of the design but had an overall lower cost associated with them and a rapid construction time. The standardised systems overall showed the highest quality of design and thoughtfulness regarding dictating spaces. They were often equally expensive, heaviest, and took the longest to construct. Therefore, the standardized system case studies were helpful in terms of space dictation rather than indicating what construction was most beneficial due to the rapid relief design's time, money, and transport restrictions.

5.1. Influential school design case studies

The main primary school case studies influencing the final design of the rapid relief primary school were the Valentino Gareri tree school, (a panelised design), and Baan Huay San Yaw primary school (a modular design). Each had low building costs, rapid construction, and high-quality features and was designed for post-disaster and post-COVID environments to provide high-quality school environments. Overall common themes in numerous high-quality school case studies were the circular programs/courtyard spaces, the strength provided through CLT, LVL, Glulam, and steel, classroom separation to reduce noise and increase natural light, interior zoning, and connection to nature.

The Huay San Yaw Primary school is earthquake and flood-resistant, using lightweight steel mirroring an enlarged version of a queen-post roof truss design with post and beam members. This design highlights how a truss and portal frame design with cross-bracing elements effectively strengthens a classroom during seismic events or high-intensity winds. Equally, showing how elevating a classroom above the ground on piles can protect the school when flooding occurs.

The Valentino Gareiri School uses laminated timber elements that fit into a trapezium shape to create a singular form catering to various programs/layouts. The curved layout creates a courtyard naturally at the center of the school, developing a community space. The timber façade helps diffuse light while allowing the room to be naturally lit and warmed by the sun, creating a comfortable interior. The treehouse-style design outlined the success of a trapezium-shaped classroom and how grouping together this shape effectively can create courtyard spaces to help connect students.

5.2. Influential rapid relief structures

The most influential rapid relief structures were panelised or modular, shown in the hexagon relief shelter and the Just a Minute rapid relief shelter. These two designs showed adaptability in space and had ease of transportation. The hexagon rapid relief design is a flat pack. The walls and roof panels are self-supporting, and the cladding can differ from pod to pod. This design also uses solar panels, a rain gutter system, and a portable water tank. The hexagon shape can replicate in form to support both larger and smaller communities and cultures with their own courtyard space.

Similarly, the Just a Minute architecture was a flat pack design that could be folded together and opened in just a minute to supply immediate housing. The structure is built by bamboo members, which create the cross-bracing wall and floor panels, with a Juta membrane exterior filled with recycled wool. Each rectangular design has a private deck divided into a range of spaces simply by putting up another lighter wall within the shelter.

The Just a Minute and Hexagon rapid relief case studies directly impacted the construction and physical modeling of the design. These case studies provided an understanding of how to compress, store and transport elements without losing their structural integrity. Physical modeling provided validity for the final compressible structure (fig 2).

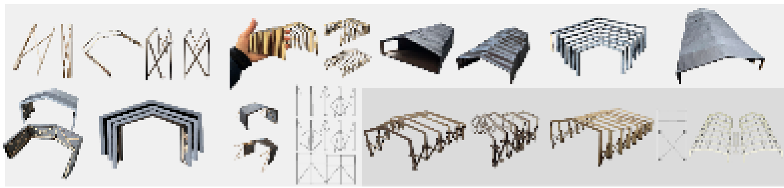


Figure 2: Final development (dark grey box), models which lead to the final development (light grey)

5.3. The ideal classroom shape and configuration

Simple patterns offered the most effective forms within the case studies, including those that focused on a repeated shape to enhance central community spaces. Most effectively, the Valentino Tree House school showed this repeated trapezium classroom shape, creating the desired natural courtyard. The final underlying layout and shape of the rapid relief classrooms creates a natural courtyard area through repeatedly curved trapezium shape classrooms. Due to the natural configuration of the classrooms, the plan curves in a C or S shape, with the smallest part of the classrooms pointing inwards to a courtyard space (Figure 3). The courtyard creates a communal place of integration between each age level, like a small town, which gradually merges the classroom zones to play areas while being in direct contact with nature, reducing the minimised feeling most boxy school layouts create. This relationship from classroom to playing creates beneficial social interaction and can provide a sense of relaxation and safety (Salameh et al., 2020). The circular plan is functional, taking advantage of natural light because the half-circle configuration reduces shade in neighbouring classrooms, enhancing the thermal conditions within the buildings (Salameh et al., 2020). In addition, the geometrical form creates a clear pathway around the site and ease of access to each area onsite. Using a repeated form like this also reduces the resources and materials required, predominantly when prefabricated in a factory, as the construction process barely varies from start to finish.

Figure 3: C – S shape variation in plan and interior classroom render

6. Design

The Wellington school region has 212 primary schools with an average of 271 students per school (Education Counts, 2022), and the average New Zealand classroom size has 25 students (OECD Indicators, 2021). Therefore, the final design is based on the calculation that this rapid relief primary school will need 8-12 classrooms with a range of 20-30 students in each classroom, with a classroom area of 100m2 to allow adequate interior zoning to adapt to the growing student population. There is no site within Wellington directly associated with this design as earthquakes are unpredictable; therefore, the primary school will be placed on unaffected sports fields, found commonly all over Wellington and New Zealand.

The average sports field could comfortably accommodate up to 18 of these classrooms, with two large common areas facing in and separate exterior common spaces in front of each classroom. The design will include four prefab toilet blocks separately brought in, placed equally between classrooms, with separate facilities for teachers and students. Each classroom will have a minimum of two storage spaces, an active play zone, quiet zones, and a tech space. The teacher's site will use the same construction/design as the classroom and include around eight offices. The separate building will include the reception space and a medical center and if needed, an extra building for a library space.

6.1. Foundation construction

Screw piles are inserted into the chosen sports pitch, with members reaching a height of 1.5 meters above the ground. Timber bearers will be laid overtop the piles for total stability, and four CLT panels per classroom will create the classroom floor. A timber deck will connect the classrooms in a C-to-S shape for circulation between buildings.

6.2. Transport and construction

Seven LVL portal frames (400mm x 90mm) construct the final repeated classroom shape, which ranges in a span of 11m and height of 3.9m, gradually increasing in height and decreasing in width to meet a span of 8m at the height of 4.4 meters. An ETFE inflatable film structure creates the roof and sides of the building lengthwise, connected over the LVL portal frames, leaving the front and back of the building open where SIP, including windows, are placed. The roof will be inflated with air after the structure is placed onsite to enable the structure to compress during transport and storage. The gable roofs open the space up, allowing for a separate 3x4 level mezzanine space within each classroom and a direction for water to flow off the roof into catchment zones, reducing pressure on the tensile fabric when heavy rain falls. Seven extendable telescopic beams (100mmx100mm) connect and brace the LVL portal frames. These beams are only adjustable in length and permanently connected to each frame on either side. Eleven steel detachable cross-bracing elements strengthen the building against seismic activity between each portal frame. The final structure is fully demountable (excluding the SIP elements and flooring). It can be driven to the site on a category two truck (4.5 x13.3), opened, and constructed within hours.

Once the truck reaches the site, a beam will hook under the portal frames, and a crane will lift it onto the CLT floor. The portal frames are each on separate trollies, the structure will open seamlessly. Once the cross-bracing and adjustable beams are locked, the structure lifts by crane once more to remove the portal frame trollies and connect the portal frame classroom to the CLT floor.

During storage and transport, the main classroom structure can be reduced from 104.5m^2 to 33.3m^2, reducing the structure lengthwise from 11m to 3.5m. The reduction in length is possible because the galvanized steel struts have been designed to concertina to a quarter in size, expanded back to the original length onsite, and locked in. Equally, the cross-bracing elements are parallel to the steel struts and connected to the portal frames by two steel plates, with a hinge joint allowing the diagonal element to move when unlocked at the bottom. When the diagonal rods detach from the brackets on the portal frames, both cross-bracing elements compress without breaking the structure. When the struts are locked in, these cross-bracing elements can be expanded and reconnected by hand.

An ETFE inflatable film structure covers the roof and walls; this is key to the design. Without the lightweight, flexible qualities of the fabric (when deflated), this design would not be able to compress. In comparison, using a classic roof and walls structure would extend the construction period and increase the overall cost of the relief project, making it a prefab design rather than rapid relief construction. The fabric roof has two layers allowing an air pocket to be inflated between each portal frame, generating 24 air pockets over each structure for comfortable thermal and sound insulation within the building.

Once expanded, SIP panels are installed on the open ends of the building. The modular corridor can then be lifted and placed between the two connecting classrooms acting as a shelter when students enter and exit the premise, the open corridors comprise LVL columns and beams with a tensile fabric cover over the top. Each corridor has an area of $8.2m^2$. Due to their size, they can be made into complete components and do not need compression during storage and transport. The corridors will be stored and delivered to the site with the SIP and floor panels on a category 1 or 2 truck.

Figure 4: Final design and construction

6.3 Conclusion

The construction process has been guided by functional research on what makes a valuable classroom and relief plan. The final design meets all the requirements of space for a classroom, with excess to meet the growing student population, creating a strong base for schools to adjust and expand to their liking, unrestricted by varying school sizes. The structure is lightweight and can withstand high winds, seismic activity, and flooding. Its unique lightweight materials, such as the ETFE inflatable cover and LVL portal frames, make the building aesthetically pleasing and enjoyable to work in. Creating an immediate architectural plan is the first step toward a supportive recovery process. The rapid relief primary school design is fast-action and instantly supports students, teachers, and parents through times of stress. Although this architecture supports primary schools, its application can range and should be used to influence future development in rapid relief shelters within NZ and around the world. A natural disaster is unavoidable in NZ; creating a recovery plan is hard but being unprepared is worse.

References

Bashawri, A., Garrity, S. and Moodley, K., 2014. 4th International Conference on Building Resilience. In: 4th International Conference on Building Resilience. [online] Salford: ANDROID Disaster Resilience Network, pp.3-4. Available at: <https://www.sciencedirect.com/science/article/pii/S2212567114010193/pdf?

Oecd-ilibrary.org. 2021. Education at a Glance 2021 OECD INDICATORS. [online] Available at: <https://www.oecd-ilibrary.org/docserver/b35a14e5-en.pdf? [Accessed 24 May 2022].

Hbemergency.govt.nz. 2022. Capability Assessment Report. [online] Available at: <https://www.hbemergency.govt.nz/assets/Documents/Reporting/Hawkes-Bay-CAR-2019.pdf> [Accessed 16 March 2022].

MaterialDistrict. 2013. Cardboard cathedral - MaterialDistrict. [online] Available at: <https://materialdistrict.com/article/cardboard-cathedral/> [Accessed 15 March 2022].

Learnz.org.nz. 2022. Effects of the Canterbury Earthquakes. [online] Available at: <https://learnz.org.nz/shakeout154/bg-standard-f/effects-of-the-canterbury-earthquakes#: [Accessed 10 June 2022].

Salameh, Dr. Muna, et al. "Courtyard Design in Schools and Its Influence on Students' Satisfaction." World Congress on Civil, Structural, and Environmental Engineering, Avestia Publishing, Oct. 2020, https://doi.org/10.11159/icgre20.197.

"Find Your Nearest School | Education Counts." Education Counts, 2022, www.educationcounts.govt.nz/find-school?

Félix, D., Monteiro, D., Branco, J., Bologna, R. and Feio, A., 2014. The role of temporary accommodation buildings for post-disaster housing reconstruction. Journal of Housing and the Built Environment, [online] 30(4), pp.683-699.

Garnock-Jones, A., 1966. Primary Schools. [online] Teara.govt.nz. Available at: <https://teara.govt.nz/en/1966/architecture-school-buildings> [Accessed 31 February 2022].

Gibbs, L., Nursey, J., Cook, J., Ireton, G., Alkemade, N., Roberts, M., Gallagher, H., Bryant, R., Block, K., Molyneaux, R. and Forbes, D., 2019. Delayed Disaster Impacts on Academic Performance of Primary School Children. Child Development, [online] 90(4), pp.1402-1412. Available at: <https://srcd.onlinelibrary.wiley.com/doi/10.1111/cdev.13200> [Accessed 20 March 2022].

Mutch, C., 2015. The impact of the Canterbury earthquakes on schools and school leaders: Educational leaders become crisis managers. [online] Nzeals.org.nz. Available at: <https://nzeals.org.nz/wp-content/uploads/2019/08/5-Mutch-JELPP-Vol30-2.pdf> [Accessed 21 March 2022].

Perez, B., 2017. Shifting School Design to the 21st Century. [online] Digitalcommons.unl.edu. Available at: <https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1185&context=archthesis.

Upton, S., 2015. Preparing New Zealand for rising seas. [online] Pce.parliament.nz. Available at: <https://www.pce.parliament.nz/media/1390/preparing-nz-for-rising-seas-web-small.pdf> [Accessed 17 March 2022].

Raju, E. & Van Niekerk, D., 'Intra-governmental coordination for sustainable disaster recovery: A case-study of the Eden District Municipality, South Africa', International Journal of Disaster Risk Reduction 4, June 2013, 92–99. 10.1016/j.ijdrr.2013.03.001 Accessed 5 June. 2020

Wagemann, E and Ramage,M., 2013. Relief for the curriculum Architecture education and disaster recovery. The Cambridge Architecture Journal, [online] (22), pp.129-133.

Wellingtonnz.com. 2022. Facts & figures. [online] Available at: <https://www.wellingtonnz.com/about-us/information-hub/facts-and-figures/> [Accessed 28 June 2022].

United Nations., 2014. Progress and Challenges in Disaster Risk Reduction. https://www.preventionweb.net, UNDRR, www.preventionweb.net/files/40967_40967progressandchallengesindisaste.pdf.

A review of life cycle sustainability assessment studies of smart building management systems

Praddeep Gobinath[1] and Robert H. Crawford[2]

[1, 2] *The University of Melbourne, Melbourne, Australia*
{p.gobinath[1], rhcr[2]}@unimelb.edu.au, ORCID-0000-0002-3912-1323[1], ORCID-0000-0002-0189-3221[2]

Abstract: The uptake of smart building management systems has increased in recent years, in both new and refurbished buildings, aided by technological advances such as smart sensors, Internet of Things (IoT), cloud-based computing and data-driven control approaches. Many studies have reported the energy saving potential of employing systems which leverage indoor environmental and occupancy information collected in real-time to better manage building services. The increased uptake of these systems means that natural resource demands and environmental effects associated with the extraction of raw materials, processing and manufacture, installation, maintenance, and replacements as well as the supporting supply chain activities have increased the embodied environmental impacts of buildings. However, these embodied impacts are often overlooked in most studies that consider the environmental benefits of smart building energy management systems. The economic feasibility of these systems is also underreported, which is important given the additional hardware and services necessary to fulfil the functional requirements of these systems; studies that reported the cost effectiveness of deploying these systems are often based on simple payback calculations. In addition, from a social perspective, the production of these systems involves many raw materials, the extraction and processing of which may potentially be associated with challenges such as human rights violation and human health concerns. Accordingly, this study reviews existing research on the life cycle sustainability assessment of smart building management systems. The findings highlight the lack of comprehensive studies on the life cycle sustainability assessment of smart building management systems in buildings.

Keywords: Life cycle sustainability assessment; smart building; smart building management system; office building.

1. Introduction

The Energy Performance of Buildings Directive (EPBD) introduced the concept of 'smart buildings' to promote the uptake of smart technologies within countries belonging to the European Union to reduce building energy consumption whilst improving indoor comfort of occupants (Directive-2018/844, 2018). Many definitions for 'smart buildings' have been proposed in the literature, encompassing a wide range

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 86–95.*

of concepts and criteria, such as being near zero-energy, having most of the energy obtained through renewable sources, and being interactive and capable of dynamically responding to varying boundary conditions (e. g. climate, energy price, user requirements, etc.). According to the European Commission, a 'smart building' should possess the ability to sense, interpret, communicate, and actively respond to changing conditions in relation to (i) the operation of technical systems; (ii) the external environment (including energy grids); (iii) and occupant demands, resulting in outcomes such as optimized energy use, automatic diagnosis and maintenance prediction, and improved occupant comfort (European Commission, 2019). A key step to enable these functionalities is the adoption of information and communication technologies (ICTs) (Morvaj *et al.*, 2011). While the rapid development of ICT, together with their increased energy efficiency, offer opportunities for environmental sustainability in other economic sectors, the direct and indirect impacts resulting from their production, use and disposal have also increased (Lange *et al.*, 2020). For example, the Global e-Sustainability Initiative (GeSI) estimated that the global carbon footprint attributed to ICT was 0.9 GtCO2e in 2011 (1.9% of global emissions), which was forecasted to reach 1.27 GtCO2e (2.3% of global emissions) in 2020 (GeSI, 2012). Another study estimated an increase in electricity use and carbon footprint of the ICT sector from 2,037 TWh (11% of global electricity use) and 1.3 Gt CO_2e in 2010 to 8,265 TWH (21% of global electricity use) and 4.8 Gt CO_2e by 2030 respectively (Andrae and Edler, 2015). In terms of waste generated, Tiseo (2021) reported that 53.6 Mt of global e-waste was produced in 2019, which represents an increase by 21% vis-à-vis the year 2015; approximately 83% of this e-waste produced is reported to not have been documented, hence, are likely to have been burnt openly or discarded illegally (Baldé, 2017; Statista, 2020). However, this increase in energy use and emissions is often justified through the enablement effects induced by the proliferation of ICTs (i.e., positive effects in the form of energy savings achieved in other economic sectors) (Lange *et al.*, 2020; Williams *et al.*, 2022).

In the context of buildings, the convergence of ICT such as IoT-based sensor networks, data-driven control approaches and cloud computing resources has enabled smart building functionalities such as adaptability to energy markets, communication with other buildings to form microgrids, and the ability to diagnose faults (De Groote *et al.*, 2017; Al-Dakheel *et al.*, 2020). These functionalities promise improved building performance compared to conventional buildings. An important addition to the amended EPBD (Directive-2018/844, 2018) to accelerate the modernisation of buildings is the requirement for building management systems (BMS) to be installed for space heating and cooling systems. Building management systems, also referred to as building automation systems (BAS), building automation and control systems (BACS) and building energy management systems (BEMS), are identified as one of the key technologies for improving the operational performance of buildings. These systems are responsible for monitoring, controlling, and recording the buildings' equipment such as heating, ventilation, and air conditioning (HVAC), artificial lighting, electric power, as well as fire and security systems. With the proliferation of ICT such as sensor-networks and data-driven controllers, novel smart building management systems have been proposed in the literature, which offer higher energy reductions relative to traditional systems. However, these systems require additional sensing hardware and computing resources to be deployed, hence, increase the natural resource demands and environmental effects associated with the extraction of raw materials, processing and manufacture, installation, maintenance, and replacement of these systems. The increased cost incurred to deploy smart building management systems also remains a barrier for their increased practical adoption. From a social perspective, the extraction of raw materials, manufacturing and end-of-life stages of ICT hardware may potentially be linked to undesirable social challenges (Ekener-Petersen and Finnveden, 2013; Pilgrim, 2017; Venkatesh, 2019).

1.1. Aim and scope

The aim of this study is to review the benefits, shortcomings, and life cycle assessment (LCA) studies considering the environmental, economic, and social dimensions of sustainability, of smart building management systems. There is a need to understand the life cycle sustainability performance of these systems to ensure they provide net benefits over the life of a building.

2. Benefits and shortcomings of smart building management system

2.1 Benefits of smart building management systems

The improved performance of buildings, through deploying smart building management systems to better measure occupancy levels and optimise HVAC and lighting control, has been reported in many studies. For example, Ekwevugbe *et al.* (2012) combined multiple sensors such as temperature, relative humidity, VOC, CO_2, LDR and PIR sensors to overcome the shortcomings of individual sensors and improve occupancy predictions. Sheikhi *et al.* (2016) proposed the use of wearable devices and structural monitoring devices to collect information about occupant location, body temperature and indoor environment to optimise the energy consumption in a residential building. In an exploratory work, Abdallah *et al.* (2016) developed an artificial neural network to estimate the Predicted Mean Vote (PMV) index using wearable devices (e.g., mobile phones and wristbands), which compared favourably with stationary comfort equipment dispensed throughout the test area. Viani *et al.* (2014) employed a distributed wireless sensor network, which consisted of temperature and humidity sensors to evaluate the real-time indoor occupancy with the aid of a data-driven procedure. In an advanced implementation of a smart energy control system, Yun and Won (2012) used temperature and humidity sensors data combined with feedback obtained from occupants through social network platforms for HVAC control. In Ryu and Moon (2016), the authors developed occupancy prediction models using machine learning techniques with information provided by CO_2 sensors, lighting and appliances energy consumption. Dikel *et al.* (2018) proposed a granular LED lighting system combined with a high-resolution sensor network, in which each lighting fixture is supplemented with a motion sensor and photosensor. Their proposed set-up gave better estimates of local occupancy and optimised daylight harvesting at each fixture, contributing to energy savings of up to 79% compared to prevailing energy code provisions for open-plan offices.

2.2. Shortcomings of smart building management systems

Compared to traditional building management systems, smart systems rely on data-driven control methods which typically require many sensors and auxiliary hardware to be deployed for data acquisition, which is leveraged to make better control decisions (Coates *et al.*, 2017; Maddalena *et al.*, 2020; Martin-Garin *et al.*, 2020). In some implementations, the storage and processing of large volumes of information necessitates the incorporation of cloud computing solutions (Ramprasad *et al.*, 2018; Maddalena *et al.*, 2020). Installing additional sensors through wired networks may not be feasible in most scenarios, hence, wireless networks, such as IoT-based networks, are usually suggested as a potential solution. However, there are several shortcomings associated with wireless networks which may hinder sustainable application of smart building management systems.

Deploying large numbers of sensors leads to additional energy to operate smart building management systems. Prasad and Kumar (2012) reported that the energy efficiency can be an issue in the implementation of wireless sensor networks due to the large number of devices required to improve the overall reliability of the network in the event of component faults. Wireless sensor networks are also usually deployed in a dense, overlapping manner with many redundant devices to ensure optimal coverage and connectivity, leading to the generation of redundant data which further contributes to additional energy requirements to operate these systems (Abdul-Qawy and Tadisetty, 2018). In a review of different network technologies applicable to smart buildings, Martin-Garin *et al.* (2020) reported that connection instability and the need for signal repeaters may incur additional operational energy.

Although many studies have demonstrated the potential of these sensor-networks for reducing the building energy needs, these studies are typically experimental in nature and often limited to small spatio-temporal scales (i.e., controlled rooms with short measurement durations). Through a real-world implementation of IoT-based lighting, temperature and occupancy monitoring, Coates *et al.* (2017) experienced several practical challenges associated with this monitoring and control system which led to unsatisfactory occupant monitoring. The authors suggested sensor fusion approaches to improve the reliability and robustness of data acquisition and transmission. However, sensor fusion approaches would further increase the operational energy needs of these systems (Lawal and Rafsanjani, 2022).

The need for auxiliary hardware to enable the functionalities of smart management system further contributes to the increase in energy consumption attributed to their raw material extraction, production, and end-of-life stages; however, little attention has been paid to these life stages of smart building management systems in literature. For example, Lawal and Rafsanjani (2022) identified the electronic wastes resulting from battery usage as a barrier to sustainable deployment of IoT-based building management system.

3. Life cycle environmental, economic, and social effects

3.1. Environmental life cycle assessment studies

Environmental life cycle assessments of ICT products and services studies have focused primarily on consumer products. However, an examination of these studies is helpful in understanding the environmental life cycle effects of smart building management systems given the similarities in components that make up these systems. Through a review of published LCA studies on ICT products and system such as computers, game consoles, and peripherals as well as business products such as networks, Arushanyan *et al.* (2014) concluded that the manufacturing and use phases have the highest impact throughout their life cycles. The use phase was found to be predominant in terms of energy consumption and global warming potential (GWP) for some products, while the manufacturing phase was the major contributor in lighter, energy efficient products. At the component level, Arushanyan *et al.* (2014) also found that the manufacturing of integrated circuits (ICs), printed circuit boards and LCD screens to be the most energy intensive processes. Boyd *et al.* (2009) performed life cycle analyses of complementary metal oxide semiconductor (CMOS) chips over seven technology generations to compare the energy demand and GWP impact trends over time. The authors concluded that, although the life cycle energy use and greenhouse gas (GHG) emissions decreased over different generations when normalized against computational power, their life cycle energy use and GHG emissions increased per-wafer and per-die due to the escalation of use-phase chip power as well as the lengthening of the manufacturing process flow and infrastructure, commensurate with the increased product complexity. In a complementary study, Boyd *et al.* (2010) performed a life cycle assessment of computer logic to include additional environmental indicators such as acidification, eutrophication, ground-level ozone (smog) formation, potential human cancer and non-cancer health effects, ecotoxicity and water use. The authors reported that the impacts per device area related to manufacturing and use phases have increased over different technology generations. Eugster *et al.* (2007) studied the life cycle environmental impacts of a desktop PC system consisting of a computer, CRT monitor, keyboard, mouse, speaker, wires, system components and disc driver, and concluded that the IC production is the most intensive process, owing to the use of heat energy, disposal of wafer production wastes, as well as gold mining and processing. In addition to ICT devices, some studies have also investigated the life cycle impacts of services and infrastructures necessary for the functionality of ICT devices such as datacentres (Honée *et al.*, 2012) and networks (Malmodin *et al.*, 2012). In general, whilst the use phase energy needs and GHG emissions were higher than other stages of the system life cycle, the manufacturing stage energy needs and GHG emissions of these infrastructures are relatively significant.

Only a few life cycle assessment studies were found on smart building management systems in literature. Manz *et al.* (2021) studied the environmental impacts of an intelligent smoke detector and included the production, use and disposal phase of a smoke detector and a smart home controller as well as the use phase of smartphones, routers, and the internet network. The authors reported that the electricity use of the smoke detector and controller was the main cause of the harmful environmental impacts considered in their study. Bates and Hazas (2013) quantified the manufacturing and transportation energy and GHG emissions attributed to a range of sensing, automation, and auxiliary devices (e.g., sensors, meters, desktop computers) and showed that an additional embodied energy of 19.8-250% and GHG emissions of 9.8-43.8% are produced relative to existing ICT devices commonly found at home. Through an interdisciplinary user-driven approach, Pohl *et al.* (2021) examined the environmental saving potential of a notional smart home system with smart heating; the results indicated that, while the primary energy demand and global warming potential attributed to producing this system is lower than the benefits of deploying this system, the same cannot be said for abiotic depletion and ecotoxicity, which primarily originate from the production of these systems. Louis *et al.* (2015) quantified the life cycle energy loads of a generic smart home automation system consisting of a smart meter, field devices (temperature sensor and smart plug), management devices (in-home display and hard disk), communication devices (internet access equipment and router) and a computing device (desktop). Based on a simulated case study of a dwelling equipped with 25 household appliances, the authors reported that the use phase consumed the largest share of the life cycle system energy needs. Smart plugs accounted for the largest life cycle energy needs, which was not compensated for by the operational energy savings of the dwelling; however, this negative energy payback can be attributed to the higher number of devices (21 smart plugs) and short period of assessment (5 years).

3.2. Life cycle costing studies

The implementation of smart building management systems must be economically justified, meaning the financial benefits of deploying these systems should be outweigh the costs of purchasing, designing, and operating these systems. As alluded to in Section 2.2, deploying smart building management systems requires additional sensing and auxiliary network hardware, which incurs higher initial investment compared with traditional counterparts. The additional computing and data storage resources for operating smart building management systems also lead to higher operating costs. Hence, it is essential for smart building management systems to be deployed and operated in such a manner that the building operational energy-related cost savings are sufficiently higher than the costs of deploying smart building management systems, relative to traditional systems.

An important analysis technique to inform whether to invest in smart building management systems over traditional systems is life cycle costing (LCC). LCC is defined as a 'technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs' (ISO, 2017). Through LCC, the trade-offs between competing options as well as the time taken to recover the initial and recurring costs through economic benefits over the period of analysis can be determined.

While there are many life cycle costing studies on structural building elements and energy systems, only a few studies relevant to building management systems have been reported. Araszkiewicz *et al.* (2020) performed a life cycle costing study to determine the cost impacts of implementing building management systems for lighting control in a public football stadium and found that automatic control of lighting incurred the least cost over a period of 25 years compared to manual control. Hagström *et al.* (2000) proposed an LCC approach that accounts for indoor environment quality and worker productivity and showed that, although individual control incurred higher overall life cycle costs compared to zone-level and central control systems, consideration of productivity loss, as a function of deviation from ideal operating temperature, meant the former is more cost-effective.

3.3. Social life cycle assessment studies

In comparison with environmental and economic life cycle studies, only a few social life cycle assessment (S-LCA) studies on ICT products have been published. Ekener-Petersen and Finnveden (2013) identified the social hotspots (i.e., location and/or activity in the life cycle where a social issue and/or social risk is likely to occur) of a generic laptop in Sweden and found that workers and local community were most at risk of negative social impacts. Social impact subcategories that were identified to be important were social security, working hours, and freedom of association access to immaterial resources, safe and healthy living conditions, community engagement, delocalisation and migration, cultural heritage, and respect for indigenous rights. In Subramanian and Yung (2018), the raw material extraction and production of basic materials were identified to have higher social risks compared to other life stages of an integrated desktop computer; the workers, local community and society stakeholder categories were reported to be at higher risk of negative social influences. Ciroth and Franze (2011) identified the social hotspots in the cradle-to-grave life cycle stages of a laptop and drew similar conclusions as Subramanian and Yung (2018); the workers, local community and society stakeholder categories were particularly vulnerable to negative social consequences caused by certain economic activities along the supply chain such as mining, informal recycling and manufacturing. Wang *et al.* (2016) proposed a framework for social life cycle impact assessment method for the Taiwanese electronics sector, which was applied in Wang *et al.* (2017) to assess how the operations of three integrated circuit (IC) factories affected the labour conditions of their factory workers. There were no S-LCA studies on BMS identified.

4. Discussion

4.1. Necessity for life cycle sustainability assessments

Based on the studies reviewed, it is evident that there is a general lack of studies which comprehensively assess all three dimensions of sustainability of ICT products and systems, much less for smart building management systems. In practical applications, the initial costs remain to be the deciding factor in whether or not to invest in smart building systems (Lilis *et al.*, 2017). Often the lack of clear added value provided by these systems renders building automation specialists sceptical about their true potential (Lilis *et al.*, 2017). The necessity for considering the life cycle environmental, economic, and social impacts of ICT products is exemplified by the stages along the life cycle where severe negative impacts occur. For example, while the use phase dominates the environmental impacts in ICT products, most of the adverse social consequences are found to be concentrated upstream of the product life cycle. Rebitzer and Hunkeler (2003) argued that 'life cycle costing, without additional assessments, cannot serve as a sole indicator for good (sustainable) life cycle management practice, unless there is a validated correlation of low life cycle costs to low environmental and social impacts for specific products.' Through an integrated life cycle sustainability assessment, the benefits and negative consequences attributable to ICT products such as smart BMS can be evaluated to help inform better decision-making processes.

4.2. Methodological considerations for environmental life cycle assessment

The environmental LCA studies of smart BMS found use process-based life cycle inventory (LCI) to model the devices and systems analysed. A major limitation of process-based LCI is the specification of precise system boundaries, leading to systematic truncation, since collecting data for specific processes can be challenging and time consuming (Majeau-Bettez *et al.*, 2011). For example, Manz *et al.* (2021) excluded several elements such as the alarm siren, wire connection port, ZigBee communication module and some microchips due to the unavailability of the information in the database used. In Pohl *et al.* (2021), the authors used a proxy device representing the smart home system components due to the difficulty modelling electronic devices as well as impossibility of assigning an average device to a specific supplier. Additionally, the assessment of the smart home system was performed based on scaled inventory data for a generic printed circuit board of a computer. Conversely, while an alternative LCI approach, an environmentally-extended input-output (EEIO) analysis, where environmental coefficients are mapped onto the monetary flows between various sectors of economy to provide estimates of environmental effects of these sectors, is comprehensive, Yao *et al.* (2010) argued that this approach may not be suitable for the ICT sector. The authors attributed this unsuitability of the EEIO analysis to rapid changes in manufacturing efficiencies, the pricing structure in the ICT sector and the non-linear relationship between product price and resource consumption. Hybrid LCI, which combines both process and input-output data and hence their individual strengths, may provide more comprehensive estimates of the environmental life cycle impacts of smart BMS (Yao *et al.*, 2010; Crawford *et al.*, 2020).

Another gap in the LCA studies on smart building management systems was the exclusion of the energy intensity of the use of the internet network. For example, only Manz et al. (2021) and Pohl et al. (2021) considered the energy intensity of the data transmission through home and access network, core and edge network, and datacentre. As alluded to by Arushanyan et al. (2014) and Pirson and Bol (2021), the use phase of ICT devices accounts for the largest share of life cycle environmental effects, hence, it is essential to include the energy use intensity of the internet network in the calculation of the life cycle environmental impacts of these devices. However, the use phase may have been shown to have the largest share of the life cycle effects because the embodied effects are underestimated due to the use of process-based LCI.

5. Conclusion

The deployment of smart building management systems to reduce building operational energy and GHG emissions through the improved occupancy detection as well as HVAC and lighting control has received strong academic support. However, these systems require additional ICT hardware and computing resources for practical real-world applications, which increases the environmental burdens related to the raw material extraction, processing and manufacture, installation, maintenance, and replacements as well as the supporting supply chain activities. This review finds a lack of comprehensive assessments that quantify both the benefits and negative environmental impacts of deploying these systems, which are needed to provide a complete picture of the actual benefits of these systems. In comparison with environmental life cycle assessment, only limited studies were found on life cycle costing and social life cycle assessment of ICT products, despite the development of assessment frameworks and methodologies. Hence, further research on smart building management systems, considering the environmental, economic, and social dimensions of sustainability, is needed to better evaluate the benefits of using these systems.

References

Abdallah, M., Vu, T., Clevenger, C. and Nguyen, A. (2016) Sensing Occupant Comfort Using Wearable Technologies, *Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan*, edited by J. L. Perdomo-Rivera, A. Gonzáles-Quevedo, C. L. del Puerto, F. Maldonado-Fortunet and O. I. Molina-Bas, San Juan, Puerto Rico.

Abdul-Qawy, A. S. H. and Tadisetty, S. (2018) Greening Trends in Energy-Efficiency of IoT-based Heterogenous Wireless Nodes, *IEEE International Conference on Electrical, Electronics, Computers, Communication, Mechanical and Computing*, Vellore.

Al-Dakheel, J., Del, C. C. P., Aste, N. and Leonforte, F. (2020) Smart buildings features and key performance indicators: A review, *Sustainable Cities and Society*, 61, 102328.

Andrae, A. S. G. and Edler, T. (2015) On Global Electricity Usage of Communication Technology: Trends to 2030, *Challenges*, 6(1), 117-157.

Araszkiewicz, K., Jakubowska, P. and Dixit, S. (2020) The Contribution of BMS Application Towards the Sustainability and Life Cycle Costs Optimization of Buildings: A Case of Public Utility Facilities in Poland, *Creative Construction e-Conference 2020*, Online, 143 - 149.

Arushanyan, Y., Eketer-Petersen, E. and Finnveden, G. (2014) Lessons learned – Review of LCAs for ICT products and services, *Computers in Industry*, 65(2), 211-234.

Baldé, C. P., Forti V., Gray, V., Kuehr, R., Stegmann,P. (2017) *The Global E-waste Monitor 2017*, United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna.

Bates, O. and Hazas, M. (2013) Exploring the Hidden Impacts of HomeSys: Energy and Emissions of Home Sensing and Automation, *UbiComp '13: The 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, edited by F. Mattern, S. Santini, J. F. Canny, M. Langheinrich and J. Rekimoto, Zurich, Switzerland, 809-814.

Boyd, S. B., Horvath, A. and Dornfeld, D. (2009) Life-cycle energy demand and global warming potential of computational logic, *Environmental Science and Technology*, 43(19), 7303-7309.

Boyd, S. B., Horvath, A. and Dornfeld, D. (2010) Life-cycle assessment of computational logic produced from 1995 through 2010, *Environmental Research Letters*, 5(1), 014011.

Ciroth, A. and Franze, J. (2011) *LCA of Eco-labelled notebook-ELCA and SLCA - Consideration of Social and Environmental Impacts Along the Entire Life Cycle*, GreenDeltaTC GmbH, Berlin.

Coates, A., Hammoudeh, M. and Holmes, K. G. (2017) Internet of Things for Buildings Monitoring: Experiences and Challenges, *International Conference on Future Networks and Distributed Systems (ICFNDS 2017)*, edited by M. Hammoudeh, R. Newman, Y. Sam and A. Abuarqoub, Cambridge, United Kingdom.

Crawford, R. H., Stephan, A. and Prideaux, F. (2020) EPiC: Introducing a database of hybrid environmental flow coefficients for construction materials, *BEYOND 2020 – World Sustainable Built Environment conference*, edited by H. Wallbaum, A. Hollberg, L. Thuvander, P. Femenias, I. Kurkowska, K. Mjörnell and C. Fudge, Online, 042052.

De Groote, M., Volt, J. and Bean, F. (2017) *Is Europe Ready For The Smart Buildings Revolution*, Buildings Performance Institute Europe (BPIE).

Dikel, E. E., Newsham, G. R., Xue, H. and Valdes, J. J. (2018) Potential energy savings from high-resolution sensor controls for LED lighting, *Energy and Buildings*, 158, 43 - 53.

Directive-2018/844 (2018) *Amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*,Official Journal of the European Union, 1-17.

Ekener-Petersen, E. and Finnveden, G. (2013) Potential hotspots identified by social LCA—part 1: a case study of a laptop computer, *The International Journal of Life Cycle Assessment*, 18, 127–143.

Ekwevugbe, T., Brown, N. and Fan, D. (2012) A design model for building occupancy detection using sensor fusion, *2012 6th IEEE International Conference on Digital Ecosystems and Technologies (DEST)*, edited by E. Damiani and A. P. Karduck, Campione d'Italia.

Eugster, M., Hischier, R. and Duan, H. (2007) *Key Environmental Impacts of the Chinese EEE-Industry*, Empa/Tsinghua University, St. Gallen/Beijing.

European Commission (2019) *Smart technologies in buildings*,European Performance of Building Directive.

GeSI (2012) *GeSI SMARTer 2020: The Role of ICT in Driving a Sustainable Future*.

Hagström, K., Kosonen, R., Heinonen, J. and Laine, T. (2000) Economic value of high quality indoor air climate, *Healthy Buildings Conference 2000*, edited by O. Seppänen and J. Säteri, Espoo, Finland, 671-676.

Honée, C., Hedin, D., St-Laurent, J. and Fröling, M. (2012) Environmental performance of data centres - a case study of the Swedish National Insurance Administration, *2012 Electronics Goes Green 2012+*, edited by K.-D. Lang, N. F. Nissen, A. Middendorf and P. Chancerel, Berlin, Germany, 1-6.

ISO (2017) *ISO 15686-5 International Standard, Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing*, International Organization for Standardization, Geneva.

Lange, S., Pohl, J. and Santarius, T. (2020) Digitization and energy consumption. Does ICT reduce energy demand?, *Ecological Economics*, 176, 106760.

Lawal, K. and Rafsanjani, H. N. (2022) Trends, benefits, risks, and challenges of IoT implementation in residential and commercial buildings, *Energy and Built Environment*, 3(3), 251-266.

Lilis, G., Conus, G., Asadi, N. and Kayal, M. (2017) Towards the next generation of intelligent building: An assessment study of current automation and future IoT based systems with a proposal for transitional design, *Sustainable Cities and Society*, 28, 473-481.

Louis, J.-N., Calo, A., Leiviska, K. and Pongracz, E. (2015) Environmental Impacts and Benefits of Smart Home Automation: Life Cycle Assessment of Home Energy Management System, *IFAC-PapersOnLine*, 48(1), 880 - 885.

Maddalena, E. T., Lian, Y. and Jones, C. N. (2020) Data-driven methods for building control — A review and promising future directions, *Control Engineering Practice*, 95, 104211.

Majeau-Bettez, G., Strømman, A. H. and Hertwich, E. G. (2011) Evaluation of Process- and Input–Output-based Life Cycle Inventory Data with Regard to Truncation and Aggregation Issues, *Environmental Science & Technology*, 45, 10170-10177.

Malmodin, J., Lundén, D., Nilsson, M. and Andersson, G. (2012) LCA of data transmission and IP core networks, *2012 Electronics Goes Green 2012+*, edited by K.-D. Lang, N. F. Nissen, A. Middendorf and P. Chancerel, IEEE, 1-6.

Manz, O., Baumgartner, C. and Meyer, S. (2021) Life cycle assessment of an Internet of Things product: Environmental impact of an intelligent smoke detector, *11th International Conference on the Internet of Things (IoT '21)*, edited by S. Mayer and B. Weber, St. Gallen, Switzerland.

Martin-Garin, A., Millan-Garcia, J. A., Bairi, A., Gabilondo, M. and Rodriguez, A. (2020) IoT and cloud computing for building energy efficiency, in E. R. Fernando Pacheco-Torgal, Claes-Goran Granqvist, Volodymyr Ivanov, Arturas Kaklauskas, Stephen Makonin (ed.), *The Smart Eco-Efficient Built Environment*, Woodhead Publishing, 235 - 265.

Morvaj, B., Lugaric, L. and Krajcar, S. (2011) Demonstrating smart buildings and smart grid features in a smart energy city, *2011 3rd International Youth Conference on Energetics (IYCE)*, Leiria, Portugal, 1-8.

Pilgrim, H. (2017) *The Dark Side of Digitalization: Will Industry 4.0 Create New Raw Materials Demands?*, PowerShift e. V, Berlin.

Pirson, T. and Bol, D. (2021) Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach, *Journal of Cleaner Production*, 322, 128966.

Pohl, J., Frick, V., Hoefner, A., Santarius, T. and Finkbeiner, M. (2021) Environmental saving potentials of a smart home system from a life cycle perspective: How green is the smart home?, *Journal of Cleaner Production*, 312, 127845.

Prasad, S. S. and Kumar, C. (2012) A Green and Reliable Internet of Things, *Communications and Networks*, 5, 44-48.

Ramprasad, B., McArthur, J., Fokaefs, M., Barna, C., Damm, M. and Litoiu, M. (2018) Leveraging existing sensor networks as IoT devices for smart buildings, *2018 IEEE 4th World Forum on Internet of Things (WF-IoT)*, Singapore.

Rebitzer, G. and Hunkeler, D. (2003) Life cycle costing in LCM: ambitions, opportunities, and limitations, *International Journal of Life Cycle Assessment*, 8, 253–256.

Ryu, S. H. and Moon, H. J. (2016) Development of an occupancy prediction model using indoor environmental data based on machine learning techniques, *Building and Environment*, 107, 1-9.

Sheikhi, E., Cimellaro, G. P. and Mahin, S. (2016) Adaptive Energy Consumption Optimization Using IoT-based Wireless Sensor Networks and Structural Health Monitoring Systems, *8th European Workshop On Structural Health Monitoring*, Bilbao, Spain.

Statista (2020) *Electronic waste generated worldwide from 2010 to 2019*,Statista.

Subramanian, K. and Yung, W. K. C. (2018) Modeling Social Life Cycle Assessment framework for an electronic screen product - A case study of an integrated desktop computer, *Journal of Cleaner Production*, 197, 417-434.

Tiseo, I. (2021) *Global E-waste—statistics and facts*.

Venkatesh, G. (2019) Critique of selected peer-reviewed publications on applied social life cycle assessment: focus on cases from developing countries, *Clean Technologies and Environmental Policy*, 21, 413–430.

Viani, F., Polo, A., Oliveri, G., Rocca, P. and Massa, A. (2014) *Crowd detection and occupancy estimation through indirect environmental measurements*,The 8th European Conference on Antennas and Propagation (EuCAP 2014), The Hague, Netherlands, 2127-2130.

Wang, S.-W., Hsu, C.-W. and Hu, A. H. (2016) An analytical framework for social life cycle impact assessment - part 1: methodology, *International Journal of Life Cycle Assessment*, 21(10), 1514–1528.

Wang, S.-W., Hsu, C.-W. and Hu, A. H. (2017) An analytical framework for social life cycle impact assessment - part 2: case study of labor impacts in an IC packaging company, *International Journal of Life Cycle Assessment*, 22, 784–797.

Williams, L., Sovacool, B. K. and Foxon, T. J. (2022) The energy use implications of 5G: Reviewing whole network operational energy, embodied energy, and indirect effects, *Renewable and Sustainable Energy Reviews*, 157.

Yao, M. A., Higgs, T. G., Cullen, M. J., Stewart, S. and Brady, T. A. (2010) Comparative Assessment of Life Cycle Assessment Methods Used for Personal Computers, *Environmental Science & Technology*, 7335-7346.

Yun, J. and Won, K.-H. (2012) Building Environment Analysis Based on Temperature and Humidity for Smart Energy Systems, *Sensors*, 12(10), 13458-13470.

A study on roaming behaviour of crowd in public space with the analysis in computer vision and Agent-based simulation

Yuansheng Wu[1], Zipei Zhang[2], Shimada Daii[3], Changlin Liu[4], Shaoyu Niu[5], Lipeng Xia[6], Liangfa Xiao[7] and Yasushi Ikeda[8]

[1, 2, 3, 4, 5, 6, 7] *Keio University SFC, Tokyo, Japan*
wuys@keio.jpl[1]
[8] *The University of Tokyo, Tokyo, Japan*

Abstract: People-flow in densely populated modern cities is a non-negligible factor to consider during urban space design. However, in the early phase of design, architects mainly deal with the static states of the human body. Other factors, such as duration and environment, should be considered when analysing crowd behaviour. The common methods for design presentation are drawings, sketches, models, etc. Dynamic visualisation of pedestrian behaviour might help architects have a better understanding of the design performance. Agent-based simulation has been explored by many researchers. Most of their pedestrian models have planned routes with origin and destination. Thus, we would like to propose a pedestrian model embedded with roaming behaviour that reflects the decision-changing process when exploring unfamiliar places. Previously, computer vision and agent-based simulation were different research streams. This paper discusses the initiative to study crowd behaviour using computer vision and agent-based simulation and examined the accuracy and validity of agent-based simulation by comparing the results from computer vision. Overall, this research aims to improve the accuracy of the agent-based simulation by utilizing the data extracted from surveillance video.

Keywords: Agent-based Simulation; Computer Vision; Crowd Behaviour; Data Visualisation.

1. Introduction

The purpose of architectural design is to create comfort for people and solve issues in a common shared space for communities. People-flow in densely populated modern cities is a non-negligible factor to consider during space design. However, in urban space design, architects mainly deal with the static states of the human body. The common methods for design presentation are drawings, sketches, models, etc. Spatial performance is yet to be well considered or presented during the design process. (Vroman and Lagrange, 2017) Architecture, which shapes the built environment, should understand and deal with people-flow. This research discusses the initiative to study crowd behaviour using computer vision and

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 96–105.*

agent-based simulation and to examine the accuracy and validity of agent-based simulation by comparing the results from computer vision.

An agent-based model is utilised to simulate people-flow through multiple design scenarios. Specifically, spatial performance can be evaluated during the early design phase, allowing designers to predict and visualise the results. Previously, many researchers and designers widely used and conducted multi-agent simulations. The simulation parameters were mostly decided by intuition, figures listed in literature reviews, and laboratory experiments. (Davidich and Köster, 2013) The impact on the crowds might be distinct in variable environments and scenarios, resulting in the uniqueness of the agent-based simulations. Furthermore, the spontaneous movements of people are influenced by their surroundings, such as signs and traffic signals. Dynamic pedestrian behaviour influenced by social interaction is yet to be deeply explored by previous studies.

In this research, we established two agent-based simulations with the software PedSim Pro and our proposed pedestrian behaviour model. For comparison and analysis, we extracted the data output from the selected surveillance video with Yolov5 and Deepsort algorithm. In the pedestrian simulations, the environment was set up based on the actual scene in the surveillance video. The location data of agents was recorded over a constant period, and heatmaps were drawn to reflect the density and distribution of agents during the time frame. However, it was difficult to consider the site influence in the simulations. By using computer vision, we analysed the surveillance video to extract the empirical data, which would make it comparable to the pedestrian simulations by data visualisation.

Overall, this paper focuses on an ongoing project exploring roaming behaviour model which aims to get more precise predictions based on the data learned from the analysis. Besides, we will apply the model to urban space design by testing the simulation using the generative design method at a later stage. Specifically, this paper demonstrates the efforts to help improve the time, cost, speed, efficiency, and accuracy of multi-agent simulations.

2. Literature Reviews

The behaviour of pedestrians in a specific environment is complex and changeable. The uncertain factors in the environment may affect the pedestrians' route choice, walking speed, etc. Although it is challenging to simulate behaviour due to the randomness of pedestrians, many researchers have developed different models to simulate pedestrian behaviour under various criteria and environments. To solve this problem, the Markov-Chain model is a common principle for explaining the uncertainty of behaviour analysis. Still, it does not consider the impact of previous results on the next prediction. (Henry *et al*., n.d.) In addition to the Markov-Chain model, Karoji *et al*. (2019) applied recurrent neural network (RNN) as a fundamental theory to develop their algorithm and simulated pedestrian behaviour in the Shinkiba station, Tokyo, Japan. They developed an algorithm based on the visual context of the pedestrian. By identifying the recognition degree of objects by agents, the influence of external factors on pedestrian behaviour in route choice from a starting point to a destination point could be evaluated. From the perspective of architectural design, an accurate pedestrian behaviour simulation can be an ideal tool for assessing the performance of the building under specific situations.

An agent-based simulation can be used for simulating individuals' or groups' decision-making, behaviour, and interaction in a particular environment. Previously, many scholars have applied pedestrian behaviour models to evacuation simulation. Helbing *et al*. (2000) created a computer model to simulate the evacuation performance of crowds based on social psychology and the relationship between panic behaviour and the structure of buildings. More specifically, they discussed the effect of placing building structures (columns) in front of the escape exits on evacuation performance. They created two scenarios: 1. There were no impediments in front of the exit 2. A column was placed in front of the exit. Unexpectedly, they pointed out that the probability of injuries is lower when the column is placed, which is counterintuitive. Later, Camillen *et al*. (2009) used Netlogo, an agent-based simulation developed by Java, and selected the Castro Ursino Museum (a castle in Catania, Italy) as the research object to simulate the visits to the museum rooms under normal conditions and analyse the pedestrian behaviour regarding the use of exits under emergency conditions. In addition to evacuation analysis, we expect to assess the spatial performance in terms of pedestrian behaviours after completing the project in the fields of architectural design and urban design.

The settings in an agent-based simulation are essential. The parameters and scenarios set by users might lead to inaccurate results. Some other researchers adopt the data from literature reviews and laboratory experiments. However, the research has a specific context, which might not suit the simulation perfectly. Besides, the empirical data collection process through experiments and on-site visits can be time-consuming. Thus, we are committed to finding a new method to evaluate the accuracy of the results by comparing the actual pedestrian data with the agent-based simulation. To obtain pedestrian data, Wu (2021) applied a deep learning method to visualise actual pedestrian trajectories. He first used an unmanned aerial vehicle (UAV) to record videos of three squares at Tianjin University, China, and then he used the YOLO, a deep learning object detection algorithm, to identify moving people in the video, from which pedestrian coordinate data was derived. The simulation of the actual pedestrian trajectory was presented by establishing heat maps and distribution maps. However, UAV usage is limited to wide-open outdoor spaces. Our research initiative is to avoid using UAVs but rather publicly available surveillance videos of public spaces because of their wide availability, low cost, and avoidance of privacy infringement.

Pan (2021) used PedSim Pro as an analysis tool to redesign the office plan according to the restrictions raised by the outbreak of COVID-19, such as social distancing. They simulated pedestrian behaviour in the office under three different scenarios. As a result, it could easily visualise the pedestrian trajectories and flows in different areas. However, in Pan's study, most of the building users are office workers who are familiar with the space and have a firm intention of reaching their destinations. Therefore, the behaviour model tends to be destination-oriented, which differs from the behaviour of visitors going into an unfamiliar place and exploring undecided destinations.

3. Methodology

The below figure shows the research methodology (Figure 1). Specifically, surveillance video was analysed using a deep learning-based algorithm. Parallelly, we set up the 3D model of the actual scene in the video by using Rhinoceros. The Grasshopper-based plug-in PedSim Pro and our proposed navigation model were utilised as pedestrian simulation tools. As for data output, we created heatmaps and boxplots for the data visualisation. A comparison was conducted to examine the difference between pedestrian simulations and data extracted from the surveillance video.

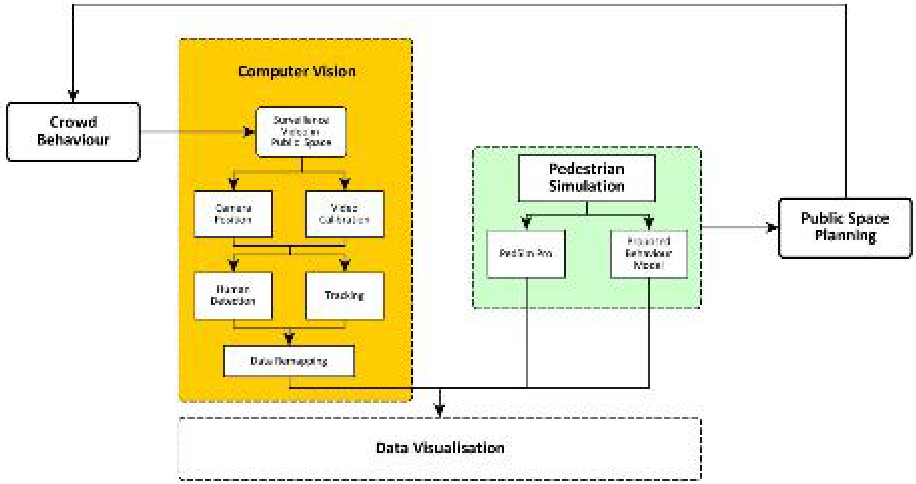


Figure 16: Research Methodology

3.1. Surveillance Video Selection

The surveillance video needs to satisfy the following criteria:

- Public space or large-scale architecture.
- Decent people-flow appears.
- Continuous live camera streaming.
- The resolution is high enough for object detection.
- It contains architectural elements.
- It does not constitute an infringement of privacy or copyright.

Figure 17: Surveillance Video captured at Fukui, Japan.

Taking these factors into consideration, Fukui Happy Terrace (Figure 2), a commercial facility located in Fukui City, Japan, was selected for our study. Specifically, the major obstacles identified in the scene are columns, food trucks, benches, and tables. Together with the shops, they become the significant factors that affect route choice in this plaza.

3.2. Video Calibration

The public camera parameters remain unknown to us. Therefore, calibrations are necessary for us to obtain accurate results from detection. We calibrated the video by considering two aspects: camera lens distortion and the position of the camera in the 3D model. The figure below (Figure 3) shows the distortion caused by the camera lens. It can be seen that the column in the left image is curved.

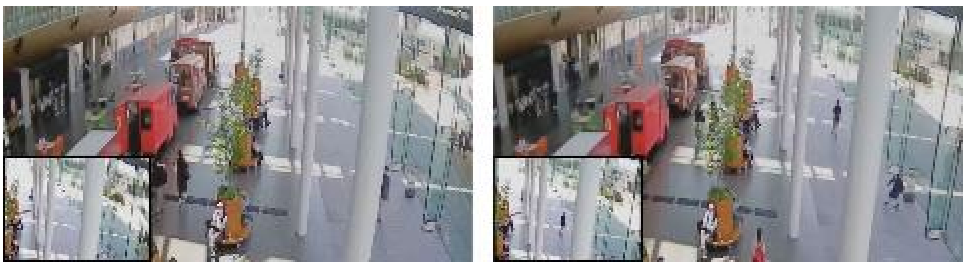


Figure 18: The distortion caused by surveillance camera.

A detailed floor plan was found on the official website of this facility, which has become the most reliable source for 3D modelling set up in Rhinoceros (Government, 2016). Besides, a simple version of the elevation drawing has been found on the building developer's official page (Facility, 2016). However, the exact positions of the food trucks, benches, and tables (Figure 2) are not included in the floor plan. First, according to the height provided by the elevation drawings, the rough location of the surveillance camera was found in the model. We adjusted the camera position in the model until the columns and roofs of the stores overlapped with the components in the actual scene. (Figure 4)

Figure 19: Model camera position calibration.

3.3. Crowd Detection

In our research, obtaining crowd behaviour data mainly relies on computer vision. Currently, we mainly focus on pedestrians' trajectories, while the actions of pedestrians will be combined in the future. For object detection, we applied YOLOv5 with Deepsort, an open-source algorithm, to detect and track pedestrians in the surveillance video. YOLOv5 is a library of object detection architectures with models pre-trained on the COCO dataset. DeepSORT is a deep-learning-based algorithm used for object tracking, assigning IDs to each object. By combining these algorithms, the movements could be tracked and recorded continuously.

Crowd movement data has been collected using YOLOv5 and DeepSORT algorithm. (Mikel, 2022) For a better detection result, we used CrowdHuman, a dataset focusing on crowd detection. Shao *et al*. (2018) created the weighted model trained based on 15,000 images with approximately 340,000 people, and the average number of people per image is around 23. Therefore, the dataset is suitable for the selected surveillance video.

Figure 20: Object detection and tracking by Yolov5 and DeepSORT.

The algorithms track each pedestrian's position and draw bounding boxes for each video frame. The frame IDs, person IDs, and coordinates are generated and exported to a text file. The data is then transferred to Excel for data sorting based on person IDs.

3.4. Remap the Location Data to the 3D Model

We remapped the location data from the images to the model through Rhino and Grasshopper to compare the results from human detection and simulations. Transforming the data into grasshopper, it was projected from the image to the model. The data has been filtered to reduce the errors resulting from human detection and tracking. We removed the coordinates data whenever the distance between two adjacent points is greater than 1 meter since the location is recorded every 0.5 seconds.

Figure 21: The sequence of camera calibration and data conversion.

3.5. Pedestrian Simulations

In the simulation of PedSim Pro, the agents move from the start gate to the destination gate along the shortest path. In the travelling process, the individual avoids other pedestrians and obstacles. Besides, the person profile is set to simulate pedestrians based on the actual travel speed. The origin and destination are fixed in the basic principle of PedSim Pro. If the interest points are added, the pedestrian trajectories will change due to the attraction and visibility of them. However, PedSim Pro does not consider route-changing behaviour. Pedestrians do not necessarily move towards the interest points or fixed destinations. Some pedestrians may wander aimlessly, and some pedestrians may always sit in their seats. This roaming behaviour is missing in the PedSim Pro. In our research, we aim to develop a pedestrian model that considers the route-changing behaviour when receiving different visual information from the surroundings.

Our proposed behaviour model aims to simulate the roaming behaviour of pedestrians. We developed an autonomous exploration pedestrian model driven by visual recordings of the points of interest. Agents can achieve events such as collision detection, information collection, avoiding others, and roaming exploration in an unfamiliar environment. In our model, agents are given starting points in advance, and multiple points of interest are set in the environmental configuration. When the simulation starts, the agent gains visual information from a random visible interesting point and walks to it. During the movement, the agent will collect information about the other points of interest based on vision, and the environmental information is saved in an activity list. To achieve this, multiple lines are connected between different interesting points and the agent. The line obstructed by obstacles will be removed. Based on the visual range of the agent set by users, the effective information can be sorted and saved. After a certain time, the agent will randomly select a location from the activity list, replace the previous interesting point, and move to it. After reaching the destination, the agent will stay for a while according to the settings and then continue to explore the environment.

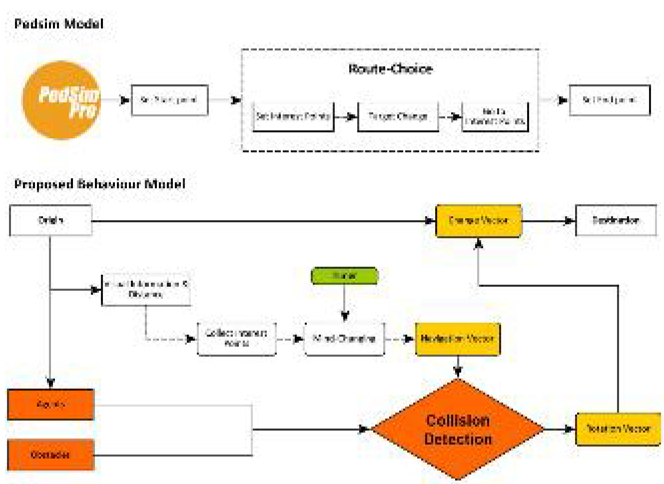


Figure 22: Diagrams of PedSim Pro (Top) and the proposed behaviour model (Bottom).

4. Result and Discussion

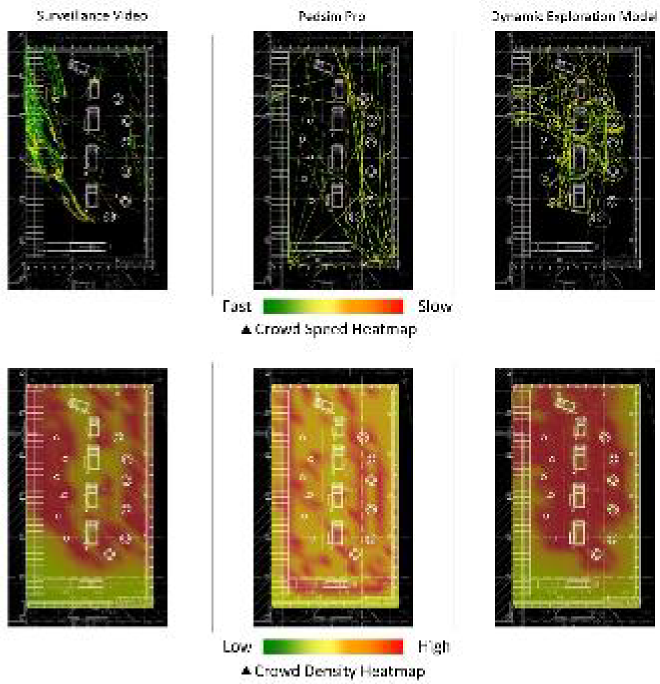


Figure 23: Result of data visualisation.

4.1. Discussion

Observing the surveillance video of our application, we can see that real-world pedestrians are passing through the site from unspecified places and the pedestrian trajectory shows a clear flow direction. In the PedSim Pro simulation, agents move from one or multiple points to the destination points. During the trip, agents have a certain probability of moving to interesting points. These origins, interesting points, and destination points are defined by users. The moving trajectories are composed of these points with obvious directionality. Our proposed behaviour model pre-sets one or multiple starting points and multiple points of interest. Though the agents are assigned destination points initially, as time passes, agents will change their original destinations with a certain probability set by the users during the travel due to the obtained information, resulting in an exploratory pedestrian simulation. The trajectories are woven into a grid through the starting point and a series of interesting points, which have obvious divergence.

From the comparison between the figures, in the real world, many factors may affect human behaviour. The PedSim Pro model focuses on the visible range of human sight in a plan view. However, our model discusses the visible range of human sight in three-dimensional space, the memory of information obtained while traveling, and the weights that have different preferences for points of interest. Crowd avoidance in reality is not as simple as volume collision detection in PC games. Through the surveillance video, it can be found that very few pedestrians have the behaviour of crossing the gap between the dining cars, while the PedSim model and our model show that a certain number of agents pass through the gap between the dining cars. In order to maintain adequate social distance and privacy, the actual avoidance behaviour may begin shortly after the obstacle or the opposite person comes into view. Some avoidance trajectories resemble a smooth tangent or sine function curve. Therefore, it might be possible to fit the results from the video by changing the parameters of obstacle avoidance in the next stage. By digitizing this behaviour pattern, it is possible to provide an accurate pedestrian behaviour model for architectural design and urban planning.

Crowd distribution, density, and types are different at different times of the day at the same location, such as peak hours and normal hours. The observed video clips concentrate on a specific period of the day. Therefore, the number and types of pedestrians passing through the site are relatively limited, which has certain limitations.

Overall, in the simulation performed by PedSim Pro, the necessity to set the origin and destination points leads to the agent's knowing the site information before departure. Therefore, this model is suitable for application to small-scale spaces such as shopping malls. In contrast to PedSim Pro, our proposed behaviour model is more inclined to explore unknown venues, such as applications to outdoor spaces such as exhibitions, amusement parks, and large commercial facilities. Recently, group phenomena have been increasingly studied in relation to the motions and dynamics of pedestrians. Sieben *et al*. (2017) state that crowds do not behave in an irrational and anti-social way. On the contrary, large groups of people usually move in quite an orderly and cooperative manner. The specific manifestation is that the individual's senses, cognition, judgment, and behavior appear in line with the behavior of most people. At the site we observed, the trajectory distribution of the crowd has obvious rules to follow, which may be due to the mutual reference of people on the site. There is an invisible force in the group that shapes the direction and distribution of the flow of people on the site. This consideration is still lacking in PedSim Pro and our proposed model.

4.2. Limitations

First of all, the video captured by only one surveillance camera meant that pedestrians could not be tracked completely throughout the building space, resulting in a missing portion of the pedestrian path in the lower left corner of the video. It was also difficult to collect richer data on pedestrian behaviour, as some popular destinations, such as access to other shopping streets and nearby bus stops, were out of this surveillance camera's field of view. Due to the limited camera range and the limitation that PedSim Pro can only simulate two-dimensional environments, it does not consider the movement of pedestrians on the second floor.

Second, the pedestrian trajectory and velocity map failed to show the complete trajectory of the pedestrian in the surveillance video. As mentioned earlier, YOLOv5 has some limitations. It cannot detect all human figures, especially when other objects block part or the whole of the human body. Random ID switching also occurs during the execution of the DeepSORT algorithm. Therefore, we had to remove some coordinate data that did not fit the pedestrian motion logic in the data cleaning, so discontinuous trajectory lines were generated. These trajectory lines cannot completely represent the actual pedestrian trajectory. In order to optimize the target detection, we may need to train with more images and find surveillance videos with higher image quality. We may also need to find another algorithm to pre-filter the data to optimize the trajectory map.

5. Summary and Future Research

This research proposes a new way to collect data by using surveillance video captured in public space and using the data to examine the accuracy of the pedestrian simulations. Compared to the previous research that collects data from laboratory experiments, field visits, or UAVs, the automated detection method can effectively collect data from the public space at a low time and labour cost. Furthermore, a pedestrian simulation considering roaming behaviour has been proposed. It is also suggested in this research that the destination-oriented pedestrian algorithm does not perfectly apply to many scenarios in public spaces.

We are in the middle stage of developing a comprehensive pedestrian behaviour model that considers wayfinding pedestrians affected by the visual information acquired from their surroundings. In the future, we will consider action recognition and define more parameters to improve the proposed behaviour model that can be applied to practical architectural design.

References

Camillen, F., Caprì, S., Garofalo, C., Ignaccolo, M., Inturri, G., Pluchino, A., Rapisarda, A. and Tudisco, S. (2009) *Multi agent simulation of pedestrian behavior in closed spatial environments*, ed.

Davidich, M. and Köster, G. (2013) *Predicting Pedestrian Flow: A Methodology and a Proof of Concept Based on Real-Life Data*, PLOS ONE, 8(12), e83355.

Facility, F. N. C. (2016) *Section drawings*. Available from: Fukui Nigiwai Commnucation Facility Happy Terrace <http://nigiwai.ftmo.co.jp/drawing/terrace/happiterrace_Sectionnal.pdf> (accessed 15 November 2021).

Government, F. C. (2016) *Plan drawings*. Available from: Fukui City Government <https://www.city.fukui.lg.jp/sisei/tkeikaku/sigaiti/nigiwai-bosyu_d/fil/zumen.pdf> (accessed 15 November 2021).

Helbing, D., Farkas, I. and Vicsek, T. (2000) *Simulating dynamical features of escape panic*, Nature, 407(6803), 487-490.

Henry, M., Worranat, P., Jeremy, J., Adrian, H., Christopher, W., Calvin, L. and Jimin, K. *Markov Chains*. (n.d.) Available from: BRILLIANT <https://brilliant.org/wiki/markov-chains/> (accessed 15 July 2022).

Karoji, G., Hotta, K., Hotta, A. and Ikeda, Y. (2019) Pedestrian Dynamic Behaviour Modeling - An application to commercial environment using RNN framework, *Proceedings of the 24th CAADRIA Conference*, Victoria University of Wellington, Wellington, New Zealand, 281-290.

Mikel, B. (2022) *Yolov5_StrongSORT_OSNet*. Available from: Gitbub <https://github.com/mikel-brostrom/Yolov5_StrongSORT_OSNet> (accessed 13 October 2021).

Pan, M. J. (2021) Redesigning the working space for social distancing: Modelling the movement in an open-plan office, *CIBSE Technical Symposium 2021*, 13-14 July 2021.

Shao, S., Zhao, Z., Li, B., Xiao, T., Yu, G., Zhang, X. and Sun, J. (2018) *Crowdhuman: A benchmark for detecting human in a crowd*, arXiv preprint arXiv:1805.00123.

Sieben, A., Schumann, J. and Seyfried, A. (2017) *Collective phenomena in crowds—Where pedestrian dynamics need social psychology*, PLOS ONE, 12(6), e0177328.

Vroman, L. and Lagrange, T. (2017) *Human movement in Public spaces: The use and development of motion-oriented design strategies*, The Design Journal, 20(sup1), S3252-S3261.

Wu, S. (2021) Approach to Auto-Recognition of Human Trajectory in Squares using Machine Learning-Based Methods - An application of the Yolo-v3 and the DeepSORT algorithm, *Proceedings of the 39th Education and research in Computer Aided Architectural Design in Europe eCAADe 2021*, University of Novi Sad, Novi Sad, Serbia, 361-370.

Active transportation in future urban environment

Negar Nili[1], Courtney Babb[2] and Parisa Izapanahi[3]

[1,2,3] Curtin University, Perth, Australia
{negar.nili[1], c.babb[2], parisa.izadpanahi[3]}@curtin.edu.au

Abstract: Transportation has become one of the integral components of cities that directly affect several aspects of human life, such as economy, communication, and environment. Cities are facing growing challenges and demand for urban transportation due to population growth, which causes harmful impacts on living conditions. Thus, authorities are seeking solutions to improve the urban environment and enhance living conditions. Active transportation (AT), specifically walking and cycling are valuable modes of sustainable transportation that can mitigate the environmental impacts of motorised transportation and improve urban environment and people's health. AT could apply technologies to facilitate the mode of transportation, improve other aspects of urban environments and contribute toward urban sustainability. Adopting technology to reduce AT barriers and make it a transport option for more people with different abilities and needs could transform the urban environment into a place that is environmentally sustainable and much more liveable. This paper investigates people's attitudes toward applying technology to increase AT. An online survey was conducted to explore general public reactions toward the applications. The general public survey results made it possible to identify which factors need more interference to meet users' needs. This survey outcome demonstrates that applications that improve safety and facility of AT are the most encouraging. The findings provide new and updated knowledge for designers, urban planners, and decision-makers on the design system to use technology in future.

Keywords: Active transportation, Technology, Urban Environment.

1. Introduction

The rapid urbanisation associated with population growth has caused cities several problems. Cities considerably impact the environment because they are the centre of social and economic activities (Mori and Christodoulou, 2012). Transportation systems, as a critical aspect of cities, influence on function and sustainability of cities. Widespread use of motor vehicles in cities leads to air pollution, emission of greenhouse gases, and climate change (Gouldson *et al.*, 2018) as well as cause physical health issues and serious health concerns worldwide (Wang and Lobstein, 2006). To address the critical issue of dependency on motorised transportation, authorities worldwide have been facilitating the use of AT to increase

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 106–115.*

physical activity and decrease the adverse influence of transportation systems. AT, which is a human-powered mode of transportation such as walking and cycling, has several advantages such as health, economic, and environmental benefits (Pérez *et al.*, 2017; Stefansdottir *et al.*, 2019) for individuals and society. However, despite the AT benefits, few people in many countries around the world use this mode of transportation regularly. For example, only 5.2% of Australians use AT for their routine destinations and 79% commute by private vehicle (Australian Bureau of Statistics, 2018). Over the past decades, researchers have sought to identify factors influencing AT behaviour. Studies show that environmental interventions can promote and simplify AT use (Billante, 2010). One of the interventions to increase the use of AT is technology that has extensively been implemented to develop urban transport systems and build the so called "smart urbanism"(Papageorgiou *et al.*, 2019).

This paper aims to explore people's attitudes toward using technology to facilitate AT. This research focuses on active transportation infrastructure (ATI) and the use of technology to reduce AT barriers and provide conditions to encourage people to select more AT. A general public survey was administered in Perth metropolitan region in Western Australia to discover people's attitudes toward applying technology to facilitate AT. In most studies, ATI refers to the pathway network, such as roads, bridges, and paths (Smith *et al.*, 2017; Connolly *et al.*, 2019; Lovelace *et al.*, 2020). This study provides compelling evidence that demonstrates ATI includes all the pathway networks of AT, as mentioned above and the other objects in transportation systems that somehow are related to AT. This includes all kinds of vehicles such as cars and buses, built facilities (e.g. end of trip facilities), and roads' equipment like traffic lights. In addition, as all of the above objects are related to cycling and walking, people are also an important part of ATI. Hence, ATI in this research study includes people, objects, and physical infrastructure for this transportation mode. This paper is part of a PhD thesis which studied how technology can contribute to encourage AT.

Technology is a broad term that includes various invented devices by humans that have been used in life to improve people's life efficiency. Smart technology is an umbrella term that refers to interconnected devices to perform different functions with greater quality than traditional (Peterson, 2020). Smart technology in this study refers to digital and electrical technologies such as sensors and actuators that can be embedded or applied to ATI to reduce its barriers and facilitate AT.

2. Technologies in active transportation system

The transportation system has used emerging technologies to meet transportation challenges and provide a comfortable space and better services for its users (Lasok-Smith, 2017). The use of technology in mobility has attracted much attention from scholars and policymakers worldwide (Manders *et al.*, 2018). AT also apply technologies in various parts of its systems in order to boost the use of AT and consequently liveability (Nikolaeva *et al.*, 2019). Other studies considered the use of technology for AT, but none of them studied the use of technologies in different parts of ATI and for both cycling and walking (Abdul Aziz *et al.*, 2018). For instance, Shladover *et al.* (2010) tested a specific technology performance at intersections and its ability to recognise a cyclist from a motor vehicle. Boudart *et al.* (2017) investigated the function of loop detection technology and demonstrated how the system helps cyclists identify the best place to wait at signalised intersections detected by the system. Chakraborty (2018) studied the smart technologies applied on bikes with different functions to increase safety and provide information about bike riders, such as route direction, speed, and fitness metrics. Some studies focused on smartphone apps and investigated how the applications can contribute to increasing the use of AT and change people's travel behaviour. Andersson *et al.* (2018) found that appealing design, feedback, contextualised, and relevant information are significant aspects of mobile applications to encourage sustainable travel behaviour. Ettema (2018) analysed the influence of smartphone apps on people's travel behaviour. He found that each app's effect differs greatly with implications for the apps' effect and use. All these studies concentrated on a specific technology or different types of technologies used for only cycling or walking. More than that users' attitudes regarding the technologies were not assessed in most of them. This research includes different types of technologies for various uses in AT systems to realise people's reactions toward technology and identify important factor/s that encourage people to select AT.

3. Methodology

This research study applied two theories - Theory of planned behaviour (TPB) (Ajzen, 1991) (Ajzen, 1991), and the Hierarchy of walking needs (Alfonzo, 2005)- to explore people's attitudes toward using technology to eliminate AT barriers. The theories postulate that people's behaviour is the outcome of external factors such as society, the physical environment, and internal factors. Travel mode choice is affected directly or indirectly by several elements such as built environment characteristics, social environment, people's attitudes and habits (Yang, 2016). Hence, predicting people's behaviour through theories that only concentrate on external elements or internal factors might not provide a precise picture of people's behaviour. This study combined the theories as each represents some aspects of people's travel behaviour and does not fully address all the involved factors in human behaviour.

Alfonzo's (2005) hierarchy of walking needs model explains the interaction between individuals and the built environment. The model categorised factors influencing travel decision-making into five levels from most basic to higher need: feasibility, accessibility, safety, comfort and pleasurabiltiy. The hierarchy of decisions is a psychological factor that describes travel decisions (Alfonzo, 2005). According to the hierarchy of decisions, higher level decisions determine the lower levels 'extent (Gehlert *et al.*, 2013). TPB describes individuals' behaviour intentions as the consequence of their attitudes, subjective norms, and perceived behavioural control (Ajzen, 1991). Attitude is an individual's hidden psychological state that is not directly observed but partly evaluated through judgments, opinions, feelings, and other indicators (Pronello and Jean-Baptiste, 2018). Based on TPB, people's attitudes are predictive variables influencing the intention of travel mode choice behaviour (Ajzen and Cote, 2008). In this study, people's attitudes toward technology were measured by including ten questions that ask likelihood of selecting AT if some specific technologies would be provided. A subjective norm is an external factor that explains engaging in a particular behaviour determined by perceived social pressure (Ajzen, 1991). Subjective norm shows the salient influence of individuals that impacts a persons' behavioural decisions (Jing et al., 2019). Subjective norm was assessed by inquiring if transport system prioritises their transport mode choice over other transport modes. Perceived behavioural control depends on the presence of items that can facilitate or impede performing a behaviour(Ajzen, 2020). The individuals perceived behavioural control regarding adding technology was also measured by asking participants to what extent applying technology on different ATI parts would encourage them to use active mode for their travel. The combination of continuous models such as TPB and stage models like the hierarchy of walking needs can assist in describing the behaviour change process.

This study adopted a quantitative approach to address the study's objectives. A general public survey was administered to discover people's attitudes toward applying technology to facilitate AT. Attitudinal questions were included in the survey to evaluate people's reactions to using technologies. The general public survey questionnaire comprised thirty-five questions in three sections, including various formats (Multiple choice questions with both single and multiple answers, Likert scales) to evaluate the individual's subjective factors related to AT barriers and their attitude toward technology if it decreases

AT barriers. The general public survey consisted of three parts: 1. Socio-demographic characteristics, 2. AT barriers, 3. Technology encouragement facilities. The socio-demographic characteristics included questions about people's usual mode of transportation, the frequency of using AT as a means of transportation and recreation, age, gender, level of education, and the number of children under 12 years old. The second part contained questions that investigated AT main barriers, which were drawn from a literature review and considering the five basic needs of walking needs in the Alfonzo (2005) model. The final section enquired about individuals' attitudes towards using technology to facilitate AT. New AT technological applications were not in general circulation in Perth when the data was collected. Therefore, it was not possible to observe their effects on this population's travel behaviour. Hence, speculative questions about what people might think of the technology do not exist were included in the third part of the questionnaire. The purpose was to discover what would be people's reaction to applying technology to ATI if it could mitigate the ATI barriers. The questions used "what if "technique to enable the study to investigate the likelihood of accepting and adapting AT that is facilitated by technology. According to this technique, respondents were asked if a specific improvement is applied to ATI what will be their reaction to walking or cycling. Questions were ordered to assess the participants` perception of ATI barriers and their attitudes toward applying technology to reduce the barriers. Participants were asked to rank 22 (12 barriers and ten technology) questionnaire items on a 5-point Likert scale. The final dataset that was analysed, included 312 out of 367 cases. Incomplete responses and participants who were from other cities except Perth were excluded from the data. The research data were collected between March 2020 and September 2020. Over half of the participants (n=178,57%) were female. Most participants' age range were between 31 to 60 (n=221, 71%) and more than half of them (n=207, 67%) reported having a graduate degree or higher.

Before conducting any statistical analysis, the validity and reliability of the barrier and technology questionnaires were evaluated. Cronbach alpha (α) was selected to measure the reliability of questions (Cronbach, 1951; Bland and Altman, 1997). The twelve barrier questions and ten technology questions were subjected to this reliability analysis. The Cronbach alpha coefficients for both questions were satisfactory. The questionnaire had a high level of internal consistency, as determined by a Cronbach's alpha of 0.73 and .83 for barrier and technology questions respectively. Checking the Inter-Item Correlation Matrix[1] for the barrier and technology questions indicated that the items measured the same underlying characteristic. Analysis showed that most items have a strong contribution to the barrier and technology questions and alpha would have decreased if any of these items were not included. Hence all the items were kept for further analysis.

The Kaiser-Meyer-Olkin (KMO) and Bartlett's Test were used to test sample validity. The minimum accepted value of KMO is 0.7 (Hair *et al.*, 2014). The KMO was 0.76 for barriers questions and 0.83 for technology questions, which exceeded the minimum value and Bartlett's Test of Sphericity reached statistical significance. Hence the factor analysis was suitable for the sample.

This study applied Pearson's product-moment correlation coefficient (*r*) to analyse the relationship between AT barriers and applying technology to reduce AT barriers. To conduct the analysis, the 12 barrier questions were subjected to principal components analysis (PCA) to identify underlying patterns among barrier questionnaire items. Factor analysis categorised the barrier questionnaire items into four factors. The suggested factors by factor analysis all were treated as uni-dimensional scales. Thus, to have a new

[1] Inter-Item Correlation Matrix illustrates the Pearson correlation values, which indicate that questionnaire items measure the same underlying characteristic.

score/variable for each factor, the items under each factor's outcome were computed to generate new variables. These new variables were then recoded to convert them back into their original scale, Likert scale. The recoded variables were SAFETY, FEASIBILITY, ENVIRONMENT, FACILITY. The ten technology questionnaire items also were computed to a new variable and then the new variable was recoded as TECHNOLOGY.

4. People's attitudes toward applying technology

In general, correlation analysis is used to determine the direction and strength of a possible linear association between two or more variables. This study applied four Pearson's product-moment correlation coefficient (*r*) to analyse the relationship between AT barriers and applying technology to reduce AT barriers. It is worth mentioning that the authors of this paper also considered other variables influencing AT as part of a wider research. However, this paper focuses on the correlation between technology and identified AT barriers (SAFETY, FEASIBILITY, ENVIRONMENT, FACILITY).

4.1. Technology and safety correlation

The Pearson Correlation coefficient, r, indicated that with a 99% coefficient and p<0.01, there is a statistically significant correlation between the safety and technology variables. Providing more safety through technology for people would increase the likelihood of using AT. According to Table 1, there is a correlation between safety and technology (r=0.28) r<0.5, suggesting a relationship between the two variables. Technology helps explain about 8.3% (r2) of the variance in participants' relevancy of safety barriers (Table 1).

Table 1: Correlation of Technology and Safety

		TECHNOLOGY	SAFETY
TECHNOLOGY	Pearson Correlation	1	.288**
	Sig.(2-tailed)		.000
	N	312	312
SAFETY	Pearson Correlation	.288**	1
	Sig.(2-tailed)	.000	
	N	312	312

**. Correlation is significant at the 0.01 level (2-tailed).

4.2. Technology and feasibility correlation

To determine to what extent decreasing feasibility barrier by technology could encourage individuals to select AT result of the Pearson Correlation coefficient, r, indicated that there is a statistically significant correlation between the feasibility and technology variables with a 95% coefficient and p<0.05. As AT feasibility is improved through technology, more people are likely to choose AT for their trips.
Table 2 shows correlation between feasibility and technology (r=0.12) r<0.5. Technology explains about 1.6% (r2) of the variance in participants' relevancy of feasibility barriers (Table 2).

Table 2: Correlation of Technology and Feasibility

		TECHNOLOGY	FEASIBILITY
TECHNOLOGY	Pearson Correlation	1	.127*
	Sig.(2-tailed)		.025
	N	312	312
FEASIBILITY	Pearson Correlation	.127*	1
	Sig.(2-tailed)	.025	
	N	312	312
*. Correlation is significant at the 0.05 level (2-tailed).			

4.3. Technology and Environment correlation

A correlation analysis was used to determine whether technological factors are linearly associated with environmental factors. The Pearson Correlation coefficient, r, indicated that with a 99% coefficient and $p<0.01$, there is a statistically significant correlation between the environment and technology variables. Creating AT environment that provides much more convenient and suitable places for cyclists and pedestrians, such as shaded paths, improves the use of AT. According to Table3, there is a correlation between safety and environment ($r=0.26$) $r<0.5$, suggesting a relationship between the two variables. Technology helps to explain about 7% (r2) of the variance in participants' relevancy of environmental barriers (Table 3).

Table 3: Correlation of Technology and Environment

		TECHNOLOGY	ENVIRONMENT
TECHNOLOGY	Pearson Correlation	1	.264**
	Sig.(2-tailed)		.000
	N	312	312
ENVIRONMENT	Pearson Correlation	.264**	1
	Sig.(2-tailed)	.000	
	N	312	312
**. Correlation is significant at the 0.01 level (2-tailed).			

4.4. Technology and Facility correlation

The Pearson Correlation coefficient, r, indicated that with a 99% coefficient and $p<0.01$, there is a statistically significant correlation between the facility and technology variables. If technology provides AT facilities, the probability of using AT among people will increase. According to Table4, there is a correlation between facility and technology ($r=0.22$) $r<0.5$, suggesting a relationship between the two variables. Technology helps to explain about 5% (r2) of the variance in participants' relevancy of facility barriers (Table 4).

Table 4: Correlation of Technology and Facility

		TECHNOLOGY	FACILITY
TECHNOLOGY	Pearson Correlation	1	.226**
	Sig.(2-tailed)		.000
	N	312	312
FACILITY	Pearson Correlation	.226**	1
	Sig.(2-tailed)	.000	
	N	312	312

**. Correlation is significant at the 0.01 level (2-tailed).

The four correlation tests were conducted to assess the relationship between AT barriers and applying technologies to decrease the barriers that were recruited 312 participants. According to these test results, there was a statistically significant, positive correlation between AT barriers and technologies to reduce the barriers. Among these barriers, SAFETY had the strongest correlation with technology followed by ENVIRONMENT, FACILITY, and FEASIBILITY. These results indicated that if technology could decrease these barriers, the likelihood of using AT by people would increase. This research study included conflict with vehicles, unsafe neighbourhoods, and crossing roads as safety barriers. Lack of End of Trip facilities, and having to drop off/pick up other people concerning facility barriers, boring scenery and lack of trees to shade paths referred to environmental barriers, long distance, and carrying a heavy load, lack of time, and challenging weather conditions were considered feasibility barriers.

5. Discussion and conclusion

This section discusses individuals' attitudes toward applying technology to ATI based on the results of the general public survey. According to the general public survey analysis, technologies that improve AT safety were the most encouraging applications that increase the likelihood of selecting AT. Lack of safety which is one of the basic needs of AT (Alfonzo, 2005) reduces individuals' control over taking AT. By decreasing safety barriers, technology enhances people's perceived behavioural control and the likelihood of selecting AT. Perceived behavioural control is postulated to be based on accessible control beliefs; the opinions are related to the existence of elements that can impede or facilitate a behaviour's performance (Ajzen, 2020). Findings of this study also demonstrate that if technology decrease other AT barriers (ENVIRONMENT, FACILITY, FEASIBILITY), people might be encouraged to select AT for their trips.

Many participants in this study who rarely or never considered transport by bike or walk reported that the likelihood of cycling or walking would increase if technology decreased the transport barriers. For example, when the safety barrier that was the most important barrier reduce by technology, the first item that impedes individuals from selecting cycling or walking has been overcome, hence the possibility of considering using AT will increase. By addressing individuals' primary needs, their perceived behavioural control over their actions will increase and facilitate their behavioural performance. Those who do not select AT as its barriers impede them from selecting AT, when finding technology decreases the transport modes' barriers, they might think about choosing cycling or walking because they notice their perceived behavioural control allows them to do the action. Using the technologies gives individuals more control over their cycling and walking. Their perceived behavioural control is stronger and positively influences their intention to select AT. Persuasive technological programs are successful strategies to change people's travel behaviour (Weiser *et al.*, 2016). In addition to the influence of technology on individuals' perceived behaviour, some technologies also affect subjective norms. Others' opinions and activities positively or negatively influence an intended behaviour of walking or cycling (Weiser *et al.*, 2016). Once individuals believe they have control over their movement augmented by new technologies, also having others' support to perform the behaviour, the likelihood of selecting cycling and walking increases. These findings suggest that by influencing perceived behavioural control and subjective norm, technology positively affects individuals' willingness to cycle and walk.

Intervention strategies differ according to the technologies' features and the area in which the technologies are applied. They can be incentivized programs in a mobile app, restriction tools in urban areas such as bollards preventing car access, and enablement of bikes to identify their users (Michie *et al.*, 2011). Generally, as the strategies satisfy individuals AT needs, they could effectively change people's travel behaviour. The study findings indicate that to facilitate AT by technology, it is important that the technologies 1) provide situations in which individuals have high perceived behavioural control that increases their confidence to cycle or walk; 2) perceive others support their action. It should be noted that satisfying cyclists' and pedestrians' needs do not necessarily lead to the occurrence of the behaviour. For selecting a travel mode, people may not take into consideration all of its benefits and instead seek out a satisfactory one. For example, someone may need fulfilment of only the most important barriers to select cycling or walking, but other people may require more than one of the barriers removed to decide to cycle or walk. Likelihood of being encouraged to cycle or walk if technology reduces AT barriers differs among individuals with different demographic characteristics. All of the differences should be considered, and the purpose group/s should be identified first when designing and applying technology to increase AT. Applying technology to ATI requires time, physical infrastructure, policy, and political persistence. Furthermore, each new application should be implemented on a trial basis to evaluate its feasibility and consider its pros and con. Due to the novelty of this idea for incorporating technology into ATI, the study suggests that trial programs should be proceeded to explore people's reactions and feedback toward the technologies. Combining the above strategies could provide a context for accepting new AT technologies.

This study's findings also indicate that applying technology to ATI is not a simple context that can be implemented everywhere without having proper conditions. Because individuals experience and perceived behavioural control over their actions that determine their attitudes toward using technologies differ from person to person and application to application (Ajzen, 2020). Providing successful outcomes of applying technology requires the consideration of various items such as the context in which the technologies will be used (e.g. social, cultural), the audience of the technologies, and the area the technologies will be used (e.g. infrastructure, app, or vehicle).

Designers, planners, and policymakers should consider the differences when designing strategies to increase AT. This study's outcomes suggest that intervention strategies that apply technologies can be encouraging if they benefit from multivariant methods considering an array of individuals and technology types. The adoption of technology to reduce AT barriers could transform the urban environment into a sustainable and liveable place for people with different abilities and needs.

The study has some limitations that could be addressed in future studies. First, many of these technological improvements were concepts unfamiliar to most respondents who therefore had imagine their use and potential benefits. Hence participants did not have first-hand experience to know how the technologies work and can assist them in their cycling or walking. Evaluating people's reactions toward real technologies could provide a clearer understanding of people's attitudes towards using technology. Furthermore, the urban context (generally city size, existing infrastructure) limited the generalizability of this study's outcomes. People in different contexts such as urban size and density, culture, and weather might react differently to technologies that decrease AT barriers.

References

Abdul Aziz, H. M., Nagle, N. N., Morton, A. M., Hilliard, M. R., White, D. A. and Stewart, R. N. (2018) Exploring the impact of walk–bike infrastructure, safety perception, and built-environment on active transportation mode choice: a random parameter model using New York City commuter data, *Transportation*, 45(5), 1207-1229.

Ajzen, I. (1991) The theory of planned behavior, *Organizational Behavior and Human Decision Processes*, 50(2), 179-211.

Ajzen, I. (2020) The theory of planned behavior: Frequently asked questions, *Human Behavior and Emerging Technologies*, 2(4), 314-324.

Ajzen , I. and Cote, N. G. (2008) Attitudes and the prediction of behavior. Frontiers of social psychology, *Attitudes and Attitude Change. Ed. WD Crano, R. Prislin. New York, Psychology Press*, 289, 311.

Alfonzo, M. A. (2005) To walk or not to walk? The hierarchy of walking needs, *Environment and behavior*, 37(6), 808-836.

Andersson, A., Winslott Hiselius, L. and Adell, E. (2018) Promoting sustainable travel behaviour through the use of smartphone applications: A review and development of a conceptual model, *Travel Behaviour and Society*, 11, 52-61.

Australian Bureau of Statistics (2018) *JOURNEY TO WORK IN AUSTRALIA*. Available from: <https://www.abs.gov.au/ausstats/abs@.nsf> (accessed.

Billante, V. (2010) *Health promotion and sustainability through environmental design: a guide for planning*, ed., Christchurch City Council.

Bland, J. M. and Altman, D. G. (1997) Statistics notes: Cronbach's alpha, *Bmj*, 314(7080), 572.

Boudart, J. P. E., Foster, N. A., Koonce, P. P. E., Maus, J. and Okimoto, L. (2017) Improving Bicycle Detection Pavement Marking Symbols to Increase Comprehension at Traffic Signals, *Institute of Transportation Engineers. ITE Journal*, 87(3), 29-34.

Chakraborty, P. (2018) *Estyle Bikes: Smart Bicycles Hit the Road*,Electronics for You, Athena Information Solutions Pvt. Ltd., New Delhi.

Connolly, C., Livy, M. R., Qiu, Y. and Klaiber, H. A. (2019) Capitalization of interconnected active transportation infrastructure, *Landscape and Urban Planning*, 182, 67-78.

Cronbach, L. J. (1951) Coefficient alpha and the internal structure of tests, *psychometrika*, 16(3), 297-334.

Ettema, D. (2018) Apps, activities and travel: an conceptual exploration based on activity theory, *Transportation*, 45(2), 273-290.

Gehlert, T., Dziekan, K. and Gärling, T. (2013) Psychology of sustainable travel behavior, *Transportation Research Part A: Policy and Practice*, 48, 19-24.

Gouldson, A., Sudmant, A., Khreis, H. and Papargyropoulou, E. (2018) The economic and social benefits of low-carbon cities: A systematic review of the evidence, *London and Washington DC*.

Hair, J. F., Jr., Sarstedt, M., Hopkins, L. and Kuppelwieser, V. G. (2014) Partial least squares structural equation modeling (PLS-SEM): An emerging tool in business research, *European Business Review*, 26(2), 106-121.

Lasok-Smith, M. (2017) Advancements in Transportation Technology Are an Unstoppable Force and Will Change Transportation in the Same Way That the Internet Has Remapped the World. However, the Law Will Struggle to Keep up, *Exeter L. Rev.*, 44, 214.

Lovelace, R., Talbot, J., Morgan, M. and Lucas-Smith, M. (2020) Methods to prioritise pop-up active transport infrastructure and their application in a national cycleway prioritisation tool, *Transport Findings*.

Manders, T. N., Wieczorek, A. J. and Verbong, G. P. J. (2018) Understanding smart mobility experiments in the Dutch automobility system: Who is involved and what do they promise?, *Futures*, 96, 90-103.

Michie, S., Van Stralen, M. M. and West, R. (2011) The behaviour change wheel: a new method for characterising and designing behaviour change interventions, *Implementation science*, 6(1), 1-12.

Mori, K. and Christodoulou, A. (2012) Review of sustainability indices and indicators: towards a new City Sustainability Index (CSI), *Environmental impact assessment review*, 32(1), 94-106.

Nikolaeva, A., te Brömmelstroet, M., Raven, R. and Ranson, J. (2019) Smart cycling futures: Charting a new terrain and moving towards a research agenda, *Journal of Transport Geography*, 79, 102486.

Papageorgiou, G., Efstathiadou, T., Efstathiades, A. and Maimaris, A. (2019) *Promoting active transportation via information and communication technologies*,IEEE EUROCON 2019-18th International Conference on Smart Technologies, IEEE, 1-5.

Pérez, K., Olabarria, M., Rojas-Rueda, D., Santamariña-Rubio, E., Borrell, C. and Nieuwenhuijsen, M. (2017) The health and economic benefits of active transport policies in Barcelona, *Journal of Transport & Health*, 4, 316-324.

Peterson, J. (2020) *What Is Smart Technology (Examples,Benefits)*. Available from: <https://theconchtech.com/automation/what-is-smart-technologyexamplesbenefits/> (accessed July).

Pronello, C. and Jean-Baptiste, G. (2018) Engaging in Pro-Environment Travel Behaviour Research from a Psycho-Social Perspective: A Review of Behavioural Variables and Theories, *Sustainability*, 10(7), 2412.

Shladover, S., Sharafsaleh, A., Cheong, A., Spring, J. and Leung, K. (2010) *Bicycle Detection and Operational Concept at Signalized Intersections Phase 2B: Testing a Bicyclist Detection System*.

Smith, M., Hosking, J., Woodward, A., Witten, K., MacMillan, A., Field, A., Baas, P. and Mackie, H. (2017) Systematic literature review of built environment effects on physical activity and active transport–an update and new findings on health equity, *International journal of behavioral nutrition and physical activity*, 14(1), 1-27.

Stefansdottir, H., Næss, P. and Ihlebæk, C. M. (2019) Built environment, non-motorized travel and overall physical activity, *Travel Behaviour and Society*, 16, 201-213.

Wang , Y. and Lobstein, T. (2006) Worldwide trends in childhood overweight and obesity, *International journal of pediatric obesity : IJPO : an official journal of the International Association for the Study of Obesity*, 1(1), 11-25.

Weiser, P., Scheider, S., Bucher, D., Kiefer, P. and Raubal, M. (2016) Towards sustainable mobility behavior: Research challenges for location-aware information and communication technology, *GeoInformatica*, 20(2), 213-239.

Yang, Y. (2016) A dynamic framework on travel mode choice focusing on utilitarian walking based on the integration of current knowledge, *Journal of Transport & Health*, 3(3), 336-345.

Adaptable and scalable housing for Australian households and stages of life

Lisa Kuiri[1] and Paola Leardini[2]

[1, 2] School of Architecture, The University of Queensland, Brisbane, Australia
l.kuiri@uq.edu.au [1]

Abstract: The housing sector in Australia continues to be dominated by construction methods based on a linear take-make-waste model: an unsustainable approach for using materials on a planet of finite natural resources and increasing population. Demand on materials for new house construction is exacerbated by the fact that contemporary Australian houses are the biggest in the world; making way for these new larger houses in suburbs, old houses are often demolished, reducing materials to rubble in landfill, as they are generally regarded by owners as functionally obsolete and are not easily adaptable to accommodate their lifestyle needs and aspirations. A transition to a Circular Economy is needed in the design and construction of Australian housing, to keep materials in use for longer by increasing the longevity of a building lifecycle or allowing materials to be used again at the building's end-of-life. Prefabrication represents an effective pathway to implement circularity in construction allowing adaptable buildings to be designed for assembly of components with reversible connections that could be easily disassembled for spatial reconfiguration on site or reuse in other buildings. This paper discusses the benefits of combining the two key circular design principles of adaptability and disassembly for developing housing types that suit spatial needs of typical Australian households at different stages of their life by the construction process of incremental growth. The study employs qualitative methods including case study analysis of contemporary adaptable, incremental housing projects and traditional vernacular housing built for growth, through the lens of circular design.

Keywords: adaptable housing; scalable housing; Design for Adaptability; incremental housing.

1. Introduction

The housing sector in Australia continues to use construction methods based on a linear 'take-make-waste' model (Ellen Macarthur Foundation, 2015), an unsustainable approach for using materials on a planet of finite natural resources and increasing population. Detached houses on land still represent the dominant type in Australia: 70% of 10.8 million dwellings in 2021 (ABS, 2022b). Demand on materials for new house construction is exacerbated by the fact that contemporary Australian houses are the biggest in the world, with an average floor area of 229.6 sqm (James and Felsman, 2020). New houses built in

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 116–126.*

established suburbs are replacing existing, older houses which are regarded by owners as functionally obsolete; this process is driven by costs of renovation, alterations and additions to the existing house being comparable to those of a new house designed to the owner's current lifestyle needs and aspirations (Williams, 2022). The common practice of house demolition, otherwise known as knock-down-rebuild (KDR), reduces building materials to rubble in landfill - even if parts of the house still have years of service life in them. Construction and demolition (C&D) material from the Australian housing industry comprises a significant 44% of waste in landfill, which has prompted a call for more recycling of building materials (Shooshtarian and Maqsood, 2021). However, recycling is a downcycling process and at the lowest end of the hierarchy of processes for sustainable handling of materials. For example, recycling concrete involves breaking it into smaller pieces for use as road base or aggregate and no longer possessing structural strength inherent in its original form. Instead, other sustainable processes aim to retain the quality of an original product or keep the material in use longer, through multiple life cycles. Known as the "10 R's", these strategies are ranked, from higher to lower effectiveness as follows: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover (Cramer, 2017). The Australian housing construction industry needs to rethink how to keep materials in use for longer; this is a key principle in designing buildings for a Circular Economy.

This paper discusses the need for transitioning the Australian construction industry to a Circular Economy and presents two key implementation strategies for circular buildings: design for adaptability and design for disassembly. The paper also discusses the importance of linking these design strategies to the users of the buildings and identifies the prevalent types of Australian households - with specific spatial needs. In the last section, precedents of housing projects designed for growth are then analysed, including post war Australian housing, vernacular housing, and international projects of adaptable and incremental housing. The concluding premise of this paper is that novel housing models designed for adaptability and incremental growth could lead to more sustainable handling of materials and potentially better suit (spatially and financially) the range of Australian households at various stages of life.

2. Transition to a Circular Economy in housing construction

2.1. The Circular Economy

The circular economy (CE) has grown internationally as an alternative approach to the current unsustainable linear economy. The CE is viewed as an ecosystem where natural resources are preserved and enhanced, renewable resources are optimised, waste is prevented, and negative externalities are designed out; the aim is to keep materials, products and components in repetitive loops of use, maintaining and handling them to preserve their value for longer (Figure 1) (ARUP, 2016). Much of the CE literature refers to the design and manufacture of products in modern society; from this viewpoint, buildings can be regarded as large products, or compilation of products assembled together. The linear economy approach sees buildings at the end of their service life demolished and materials sent to landfill, described as a "cradle to grave" approach in the pivotal book *Cradle to Cradle* by McDonough & Braungart (2002). In a CE instead, a "cradle-to-cradle" approach keeps buildings and materials in loops of use (McDonough and Braungart, 2002). Literature about designing buildings for a CE, termed 'circular design' (CD) (Cheshire, 2016; Baker-Brown, 2017), has expanded in the last few years (Munaro et al., 2020). A key concept underpinning the reuse of materials and component in construction is Brand's "shearing layers of change" (Brand, 1995); it acknowledges in the design of buildings that the outer layers of 'site', 'skin' and 'structure' have longer life spans than the inner layers of 'space' and 'stuff', thus change or replacement of the inner layers can be enabled without affecting the integrity of the outer layers (Brand, 1995; ARUP and Ellen Macarthur Foundation, 2020). At a larger scale, the Ellen Macarthur Foundation, advocacy and research organisation for the transition to a CE, has developed, in collaboration with ARUP, the conceptual ReSOLVE framework, which is applicable to products, buildings, neighbourhoods and cities, implementing circularity through six 'actions': regenerate, share, optimise, loop, virtualise and exchange (ARUP, 2016). Of these actions, 'optimise' and 'loop' are particularly applicable to the reuse of buildings and the materials they are constructed from.

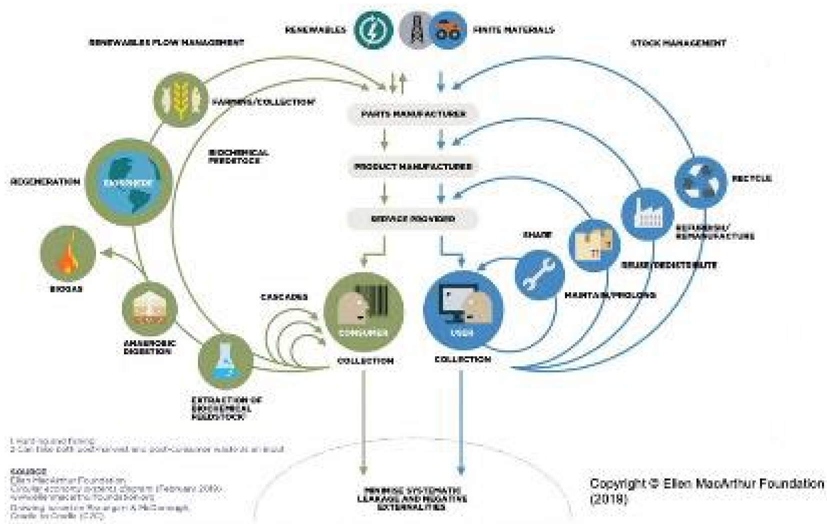


Figure 24 Biological and technical cycles of a Circular Economy (Source: EMF 2022)

2.2. Design for Adaptability

A logical way to keep construction materials in use for longer is to extend the service life of buildings. In the CD literature, a key approach to increasing building longevity is to design buildings that are flexible and adaptable to the changing needs of their occupants and contexts (Cheshire, 2016; Manohar, 2017; ARUP and Ellen Macarthur Foundation, 2020; Cimen, 2021). Hence a growing area of research in the transition of the construction industry to a CE is Design for Adaptability (DfA) (Geldermans, 2016; Geldermans *et al.*, 2019; Aziz *et al.*, 2020; Askar *et al.*, 2021; Askar *et al.*, 2022). In the DfA literature, the two terms 'flexible' and 'adaptable' are both used and sometimes interchanged in meaning (Askar *et al.*, 2022). In this paper, the definitions for flexible and adaptable buildings are based on the work of Schmidt & Austin (2016); through case study analysis of over 300 adaptable buildings, they developed a comprehensive theory for adaptable architecture that defines six levels of adaptability: adjustable (change in furniture), versatile (change in space), refitable (services), convertible (use), scalable (size) and movable (location). These levels are in order of increasing change to the building: from 'flexible' buildings, that can be modified by the occupants themselves with little change to the building, to 'adaptable' buildings, which range from changing building parts, to changing the size of the building, to moving it entirely to another location. Schmidt and Austin's case study analysis found that more than a third of buildings were both versatile and convertible; however, very few were scalable, and none were movable.

To enable buildings to change without damaging the materials they are constructed from, they need to be designed for future change (Friedman, 1997; Kronenburg, 2007; Schneider and Till, 2007; Schmidt and Austin, 2016).

2.2. Design for Disassembly

Achieving the adaptability levels defined by Schmidt and Austin (2016) as convertible, scalable, and movable, requires the method of construction to accommodate anticipated changes. Prefabrication, through off-site construction of building parts to reduce on-site assembly of near finished components (Davies, 2005; Smith, 2010; Aitchison, 2018), has the potential to allow for changes in building configuration. By using modular, standardised components with reversible connections, buildings could be adapted and reconfigured (Askar et al., 2022). Prefabricated modular construction that is designed for adaptability and disassembly could keep building materials in loops of reuse, reducing construction waste (Dams *et al.*, 2021). Design for Disassembly (DfD) is an emerging branch of prefabrication that enables components to be disassembled at the end of one building's service life, to be reassembled in another location, for the same or for other projects. Few recent examples exist to demonstrate these concepts in reality (Kuiri and Leardini, 2022); for example, the *Cellophane House* by Kieran Timberlake is a seminal project built from aluminium off-the-shelf components (Kieran and Timberlake, 2011). In this demonstration project, disassembly was made possible using bolt and plate connectors between the aluminium post and beams, visible through glass wall cladding and flooring. The four-storey building was constructed off-site in completed parts called 'chunks', delivered to site in front of MOMA in New York and assembled in a specific order, on display for ten months, then disassembled completely with like materials collected into piles for storage and future use (Kieran and Timberlake, 2011).

2.3. Links between construction waste, housing design and householders

The links between construction waste piling up in landfill, the need to design housing for the CE and the potential impact on householders, are not yet apparent. Pomponi and Moncaster (2016) provided a conceptual research framework for CD and argued that, while the macro-level of urban context and the micro-level of building components have been largely investigated, there is a lack of interdisciplinary research which is critical for understanding and applying the CE to the meso-level of buildings. They suggested research should explore links between technological and societal challenges to develop solutions to be well received by intended users (Pomponi and Moncaster, 2016).

One such study was conducted by Geldermans et al. (2019) to investigate adaptable housing design in a CE for an increasing cohort of users: the multi-family household. The authors analysed adaptable housing projects built in the Netherlands, Japan and Sweden with flexible interior partitioning systems, and developed eleven *Circ-flex* criteria for housing, which were grouped into three categories of 'flexibility capacity', 'circularity capacity' and 'user capacity' - extending the circular building discourse to the user domain (Geldermans *et al.*, 2019). Their hypothesis was that "without tapping into the user domain, circular building cannot reach economies of scale in a sustainable way" (Geldermans et al., 2019, p.16). Although combining the two approaches of DfA and DfD facilitates the implementation of CD principles through prefabrication, to have greater impact, new models of housing need to be developed with an understanding of the end user perspective. Hence it is important to understanding householder types and the spatial needs of their housing in the current Australian context for designing adaptable housing in a future CE.

3. Australian households

3.1 Demographic changes in Australian households

Demographic changes have occurred in Australian households as in other countries: improved health care has led to longer lives, resulting in an increasing ageing population (James *et al.*, 2019b; Cokis and McLoughlin, 2020); birth rates of women have fallen; divorce rates have increased, creating more single parent families (AIHW, 2021); more people are living alone (AIHW, 2021); and migrant groups bring other cultural expectations of housing (Schneider and Till, 2007; Furlan, 2015; Levin, 2016; Lozanovska, 2019). According to the Australian Bureau of Statistics, in 2021, Australia had 10.8 million households that fell into three main categories: family, the most common at 70.5%, single person (25.6%) and group households (3.9%) (ABS, 2022b).The family category is further divided into four household types: couples with children, couples without children, single parent families and other families. Comparing the percentages of family household types with the other household types, shows that almost a third of all households are couple families with children (31%), yet more than half (53%) of Australian households consist of one to two persons (Figure 2).

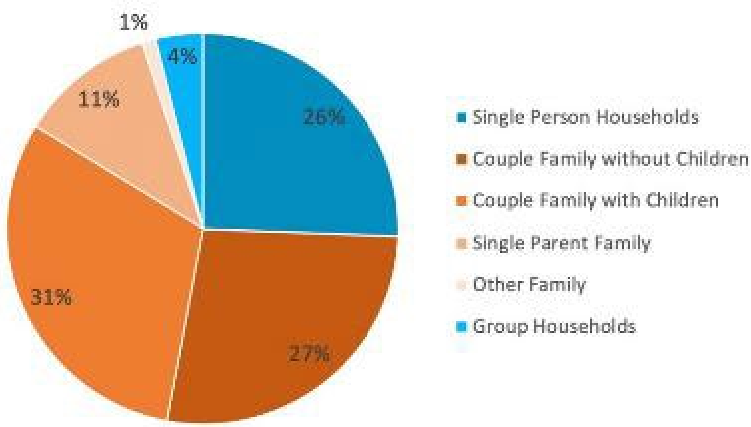


Figure 25 Percentages of Australian Households in 2021 (Figure elaborated from ABS data 2022)

Couples with children have been the perceived prevailing household type for decades and houses have been built to the needs of this family type, regardless of changes in household's lifecycle. In 2021, the detached house on land was the most common dwelling type in Australia at 70%, with 7.56 million dwellings (ABS, 2022b). However there is a mismatch between household types and the dwellings they occupy; for example, some single and couple households would prefer to live in smaller dwellings but there is a lack of choice in the suburbs (Kelly *et al.*, 2011).

3.2 Understanding different households' needs at various stages of life

Changing demographics is one of the three main issues that have affected housing design over the last two decades, together with environmental concerns and the affordability crisis (Murray *et al.*, 2008). Housing affordability continues to drive research into the state of housing, with outputs including reports by the Australian Housing and Urban Research Institute (AHURI) (Stone *et al.*, 2020); a housing conditions data set by Baker *et al.* (2019) and reports by the Australian Government into the welfare of Australians (AIHW, 2019; 2021). AHURI has extensively researched housing aspirations of three generation cohorts of Australians: young (18-34 years), mid-life (35-54 years) and later life adults (55 years and older), with over 4000 participants surveyed across three states - NSW, Vic, SA (Stone *et al.*, 2020). Their research found a large majority of Australians across the age cohorts, income groups and housing tenures are currently housed well; however, while the house (separate or attached) meets 85% of aspirations for mid-life and older cohorts, it falls to two-thirds of young adults (Stone, Rowley, et al., 2020). Almost a fifth of young adults would like to move from a house to an apartment in areas with higher level of amenity; on the other hand, half of those young people living in an apartment stated that living in one would not meet their longer-term aspirations, suggesting that living in an apartment with high level of local amenity only suits the stage of a young person's life. Although the AHURI research provides substantial social context to understanding housing aspirations of age cohorts, household types (single person, couple family, etc.) are not specified, nor are alternative house types discussed to address their diverse spatial needs. Addressing this gap, this paper presents preliminary results of research currently undertaken at the University of Queensland, which aims to understand housing needs for diverse Australian household types at various stages of life to inform a novel adaptable housing models for a future Circular Economy.

3.3 Housing models for diverse household types

Currently building a new house in Australia follows a linear construction process, where materials are fixed in a rigid configuration to suit the living needs of the first house owners – either actual or projected. When the living needs of the household change, the dwelling is 'adapted', when feasible, by an extension or other alterations to the building fabric, which can involve significant costs and disruption to the household. Alternatively, the household have to move to another building and location, which requires establishing new connections to the neighbourhood and amenities and can be particularly difficult for elderly people, who prefer to age in their own home (James *et al.*, 2019a).

Analysis from the Australian Bureau of Statistics has found that housing mobility is strongly related to the age of persons in a household. Households with a reference person over 65 years moved less frequently than other age groups; 82% had lived in their home for more than five years, whereas 46% of households with a reference person in the 15-24 age group had moved three or four times in the last five years (ABS, 2022a). The main reasons for moving also relates to age: households with a person aged 65 years or over mostly want to downsize (22%) or be close to family and friends (13%); households in the age bracket 35-64 move into a purchased home (22%), or for family reasons such as to form a family or change in family size (15.4%), or because want a bigger or better home (17%); these three reasons were similar for households aged 25-34; households aged 15-24 move to be independent (14%) or close to education (13%). These life stages of households could be more effectively be met by adaptable housing, reducing stresses involved in moving elsewhere or costs of undertaking expensive alterations.

Yet houses in Australia are generally designed and built to fulfill requirements for when they have the most occupants: for a family. The nuclear family model of two parents and two children has remained the default household model for housing since the baby boom but is now outdated; more variety in housing models is needed to address functional and spatial needs of smaller households of one to two people, with solutions that can adapt to changing household needs through stages of life.

4. Adaptable and scalable housing

4.1 Scalable housing in Australia's past

Australia has experienced a time when housing designed for growth was considered commonplace. Immediately after World War II, immense demand for new housing combined with material shortages forced architects to design modest homes, usually climate responsive (London *et al.*, 2017). House plans were available from the architect-initiated Small Homes Service which gave low-income families access to quality, affordable home design (Maher, 2018; Monash University, 2018); some plans were designed for future room extensions when the family size and income grew (Monash University, 2018). Plans featured in newspapers and magazines, with the cost of full construction documents equivalent to several hundred dollars in today's currency (Boyd, 2015; Maher, 2018). The Service began in Victoria in 1947, expanded to New South Wales and South Australia in 1953, then Canberra in 1958 (Boyd, 2015). The typical Australian home from the 50s to the 70s was built on a lot big enough for tree in the backyard, in new suburbs away from the city, enabled by private car ownership (O'Callaghan and Pickett, 2012).

In the 80s though, Australian house sizes began to grow, due to the 'supersized' lifestyles model imported from the United States, aspirations of new European migrants, and gentrification of older dwellings in inner city suburbs, spurring an interest in real estate to create personal wealth (O'Callaghan and Pickett, 2012; ABC, 2016). Australians could afford to build large homes to accommodate their aspirations - and builders readily built them. Since the early 70s, house construction has been dominated by volume builders and market driven living styles, accommodated in extra rooms designed to suit specific functions. Current market styles include two or more bathrooms, two living areas, media and mud rooms (James and Felsman, 2020). Although volume builders offer large number of rooms in house plans, little or no customisation of the configuration is available to prospective house owners (Noguchi, 2016). From 1920 to 2020, house sizes have doubled (from 125sqm to 230sqm), lot sizes in the suburbs have decreased (600sqm to 400sqm or less) and the average number of people in a household has almost halved (from 4.5 to 2.4) (Ramirez-Lovering, 2013; ABS, 2022b; Wheeler, 2022).

4.2 Vernacular housing for adaptability and growth

Certain vernacular housing has proven to be flexible to households' needs over time. Houses with rooms of equivalent size have inherent flexibility as they can be used for different functions, such as London cottages (Schneider and Till, 2007), Victorian terrace houses (Brand, 1995) and timber Queenslander houses (Watson, 1981). In addition, Australia has a history of prefabricated houses constructed in Great Britain, shipped and assembled in the new settlement (Archer, 1996). Since early days, lightweight timber Queenslanders were relocated, extended or reconfigured (Fisher, 2016). This history of movable houses could provide the basis for cultural acceptance of novel scalable housing types in Australia.

Adaptable and scalable features are evident in some Asian vernacular housing. Traditional Japanese houses allow daily changes of occupant use in standardized room sizes based on the *tatami* mat and sliding screens (*fusuma* and *shōji*) divide rooms when needed (Schneider & Till, 2007a, p. 55). The traditional Malay *kampong* house can grow incrementally over time to suit a family's changing needs and has terminology to describe ways a house can be extended (Brand, 1995; Knapp, 2003; Rashid and Ara, 2015). Other traditional Asian houses comprise of a core house that can be extended: the Japanese house by lean-to roofs (*hisashi*); the Beijing courtyard house *(siheyuan)* within a walled enclosure has extra rooms around the courtyard; in Bangladesh, the core house (*kimma*) expands with modules (*kim-tom)* parallel to it, or rooms in the verandah *(machan)* (Rashid and Ara, 2015).

Traditional building types of warehouses, barns and factory buildings are regarded as the most adaptable types, due to their double height space and wide roof structure spans allowing an infill structure of mezzanine floor and walls for conversion into residential or other uses (Schmidt & Austin, 2016). A modern building approach for flexible buildings, conceptually similar to the convertible barn, is the Open Building movement. An Open Building is in two parts: a building shell or 'skeleton' with a longer life span and a shorter life span 'infill' organised by the occupants (Kendall, 2022). Dutch pioneers of Open Building, Habraken and the Stichting Architecten Research group, developed concepts of building 'supports' and 'infills' in the 60s and 70s for new housing projects, responding to the repetitive, inflexible mass housing built post World War II (Habraken *et al.*, 1976). At the same time in Japan, 'skeleton and infill' housing was designed by Utida and Tatusmi in the Kodan Experimental Housing Project (Ikeda and Amino, 2000; Minami *et al.*, 2022). Open Building is similar to "loose-fit" office design, where the shell is provided by the building owner and the tenant fits out the interior according to their spatial needs (Lifschutz, 2017).

4.3 Incremental housing

Incremental housing is a staged approach in house construction, with precedents in some vernacular housing types (Rashid and Ara, 2015), that addresses the issue of affordability by lowering initial construction costs. The concept is to build a minimum core as a starter home, which is then added on later by the owner as self-builder, when needs change and the household can afford the building work. This progressive spatial growth is demonstrated in *Quinta Monroy* by Elemental (Aravena and Iacobelli, 2020); the housing project provides a minimum core and space for growth through an organising concept of modular masses and adjacent voids. Each building core is a single room in width, with two habitable floors, and there are timber floor beams that span between cores to allow for future rooms to be built in. As each owner chooses the materials of built-in rooms based on availability and affordability, each dwelling attains an individual appearance that provides identity and difference - although the lack of consistency may result in a haphazard aesthetic which may not transfer well to all contexts.

4.4 Housing for growth

While similar adaptable and scalable projects at the lower density scale of detached and semidetached houses are rare, a good precedent is the *Grow Home*, a terrace house designed by Avi Friedman with unfinished space in the attic and the basement, which allows the owner to finish it according to their needs (Friedman, 2001). This concept was successfully implemented in Montreal, Canada, with 6000 units built from 1991-1999; most of the occupants (89.4%) were first home buyers (Friedman, 2000). Friedman theorised that detached houses and row houses can be extended in future stages in various ways, which he described as 'add-on' and 'add-in' methods (Friedman, 2002). The *Grow Home* was an example of 'add-in' methods, where additional rooms can be created within the building envelope. A house extended by 'add-on' methods, instead, requires space around or above it to accommodate additional volumes, and undertaking these extensions using conventional construction requires partial demolition of the house. In this scenario, prefabrication of building parts, designed for easy assembly and disassembly, could result in reduction of demolition waste when adapting a house to changing needs: an alignment of Friedman's extendable house concept with CD principles. The emerging technology of DfD combined with DfA has the potential to provide future housing models for changing households and contexts; however, there is need for cutting-edge research in this still largely unexplored combined field of design.

5. Conclusion

Much of the CD literature provides theoretical concepts that apply to buildings of any type, with limited application to housing of smaller scale than apartment buildings, which are more prevalent in Australia. To move from theory to practice, two key emerging approaches in CD are DfA and DfD, when combined, they could inform novel adaptable and scalable housing models that are implementable in low-density development for the Australian housing context.

Building only what is needed (functionally and spatially) for each life stage of a household has the potential to reduce construction waste by looping components in use. This approach has precedents in vernacular architecture and is known as incremental housing; in modern times, architects have theorised and built houses that can grow in stages. DfD may augment this building approach, enabling housing to grow and contract in size to achieve the adaptability level of scalable housing. In Australia, a starter home for one or two persons could be small, using less materials and costing less to build than a large, family-sized home at the outset; scalable housing could offer an affordable pathway to home ownership. Focussing on the home as a place to live, rather than an economic asset, and creating a framework for adaptable, scalable housing that suits diverse households at different stages of their life, could unleash a new system of handling building components for reuse on a planet with limited natural resources.

References

ABC (2016) *Streets of your town*, in T. Ross (ed.), ABC.

ABS (2022a) *Housing Mobility and Conditions*. Available from: Australian Bureau of Statistics <https://www.abs.gov.au/statistics/people/housing/housing-mobility-and-conditions/latest-release> (accessed.

ABS (2022b) *Snapshot of Australia: National summary data*. Available from: Australian Bureau of Statistics <https://www.abs.gov.au/statistics/people/people-and-communities/snapshot-australia/2021#our-families-and-households> (accessed 3 Aug 2022).

AIHW (2019) *Housing assistance in Australia 2019*. Available from: Australian Goverment <https://www.aihw.gov.au/reports/housing-assistance/housing-assistance-in-australia-2019/contents/social-housing-dwellings> (accessed 11/04/2022).

AIHW (2021) *Home ownership and housing tenure*. Available from: Australian Institute of Health and Welfare, Australian Government <https://www.aihw.gov.au/reports/australias-welfare/home-ownership-and-housing-tenure> (accessed 11/04/22).

Aitchison, M. (2018) *Prefab housing and the future of building: Product to process.* , ed., Lund Humphries, London.

Aravena, A. and Iacobelli, A. (2020) *Elemental: Incremental housing and participatory design manual*, Second edition ed., Hatje Cantz Verlag, Berlin, Germany.

Archer, J. (1996) *The Great Australian Dream: The history of the Australian house*, ed., Harper Collins Publishers, Sydney.

ARUP (2016) *The Circular Economy in the Built Environment*, ed., Arup London.

ARUP and Ellen Macarthur Foundation (2020) *From principles to practices: Realising the value of circular economy in real estate*, Arup Group, London, 106.

Askar, R., Braganca, L. and Gervasio, H. (2022) Design for Adaptability (DfA) - Frameworks and assessment models for enhanced circularity in buildings, *Applied System Innovation*, 5(24), 25.

Askar, R., Bragança, L. and Gervásio, H. (2021) Adaptability of buildings: a critical review on the concept evolution, *Applied Sciences*, 11(10), 32.

Aziz, S. S., Alobaydi, D. and Salih, A. B. (2020) Studying Flexibility and adaptability as key sutstainable measures for spaces in dwelling units: a case study in Baghdad, *3rd International Conference on Sustainable Engineering Techniques (ICSET 2020)*.

Baker, E., Beer, A., Zillante, G., London, K., Bentley, R., Hulse, K., Pawson, H., Randolph, B., Stone, W. and Rajagopolan, P. (2019) *The Australian Housing Conditions Dataset*, in A. Dataverse (ed.).

Baker-Brown, D. (2017) *The re-use atlas: A designer's guide towards a circular economy*, ed., RIBA Publishing, London.

Boyd, N. (2015) *A home for every taste: the NSW Small Homes Service*,Architecture Bulletin.

Brand, S. (1995) *How buildings learn: What happens after they're built*, Second edition ed., Penguin Books, USA.

Cheshire, D. (2016) *Building revolutions: Applying the circular economy to the built environment*, ed., RIBA Publishing, Newcastle upon tyne.

Cimen, O. (2021) Construction and built environment in circular economy: A comprehensive literature review, *Journal of Cleaner Production*, 305, 30.

Cokis, T. and McLoughlin, K. (2020) *Demographic trends, household finances and spending*,Australian Economy, Reserve Bank of Australia.

Cramer, J. (2017) *The raw materials transition in the Amsterdam metropolitan area: Added value for the economy, well-being, and the environment*,Envrionment: Science and policy for sustainable development www.tandfonline.com, 14-21.

Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P. and Emmitt, S. (2021) A circular construciton evaluation framework to promote designing for disassembly and adaptability, *Journal of Cleaner Production*, 316.

Davies, C. (2005) *The Prefabricated Home*, ed., Reaktion Books, London.

Ellen Macarthur Foundation (2015) *Growth within: A circular economy vision for a competitive Europe*, Ellen MacArthur Foundation

McKinsey Center for Business and Environment, 98.

Fisher, R. (2016) *Queenslanders: their historic timbered homes*, ed., Brisbane History Group, Brisbane.

Friedman, A. (1997) Design for change: flexible planning strategies for the 1990s and beyond, *Journal of Urban Design*, 2, 277-295.

Friedman, A. (2000) Preferences of first-time buyers of affordable housing: evidence from Grow Homes in Montreal, Canada, *Candian Journal of Urban Research*, 9(1), 24.

Friedman, A. (2001) *The Grow Home*, ed., McGill-Queen's University Press, Canada.

Friedman, A. (2002) *The Adaptable House: Designing homes for change*, ed., McGraw-Hill USA.

Furlan, R. (2015) Cultural traditions and architectual form of Italian transnational houses in Australia, *Archnet-IJAR, International Journal of Architectural Research*, 9(2), 45-64.

Geldermans, B., Tenpierik, M. and Luscuere, P. (2019) Circular and flexible infill concepts: Integration of the residential user perspective, *Sustainability*, 11, 19.

Geldermans, R. J. (2016) Design for change and circularity - accommodating circular materials and product flows in construction, *Energy Procedia*, 96(SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016).

Habraken, N. J., Boekholt, J. T., Thijssen, A. P. and Dinjens, P. J. M. (1976) *Variations: The systematic design of supports*, ed., Laboratory of Architecture and Planning, MIT, Cambridge, Massachusetts.

Ikeda, S. and Amino, M. (2000) KSI Experimental Housing Project - Pilot Project of Kodan Skeleton Infill Housing, *Continous Customization in Housing*, Tokyo, Japan, 16-18 October 2000.

James, A., Parkinson, S., Rowley, S. and Stone, W. (2019a) *What sort of housing do older Australians want and where do they want to live?*,The Conversation.

James, A., Rowley, S., Stone, W., Parkinson, S., Spinney, A. and Reynolds, M. (2019b) *Older Australians and the housing aspirations gap*,Housing aspirations and constraints for lower income Australians, Australian Housing and Urban Research Institute, Melbourne, 116.

James, C. and Felsman, R. (2020) *Australian houses are again the world's biggest: CommSec Home Size Trends Report*. Available from: <https://www.commbank.com.au/articles/newsroom/2020/11/commsec-home-size-trends-report.html> (accessed.

Kelly, J.-F., Ben, W. and Walsh, M. (2011) *The Housing We'd Choose*, The Grattan Institute,, Melbourne, 65.

Kendall, S. (2022) *Residential architecture as infrastructure: Open Building in practice*, ed., Routledge.

Kieran, S. and Timberlake, J. (2011) *Cellophane House*, ed., Kieran Timberlake, Philadelphia.

Knapp, R. (2003) *Asia's old dwellings: Tradition, resilience, and change*, ed., Oxford University Press, Hong Kong.

Kronenburg, R. (2007) *Flexible architecture that responds to change*, ed., Laurence King Publishing Ltd, London.

Kuiri, L. and Leardini, P. (2022) Design for Adaptability and Disassembly: Towards zero construction waste in the Australian Housing Sector, *International e-Conference on Green & Safe Cities (IeGRESAFE)*, Cawangan Perak, Malaysia, 21 September 2022, 29.

Levin, I. (2016) *Migration, settlement, and the concepts of house and home*, ed., Routledge, New York.

Lifschutz, A. (2017) *Loose-fit architecture: Desiging buildings for change*, Architectural Design ed., John Wiley & Sons.

London, G., Goad, P. and Hamann, C. (2017) *An unfinished experiment in living: Australian houses 1950-65*, ed., UWA Publishing, Crawley, Western Australia.

Lozanovska, M. (2019) *Migrant housing: Architecture, dwelling and migration*, ed., Routledge, New York.

Maher, L. (2018) *How the post-war small home movement helped deliver the great Australian dream*. Available from: ABC News <https://www.abc.net.au/news/2018-06-14/treasure-trove-small-homes-helped-deliver-great-australian-dream/9861204> (accessed.

Manohar, S. (2017) *Translating with optimism: Exploring flexibility in design for a positive future.*, Masters, Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden.

McDonough, W. and Braungart, M. (2002) *Cradle to cradle: Remaking the way we make things*, First edition ed., North Point Press, New York.

Minami, K., Chiba, S., Ma, L. and Suzuki, A. (2022) Residential history, repair, and renovation of housing complexes: KEP estate Tsurumaki 3 complex, a mid-rise building, *Japan Architectural Review*, 5, 106-118.

Monash University (2018) *Small Homes Service: Victorian post-war architect-designed homes: Do you have a story?* Available from: <https://www.monash.edu/mada/news/2018/small-homes-service> (accessed.

Murray, S., Ramirez-Lovering, D. and Whibley, S. (2008) *rehousing: 24 housing projects*, ed., RMIT publishing, Melbourne.

Noguchi, M. (2016) *ZEMCH: Toward the delivery of zero energy mass custom homes*,Springer tracts in civil engineering, Springer, Switzerland.

O'Callaghan, J. and Pickett, C. (2012) *Designer suburbs: Architects and affordable homes in Australia*, ed., NewSouth Publishing, Sydney.

Pomponi, F. and Moncaster, A. (2016) Circular economy for the built environment: A research framework, *Journal of Cleaner Production*, 143, 710-718.

Ramirez-Lovering, D. (2013) *The space of dwelling: and investigation into the potential for spatial flexibility to improve volume housing in Australia*, Faculty of Art, Design and Architecture, Monash University, Melbourne.

Rashid, M. and Ara, D. R. (2015) Modernity in tradition: Reflections on building design and technology in the Asian vernacular, *Frontiers of Architectural Research*, 4, 46-55.

Schmidt, R. and Austin, S. (2016) *Adaptable architecture, theory and practice*, ed., Routledge, Florence.

Schneider, T. and Till, J. (2007) *Flexible housing*, ed., Elsevier, Oxford, UK.

Shooshtarian, S. and Maqsood, T. (2021) *Australia needs construction waste recycling plants - but locals first need to be won over*,The Conversation, Australia.

Smith, R. E. (2010) *Prefab Architecture: A guide to modular design and construction*, ed., Joh Wiley & Sons Inc, Hoboken, New Jersey.

Stone, W., Rowley, S., Parkinson, S., James, A. and Spinney, A. (2020) *The housing aspirations of Australians across the life-course: Closing the 'housing aspirations gap'*,AHURI Final Report, Australian Housing and Urban Research Institute Limited, Melbourne Australia, 69.

Watson, D. (1981) *The Queensland house: A report into the nature and evolution of significant aspects of domestic architecture*, ed., The National Trust of Queensland, Brisbane.

Wheeler, T. (2022) *Tone on Tuesday: Surbuban housing: a history in 7 images*. Available from: Architecture and Design <https://www.architectureanddesign.com.au/people/tone-on-tuesday-suburban-housing-a-history> (accessed 18/04/22).

Williams, S. (2022) *Renovate, Rebuild or Relocate: How to decide what's right for you*. Available from: Domain <https://www.domain.com.au/living/renovate-rebuild-or-relocate-how-to-decide-whats-right-for-you-1129763/> (accessed 15 October 2022).

An architecture of inclusion: Can the profession adapt to the diversity of design demanded by people with a disability?

Kirsten Day[1] and Andrew Martel[2]

[1,2] University of Melbourne, Parkville, Australia
{dayk[1], aamartel[2]}@unimelb.edu.au,
ORCID-0000-0002-3372-229[1], ORCID-0000-0003-2008-7636[2]

Abstract: From the 1840s, Australia encouraged the committing of people with disabilities to institutions and asylums. By the 1970s the preference was to house people in group homes—domestic in scale but still institutional in design and regulation. Consequently, knowledge of designing for people with disabilities within the architectural profession was low and teaching the design skills required within universities negligible. The United Nations Charter of Rights for People with Disability (adopted by Australia in 2009), and the introduction of the National Disability Insurance Scheme (2014), have highlighted the need for education and knowledge among architects and architectural students. The tendency has been to conform to existing regulations, rather than being a driver of innovation. New references in the National Standard of Competency for Architects around designing for disability require demonstrating these competencies by graduates. Using the experience of the inclusion of Indigenous competencies in the National Standard, this paper explores the difficulties the profession and teaching institutions may encounter around identifying people with lived experience working in architecture, or as design teachers. Issues around who is allowed to speak for—and engaging with people with an intellectual disability or neurodiversity pose serious challenges to rectifying decades of neglect.

Keywords: Architecture; Design; Disability; Inclusion.

1. Introduction

When we talk about Universal Access being a design for 'everyone' Aimi Hamraie makes the important point "when the goal is to design for 'everyone', I ask who counts as everyone and how do designers know?" (2017: xiv)

In 2021, the Architect's Accreditation Council of Australia (AACA), the national body comprising representatives of State registration boards, launched a revised National Standard of Competencies (NSC) defining "the skills, knowledge and capabilities required for the general practice of architecture in Australia" (AACA, 2021). For the first time these competencies have included requirements specific to

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 127–134.*

Indigenous knowledge (six new competencies) and the design and delivery of accessible built environments (three new competencies). While the introduction and acknowledgement of the importance of these skills to contemporary architectural practice is welcome, it is not a straightforward process. This paper focuses on the proposal for competencies around designing with disability—both physical and cognitive—and highlights several of the difficulties in engaging with the disability community. These difficulties stem from several sources. A major structural issue regarding building regulations exists. As will be elaborated in the next section, the history of the treatment of people with a disability in Australia and designing for them has been largely based on institutional models imported from England and this history has been embedded in current building regulations (Martel and Paton-Cole, 2022). This is a design legacy based on not consulting, listening, or involving people with a disability on matters that directly affected them. With the ratification of the United Nations Charter on the Rights of People with Disability (2006) (UN CRPD) and the introduction of the National Disability Insurance Scheme (NDIS) in 2014, government policy, community attitudes, and people with a disability's own expectations have moved farther and faster than the building regulations to which designers must adhere. Requiring competencies in accessibility and universal design from all architects is a further step in this direction.

Current best practice for engaging and designing with people with a disability centres on the principle of co-design, based on the philosophy of nothing about us without us that also informs the evolution of designing with Indigenous clients. Effective co-design requires the 'expert' to 'take off that hat' and work on an equal level with someone who is an 'expert in their own lives' (Blomkamp, 2018). This is a challenge to the current principles behind much architectural education and training. A third concern centres on legitimacy and agency—who has the right to speak for people with a disability? Are there sufficient industry practitioners with lived experience of disability to facilitate the professional development of the architectural industry in Australia? Are there enough qualified academics and teachers in the university system to train the next generation of designers to engage meaningfully with the way that the built environment affects people with disability? Is architectural education in Australia inclusive? In addressing these issues, this paper will look to recent experience with the introduction of Indigenous specific competencies into academic curriculum, recognising that representation requires normalisation, not only in staffing, knowledge, and curriculum, but within society at large (Huppatz and Day, 2022).

2. Disability, regulation, and architecture

2.1. 1800 to 1999: A short history of disability models, architectural responses and building regulations in Australia

In the early years of the settlement of Australia many social expectations and norms were transplanted from England. Similarly, building styles and typologies, and the earliest building regulations were directly sourced from England, and in particular London (Freeland, 1972). In terms of the treatment of people with a disability, the prevailing orthodoxy, known as the charity model, advocated placing people with severe disability in institutions or asylums, where they remained out of sight for the rest of their lives (Jackson, 2018; People with Disability Australia, 2022). This practice was long-standing in England and can be traced back to the establishment of the Bethlehem Hospital (Bedlam) in London in the 1200s and its housing of the 'insane' from the 1300s (Vrklevski et al., 2017). In Australia, the first lunatic asylum was established at Castle Hill in New South Wales (NSW) in 1811 at a refurbished army barracks. After moving to Liverpool in 1826, the first purpose-built asylum was constructed at Gladesville (also known as the Tarban Creek Lunatic Asylum) in 1838. In Melbourne, the Yarra Bend Asylum opened in 1848, and in 1856 construction started on the Kew Asylum, modelled on London's Colney Hatch Asylum which had opened in 1851 (Day, 1998; Vrklevski et al., 2017). The timelines of the introduction of building regulations into Australia correspond to the development of the asylum system closely. Governor Macquarie in NSW introduced the first building regulations into the Hawkesbury River area in 1810, and introduced to Sydney in 1837 (a year before the opening of Gladesville). This was modelled on the London Building Act of 1774 (itself an update of the original London Building Act of 1666 after the Great Fire of London). In Melbourne, its first Building Act was introduced in 1849 (Freeland, 1972; Tinniswood, 2011). Consequently, the contents of Australia's first building regulations reflected the treatment of people with a disability in institutions disconnected from everyday society.

By the mid-1940s, reflecting in part the physical consequences of two wars, the charity model of disability gave way to the medical model. The premise of this model was that the person with a disability had something wrong with them, and that the medical system of doctors and scientists would work to fix them (Jackson, 2018). Architecturally and operationally the medical model of disability was still largely institutional in nature. The period after World War 2 also saw the start of a large construction boom to house returned service personnel, and the subsequent development in Victoria of the Uniform Building Regulations (UBRs). First tabled in Victoria's parliament in 1945 (Macintyre, 2018; Victoria Government, 1945). Originally optional for adoption by local councils, the UBRs continued to reflect the institutionalisation of people with a disability.

By the 1970s, the social model of disability was encouraging a move away from large-scale institutionalisation and advocating for a more community-based approach to the housing and treatment of people with disability (Jackson, 2018). In architectural, and built form, this involved the development of Community Residential Units (CRUs), which comprised small group homes for 5 to 8 residents (typically with similar disabilities) with individual bedrooms and common areas. Treatment or day-to-day management was carried out on the same premises or a service centre nearby, and the residents had limited control over where they lived, who they lived with or what their daily routines were. In this sense, although the scale had been reduced, the institutionalisation remained (Connellan, 2018). In 1974, UBRs became compulsory for councils to apply to new buildings, and once again, their contents reflected the prevailing attitude towards the housing of people with disability.

By the 1990s, Australia had moved to a national building standard, the Building Code of Australia (BCA), the first edition published in 1988 and adopted in Victoria in 1990. The following year, the Australian Uniform Building Regulatory Coordinating Council (precursor to the Australian Building Codes Board ABCB), commissioned the development of the Model Building Act designed to assist State level governments in introducing standardised building acts across the country (Lovegrove, 2021). Victoria introduced its Building Act in 1993, based largely on the Model Building Act. At this time, the BCA did not refer to disability in the sections on domestic dwellings (Buildings classified as Class 1 or 2). The sole reference being contained in the definition of a Class 3 building. A Class 3 building is one intended to house unrelated people in sole-occupancy units. Examples include boarding houses, hotels, student accommodation, detention centres and accommodation for the aged, children, or people with a disability (National Construction Code, 2022).

2.2. 2000 to 2022: The changing nature of designing with disability

As Australia's building regulations were becoming more standardised nationally, attitudes towards people with a disability in the community were continuing to evolve. In 1992 there was the introduction by the Commonwealth Government of the Disability Discrimination Act (Federal Register of Legislation, 1993).

This covered many areas of people's lives including work, education, and personal relationships, but also had impacts in the built environment. In the architectural field, the development of accessibility, useability, and universal design concepts challenged the prevailing view of the built environment as a neutral place that needed occasional modification to accommodate the disability of a particular person (Iwarsson and Stahl, 2003). The rise of a person-centred model of disability was most clearly elaborated by the United Nations Convention on the Rights of People with Disabilities (UN CRPD) (United Nations. Dept. of Economic and Social Affairs. Disability Division, 2006). The convention—and Optional Protocol—was ratified by the Australian Parliament in 2009 (Australian Government Department of Social Services, 2022). This model recognises the role of the built environment itself in creating disability and places the emphasis back on designers to create spaces where everyone has choice and control over their activities and can contribute as citizens in their society to the fullest of their ability (Kirkman, 2010). In 2010, in response to the need for a practical application of the 1992 Disability Discrimination Act and responsibilities under the 2006 UN CRPD, the first Access to Premises Standard (Australian Standard AS 1428) was produced (Australian Government, 2010). This standard mandated access (and other criteria like accessible toilets) be provided for all public buildings. Notably, the standard did not apply to domestic dwellings like Class 1 housing, and only to common areas in Class 2 buildings (apartments).

The next major structural change in Australian societal attitudes towards disability came with the introduction of the National Disability Insurance Scheme (NDIS) in 2014. Initially rolled out over a five-year period between 2014-2019, the NDIS is primarily designed as a funder for service provision using a personalised choice and control philosophy derived from the UN CRPD. However, the scheme recognized that some housing provision would be required for people whose disabilities made it impossible for them to access appropriate housing in the existing market (this housing part of the NDIS is known as Special Disability Accommodation SDAs) (NDIS, 2020). In a major shift from previous government policy that prioritised state-run housing for people with disability, the NDIS stated that people should be able to live wherever they wanted in the community, and that services they required would come to them not the other way around as had previously been the case with CRUs. Provision of these appropriate and 'anywhere in the community' based houses would be up to the private housing market with funding incentives provided by the NDIS (Bonyhady, 2014). These provisions moved far in advance of the current versions of the BCA which continued to say nothing about disability at the domestic building scale and continued to reference disability regarding Class 3 buildings. NDIS design guidelines for SDA housing contained several different criteria to be acceptable to the NDIS but the guidelines are ambiguous when it comes to building classification under the BCA, referring simply to conforming to the BCA (NDIS, 2021).

Bringing changes to the BCA (also referred to as the National Construction Code NCC), can be a prolonged process, however changes approved for the latest edition (NCC 2022) include accessibility criteria that will apply to all new dwellings from 2023 (these are substantially based on the silver level of design from the Livable Housing Australia guidelines) (ABCB, 2018, 2022). It should be noted that not every jurisdiction in Australia has committed to adopting the new standards with NSW, SA, and WA currently uncommitted. This brings a step closer the requirement for all new buildings—domestic, public, or commercial—to be accessible and use-able for all people. Consequently, this puts people with a disability at the forefront of design thinking for the built environment, with obvious implications for the design professions.

3. National Standards of Competencies

3.1 Background and recent changes

Ostwald et al. explains architectural education in Australasia using the analogy of fabric with four fixed points. The first, are the accreditation requirements defined by the profession. Recently the AACA have taken a larger role of developing these with the Australian Institute of Architects (AIA) taking a lesser role. Until recent reforms these have been ‘normative’ with accreditation requirements added—demanding more in this ‘fabric’ of architectural education (2008). The second corner are the needs of architectural practices and alignment with requirements for architectural registration. The third corner represented by the shaping of architectural education in the community—more aligned to ethics, moral and sustainable concepts. The final is the system of architectural education and the implementation by the university system.

The NSCA competencies are arranged into four general categories: Practice Management and Professional Conduct; Project Initiation and Conceptual Design; Detailed Design and Construction Documentation; and Design Delivery and Construction Phase Services. The 2021 National Standard updated the previous iteration (2015) simplifying the format and introducing new criteria.

The NSCA set out 60 Performance Criteria (PC) across three core areas: Professionalism, Communication and Environmental Practice. These comprise the requirements for Graduates, Candidates for Registration and Post-Registration Architects in Australia. Of the 60 Performance Criteria, 43 are applicable to Graduates (and therefore directly impact pedagogy), the rest are for Candidates for Registration and Post-Registration (that is, professionals). A comparison between the 2015 and 2021 documents, demonstrates a significant new emphasis: six new criteria for Indigenous knowledge and country and three for knowledge on accessibility. These requirements were not part of the early iterations.

Units of competency for graduates from an architectural program in 2021 guidelines:

- PC12: Understand how relevant building codes, standards and planning controls apply across architectural practice, including climate change implications, the principles of fire safety, and barriers to universal access (AACA, 2021: 5)
- PC46 Understand the processes for producing project documentation that meets the requirements of the contract and procurement procedure and complies with regulatory controls, building standards, codes, and conditions of construction and planning approvals (AACA, 2021: 7)

Performance criteria across graduates, point of registration and post registration:

- PC28 Be able to draw on knowledge from building sciences and technology, environmental sciences, and behavioural and social sciences as part of preliminary design research and when developing the conceptual design to optimise the performance of the project (AACA, 2021: 6)

While ACCA’s initiative to lead here is needed, it highlights an underlying tension between the diversity, equity, and inclusion. While these are much needed skills—these are not supported via legislation. For accredited architecture courses within Australian universities, these new additions present significant challenges: first, the lack of design for disability knowledge, and the lack of Indigenous knowledge. Second, the structural and systematic limitations of universities in terms of curriculum, delivery modes and time limitations. The latter includes balancing teaching competencies and university requirements including student demands and expectations, changing university structures and formats (such as online teaching) and shifting government policy.

Historically, the competency standards were based on 'risk' in a legal sense around the administration of architectural practice such as tender negotiations, contracts administration etc. However, the 2021 iteration has taken on progressive themes including care for Country and equity in access and how this then informs architectural design. Universities worldwide are dealing with issues around decolonisation. The challenge to embedding indigenous knowledge into the curriculum is the lack of architects and academics in architecture with lived experience (Huppatz and Day, 2022). Similarly, there are few voices of people living with disability as role models/representation. Representation requires normalisation. This includes the staff, students, knowledge, and the academic curriculum.

4. Conclusions

As noted in this paper, the architectural profession has had a long history of not engaging substantively with people with a disability because of the institutionalisation of disability in Australia. Recent developments in government policy, community attitudes and a growing assertion of their rights from people with lived experience with disability have made this level of disengagement unsustainable. In response, the profession is actively looking to rectify this situation—and the introduction of disability specific competencies into the National Framework is part of that (worthy) effort. However, the profession starts from a long way back. We could find no contemporary data on the number of practicing architects in Australia who identify as having a disability. Similarly, there was limited information on the diversity of architecture students and graduates—limited to gender/s and domestic or international. There is no mention of disability in recent reports on the profession (AACA, 2019). Some survey studies out of the UK (Pitcher, 2020), Canada (Condon, 2022), and the USA (Glissen, 2018; Massey, 2018) suggest that only a very small percentage of designers surveyed had lived experience of disability. In the UK, Pitcher identifies the lack of information:

Although one in five working-age adults in the UK are classed as disabled, according to charity Scope, latest figures suggest a significantly lower proportion for those working in architecture. Fewer than 1% of respondents to a survey by the Architects' Registration Board this August described themselves as having a disability (2020).

As we have learnt from the introduction of Indigenous competencies, where the profession has very few people to draw on as experts with lived experience, several difficulties arise. Who sets examples in offices? Who can design and evaluate professional development opportunities for architects without lived experience but who must now demonstrate competency? Who teaches the next generation of architects through the university system? In short, who can speak for disability? If we are to remedy this lack over the coming years, we face a further, more fundamental issue with the education and training of architectural students. Is architectural training inclusive? Does the current pedagogy of the 'studio' present enough opportunity for a diverse body of students, physically and neurologically? Classic Universal Design principles tell us that not only the physical layout of a space needs to be accessible, but the tools and technologies we use must also be universal, as well as workplace policies, communication systems and safety. Architectural studios are awash with technology—but rarely assistive technology. Presentation techniques invariably favour sight over all other senses.

Professional competencies are an unusual place to transition an industry that is focused on time, cost, and efficiency but they may act as an incentive to tackle the more fundamental biases in the profession and its schools. Regardless, the profession is on a journey towards 'normalisation and representation' like the larger society that it serves.

References

AACA (2021) National Standard of Competency for Architects 2021. Architects Accreditation Council of Australia. Available at: https://aaca.org.au/wp-content/uploads/2021-NSCA.pdf

ABCB (2018) Accessible Housing: Options Paper. Australian Building Codes Board. Available at: https://www.abcb.gov.au/sites/default/files/resources/2022/Options-paper-accessible-housing-2018.pdf.

ABCB (2022) Livable Housing. Available at: https://www.abcb.gov.au/initiatives/livable-housing

Australian Government (2010) Disability (Access to Premises — Buildings) Standards 2010

Australian Government Department of Social Services (2022) Disability and Carers. Available at: https://www.dss.gov.au/our-responsibilities/disability-and-carers/program-services/government-international/international-participation-in-disability-issues#:~:text=On%2017%20July%202008%20and,international%20leader%20in%20disability%20rights

Blomkamp E (2018) The Promise of Co-Design for Public Policy: The Promise of Co-Design for Public Policy. *Australian Journal of Public Administration* 77(4): 729–743. DOI: 10.1111/1467-8500.12310

Bonyhady B (2014) *The National Disability Insurance Scheme: A Catalyst for Large Scale, Affordable and Accessible Housing for People with a Disability*. Canberra, Australia: Housing, Disability and the NDIS Forum

Condon D (2022) Canadians want architects to help create more inclusive and accessible communities. Available at: https://www.canadianarchitect.com/canadians-want-architects-to-help-create-more-inclusive-and-accessible-communities/

Connellan J (2018) *Two Hands: Delivering More and Better Housing for Australia's National Disability Insurance Scheme (NDIS) Participants*. 1st ed. McTwo

Day C (1998) *Magnificence, Misery and Madness: A History of the Kew Asylum 1872-1915*. University of Melbourne, Department of History. Available at: https://books.google.com.au/books?id=pJkXOAAACAAJ.

Federal Register of Legislation (1993) Disability Discrimination Act 1992. Australian Government. Available at: https://www.legislation.gov.au/Details/C2016C00763

Freeland JM (1972) *Architecture in Australia: A History*. Pelican books. Ringwood, Victoria, Australia : New York, N.Y., U.S.A: Penguin Books Australia ; Viking Penguin

Glissen D (2018) Why are there so few disabled architects and architecture students? Available at: https://www.archpaper.com/2018/06/disability-education-of-architects/

Huppatz D and Day K (2022) Australian architectural education in the pluriverse. In: *DRS2022: Bilbao*, 16 June 2022. DOI: 10.21606/drs.2022.278.

Iwarsson S and Stahl A (2003) Accessibility, usability and universal design positioning and definition of concepts describing person-environment relationships. *Disability and Rehabilitation* 25(2): 57–66. DOI: 10.1080/0963828021000007969

Jackson MA (2018) Models of Disability and Human Rights: Informing the Improvement of Built Environment Accessibility for People with Disability at Neighborhood Scale? *Laws* 7(1): 10. DOI: 10.3390/laws7010010

Kirkman M (2010) Literature Review: Person-centred Approaches to Disability Service Provision. *Person-centred Approaches to Disability Service Provision*: 56

Lovegrove K (2021) The Model Building Act in Australia – The Regulatory Template that Overhauled Liability Regimes Not Limited to Joint and Several Liability in the Early 1990s. Available at: https://lclawyers.com.au/model-building-act-regulatory-template-re-shaped-modern-day-building-control/

Macintyre S (2018) Owners and Tenants: The Commonwealth Housing Commission and Post-War Housing, 1943-1949: Commonwealth Housing Commission. *Australian Economic History Review* 58(3): 265–282. DOI: 10.1111/aehr.12160

Martel A and Paton-Cole V (2022) Human Rights, Disability, and Construction: How responsive are building regulations to changing community attitudes towards housing for people with a disability?,. In: *World Building Congress 2022*, RMIT University, 28 July 2022

Massey J (2018) How can architects build the equitable discipline we deserve? Available at: https://www.archpaper.com/2018/09/how-can-architects-build-equitable-discipline/

National Construction Code (2022) Understanding the NCC: Building Classifications. Australian Building Codes Board. Available at: https://www.abcb.gov.au/sites/default/files/resources/2022/UTNCC-Building-classifications.PDF

NDIS (2020) Home Modifications: Guidance for Builders and Designers. National Disability Insurance Agency

NDIS (2021) SDA Design Standard. Available at: https://www.ndis.gov.au/providers/housing-and-living-supports-and-services/specialist-disability-accommodation/sda-design-standard

Ostwald MJ, Williams A, and Australian Learning & Teaching Council (2008) *Understanding Architectural Education in Australia*. Strawberry Hills, N.S.W.: Australian Learning and Teaching Council

People with Disability Australia (2022) History Of Disability Rights Movement In Australia. Available at: https://pwd.org.au/about-us/our-history/history-of-disability-rights-movement-in-australia/

Pitcher G (2020) Is disability architecture's final taboo? Available at: https://www.architectsjournal.co.uk/news/is-disability-architectures-final-taboo

Tinniswood A (2011) *By Permission of Heaven: The Story of the Great Fire of London*. Available at: https://nls.ldls.org.uk/welcome.html?ark:/81055/vdc_100048694109.0x000001 (accessed 15 July 2022).

United Nations. Dept. of Economic and Social Affairs. Disability Division (2006) Convention on the Rights of Persons with Disabilities (CRPD). United Nations. Available at: https://www.un.org/disabilities/documents/convention/convoptprot-e.pdf

Victoria Government (1945) *Victoria Government Gazette: Uniform building regulations*. 87, 28 June. Available at: http://www.austlii.edu.au/au/other/vic_gazette/1945/87.html

Vrklevski LP, Eljiz K and Greenfield D (2017) The Evolution and Devolution of Mental Health Services in Australia. *Inquiries Journal* 9(10). Available at: http://www.inquiriesjournal.com/a?id=1654.

An investigation into quality management systems and factors affecting construction productivity: The New Zealand residential construction industry

Mark Kirby[1], Funmilayo Rotimi[2] and Nicola Naismith [3]

[1, 2, 3] Auckland University of Technology, Auckland, New Zealand
{mark.kirby [1], funmilayo.ebun.rotimi [2], nicola.naismith [3]}@aut.ac.nz

Abstract: Poor construction productivity is described as a systemic issue globally. In New Zealand (NZ), it is known as a substantial and enduring socio-economic problem. Among the numerous factors, quality is often correlated as a contributory factor to improving construction productivity. However, yet explicitly explored in the NZ residential construction sector as a more comprehensive strategic management approach. Thus, the aim of this study is to provide new insights into strategies for improving construction productivity from a quality management perspective in the NZ residential construction subsector. This preliminary literature review uses a mixture of Q1 and Q2 journals and selected 38 papers using the keywords "construction productivity, improvement, factors, residential construction, and quality management". A range of papers was chosen to span 40 years in research from the mid-1980s to 2021, with the largest representation of papers within the last 10 years, as the topic became more prolific globally. The preliminary literature review findings highlight that quality management systems are positively linked to improved productivity and further defined the characteristics of quality management systems thought to benefit the NZ residential construction sector. Theoretically, it is hoped that this research makes a valuable contribution to the existing productivity literature.

Keywords: Construction productivity; quality management; management strategies; residential building.

1. Introduction.

It is known that construction sectors globally play a notable role and are a central driver of a nation's continued and sustained economic growth (Hasan *et al.,* 2018; OECD, 2021). Moreover, as in most countries, the New Zealand construction sector contributes to Gross Domestic Product (GDP), providing around 7% (Ministry of Business, Innovation & Employment, 2020; Productivity Commision, 2021). Of interest, the NZ construction sector is one of the larger sectors by total employment, contributing around 10% (MBIE, 2021). In addition, the NZ residential subsector now compromises approximately 40% of all consented works (Stats NZ, 2021). Further confirmed is the importance of construction productivity at the NZ industry level, where a one per cent annualised increase in construction productivity returns to a rise in GDP of around $139m (Pricewaterhousecoopers, 2016; Tran and Tookey, 2011). Moreover, is

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 135–143.*

considered a direct link toward improved societal living standards (Small *et al.,* 2021). Paradoxically, the NZ construction industry currently shows signs of rapid growth, although often criticised for its poor productivity (Hasan *et al.*, 2018; OECD, 2021; Productivity Commision, 2021). Subsequently, it is reasoned that New Zealanders' are working (10%) more (Nolan *et al.*, 2018; Commission, 2020; Productivity Commision, 2021) and producing less (20%), highlighting the substantial and enduring socio-economic problem (Tran and Tookey, 2011; Nolan *et al.,* 2019).

A significant link between quality and productivity exists today as before (Lam *et al.,* 2008; Small *et al.,* 2021). Further, some note quality management as a contributory factor in enhancing construction productivity (Ghodrati *et al.,* 2018; Hwang *et al.*, 2020; Seadon and Tookey, 2019; Small *et al.,* 2021). According to Deming (1982), the benefits of enhanced quality through integrated processes are seen through sustained quality improvements as well as greater productivity and improved profits organizationally (Iyer et al. 2013). Based on the ideas of Latham (1994), Crosby (1989), Arditi and Mochtar (1996) and Small *et al.* (2021), it can be argued that quality management is considered effective in improving construction productivity. A factor considered equally important today (Ghodrati et al., 2018; Hasan et al., 2018). Additionally, productivity is critical to the survival of organisations.

In terms of organisational improvement, quality has been linked to construction productivity since the mid-1990s (Arditi and Mochtar, 1996). Highlighted through a study from Small *et al.* (2021), who quantified the positive link between quality management systems and construction productivity. Regardless, in NZ, it is purported that construction companies experience similar limiting factors at the organisational level. Factors like poor productivity, persistent lack of standards, high industry fragmentation and low-quality control in all contribute to the prolonged negative industry performance (Bloom *et al.*, 2016; Nasir *et al.*, 2016). Conversely, the benefits of enhanced productivity organizationally are shown through corporate competitiveness, reduced costs, and increased profits, all of which directly affect end-user costs (Arditi and Mochtar, 1996; Hasan *et al.,* 2018). However, irrespective of the importance of existing literature, continued research efforts, technological advancements, governmental strategies, and educational opportunities focused on productivity gains, over time, productivity growth levels in the NZ construction industry have generally remained stagnant (Tran and Tookey, 2011; Nolan *et al.,* 2018).

2. Research Methodology.

This paper forms part of a PhD Thesis. A preliminary literature review and analysis of the existing literature is undertaken relative to quality management systems and common factors linked to improved construction productivity at the project, industry, and organisational levels. The purpose of this paper is to identify characteristics of various quality management systems that may benefit the NZ residential construction sector. In line with research from Tranfield *et al*. (2003), Emerald Insight, ASCE, ScienceDirect and google scholar were the chosen search engines for the desktop review. The "title/abstract/keyword" fields are the search parameters used. Of those search engines, this study used a mixture of Q1 and Q2 journals and selected 38 papers using the keywords; "Construction productivity, improvement, factors, residential construction, and quality management". A range of papers was chosen from the early 1980s to 2021, with the largest representation of papers within the last 10 years, as the topic has become more globally prolific. The search boundaries extended to quality management systems and factors affecting construction productivity and used the following journals due to their relevance to the research objectives; *Journal of Management in Engineering, International Journal of Production Economics, International Journal of Lean Six Sigma, Administrative Science Quarterly, Construction management and* *economics, Production and Operations Management and Engineering Construction and Architectural Management.*

The preliminary literature review highlights the importance of quality management systems and their positive relationship to construction productivity (Small *et al.,* 2021). Further, defined the characteristics of Lean Six Sigma (LSS) and Total Quality Management (TQM) and the ISO9001 standards. Additionally, TQM or ISO9001 as quality management systems may benefit the NZ residential sector. To this author's best knowledge, quality has only been recognised as a contributory factor in isolation and yet explored in NZ residential construction sector as the broader strategic management approach towards improving construction productivity. Additionally, Hwang *et al.* (2020) identify that few have quantified how quality affects productivity at the organisational level. Continued research is needed to understand the effect quality management as a management strategy at the organisational level has on construction productivity in the NZ residential construction sector.

2.1 Research Objectives.

The following 2 research objectives will be pursued further through the preliminary literature review and help define this proposed research.

- Define the common factors that positively affect construction productivity.
- Determine the characteristics of quality management systems suitable for use in NZ residential construction organisations

3. Literature review.

3.1. Factors affecting construction productivity.

Due to its significance, identifying factors that affect construction productivity has been researched extensively, albeit with mixed results (Hasan *et al.*, 2018; Seadon and Tookey, 2019). That it is researched extensively implies its global importance. It follows that a commonality exists over time in agreed factors in enhancing productivity. Some authors (Nasir *et al.,* 2016; Hasan *et al.,* 2018) highlight the non-availability of materials, inadequate supervision, change orders and weather as factors that limit productivity. Additionally, others (Hasan *et al.,* 2018; Hwang *et al.,* 2020) take a human resourcing perspective and highlight factors around the workforce. Likewise, Hasan *et al.* (2018) agree with Nasir *et al.* (2016) and (Dixit *et al.*, 2019) and note poor communication and a lack of tools and equipment as limiting factors. However, a reasonable agreeance globally recurring factors affecting construction productivity (see Table 1) does exist, although not universal (Hasan *et al.* 2018). Thus a sound basis for the agreeance is because of the research over an extended time frame, global reach, the inclusion of countries regardless of socioeconomic development, and varied project environments (Ghodrati *et al.,* 2018). Conversely, although comprehensive, the research is somewhat limited by scope, sector and origin, which may explain the variability in factors noted within the study. In addition, other factors such as; management strategies, project culture, sustainability initiatives, Government influences, legislation, site amenities, emerging technologies and workers' welfare initiatives are also noted as possible contributors but beyond the scope of the study (Hasan *et al.,* 2018).

Table 11: Recurring global productivity factors among authors

Recurring Global Productivity Factors	Source
non-availability of materials	Hasan et al. (2018), Nasir et al. (2016),
inadequate supervision,	Hasan et al. (2018), Nasir et al. (2016),
skill shortage, training, unskilled workers	Hasan et al. (2018), Hwang et al (2020). Ofori et al (2020),
lack of proper tools and equipment,	Hasan et al. (2018), Nasir et al. (2016), Gurmu et al (2016)
incomplete drawings and specifications,	Hasan et al. (2018), Nasir et al. (2016)
poor communication,	Hasan et al. (2018), Nasir et al. (2016), Gurmu et al (2016)
rework, poor site layout,	Hanna Heale (1994), Hasan et al. (2018), Nasir et al. (2016),
weather conditions and change orders, ,	Hasan et al. (2018), Nasir et al. (2016)
motivation, , legal constraints, weather,	Hanna Heale (1994), Hasan et al. (2018), Nasir et al. (2016)
quality, Site-management	Adrian (1995) Gurmu (2016), Lam (2008) Small et al. (2020)

3.2. Quality Management Systems and construction productivity.

3.2.1 Total Quality Management (TQM).

Indeed, quality as a management function has been linked to improved construction productivity since the mid-1990s (Arditi and Mochtar, 1996), and various quality management systems (QMS) exist that can be used organizationally within the construction industry (Hwang et al., 2020). In terms of a QMS, in the mid-1980s, Total Quality Management (TQM) was proposed as a solution to organisational improvement worldwide. TQM was seen as an integrated management strategy for organisations globally, viewed favourably as a future advantage for organizational competitiveness (Deming, 1986; Crosby, 1989; Small *et al.*, 2021). Chini and Valdez (2003) define TQM as a management philosophy intertwined with four principles; people, quality, organisations, and the role of senior management that help guide its normative outcomes (Hackman and Wageman, 1995). Fundamentally TQM is founded on the belief that the costs of poor quality (cost of quality) are more than the perceived costs associated with developing processes to produce higher-quality goods and services.

The benefits of TQM are purported through lower costs in production and improved customer-centricity organizationally (Baron and Kreps, 1999) as well as the ease of integration strategically with planning and design coordination. Barriers to uptake globally are thought to be; a lack of human resource development, lack of planning for quality, lack of leadership for quality, lack of customer focus and lack of resources needed for TQM implementation, considered similarly in the local NZ residential sector. Organizationally, TQM provides a competitive edge and is linked to improved productivity and performance among manufacturing companies (Maani *et al.,* 1994). By way of example, Small *et al.* (2021) quantified the positive effects of quality management in improving construction productivity in the Middle East/North African (MENA) region. Although limited to Mechanical, Engineering, and Plumbing (MEP) trades in the commercial construction sector, it concluded, Mechanical works were seen to improve productivity outputs by around 40% (Small *et al.* 2021). The study by Small *et al.* (2021) is restricted by sector and trade. However, it quantifies using quality management as a holistic, integrated management strategy to improve construction productivity, thought beneficial locally, although needing further research.

3.2.2 Lean Six Sigma (LSS).

A recent adaptation to Six Sigma is Lean Six Sigma (LSS), which combines lean principles and techniques with Six Sigma (Singh and Rathi, 2018). LSS is a business strategy explicitly aiming to increase quality and enhance organisational productivity, highlighting the strategic significance between quality and productivity (Lam et al., 2008; Small et al., 2021). Like Six Sigma, LSS is process-driven and is considered a lean construction methodology that eliminates defects and reduces variation within a process (Chakravorty, 2009; Sreedharan and Raju, 2016). A data-driven methodological approach that quantitatively assesses a processes performance through statistical representation, aiming to define, analyze, improve, measure and control organisational processes (DMAIC) to eliminate defective works

(Singh and Rathi, 2018). Often considered effective in managing operations and achieving improved quality (Sreedharan and Raju, 2016). Barriers to uptake are a lack of an industry road map, operational expertise in practice, certification, a lack of data for analysis and time and cost implications (Chakravorty, 2009; Singh and Rathi, 2018). LSS is suited to larger organisations due to their capacity to resource effectively and provide adequate funding and time (Singh & Rathi, 2018). By comparison, it can be reasoned that the NZ construction sector profile, being mainly consistent with micro-companies, may lack the human capital, financial resource, and specific expertise relevant to successfully implementing LSS as a quality management strategy and is therefore considered less adaptive to the NZ construction sector than TQM.

3.2.3 Industry standards- ISO 9001.

Quality management has been recognized as an international standard since (ISO9001) 1987 and is a well-regarded global QMS (Dissanayaka *et al.*, 2001; Chini and Valdez, 2003; *ISO - About us*, no date). The integral point of difference with ISO 9001 is in the form of a set of standards as opposed to other quality management systems, TQM, and LSS, which are reasoned as management philosophies (Chini and Valdez, 2003). Furthermore, the ISO 9001 family is based on 8 principles of Quality management: customer focus, leadership, people involvement, process approach, systematic approach to management, continual improvement, factual approach to decision-making, and mutually beneficial supplier relations. This QMS requires training, certification, and audit organizationally, ensuring a robust, effective, and adaptable solution to organisational and industry-wide QM. It is an international standards system that provides versatility and integration at the organizational and industry sector levels (Dissanayaka *et al.*, 2001; Ofori, et al., 2020). The generic nature of the ISO 9000 standards allows for adaptability in meeting organisational needs. Providing a level of freedom organizationally to integrate other relative but less structured internal policies, processes, and procedures (Chini & Valdez, 2003). Resulting in a less prescriptive approach to organisational quality management (Dissanayaka *et al.*, 2001). Considered beneficial in the NZ construction sector regardless of organisational size and may be used as a government strategy at the industry level to lead a more holistic integrated strategy towards improved productivity and quality enhancements throughout the industry.

Conversely, some debate exists about whether quality management as a strategy adds any significant increase in performance (Lee et al., 2011). For example, Haupt and Whiteman (2004) identified excessive paperwork as a negative factor. Georgiou (2010) agrees with Keenan & Rostami (2019) that the industry acceptance of defects as standard practice is a barrier to QMS implementation. A human resource approach highlights the transient workforce and a lack of subcontractor involvement (Ofori et al., 2020; Keenan & Rostami, 2019) as limitations. Other factors like measuring results, staff unwillingness, cost and time implications also rate highly in the research (Keenan and Rostami, 2019) as problems that may affect the implementation of QMS organizationally. Needing further review in the local context. Although empirical data identifies the importance of quality management systems and their positive relationship to construction productivity (Small *et al.,* 2021), few have quantified how quality management systems at the organisational level affect construction productivity (Hwang *et al.,* 2020). This highlights the need for further research.

3.3 Quality management as a management strategy.

Hackman and Wageman (1995) agree with Deming (1986) and Ishikawa (1985), reasoning that the ultimate purpose of an organisation is to remain profitable and provide sustainable growth for both its people and society through the generation of services and products. Indeed since the 1980s, governments have used quality management (Australia, Hong Kong, Singapore) to help guide their industry quality objectives (Adrian, 1987; Ofori *et al.,* 2020). However, it is reasoned that consistently providing justifiable levels of quality over time has proven more difficult across the wider industry. It is known that quality management systems are critical to project performance and are linked as direct drivers for enhancing productivity (Crosby, 1989; Deming, 1986; Seadon and Tookey, 2019). They are observed as far back as the late 20th century when improved productivity was identified as reflecting positively on quality and safety and innumerable other factors (Adrian, 1987). Moreover, where previously viewed through a lens of reactivity as a site-based tool, construction quality management (QM) today has adapted and evolved as an essential strategic business function. An integral point of difference for today's construction companies.

Of equal importance organisationally, quality management should also be viewed as a strategic system that may enhance construction productivity by increasing overall outputs and consistency in product delivery (Nasir *et al.,* 2016; Hwang *et al.*, 2020). Through the use and adherence to industry standards, product specifications and integrated management processes, organisational QM performance evolved more holistically than separately when viewed from the global industry perspective. QM, as a management strategy, creates corporate competitiveness. Adding further context, Love and Smith (2003) consider that through incorporating lean principles, a comparison of rival organisations can be benchmarked, adding value, adaptability, and versatility at the organisational and industry level. Hence an integrated management strategy focused on QM simultaneously identifies an opportunity to use QM as a management strategy to improve construction productivity in the NZ residential sector. Compared to the economic wastage (approx. 12%) realised from poor project performance on construction projects globally, a QMS may be a sustainable and cost-effective solution to improved organisational and industry performance (PMI, 2016) and provides a competitive edge among organisations as projected many years prior (Deming, 1986; Crosby, 1989). Moreover, a QMS benefits organisations through improved customer satisfaction increased profit, and fewer reworks (Small *et al.,* 2021).

An element of quality exists within most construction project deliverables regardless of the industry sector, whether civil, commercial, or residential. Therefore, it can be argued that when viewed globally, quality can be seen broadly as a universal factor that is significant, unique, and high in propinquity among contractors, clients, and other stakeholder groups. Moreover, it is a measurable and controllable factor that produces tangible results. A QMS can be integrated at the project and organisational levels and may also provide benefits at the government and industry levels. However, despite the innumerable factors presented in the various literature over time, (Nasir *et al.,* 2016; Hasan *et al.,* 2018; Hwang *et al.,* 2020) quality has only been recognised as a contributory factor in isolation and yet explored in NZ residential construction sector as the broader strategic management approach towards improving construction productivity. Highlighting the need for further research. It is considered that through construction organisations addressing quality management strategically, improvements to productivity will be a by-product of effective management practices, highlighting a significant strategic shift in thinking around improving productivity in the residential construction sector.

4. Potential benefits of the research.

The current study contributes to the existing body of knowledge in productivity literature by highlighting common factors affecting construction productivity and defining quality management systems suitable for use in NZ residential construction organisations. This proposed research may benefit residential construction organisations and the wider NZ construction industry. When construction organisations strategically address quality management as an integrated strategy, enhanced productivity is reasoned. Moreover, it may contribute to other areas of future research, including industry longitudinal studies in construction productivity and adaption to other subsectors within this and other industries. Limitations to the proposed research exist throughout the residential sub subsector to the uniqueness of construction projects and the variability within the current sector through NZ market conditions.

5. Conclusions and further research.

Improving construction productivity is a global problem. This preliminary literature review highlights common factors affecting construction productivity over a 40-year period. Although a commonality of various factors correlated to enhancing construction productivity from many global perspectives exists, construction productivity in NZ remains an enduring socio-economic problem. This research highlights the characteristics of Lean Six Sigma (LSS) and Total Quality Management (TQM), and the ISO9001 quality management standards. This paper analysed the benefits of each QMS relevant to the local NZ residential construction sector. Additionally, identifying TQM or ISO9001 as quality management systems beneficial to the NZ residential sector. Furthermore, the different factors noted as effectively increasing construction productivity are mainly considered in isolation than against the broader productivity problem. Additionally, as before, a significant link between quality and productivity exists. Indeed, as far back as the mid-1990s, integrated management functions are linked to improved construction productivity. Consequently, quality management systems are critical to project performance and are linked as direct drivers for enhancing productivity. Hence an integrated management strategy focused on quality management simultaneously identifies an opportunity to use quality management to improve construction productivity in the NZ residential sector. It is hoped that after this research, quality management at the organisational level will be shown to be effective as a management strategy in improving construction productivity in the NZ residential construction sector. Pursuing the need to be more productive is essential to organisational survival and improving societal living standards, benefiting all of NZ.

References

Adrian, J.J. (1987) *Construction productivity improvement*. Pearson College Div.

Arditi, D. and Mochtar, K. (1996) ‘Productivity improvement in the Indonesian construction industry.’, *Construction Management & Economics*, 14(1), p. 13.

Baron, J.N. and Kreps, D.M. (1999) ‘Consistent human resource practices.’, *California Management Review*, 41(3).

Bloom, N., Sadun, R. and Van Reenen, J. (2016) *Management as a Technology?* Working Paper 22327. National Bureau of Economic Research. Available at: https://doi.org/10.3386/w22327.

Carson, C. and Abbott, M. (2012) 'A review of productivity analysis of the New Zealand construction industry', *Australasian Journal of Construction Economics and Building, The*, 12(3), pp. 1–15. Available at: https://doi.org/10.3316/informit.757773916867826.

Chakravorty, S.S. (2009) 'Six Sigma programs: An implementation model', *International journal of production economics*, 119(1), pp. 1–16.

Chini, A.R. and Valdez, H.E. (2003) 'ISO 9000 and the US construction industry', *Journal of management in engineering*, 19(2), pp. 69–77.

Cloete, B.C. and Bester, A. (2012) 'A Lean Six Sigma approach to the improvement of the selenium analysis method : original research', *Onderstepoort Journal of Veterinary Research*, 79(1), pp. 1–13. Available at: https://doi.org/10.10520/EJC129093.

Commission, P. (2020) 'Australia's long term productivity experience - PC Productivity Insights 2020'. Available at: https://policycommons.net/artifacts/1560822/australias-long-term-productivity-experience/2250617/ (Accessed: 16 April 2022).

Crosby, P. (1989) 'Crosby talks quality', *The TQM Magazine*, 1(4). Available at: https://doi.org/10.1108/eb059474.

Deming, W.E. (1986) *Out of the crisis : quality, productivity and competitive position*. Cambridge: Cambridge University Press.

Dissanayaka, S.M. *et al.* (2001) 'Evaluating outcomes from ISO 9000-certified quality systems of Hong Kong constructors', *Total Quality Management*, 12(1), pp. 29–40. Available at: https://doi.org/10.1080/09544120020010075.

Dixit, S. *et al.* (2019) 'Evolution of studies in construction productivity: A systematic literature review (2006–2017)', *Ain Shams Engineering Journal*, 10(3), pp. 555–564.

Georgiou, J. (2010) 'Verification of a building defect classification system for housing', *Structural Survey* [Preprint].

Ghodrati, N. *et al.* (2018) 'Role of Management Strategies in Improving Labor Productivity in General Construction Projects in New Zealand: Managerial Perspective.', *Journal of Management in Engineering*, 34(6), pp. 1–11.

Hackman, J.R. and Wageman, R. (1995) 'Total quality management: Empirical, conceptual, and practical issues', *Administrative science quarterly*, pp. 309–342.

Hasan, A.(1) *et al.* (2018) 'Factors affecting construction productivity: a 30 year systematic review', *Engineering, Construction and Architectural Management*, 25(7), pp. 916–937. Available at: https://doi.org/10.1108/ECAM-02-2017-0035.

Haupt, T.C. and Whiteman, D.E. (2004) 'Inhibiting factors of implementing total quality management on construction sites', *The TQM magazine*, 16(3), pp. 166–173.

Hwang, B. *et al.* (2020) 'Prioritizing Critical Management Strategies to Improving Construction Productivity: Empirical Research in Singapore', *SUSTAINABILITY*, 12(22). Available at: https://doi.org/10.3390/su12229349.

Ishikawa, K. and ISHIKAWA, K.A. (1985) *What is total quality control? The Japanese way*. Prentice Hall.

ISO - About us (no date) *ISO*. Available at: https://www.iso.org/about-us.html (Accessed: 3 May 2022).

Iyer, A., Saranga, H. and Seshadri, S. (2013) 'Effect of quality management systems and total quality management on productivity before and after: Empirical evidence from the Indian auto component industry', *Production and Operations Management*, 22(2), pp. 283–301.

Keenan, M. and Rostami, A. (2019) 'The impact of quality management systems on construction performance in the North West of England', *International Journal of Construction Management* [Preprint]. Available at: http://www.tandfonline.com/doi/abs/10.1080/15623599.2019.1590974 (Accessed: 27 August 2022).

Lam, K.C., Wang, D. and Lam, M.C.K. (2008) 'The TQM journey of Hong Kong building contractors: from a self-assessment perspective', *The TQM Journal* [Preprint].

Lee, D., Lim, T. and Arditi, D. (2011) 'An expert system for auditing quality management systems in construction', *Computer-Aided Civil and Infrastructure Engineering*, 26(8), pp. 612–631.

Love, P.E.D. and Smith, J. (2003) 'Benchmarking, Benchaction, and Benchlearning: Rework Mitigation in Projects.', *Journal of Management in Engineering*, 19(4), pp. 147–159.

Maani, K., Putterill, M. and Sluti, D. (1994) 'Empirical analysis of quality improvement in manufacturing', *International Journal of Quality & Reliability Management* [Preprint].

MBIE (2021) 'Building and construction sector trends annual report 2021.', p. 42.

Ministry of Business, Innovation & Employment (2020) 'Construction fact sheet- July 2020 Impacts of COVID-19 and future outlook'. mbie.govt.nz. Available at: https://www.mbie.govt.nz/dmsdocument/11600-construction-factsheet-july-2020.

Nasir, H.(1) *et al.* (2016) 'An integrated productivity-practices implementation index for planning the execution of infrastructure projects', *Journal of Infrastructure Systems*, 22(2). Available at: https://doi.org/10.1061/(ASCE)IS.1943-555X.0000275.

Nolan, Fraser and Conway (2018) 'Moving on from New Zealand's productivity paradox', *Policy Quarterly*, 14(3). Available at: https://doi.org/10.26686/pq.v14i3.5080.

Nolan, P., Pomeroy, R. and Zheng, G. (2019) *Productivity by the numbers: 2019*. New Zealand Productivity Commission.

OECD (2021) 'OECD Compendium of Productivity Indicators'. Available at: https://doi.org/doi:https://doi.org/10.1787/f25cdb25-en.

Ofori, G., Zhang, Z. and Ling, F.Y.Y. (2020) 'Key barriers to increase construction productivity: the Singapore case.', *International Journal of Construction Management*, pp. 1–12.

Pricewaterhousecoopers (2016) *Valuing the role of construction in the NZ economy*. Construction Strategy Group, p. 67. Available at: https://www.pwc.co.nz/insights-and-publications/2016-publications/valuing-the-role-of-construction-in-the-new-zealand-economy.html.

Productivity Commision (2021) *New Zealand Productivity Commission (2021) Productivity by the numbers. Available from www.productivity.govt.nz/research Date: May 2021 ISBN: 978-1-98-851964-7 (online)*, *Productivity Commision*. Available at: www.productivity.govt.nz/research.

Seadon and Tookey (2019) 'Drivers for construction productivity', *Engineering, Construction and Architectural Management*, 26(6), pp. 945–961. Available at: https://doi.org/10.1108/ECAM-05-2016-0127.

Singh, M. and Rathi, R. (2018) 'A structured review of Lean Six Sigma in various industrial sectors', *International Journal of Lean Six Sigma* [Preprint].

Small, E.P., Bakry, I. and Ayyash, L. (2021) 'Evaluating the effect of TQM on MEP construction productivity and project delivery in Dubai', *International Journal of Construction Management*, 21(10), pp. 1061–1075. Available at: https://doi.org/10.1080/15623599.2019.1602584.

Sreedharan, V.R. and Raju, R. (2016) 'A systematic literature review of Lean Six Sigma in different industries', *International Journal of Lean Six Sigma* [Preprint].

Stats NZ (2021) 'Building consents issued:January 2021'. Stats.govt.nz. Available at: https://www.stats.govt.nz/information-releases/building-consents-issued-january-2021.

Tran, V. and Tookey, J. (2011) 'Labour Productivity in the New Zealand Construction Industry: A Thorough Investigation', *Australasian Journal of Construction Economics and Building, The*, 11(1), pp. 41–60. Available at: https://doi.org/10.3316/informit.889725358727409.

Tranfield, D., Denyer, D. and Smart, P. (2003) 'Towards a methodology for developing evidence-informed management knowledge by means of systematic review', *British journal of management*, 14(3), pp. 207–222.

Augmented Geelong: Digital technologies as a tool for place - A case of regional town of Geelong

Md Mizanur Rashid[1], Chin Koi Khoo[2] and Surabhi Pancholi[3]

[1, 2, 3] Deakin University, Geelong, Australia
{md.rashid [1], chin.khoo [2], surabhi.pancholi [3]} @deakin.edu.au
ORCID-0000-0002-7427-240X[1], ORCID-0000-0001-5686-9133 [2], ORCID-0000-0002-8649-2813 [3]

Abstract: To address global competitiveness, contemporary cities are investing into creating and establishing a unique brand identity by revitalisation and resurrection of the past using heritage structures that sets them apart from other locations. In this context, application of digital technologies has unravelled new opportunities in terms of augmenting the experience of space. However, despite their increasing application for branding purposes, there still exist few key questions to be explored in depth: How to define the role and significance of digital technologies such as augmented reality (AR) platforms as a place making tool for developing an informed and inclusive community? What are the key opportunities and challenges in the process of integration of digital resurrection of lost heritage structures aimed at facilitating place making? This design research sets out to address these questions by an initial investigation for the digital resurrection of the industrial past in the regional Geelong. This design-based research develops an early AR platform and applies qualitative methodology for the analysis of data collected from questionnaire surveys from two public workshops based on the applications of the proposed AR platform as showreel and initial AR model. The findings of this paper will provide valuable insights for local and regional decision-making in terms of opportunities and challenges in integrating AR for past resurrection of current heritage structures for developing a sense of place. This outcome introduces a novel way to comprehend digital technologies as a key tool for facilitating place making in developing communities that are inclusive and informed.

Keywords: Digital narrative; Reconstruction; Memory; Placemaking.

1. Introduction

1.1. Background (memories and place-making)

Collective memories are attached to the development of a sense of place and have attachment to its users. Built heritage as a tangible expression of the past is key to re-activate those memories. A building of the past is thus intrinsically attached to the process by which it was produced, and the way it was experienced and perceived through time and space. Thus, the architecture of a city in the collective memory sits intrinsically at the intersection of multiple narratives as palimpsest. Hence capturing the

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 144–155.*

memories, its associated meaning and the lost historical layers are crucial to preserve the built heritage of a place.

To capture the tangible and intangible dimensions of memories or the meanings that people attach, the governments, companies and researchers are exploring creative and community-centred solutions by the integration of digital technologies (Richard and Duif, 2018). Digital placemaking ideas and practical applications–such as immersive experiences, pedagogy and digital simulations–therefore, have seen a wider acknowledgement in the field of creative industries and cultural heritage in the past five years (Basaraba, 2021). Based on the idea of 'narrative geography', i.e., theoretical interaction between space and narrative, put forward by Ryan et al. (2016), Basaraba (2021) argues the proposition of narrative-focused digital place making. In addition to reviving memories, interactive digital narratives are seen as holding a significant potential to create 'edutainment' experiences where the user is educated in areas such as heritage significance in an entertaining manner (Pan et al., 2008). Digital technologies are primarily integrated for creative, artistic, and cultural purposes as a tool for not just increasing awareness on history and culture but also for branding a city image (Cornelio and Ardévol, 2011; Fosh et al, 2013; Pancholi et al. 2015). The role of digital technologies for place making is quite evident by its increasing application to the public spaces to bring together urban audiences around issues of public interest as well as better comprehension of human perception of public spaces (Avouris and Yannoutsou, 2012; Malegiannaki and Daradoumis, 2017; Tierney, 2013; Truijen, 2013; Quercia et al, 2014; Traunmueller at al, 2015; Yoshimura et al, 2020). However, despite its popularity, the concept of digital placemaking–that lies at an interesting threshold criss-crossing different disciplines–still lies at its infancy stage. This research gap leads us to the key research questions that this study aims to address are: How to define the role and significance of digital technologies such as augmented reality (AR) platforms as a place making tool for developing an informed and inclusive community? What are the key opportunities and challenges in the process of integration of digital resurrection of heritage structures aimed at facilitating place making? To address these questions, the current research team selected Geelong as a case study and is recently running a pilot project to test and demonstrate the role and scope of digital technologies for the revival of the lost architectural narrative of Geelong's wool industry.

At this stage, this design-based research proposed an AR platform that represented in a showreel which recreating an interactive digital model of Dennys Lascelles wool store (Bow Truss building) and a small part of the Dalgetty and Co is currently the school of A+B, building of Deakin University) and applies quantitative methodologies for the analysis of data collected from questionnaire survey from two public workshops based on the application of the proposed AR platform. The findings of this paper will provide valuable insights for local and regional decision-making in terms of opportunities and challenges in integrating AR for past resurrection of current heritage structures for developing a sense of place. In doing so, it introduces a novel way to comprehend digital technologies as a key tool for facilitating place making in developing communities that are inclusive and informed.

1.2. The case of the City of Geelong:

In this regard, the city of Geelong posits an interesting case. The city and its hinterland are in the process of transformation as its major industries are shutting down. Luxury housing, hotels, and modern office buildings are sprouting in those industrial sites, resulting in a complete erosion of Geelong's industrial past. This vacancy resulted in a discontinuity into heritage narrative (void/ vacancy/ problem). Hence, the architecture of the city of Geelong in collective memory and its historic narrative raise questions about gaps, or histories untold. The rise of the wool industry and the development of the port town of Geelong could be dated back as early as 1836 (Williangham, 1990). Since then, development and growth of the town has been closely connected with the wool industry for the next one and half a century. As wool became a booming industry for Geelong, the space for wool stores became premium and, hence, in the next few decades, collection of wool stores and warehouses became the main feature of Geelong's urban fabric. Major streets, such as Moorabool Street, Malop Street, Brougham Place, etc., in the Geelong's Central Business District (CBD), are studded with great varieties of new buildings related to the wool industry. The whole central city area was physically reshaped and redesigned to accommodate the new growing business, which had tremendous social and cultural impact on everyday life of the local community of that time.

The rapid rejuvenation of the city of Geelong in the late 1980s forced most of the industrial buildings to be relocated from the city centre, which resulted in the heritage overlay of the city to (gradually) wipe out. The lasting legacy of wool making, as well as industrial architecture, like the legendary Bow Truss Building (Dennys Lascelles wool store), Dalgetty and Co, etc and many others, is eventually on the verge of getting lost from the memories of city dwellers, either because of demolition or major renovation. Tangible and intangible memories are being lost at the cost of development.

As most of the buildings related to Geelong's booming wool industry, including our cases, are demolished, its architectural impact on the morphology of the town is almost lost. Recollection and reconstruction of memories related to wool industry architectural objects and artefacts, and activities tied to it, varies, based on the physical presence of the building in question, because human memories are directly attached to the physicality of our environment. Consequently, the physical disappearance of the wool industry artefacts often means the disappearance of the memories related to it.

2. Digital historic narrative:

Drawing on the latest discoveries in the fields of neuroscience and cognitive psychology, Goldhagen (2017) observes that the physical environment that we inhabit during a particular experience plays the dominant role in memory itself. These findings are hardly novice, as they represent conformation and an addition to many studies that have been conducted in the last century throughout different scholarly fields on the relation of place and memory. Goldhagen explains: "In the contemporary world, where our environments are overwhelmingly built environments, what this means is that building, landscapes, and urban areas we inhabit are central to the constitution of our autobiographical memories, and therefore to our sense of identity" (Goldhagen 2017, p. 83]. Therefore, visualized place-based experiences create a unique framework for self-understanding and perception of who we are.

In The City of Collective Memory, Boyer writes: "Architecture and city monuments can become artifacts and traces that connect the past with the present in imaginative and inventive ways and help to build a sense of community, culture, and nation" (Boyer,1996, p. 309). As such, the value of a finalized physical building is not limited only to its immediate purpose – to protect and organize our lives in a creative, effective and comfortable manner – but its significance lays in an array of intangible meanings that are assigned, through time, to its physical existence and people's interaction with it as a part of the broader urban landscape. Some would argue the immaterial aspect of architecture that only occurs after the building assumes its physicality represents the greatest value that a material edifice can attain because it aids human thought process, recollection, and is a witness of people's lives and histories through time.

2.1. Experiment 1: Interactive Digital Model of Bow Truss Building:

The Dennys Lascelles Concrete wool store, popularly known as Bow Truss Building, is an early 20th century industrial building with an expansive concrete roof; it once stood on Brougham Street, where the modern steel and glass Transport Accident Commission (TAC) building stands today. Along with the Barwon Sewer Aqueduct, this particular building is one of the two most celebrated engineering achievements by Edward Giles Stone, a civil engineer who pushed design boundaries with reinforced concrete in the early 1900s. It was claimed as being the largest flatroof space in the world (almost an acre) without visible support; thus, creating a flood of natural light on the showroom tables by means of roof lighting (Geelong Advertiser, 1910). The site was considered unique and was listed on several heritage registers, including the Register of National Estate and the National Trust register. The building was even nominated as a world heritage listing, which was supported by several inter-national referees. Although this four-storied warehouse was not the first large rein-forced concrete commercial building in Victoria, it is now the most (original) known, and possesses a number of unusual features. Its bowstring roof trusses span 182 feet and contribute a technological feat to the building and a strong visual element to the Geelong skyline. The external cladding is also of reinforced concrete and, thus, is structural, as well as decorative, in a simple Art Nouveau style. As part of a complex (in present day, the National Wool Museum), which began on its site in 1872 under C.J. Dennys, this building perpetuates the advances made in wool marketing by the firm in their earlier buildings.

The fragmented visual and documents resources possess as the main hindrance for the reconstruction of the lost building. This challenge has been addressed using following method (Figure 1):

Stage 1: collection and organization of insufficient heritage data, both tangible and intangible. In this stage, a thorough search was made by the team into all the available digital archives in Australia. Using TROVE (an online database by Australian National Library) as the starting point, the team browsed through different national, state level, and local databases for images, maps, publications, newspaper articles, and any other relevant information regarding the building itself, city of Geelong, and the wool industry in the region. This fragmented information was initially organized chronologically using the online software Sutori, as an online interactive digital platform. Due to the lockdown in Victoria, Australia, the research team members could not meet physically and, hence, Sutori was a very good platform to interact with the information collected by different team members and edit if necessary.

Stage 2: identification of the main historical narratives. Once the collected data were initially organized chronologically, the team focused on identifying different historical narratives associated with building. The team identified three major historical narratives: the narrative of wool industry in Geelong region, the narrative of concrete architecture, and the narrative of urban development in Geelong. The initial database in Sutori was then collated according to the three narratives and different research team members were assigned to look into different narratives, focusing on creating a storyline for dissemination.

Stage 3: reconstruction of the digital model based on the archival evidence. Once the draft storyline of the three narratives were created and a case study building was placed on the intersection of the three narratives, all of the information relevant to the building and its architecture was collated, and a 3D virtual model of the building and the site was made using Rhino based on the available date. The detailed process of the model making, based on the fragmented resources, was described in an earlier section.

Stage 4: collating the narratives into one storyboard. This stage involved collating all three narratives and the virtual model of the building into one storyboard for the general user. The storyboard was designed in a simple and easily accessible way, avoiding all the research related jargon so everyday users could easily grasp the content. However, information of a more complicated nature was linked in such a way that whoever is interested, could also have easy access.

Stage 5: dissemination of the storyboard via an interactive website. The final stage of the research involved developing a bottom-up user-based web framework for capturing the narrative of the building, available at www.dennys lascelles.net (Figure 2). This website is, at this moment, open for user feedback and comments, and contribution through interactive forums. Any user who has memories associated with this building, as well as any images, drawings, or photographs that are relevant, are encouraged to share them through the website. It is anticipated that, after one year of running the website, feedback and contributions will be collated with the main storyline. Hence, a web portal will work in both ways.

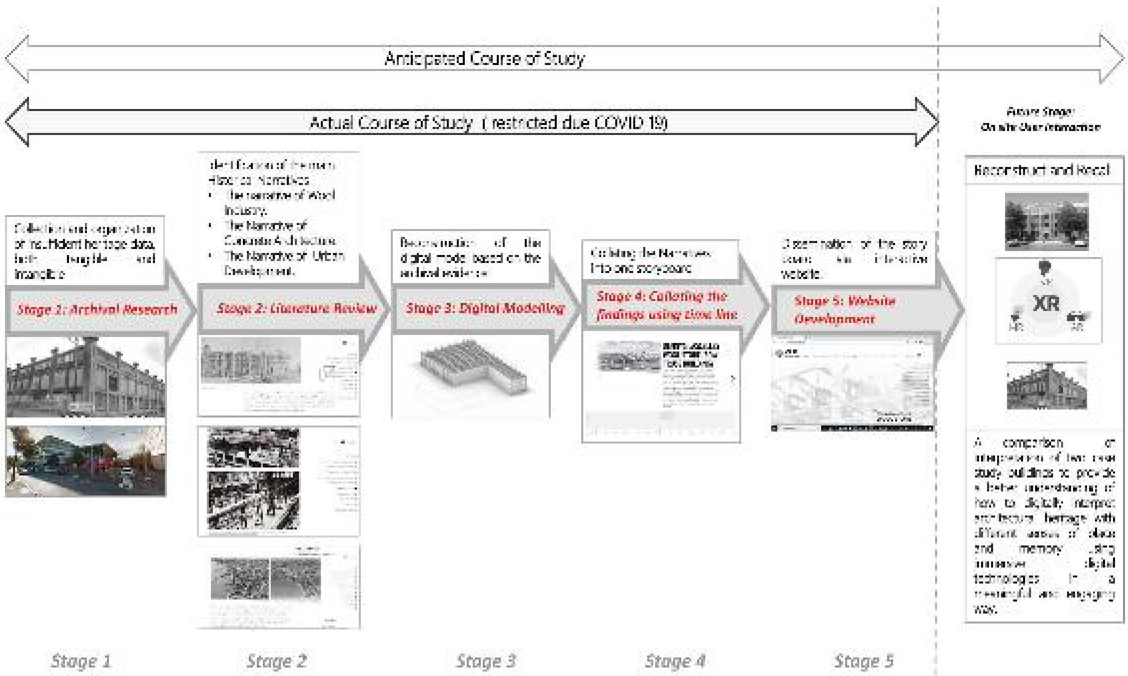


Figure 1. Flow diagram showing the anticipated and actual study of the specific five stages and the proposed future stage (Source: Author 2021).

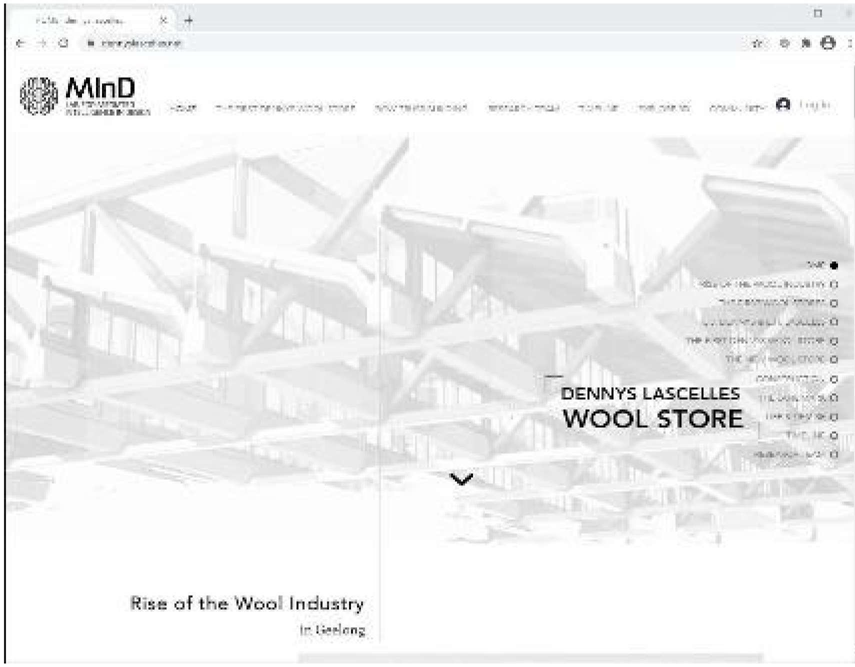


Figure 2. The bottom-up user based interactive website for the project. (Source: Author 2020)

2.2. Experiment 2: The initial AR framework of the Augmented Geelong

The initial proposed Augmented Reality (AR) experiment (to be used in smartphone and tablet) with the onsite QR code, aims at creating augmented virtual walking tours along the memory lanes-specifically for three of the most significant buildings related to Geelong's past, i.e., the lost building of Dennys Lascelles wool store, the renovated Building of Dalgetty and Co, and Cunningham pier. This tour will provide AR experience of indigenous, cultural, and historical significance to the lost heritage of these sites, as well as promote the tourism and local hospitality businesses in Geelong.

It is anticipated that the open-air setting of the QR code will make it easier for a visitor to quickly browse through the memory lane of the town instead of just visiting a conventional museum, library, or archives. With the aim of improving the access of general audiences to the interactive digital heritage content of Geelong’s industry history, the experiment aims to deliver a tangible outcome as a showreel video collates the narratives into a single storyline for AR tour via the proposed feasible AR platform. This showreel visualises the proposed AR platform to illustrate a simulated ‘tour’ with narrative storyboard of the three selected buildings/places to provide the insight of the AR experience that based on the analysed study outcome for the cultural, political and historical significance to the lost heritage of Geelong as well as potential to promote the local tourism and hospitality businesses. This showreel also served as the evaluation tool for the semi structured questionnaire survey for participants to receive the early feedback and comments of the proposed AR platform.

Figure 3: The captures of the showreel to illustrate the proposed Augmented Geelong platform with QR code to illustrate the gamified ‘outdoor museum’ setting (Source: Author, 2022)

2.3. Workshop 1: Showreel and the structured google questionnaire

As this particular project had limitations due to the COVID 19 situation in terms of budget and accessibility and considering the two significant changes of situation, limitation of budget and limitation of time, the research team has decided that instead of providing an initial AR experience for public interaction, the amended proposal would aim towards developing a showreel of the proposed AR app for capturing the interactive AR narrative of the three buildings and evaluate it through a workshop with selected participants and the structured questionnaire (Figure 3).

A workshop was designed run with the 35 students, who are attending the unit of History of Architecture as part of their study. The workshop was designed online due to the pandemic and questioners were answered using Google from. The students were asked questions regarding the show reel and whether it will let them immerse more into the past than the usual way of doing it via archive, museum and library. This workshop serves as the initial evaluation for the proposed AR platform via the showreel and feedback from the participants.

Figure 4: Students and participants to evaluate the AR experience of the original interior space of the old Dalgetty and Co. wool factory (1900s) in the current A+B gallery space through the AR app and the tablets (Source: Author, 2022)

2.4. Workshop 2: AR model of School of A+B Space

Based on the feedback from the first workshop, a second workshop is planned for September 28th, 2022, with 27 students and other participants. The students participated in an onsite prototype AR installation of the original interior space for the old Dalgetty and Co. wool factory (1900s) that experienced through the off the shelf AR app and tablet at the current A+B gallery space of Deakin University and provided feedback through a Google form survey (Figure 4). The survey had eight statements to be rated on a scale of 1-7, with 1 being the least valuable and 7 being the most valuable. The statements are intended to evaluate the level of immersion in the past provided by Augmented Reality (AR) experiences with a reconstructed digital model as well as comprehending the three aspects. To begin, determine whether an understanding of the past is required to engage with a place. Second, determine how engaging and immersive the current AR model under test is for the user, and finally, determine whether AR could be used as a more user-friendly tool to supplement existing digital technologies in heritage dissemination and place making. The workshop and survey results are promising, with more than 77% rating all statements between 5-7 (Figure 5). That is, the majority of participants believed that AR technology could be a more innovative and engaging way of disseminating heritage and providing a sense of place. The research is ongoing, and the following workshop is planned to cater to a larger audience during Geelong Design Week 2023.

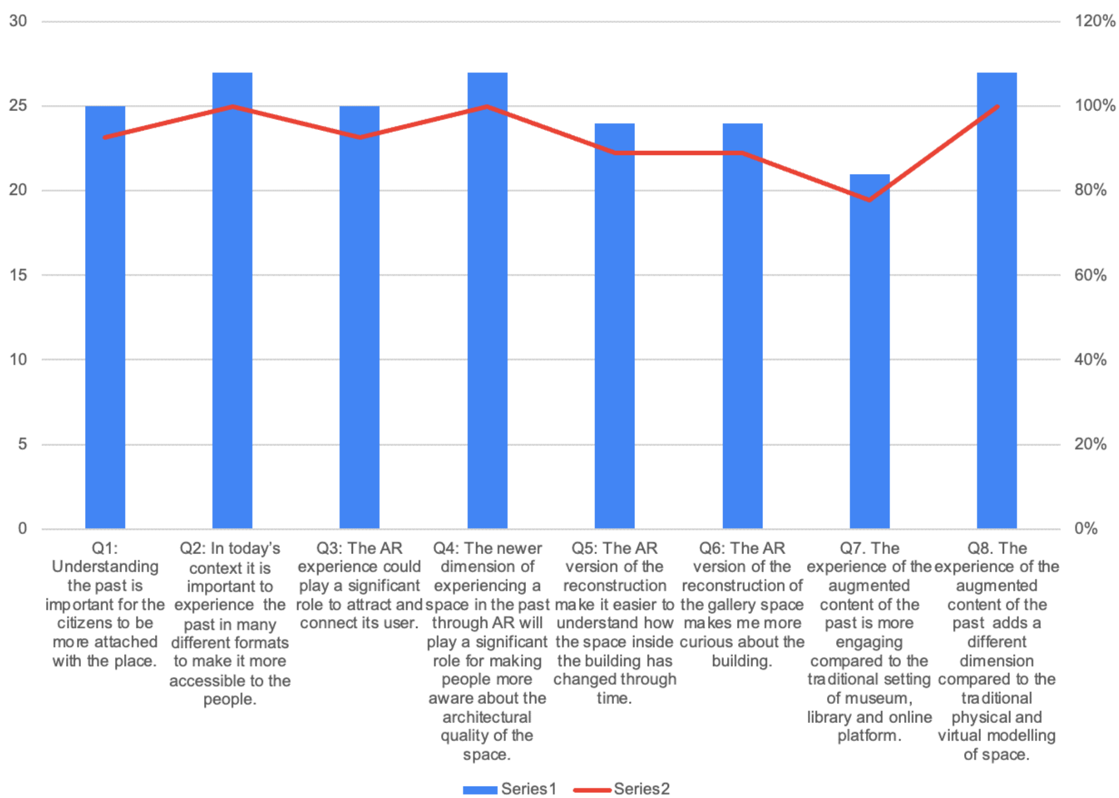


Figure 5: The chart is showing the number and percentage of the responded who rated the statements between 5-7

3. Discussion

The outcome of the project reemphasizes that the meaning of the building and as-sociated collective memories are intrinsically embedded in the process through which the building was conceived, produced, and endured a series of socio-cultural changes (Arendt, 1958). Hence, the history of our built heritage should be centered on the understanding of human experiences, history, and narratives through historic fabric, structures, and remains (Smith, 2006). Being in a telescopic distance, it is always difficult for present day users to be immersed in the past, embodying the memories and meaning of a building, without participating in the performance of rituals and social acts (Abdelmonem, 2016). Buildings of the past, with their very existence, are attached to collective memories of certain groups (Connerton, 1989). Thus, architecture becomes the most tangible and durable object of remembrance, though it could be paradoxical and contested when it engages with collective memory (Kuechler, 1999).

Virtual heritage has significant implications on non-invasive restoration and preservation of the monuments. It generally provides an immersive multimedia experience through a computer-simulated environment that can simulate physical presence in places in the real world (Abdelmonem, 2017). It further provides scope for an interdisciplinary research environment by developing a rich database of the digital assets for the conservators, historians, and archaeologists, to restore the historical sites, as well as heritage preservation. Although, for most of the cases, the 3D virtual models contain accurate data and help with restoration, whether they could capture the associated meanings and memories, especially the intangible values, are a big question for an architectural historian. Thus, the concept of building as "place" along with 3D articulation of the lost building comes in front. "Place" through the articulation of space has been at the concern of architectural theory and practice for the last few decades, and a widely discussed topic of architectural history and theory. Place can be understood in relation to space, though it is not created by mere three dimensionality of space. It is rather 'about the practices and politics of place and identity formation—the slippery ways in which who we are becomes wrapped up with where we are.' (Dovey, 2010). While the assumption of 'place', in the context of this research, is a meaningful interaction to a space where the user, environment, and the memory 'tell it's past… [and] contains it like the lines of a hand' (Calvino et al, 1997), the 3D model of architectural space generally addresses the metric expression of form, shape, and material physicality.

The discipline of history and theory of architecture traditionally focus on the aspects of visual culture best represented by the most advanced image reproduction technique of that time (Langmead, 2018). Introduction of virtual reality (VR) and augmented reality (AR) certainly transformed our capacity to understand structures and resolve issues of plausible historic design that no longer exist (Bruzelius , 2017). With the incorporation of digital humanities into the mainstream research and dissemination process of architectural history, virtual imagery would certainly dominate the entire architectural realm. However, the question remains, to what degree (and how) virtual imagery should be used to convey meanings and memories, as well as interpret them correctly, particularly due to the heavy reliance and ocular-centric nature of these technologies. While these virtual realities may allow us to investigate and recreate the lost architecture, "…they are not likely to help us experience inhabiting that place, moving through that place, or understanding the dynamic and ever-changing relationship of people and place." (Champion , 2011) . The reason may be the overemphasis on the fidelity of the created objects and understanding of ocular engagement in fully understanding "place". Imagery has always been considered as factual and is used to provide evidence in "… legal cases and in science, photographs operate within the modality of actuality. The photographs [the visual] are meant to allow us to discern what actually occurred" (Dovey, 2010); however, it could be misleading if we put them in the wrong context. This is no different to evidence of the historical facts. Therefore, when utilizing visual technologies, such as VR and AR to portray architectural history, a place should be understood to its fullest within the context. We know that icons and symbols provide meaning to architectural form, and these meanings are the intangible aspects of the heritage. As Pallasmaa argued, "... technological culture has ordered and separated the senses... Vision and hearing are now the privileged sociable senses, whereas the other three are considered as archaic sensory remnants with a merely private function, and they are usually sup-pressed by the code of culture " (Pallasma, 2012) . This suppression of other senses and the ocular facilities might provide a false sense of place by conveying a different meaning or sometimes creating a new one. By just creating an ocular narrative of a place through virtual and augmented realities, we could ultimately be removing the intangible feelings, emotions, and cultural memories attached to a space. Without the true encompassing narrative "…no matter how indexical, suitable, or numerous the representations of an object are, what is on the screen will always resolutely remain a representation that stands in for something else" (Langmead , 2018). This re-production of a space becomes its own entity and "establishes their own versions of the past" (Kalay et al. 2007).

Hence, in this particular project, visual aspects of the reconstruction, i.e., photo realization, is considered as part of the narrative of the building. It is considered as just the beginning of disseminating heritage value and connecting the user rather than the product. As discussed earlier, architectural heritage is something more than the physical form. A building is a place for doing different activities in and around. To understand the architecture of this monument, mere virtual reconstruction of the three-dimensional form would not be sufficient. In order to create a virtual environment embodying the essence of place is inevitable. Usually the role of "place" is a virtual environment as a locator of objects (Champion et al, 2002). Thus, the architectural heritage in the collective memory sits intrinsically at the intersection of multiple narratives as palimpsest. Hence, to recover the memories of this building, it is required to identify and examine these narratives along with the virtual modelling. The issue of 'place' becomes crucial while reconstructing the past with limited resources in hand, which are fragmentary and inconspicuous in nature. The temporal distance and the lack of understanding between photo realization of the actual architecture and creating an unbiased sense of place remains at the crux of the problem.

From that aspect, the digital narrative of the Bow Truss wool store building and the interior space of the old Dalgetty and Co. wool factory opened up new opportunities to the public, to communicate and interact with the state's heritage significance. The same approach with the 3D model can also be applied to bring back other damaged, unbuilt, or demolished buildings. For future work, it is planned to scale up the project to use a case study research strategy and the content of Geelong's wool industry heritage to empirically investigate how to communicate architectural buildings with different social values and collective memory (of renovated vs. demolished buildings) among the local community.

4. Conclusion:

After the completion of the 2nd workshop, we anticipate to learn what it means to detach the heritage material from the physical location of origin, and consequently, how it could create a novel "digital heritage space" for the user. Throughout these two experiments and workshops, the attempt is to understand the advantages and drawbacks of construction of "virtual" versus "physical" space in terms of representation of heritage material, and to understand how both can be utilized in a more creative and efficient way. Hence, the team has focused more on developing the AR model for exploring the historic narrative instead of a photo realization of the original building. The key idea was to initiate and demonstrate the process of understanding how digital placemaking can complement physical placemaking, and vice-versa, through utilization and reconstruction of collected heritage material. In other words, the aim was to open the discussion, omitted so far, on construction of memory when the participant's experience was obtained through engagement with "virtual historical space" compared to traditional means of heritage representation related to specific physical space (traditional museums, galleries, monuments, etc.).

The novelty of these two creative reactivation projects lies in the unique, intertwined, and inclusive narrative of the past and its dissemination to the wider audience with a simpler user interface. These dynamic and hybrid narratives will create an immersive heritage experience, through spatial and non-linear story-telling, which will help revive and communicate entangled cultural memories within the community and facilitate unique and creative interpretation of memories in connection to place. in Geelong's CBD, depicting the changing forms and patterns of storytelling of this industrial town over time, and related official historical narratives, is an innovative and a novel research outcome, which will serve to reconstruct the lost heritage building to define its place in the collective conscience of the present-day Geelong Community and beyond in a tangible and accessible format. At this stage the research team is testing the scope of developing an app "Augmented Geelong" (AG) that could be used via QR (Quick Response) code to interact with the past of the city of Geelong. The QR codes, set up in different historical locations in the city, would allow anybody including visitors and tourists an easy access to the interactive mixed-reality historical narrative of the specific place and the town. The whole idea is to reactivate the past in a gamified 'outdoor museum' setting. By engaging in this digital resurrection of the past, the user will be informed and be able to experience the historical narrative in an interactive manner and, moreover, develop a sense of pride and belonging in the process.

Acknowledgements

We acknowledge Chun Wang and Sophanara Sok for his support to do the 3D modelling and showreel and Raihan Rafiq for developing the website. This research was supported by the SEBE Grant Submission Support Fund 2021 and Industry and Community Engagement Support Fund 2022.

References

Abdelmonem, M.G.(2016) The Architecture of Home in Cairo; Socio—Spatial Practise of Hawari Everyday Life; Routledge: London, UK.

Abdelmonem, M.G. (2017) Architectural and Urban Heritage in the Digital Age; Dilemmas of Authenticity, Originality and Repro-duction. ArchNet–IJAR Vol.11, 5–14, doi:10.26687/archnet-ijar.v11i3.1415.

Arendt, H. (1958) The Human Condition, Chicago; Chicago University Press, Chicago.

Avouris, N. M., & Yannoutsou, N. (2012). A review of mobile location-based games for learning across physical and virtual spaces. Journal of Universal Computer Science, 18 (15), 2120–2142.

Basaraba N (2021) The emergence of creative and digital place-making: A scoping review across disciplines. New media & society 1–28.

Boyer, M., Christine, B. (1996) The City of Collective Memory: Its Historical Imagery and Architectural Entertainments, 1st ed.; The MIT Press: Cambridge, MA, USA.

Bruzelius, C. (2017) Digital Technologies and New Evidence in Architectural History. J. Soc. Archit. Hist. Vol. 76, 436–439, doi:10.1525/jsah.2017.76.4.436.

Calvino, I.; Weaver, W. (1997) Invisible Cities; Vintage Classics, Vintage: London, UK.

Champion, E.; Dave, B. (2002) Where is This Place. Thresholds Between Physical and Virtual; Proceedings of ACADIA Pomona (California) , USA pp, 87–97,

Champion, E. (2011) Playing with the Past; Human-Computer Interaction Series Springer: New York, NY, USA.

Champion E (2015) Experimental realism in digital-placemaking. Metaverse Creativity (new title: Virtual Creativity) 5(1): 51–66.

Connerton, P. (1989) How Societies Remember; Cambridge University Press: Cambridge, UK.

Cornelio GS and Ardévol E (2011) Practices of place-making through locative media artworks. Communications 36: 313–333.

Dovey, Kim. (2010) Becoming Places: Urbanism/Architecture/Identity/Power; Routledge: London, UK; New York, NY, USA.

Geelong Advertiser,(1990) 11 November 1910, p. 2. (available at State Library of Victoria, Australia)

Fosh, L., Benford, S., Reeves, S., Koleva, B., & Brundell, P. (2013). See me, hear me, touch me, feel me: Trajectories and interpretation in a sculpture garden. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 149–158). New York, US: ACM.

Goldhagen, S.W. (2017) Welcome to Your World: How the Built Environment Shapes Our Lives, 1st ed.; Harper Paperbacks: New York, NY, USA, 2017.

Kalay, Y.; Kvan, T. (2007) Affleck, J. New Heritage; New Media and Cultural Heritage: Florence, CA, USA.

Kuechler, S. (1999) Forty, A. The Art of forgetting; Berg: Oxford, UK.

Langmead, A. (2018) Art and Architectural History and the Performative, Mindful Practice of the Digital Humanities. J. Interact. Technol. Pedagog. Issue 12. (online version available at https://jitp.commons.gc.cuny.edu/art-and-architectural-history-and-the-performative-mindful-practice-of-the-digital-humanities/)

Malegiannaki, Irini & Daradoumis, Thanasis. (2017). Analyzing the educational design, use and effect of spatial games for cultural heritage: A literature review. Computers & Education. 108. 10.1016/j.compedu.2017.01.007.

Pallasmaa, J. (2012) The Eyes of the Skin: Architecture and the Senses; John Wiley & Sons, Incorporated: Somerset, UK.

Pan Z, Zhang X, El Rhalibi A, et al. (eds) (2008) Technologies for E-Learning and Digital Entertainment: Third International Conference, Edutainment 2008, 5093:25–27. Springer: Nanjing, China.

Pancholi, S., Yigitcanlar, T., & Guaralda, M. (2015). Public space design of knowledge and innovation spaces: learnings from Kelvin Grove Urban Village, Brisbane. Journal of Open Innovation: Technology, Market, and Complexity, 1(1), 13

Quercia, D., Schifanella, R., & Aiello, L. M. (2014). The shortest path to happiness: Recommending beautiful, quiet, and happy routes in the city. In Proceedings of the 25th ACM conference on hypertext and social media, 116–125. New York, US: ACM.

Richards, G and Duif L (2018) Small cities with big dreams: Creative placemaking and branding strategies. New York: Routledge.

Ryan ML, Foote K and Azaryahu M (2016) Narrating space/spatializing narrative: Where narrative theory and geography meet. The Ohio State University Press

Smith, L. (2006) Uses of Heritage; Routledge: Oxford, UK.

Tierney, T.. (2013). Positioning Locative Media: A Critical Urban Intervention. Leonardo. 46. 253-257. 10.2307/23468272.

Traunmueller, M., Marshall, P., & Capra, L. (2015). Crowdsourcing safety perceptions of people: Opportunities and limitations. In T. Y. Liu, C. Scollon, & W. Zhu (Eds.), Social informatics. Springer.

Truijen, K. (2013). Urban dialogues. In Media interventions as assembling devices. Master thesis. University of Amsterdam.

Willingham, A. (1990) The and Death of the Bow Truss wool store (Geelong, Vic): Catch 22 on Corio Bay. Vic. Hist. J. Vol. 61, 96–120.

Yoshimura, Y., He, S., Hack, G. et al. (2020). Quantifying Memories: Mapping Urban Perception. Mobile Netw Appl **25**, 1275–1286. https://doi.org/10.1007/s11036-020-01536-0

Can we design buildings within planetary boundaries? An exploration into using a top-down benchmarking approach for embodied carbon

Emily Newmarch[1], Michael Donn[2], David Dowdell[3], Antony Pelosi[4], Fiona Short[5] and Simon Twose[6]

[1] Victoria University of Wellington, Wellington, New Zealand
{Emily.newmarch [1], Michael.donn [2], Antony.pelosi [4]} @vuw.ac.nz
[3]Building Research Association of New Zealand, Wellington, New Zealand
David.dowdell@branz.co.nz[3]
[5] Warren and Mahoney Architects, Christchurch, New Zealand
Fiona.short@warrenandmahoney.com[5]

Abstract: The way we build, occupy, and dismantle architecture contributes heavily to the global problem of climate change. Accounting for the embodied emissions from buildings is just as important as measuring operational emissions. It's widely recognised that including Life Cycle Assessment (LCA) during design can inform decisions to reduce emissions. However, it is difficult to complete a LCA during the early stages and to define appropriate targets for achieving a project that is within the planetary boundaries (a concept involving earth system processes). Therefore, there is a need for benchmarks that respond to the scale of design decisions and allocate carbon emission targets for different building elements. To support designers in early decision making, this paper explores how a top-down benchmarking approach can be applied to both the building and elemental levels of LCA results. Functional units are applied using full-time employee to create a cap. The approach is applied to typical and non-typical building typologies from the same case study, a koala rehabilitation centre in Queensland, Australia. The case study was selected to form a discussion around the application of top-down building and elemental benchmarks in commercial architecture practice and test limitations. The paper asks the question: how can top-down benchmarks best support early design decisions to reduce the environmental impact of a building? The results show that whilst top-down benchmarks are good at connecting building scale benchmarks with a global carbon budget, the sharing principles used to achieve the benchmark limit their application on non-typical building typologies.

Keywords: Top-Down Benchmark, Embodied Carbon, Commercial, Early Design, Life Cycle Assessment, Planetary Boundaries.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 156–166.*

1. Introduction

1.1. Targeting zero through whole life carbon

New buildings are being constructed at an unprecedented rate, with 260 billion square metres of new construction expected to be added in the next 40 years, the equivalent of rebuilding a city the size of Paris every single week (Lebot 2017). Globally, the building and construction industry contributes 39% of all carbon emissions (Lebot 2017). Many countries have committed to making this industry net zero by 2050 (United Nations 2015). To achieve net zero, consideration throughout the design process needs to be in the context of whole life carbon, which includes both operational and embodied carbon (LETI 2020). In many cases off-setting carbon emissions will compensate for emissions that cannot be designed out. To reduce the reliance on this strategy the Living Future Institute released a Zero Carbon standard limiting projects to 500 $kgCO_2/m^2$ over the full life cycle, before a project can begin to explore offsetting strategies (International Living Future Institute 2020). The London Energy Transformation Initiative (LETI) also presents recommended limits in a similar range. For non-domestic buildings, 1000 $kgCO_2/m^2$ is presented as a baseline, 600 $kgCO_2/m^2$ is presented as best-practice for 2020, and 350 $kgCO_2/m^2$ is presented as best-practice for 2030 (LETI 2020). All these values are targeted towards commercial buildings with a reference service life of 60 years. They also claim to be linked to the initiative to limit global warming to 1.5°C by the IPCC (IPCC 2018). However, none have been transparent about how or even if they have accounted for a global carbon budget or either 50 or 66% confidence.

1.2. Benchmarks to support the Design Process

Between academic literature and green building rating systems, a wide range of benchmarks can be found for the environmental performance of buildings. The term 'benchmark' has many different meanings, and other terms can also be used in its place. EN 16231 outlines the act of benchmarking as a "process of collecting, analysing and relating performance data of comparable activities with the purpose of evaluating and comparing performance between or within entities" (European Committee for Standardization 2012). In this context, the benchmark becomes a "reference or standard value for comparison derived from the benchmarking" (European Committee for Standardization 2012). However, these definitions are still very broad and require a more descriptive framework. The literature provides very few systematic frameworks to set benchmarks and the earliest approaches are documented in the final results of IEA Annex 31 and in the results from working group 4 of ISO TC 59 SC17. ISO 219331-1 (Hernandez Iñarra 2012).

1.3. Spectrum of Performance

Many of the existing benchmarks that can be found in academic literature, building legislation, and building rating systems, fall along a spectrum. Positions along this spectrum have been defined by Häkkinen et al (2012) and Lützkendorf (2012), who differentiate between limit, reference, best practice, and target values (Table 1).

Table 12: Spectrum of Performance

Value	**Definition**
Limit	Minimum acceptable performance
Reference	Average performance or 'Business as Usual'
Best-Practice	Top 10% or 'Best in Class'
Target	Aspirational level of performance

1.4. Top-Down and Bottom-Up Benchmarks

Top-down benchmarks are generated through approaches that scale global carbon budgets down to an industry level. The global budgets typically used are the 2-degree target from the Paris agreement or 2000 Watt Society (Jochem et al. 2004). More recently, global budgets have been developed from reports produced by the Intergovernmental Panel on Climate Change (IPCC 2018). Top-down benchmarks can be considered as "externally motivated benchmarks" (Braune and Wittstock 2011), and must be "translated into building specific targets" (Häkkinen 2012). In New Zealand, studies have presented a framework for translating the 2˚C and 1.5˚C into a residential housing budget (Chandrakumar et al. 2019; McLaren et al. 2020). These studies produced a top-down benchmark in the form of a target value that could then be broken down into operational and embodied benchmarks

Bottom-up benchmarks can generate reference or best practice values for the whole building or relating to parts of the building. These benchmarks can be calculated from studies on assessing reference buildings (Thomas Lützkendorf, Kohler, and König 2012; Ji et al. 2016). or bottom-up benchmarks to be successful, the data needs to be not only available, but also up to date. Research has identified that bottom-up benchmarks found in the literature are context specific and cannot be as easily adopted by another country or transferred from residential to commercial buildings (Lavagna et al. 2018).However, a key benefit of bottom-up benchmarks is the direct association with specific parts of the building, allowing a design team to quickly focus problem solving efforts.

1.5. Problems with benchmarks for application in the design process

Many of the benchmarks that exist today were developed to regulate the performance of the whole building. Hollberg, et al. argued that an issue with the holistic development of benchmarks is that "they only provide limited guidance during the design process" (Hollberg, Lützkendorf, and Habert 2019). This is due to the whole-building benchmark value only indicating if the design does or does not meet the desired performance. As designing for the reduction of embodied carbon is an emerging area, "the designer does not have the 'feeling' of how much better the building could perform" (Hollberg, Lützkendorf, and Habert 2019). For this reason, Hollberg, et al. argued that there is a need for bottom-up benchmarks on an elemental level to support design decision making. Yet, attempting to use both a bottom-up elemental and top-down whole-building benchmark creates another issue, as there is a disconnection between the units used for each, making the two hard to link. These benchmarks are also generated using different methods which do not always align with one another. Therefore, it is difficult to connect decisions on building structure or material selection back to determining if the building overall is within the planetary boundaries. To resolve the disconnection issue, this paper aims to generate a top-down building benchmark and apportion it down to a top-down building benchmark to support designers and the scales they work within.

2. Method

The proposed method uses planetary accounting principles to create a top-down building benchmark for designers. To benefit the design process in a similar way to Hollberg, et al., whose approach combined top-down and bottom-up benchmarks (Hollberg, Lützkendorf, and Habert 2019), the top-down building benchmark is divided into top-down elemental benchmarks. The top-down building and elemental benchmarks are both being presented as a target values, as they define an aspirational level of performance. The aim of this approach is to encourage optimisation of the different building elements and support the analysis of the building's environmental impact during early design but can be applied at all design stages.

2.1. Generating Top-down Building Benchmarks

In this paper the 1.5°C carbon budgets, at 50% and 66% confidence, published from the IPCC (IPCC 2018) are used as a starting point. Planetary accounting methods provide guidance on applying sharing principles to divide the global carbon budget down to a fair share for new construction. Equation 1 represents the approach mathematically.

Equation 1 – Commercial Top-Down Benchmark

$$TF=\left(\left(\left(\left(CB_G \times \left(\frac{P_C}{P_G}\right)\right) \times \left(\frac{E_C}{E_T}\right)\right) \times \left(\frac{V_C}{V_C+V_R}\right)\right) \times \left(\frac{M_C}{M_C+M_R}\right)\right)$$

Where: TF – Top-Down Building Benchmark per m2, CBG – Carbon Budget Global 2020-2050 1.5ºC, PC – Population Country, PG – Population Global, EC – Emissions for the Construction Industry, ET – Emissions Total for country, VC – Economic Value of Commercial Sector 2020-2050, VR – Economic Value of Residential Sector 2020-2050, MC – Average Cost per Square Meter for Commercial Buildings, MR – Average Cost per Square Meter for Residential Buildings.

The sharing principles used to calculate a top-down benchmark are one possible method to achieve a calculated value. The intention of this paper is not to investigate the effect of applying different top-down sharing principles. The method selected is for demonstration purposes only.

2.3. Capping the Top-Down Building Benchmark

The above approach to generate a top-down building benchmark provides a square meter rate that can be used to check the total performance of proposed buildings. An issue with a square metre rate is that it allows projects with larger areas to consume a larger proportion of the budget regardless of how many people occupy it. This issue conflicts with the first sharing principle, where every person is entitled to an equal share of the global carbon budget. Therefore, there is a need to cap the top-down building benchmark using functional units specific to a project. To generate a cap, the last economic sharing principle is replaced with a per full-time employee sharing principle. Here project specific characteristics are used to derive a cap value per equivalent full-time employee.

Equation 2 – Top-Down Building Benchmark Limit per Employee

$$T_E = \left(\left(\left(\left(CB_G \times \left(\frac{P_C}{P_G} \right) \right) \times \left(\frac{E_C}{E_T} \right) \right) \times \left(\frac{V_C}{V_C + V_R} \right) \right) \times \left(\frac{\left(\frac{V_C}{P_C} \right)}{\left(\frac{T_{LC}}{T_J} \right)} \right) \right)$$

Where: T_E – Top-Down Building Benchmark per Employee, T_{LC} – Building Life Cycle Length in years, T_J – Average Job Length in Years

2.4. Top-Down Elemental Benchmarks

Top-down benchmarks at an elemental level serve the designer in supporting an understanding of embodied carbon emissions in different parts of the building and when those emissions occur over the building's life cycle. Dividing up the top-down building benchmark creates elemental target values that enable carbon hot spots to be identified during concept design without a full data set available. As top-down elemental benchmarks, they can be used to answer the question: are all parts of the building within their carbon budgets? In this paper, these values are generated from the results of an externally validated, independent reference building. The target values are used to create guides for operational and embodied emissions.

2.5. Calculating LCA of the Case Study Building

To calculate the embodied carbon emissions over the life cycle of the case study, etoollcd was used as the material library is localised to Australia. The service life was set to 60 years. As the project is in the concept stage, templates were made to standardise the wall, floor and roof construction assemblies.

2.6. Case-Study – Koala Rehabilitation Centre

The case study selected for this paper is to test the top-down benchmarking approach and is not to be used as a reference or benchmarking building for other buildings. This case study is a concept design for a Koala rehabilitation center in Queensland, Australia. Two buildings from the proposal have been selected, an office with standard number of employees per floor area to represent a typical typology and a koala rehabilitation center with low employees per floor area to represent a non-typical typology. Of course, employees in each building are not necessarily mutually exclusive. The comparison between typical and non-typical building typologies tests the top-down benchmarking approach against a spectrum of commercial building typologies.

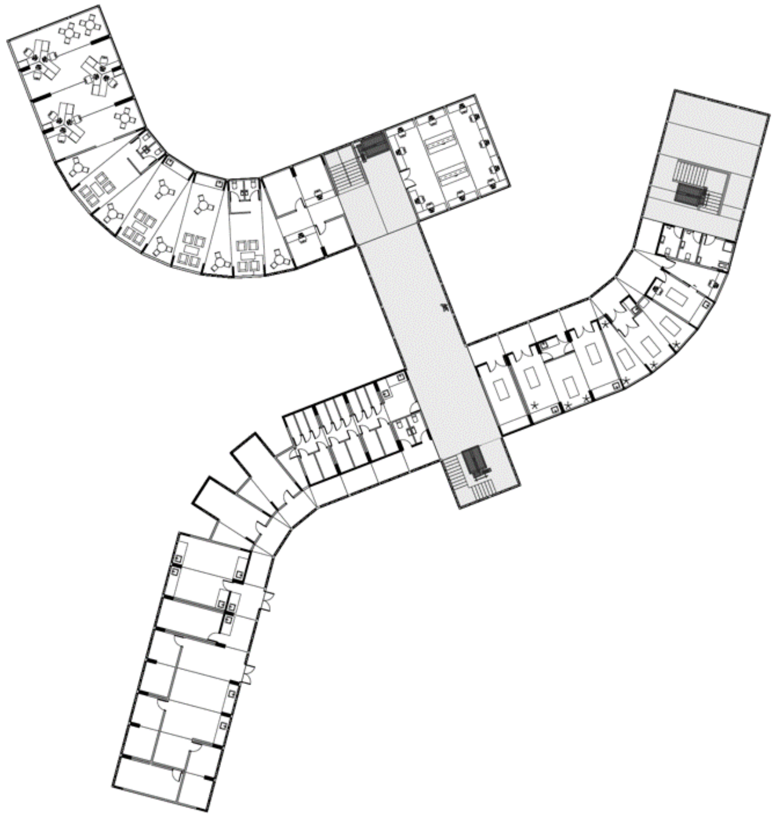


Figure 26: Representative floorplan of both buildings. Office building above and Koala clinic below.

3. Results

3.1. Top-Down Building Benchmarks

Based on the method outlined in this paper, the calculated target values for commercial buildings in Australia were 215 $kgCO_2/m^2$ and 160 $kgCO_2/m^2$ using the IPCC 1.5ºC budget at 50% and 66% confidence. These benchmarks can be considered against the target value in the Carbon Zero Standard by the Living Futures Institute, which is set at 500 $kgCO_2/m^2$ (International Living Future Institute 2020).

3.2. Top-Down Elemental Benchmarks

To support designers in early detection of embodied carbon hotspots, the top-down building benchmark is divided up using percentage ratios from a reference building. The reference building was a commercial typology available within eToolLCD and is assumed to be a representation of a standard Australian office building. No other building typologies are offered as reference buildings within the tool, so the office building has been applied to the analysis of the non-typical typology. Table 2 shows an example of the target values calculated using a reference office building.

Table 2: Office Building Element Level Benchmarks

Building Elements	**CB·50% (kgCO2/m2)**	**CB·66% (kgCO2/m2)**
Equipment	4.49	3.32
Substructure	22.22	16.45
Superstructure	11.32	8.38
Internal Finishes	5.55	4.11
Services Equipment	5.34	3.95
External Works	0.21	0.16
Operational Energy	162.99	120.65
Water Use	1.50	1.11

CB* = Carbon Budget at 1.5°C, Equipment* = Construction equipment and earthworks

3.3. Case Study Carbon Emissions

Figure 2 shows the partial LCA performance simulation results broken down into building element categories. Note that the substructure and operational energy were outside of the scope of the LCA for the case study and the focus was on the superstructure and internal finishes to evaluate the concept design. The top-down elemental benchmarks calculated above are shown as two lines to guide the expected distribution of emissions to achieve the top-down building benchmark. Representing the simulation data in this way shows how top-down elemental benchmarks can identify what parts of the building are using above their calculated share.

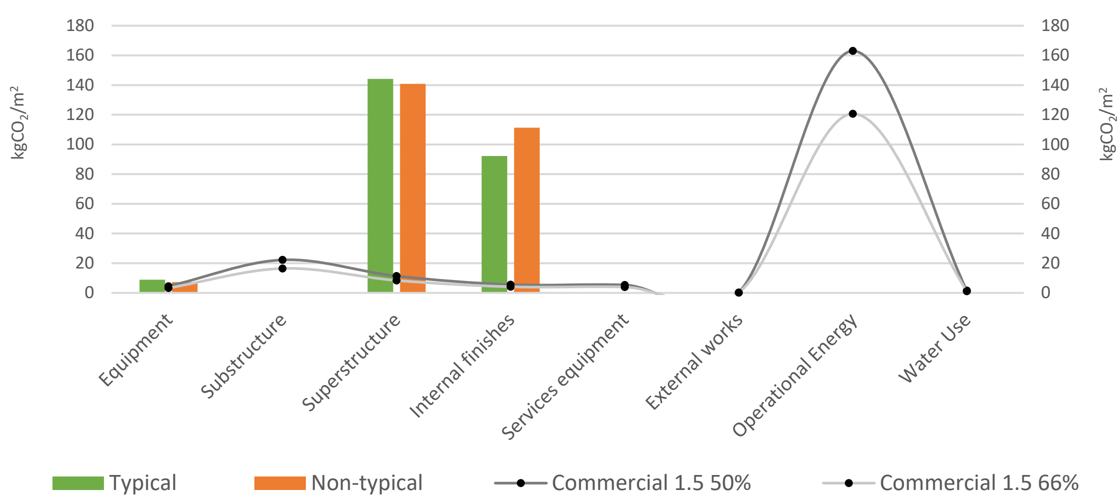


Figure 2: Top-Down Elemental Benchmarks using Building Element Categories

3.4. Caps Using Full-time Employee

To relate the top-down building benchmarks to project brief requirements of different buildings within the same project, a top-down building benchmark per equivalent full-time employee was calculated.

Table 13: Top-Down Building Benchmarks per Full Time Employee (rounded)

	CB 1.5 (50%)	**CB 1.5 (66%)**
kgCO2/employee	4200	3110

3.5. Top-Down Limit Benchmarks

The cap value was generated by multiplying the top-down benchmark per employee by the number of employees in the brief. This was then divided by the top-down building benchmark per floor area to generate a recommended area. Figure 3 shows a comparison between the recommended area and the area in the concept design. The consistency between the results for 50% and 66% (confidence from IPCC budgets) are aligned due to the top-down building benchmark per employee and per floor area being proportionally different by the same amount. The difference between the results for typical and non-typical building typologies are discussed below.

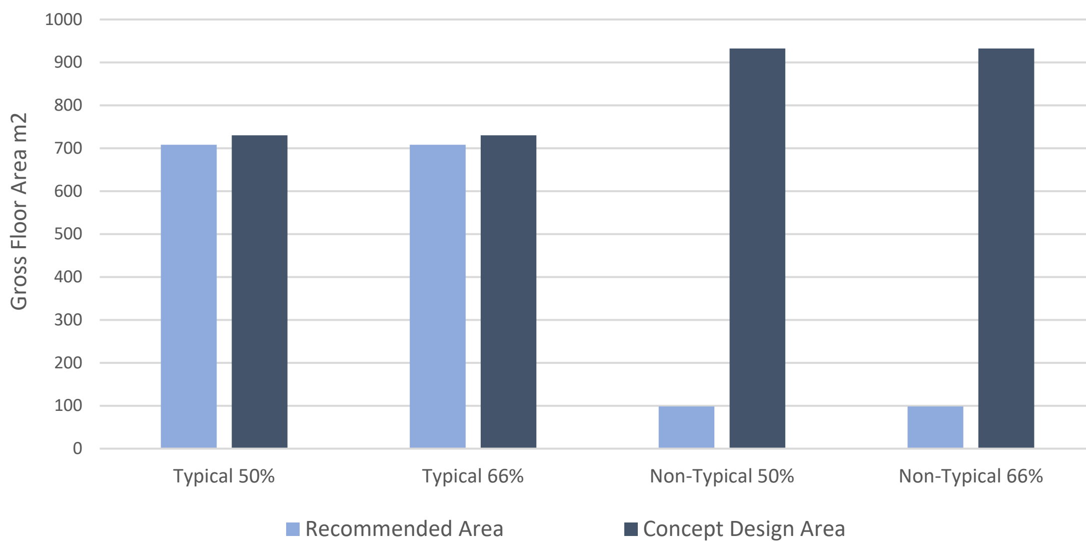


Figure 3: Recommended area v concept design area for typical and non-typical buildings

4. Discussion

4.1. Using top-down elemental benchmarks to guide decisions.

Top-down elemental benchmarks have the clear benefit of foresight, allowing the design team to plan for the distribution of carbon emissions in a project before all the full analysis has been completed. In the context of this paper the top-down elemental benchmarks are limited to the building element categories within the LCA software, eToolLCD. They benefit the design process as they enable easy analysis of the building in parts and allow a design team to identify opportunities to make reductions early. The top-down elemental benchmarks are only meant to guide designers towards a recommended pathway to meeting the top-down building benchmark. As a guide the design team has the freedom to reallocate the area under the line graph (fig 4) to customise their own pathway. For example, in the context of the case study, the materials used for the superstructure and internal finishes are very high but could be balanced out by achieving large reductions in operational emissions. Overall, top-down elemental benchmarks enable the ability to make decisions between embodied and operational emissions early in the design. These benchmarks provide an opportunity for designers to be creative and innovative with creating new pathways to achieving reduction targets. Understanding how different pathways to achieving reduction targets can be specific to building typology is a large area for future research.

4.2. Is a top-down benchmarking approach fair?

This paper incorporates several sharing principles to calculate a carbon budget from the use of, per capita, grandfathering (assuming the same proportion of emissions from a previous period to apply to the next) and economic sharing principles. These were used to generate top-down building benchmarks per square meter of floor area. The foundational sharing principle assumes all people are entitled to an equal share of the global budget. A top-down building benchmark, using full time employees as a functional unit, has also been calculated to restrict financial privilege. Using functional units as a way of representing top-down building benchmarks has the potential to be applied in pre-design before any concept has been created using the method to generate a recommended area. This exercise could help design teams allocate targets for individual buildings in a large commercial project where there are several different functional requirements.

In the application of the top-down building benchmarks to the case study, figure 3 compared the size recommendations against the concept design area for a typical and non-typical building. The typical building had a very close match due to the program of the space being composed of different working stations creating a high employee per floor area ratio. Therefore, the number of functional units increased for this building, which increased the total budget and total floor area. On the other hand, the non-typical building (koala clinic), which hosted much of the koala rehabilitation facility had a very low carbon budget based on functional units. The large difference between the recommended area and concept design area is due to a low number of employees per floor area, as the building's primary purpose is to serve koalas.

Whilst allocating a carbon budget for animals kept as pets or grown for food would be possible, wildlife is a form of biomass that is assumed to be in a net zero or carbon positive life cycle. As the world experiences the negative effects of climate change, such as the destruction of natural environment and large species loss (as witnessed in Australia's unprecedented bushfire season), there is a growing need for architecture to supplement and support these animals. However, as an architectural typology that is considered as non-typical when compared to an office building, it falls outside of the scope of the top-down benchmarking approach used in this paper. The finding that a non-typical building typology may not always conform to a top-down benchmarking approach that works for office buildings is useful to be aware of for any commercial architectural practice, as the world does not just build offices.

5. Conclusion

In a time where climate change is one of the biggest threats to all life on earth, it is critical that the way we design buildings is within global carbon budgets set to limit warming to 1.5°C. As LCA becomes more frequently integrated into standard practice, different professionals and stakeholders have a need for environmental top-down benchmarks. For investors, building owners and clients top-down benchmarks help define full project target values that are within the planetary boundaries. For designers, these target values can be worked towards through the support of top-down elemental benchmarks to guide the design process and help manage external consultants, for example structural engineers. This paper also demonstrated that top-down elemental benchmarks can be used to enable partial building analysis with the context of other elemental target values as placeholders to allow for early detection of carbon hotspots.

Incorporating functional units into the framework for calculating a top-down building benchmarks allows caps to define how big a building should be relative to the project brief. In the context of the case study, top-down building benchmarks could be calculated per equivalent full-time employee. In the typical building (office) these benchmarks provided a close match to the designed building size. However, these cap values failed to adequately generate an appropriate size for the non-typical building (koala rehabilitation facility) as there were significantly less employees per floor area compared to the typical building. Additionally, wild animals could not be used as a functional unit to form a top-down benchmark. This limitation could also apply to other buildings that have non-typical programmes, meaning alternative functional units should be considered.

The application of the top-down benchmarking approach developed in this paper on typical and non-typical buildings ultimately calls for further discussions around how to appropriately generate, define and use benchmarks to support the design process. The proposed approach and case study analysis is one contribution to this discussion.

References

BRANZ, Building Research Assoication New Zealand. 2017. 'Building Life Cycle Assessment'. BRANZ. BU608.

Braune, A., and B. Wittstock. 2011. 'Measuring Environmental Sustainability: The Use of LCA Based Building Performance Indicators'. In Life Cycle Manag Conf.

Bruce-Hyrkäs, Tytti. 2018. '7 STEPS GUIDE TO BUILDING LIFE CYCLE ASSESSMENT OR WHY YOU NEED LCA TO BUILD SUSTAINABLY'. Guide. One Click LCA.

Chandrakumar, C., S. J. McLaren, D. Dowdell, and R. Jaques. 2019. 'A Top-down Approach for Setting Climate Targets for Buildings: The Case of a New Zealand Detached House'. IOP Conference Series: Earth and Environmental Science 323 (September): 012183. https://doi.org/10.1088/1755-1315/323/1/012183.

European Committee for Standardization, CEN. 2012. 'CEN - EN 16231: Energy Efficiency Benchmarking Methodology'. CEN.

Frischknecht, R., H. Birgisdottir, C.-U. Chae, T. Lützkendorf, A. Passer, E. Alsema, M. Balouktsi, et al. 2019. 'Comparison of the Environmental Assessment of an Identical Office Building with National Methods'. IOP Conference Series: Earth and Environmental Science 323 (September): 012037. https://doi.org/10.1088/1755-1315/323/1/012037.

Frischknecht, R., L. Ramseier, W. Yang, H. Birgisdottir, Ch U. Chae, T. Lützkendorf, A. Passer, et al. 2020. 'Comparison of the Greenhouse Gas Emissions of a High-Rise Residential Building Assessed with Different National LCA

Approaches – IEA EBC Annex 72'. IOP Conference Series: Earth and Environmental Science 588 (November): 022029. https://doi.org/10.1088/1755-1315/588/2/022029.

Häkkinen, Tarja. 2012. Sustainability and Performance Assessment and Benchmarking of Buildings: Final Report. VTT Technical Research Centre of Finland. https://cris.vtt.fi/en/publications/sustainability-and-performance-assessment-and-benchmarking-of-bui.

Hernandez Iñarra, Patxi. 2012. 'Developing Benchmarking Criteria for Sustainable Buildings'. In Sustainability and Performance Assessment and Benchmarking of Buildings, 190–233. VTT.

Hollberg, Alexander, Thomas Lützkendorf, and Guillaume Habert. 2019. 'Top-down or Bottom-up? – How Environmental Benchmarks Can Support the Design Process'. Building and Environment 153 (April): 148–57. https://doi.org/10.1016/j.buildenv.2019.02.026.

International Living Future Institute. 2020. 'Zero Carbon Standard'. International Living Future Institute.

IPCC. 2018. 'Global Warming of 1.5 oC'. Special Report.

Ji, Changyoon, Taehoon Hong, Jaewook Jeong, Jimin Kim, Minhyun Lee, and Kwangbok Jeong. 2016. 'Establishing Environmental Benchmarks to Determine the Environmental Performance of Elementary School Buildings Using LCA'. Energy and Buildings 127 (September): 818–29. https://doi.org/10.1016/j.enbuild.2016.06.042.

Jochem, Eberhard, Göran Andersson, Daniel Favrat, Heinz Gutscher, Konrad Hungerbühler, P. R. von Roh, Daniel Spreng, Alexander Wokaun, and Mark Zimmermann. 2004. 'A White Book for R&D of Energy-Efficient Technologies'. CEPE-NOVATLANTIS Sustainability Forschung Der ETH Zürich, Zürich.

Lavagna, Monica, Catia Baldassarri, Andrea Campioli, Serena Giorgi, Anna Dalla Valle, Valentina Castellani, and Serenella Sala. 2018. 'Benchmarks for Environmental Impact of Housing in Europe: Definition of Archetypes and LCA of the Residential Building Stock'. Building and Environment 145 (November): 260–75. https://doi.org/10.1016/j.buildenv.2018.09.008.

Lebot, Benoit. 2017. 'Global Status Report 2017', 48.

LETI. 2020. 'LETI Climate Emergency Design Guide'. London, United Kingdom: London Energy Transformation Initiative.

Lützkendorf, T., N. Kohler, H. König, and M. Balouktsi. 2012. 'Building Sustainability Assessment—from Calculation to Valuation'. In BSA 2012-Proceedings of the 1st International Conference on Building Sustainability Assessment. Green Lines Institute for Sustainable Development Porto.

Lützkendorf, Thomas, Niklaus Kohler, and Holger König. 2012. 'Integrated Life Cycle Assessment : Benchmarks and Uncertainty', 27.

McLaren, S. J., C. Chandrakumar, D. Dowdell, L. Bullen, and R. Jaques. 2020. 'Application of Absolute Sustainability Assessment to New Zealand Residential Dwellings'. IOP Conference Series: Earth and Environmental Science 588 (2): 022064. https://doi.org/10.1088/1755-1315/588/2/022064.

Sturgis, Simon. 2017. Targeting Zero: Embodied and Whole Life Carbon Explained. Newcastle upon Tyne: RIBA Publishing.

United Nations. 2015. 'PARIS AGREEMENT'.

Circular economy software tools at the material and product level: A scoping review

Santiago Muñoz[1], M. Reza Hosseini[2] and Robert H. Crawford[3]

[1, 2] Deakin University, Geelong, Australia
{Smunozvela [1], reza.hosseini [2]} @deakin.edu.au, ORCID-0000-0003-2249-7831[1], ORCID-0000-0001-8675-736X [2]
[3] The University of Melbourne, Melbourne, Australia
rhcr@unimelb.edu.au, ORCID-0000-0002-0189-3221 [3]

Abstract: There has been an increasing interest towards measuring the environmental performance of circular economy (CE) strategies. To this end, a wide range of software tools (STs) has been developed, each one with different guidelines that rely on specific indicators and approaches to measure the environmental performance of CE strategies. An overview of this topic is, however, missing in the literature. This paper aims to address this gap by providing an updated picture of the research landscape on current indicators and STs available for measuring the environmental performance of CE at the material/product level. A scoping review is conducted to provide a comprehensive list of available STs for measuring the environmental performance of CE strategies at the material and product level, and identifying the overarching guidelines and indicators STs are based on. Findings demonstrate a comparative analysis of the benefits and weaknesses of each ST and overarching guidelines. Besides providing a list of the most common environmental assessment techniques, this scoping review explores the level of expertise required for each ST based on the STs interactions, available guidelines and learning sources. This paper contributes to the field by providing an updated picture of current STs. As the first attempt of this kind, this article reveals the availability of STs for measuring the environmental performance of CE at the material and product level, providing a fertile ground for future research. In practical terms, a comprehensive point of reference for measuring the environmental performance of CE is offered for policymakers and practitioners.

Keywords: life cycle assessment, circular economy, tools, indicators.

1. Introduction

A transition from the current linear economic model to a more circular one has been proposed as one key approach for reducing the environmental impacts that human activities generate (Ellen MacArthur Foundation, 2012). Circular economy (CE) has several definitions. For the authors, one of the most

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 167–176.*

comprehensive ones is the definition proposed by Zhai (2020, p. 24), which defines CE as "*an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and eliminate the waste through the superior design of materials, products, systems and business models. It operates at the micro-level (e.g., products, companies, consumers), meso-level (e.g., eco-industrial parks), macro-level (e.g., city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously increase environmental quality, economic prosperity and social equity, and benefit current and future generations*". This definition identifies that CE is not only about waste reduction practices, but also about reducing environmental impacts at all levels (Figure 1).

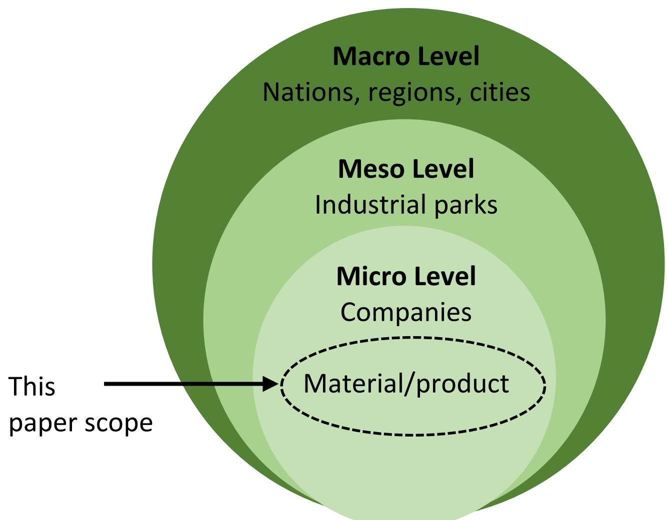


Figure 27. Circular economy system levels. Adapted from Vanhamaki *et al.* (2019)

Within CE definition, several frameworks have been proposed. For instance, the 10R framework defines ten strategies. From the most effective to the least one, the 10R strategies are: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover (Kirchherr *et al.*, 2017; Potting *et al.*, 2017). Similarly, the RESOLVE framework defines six actions businesses and governments can do to transition to a CE. The six actions are: REgenerate, Share, Optimise, Loop, Virtualise, and Exchange (Ellen MacArthur Foundation, 2015b). Indeed, these frameworks define different approaches to implementing CE at all levels.

Although CE is considered a possible solution to human environmental impacts (Ellen MacArthur Foundation *et al.*, 2018; Ghisellini *et al.*, 2018; PwC, 2021), CE scenarios must be assessed, as they do not always achieve environmental benefits. For instance, Buyle *et al.* (2019) found that applying a CE model to a product does not necessarily mean it is more sustainable. Furthermore, Stephan *et al.* (2020) identified that the heaviest materials are not always the ones with the highest environmental impacts. Indeed, the relationship between material/product waste and environmental impacts is not always linear. Thus, sustainable assessment approaches for evaluating and measuring CE environmental impacts are necessary as means towards ensuring that the real intentions of CE are achieved.

Several review studies on CE have been done to identify the best sustainable approaches at each system level. These include studies by Su *et al.* (2013) at the macro-level, Lieder and Rashid (2016) at the meso-level, and Pieroni *et al.* (2019) at the micro-level. Despite the added value of these reviews, they focus largely on theoretical aspects, as a result of which, identifying and analysing related software tools (STs) at each CE level has remained a gap in the literature. For this article, STs relate to any software program or application used in electronic devices such as computers and phones. STs can perform specific functions, providing an interface for end-users, and facilitating the process to achieve an outcome (Cambridge Dictionary; Oxford reference). To help practitioners and researchers consider the environmental implications of CE scenarios, this article aims to generate a scoping review of STs now available to assess the environmental performance of CE strategies and principles at the material/product level. The main questions and sub-questions that this paper intends to answer are hence formulated as:

Main question

- Which STs are available to assess the environmental performance of circular economy (CE) strategies and principles at the material and product level?

Sub-questions

- Which overarching guidelines/standards are implemented in the identified ST?
- Which environmental indicators are implemented in the identified ST?

2. Research Methods

This paper has been framed as a scoping review. Unlike other systematic review methods, which aim to address specific questions, scoping reviews can be used to map the key concepts that underpin a field of research (Arksey and O'Malley, 2005). Indeed, scoping reviews have a clear bias towards exploring the current state of literature, mapping and summarising scientific evidence, and inform future research (Tricco *et al.*, 2016). Scoping reviews are therefore ideal in nascent fields where traditional systematic reviews do not exist (Gutierrez-Bucheli *et al.*, 2022). To provide consistency, this scoping review paper follows the JBI manual for evidence synthesis, and the final text was verified with the PRISMA scoping review checklist (Tricco *et al.*, 2018; Munn Z Aromataris E, 2021). The filled PRISMA checklist can be accessed through figshare (Muñoz, 2022).

2.1. Search strategy

The PRISMA flow diagram has been omitted for space limitations, but below there is a detailed description of the steps generated. A preliminary review of academic articles was conducted through Scopus database to identify the most suitable one. It was found that although some academic publications state the development of CE environmental assessment ST, the actual tools were not included within to the articles (Griffiths and Cayzer, 2016; Favi *et al.*, 2019). In essence, no major scholarly work presented an accessible ST. Considering that scoping reviews put greater attention to grey literature (Gutierrez-Bucheli *et al.*, 2022), and to centre the discussion on STs that can be easily accessed, Google search was selected as the searching database. Google search considers grey literature, key for achieving this article’s aim, as companies and not-for-profit organisations develop several commercial STs. Even more, as found in the preliminary search on Scopus, the final STs that become available after academic research are more likely to be accessed through the Google search engine rather than academic databases. The search string used was:

"Circular economy" AND "software" OR "online tool" AND "material" OR "product"

Generating the mentioned string search on the 20th June 2022, 190 websites appeared. Excluding PDF links, all websites were reviewed. In cases where the website redirected to articles, news or any type of text link, a complete revision of the text was generated to identify if any suitable STs was described. Only STs in English language that had the environmental assessment CE strategies and principles at the material/product level as its primary aim were included.

2.2. Screening process

From the initial search, 33 STs were found. After revising their website, STs categories were categorised based on their CE systems levels. 13 tools were oriented at the business level, with six being administrative tools with plugins or sections oriented to CE. Moreover, three STs were oriented towards entire buildings. STs that aimed at entire buildings, companies, meso or macro levels were excluded (refer to Figure 1). Contemplating the focus of this article on STs at the material/product level, 17 STs were found. These were considered for the next stage of the analysis.

3. Findings

The 17 material/product STs were deeply analysed, including their website, guidelines, reports and free trial versions (if available). The inclusion criteria for the chosen STs were: 1) they had as their primary purpose the environmental assessment of CE, and 2) the STs website was publicly available. For instance, STs for administrative purposes that could be used partially for environmental measurement were not considered. Five STs did not comply with one or both of these criteria, reducing the final number 12 STs, as tabulated in Table 1.

Seven of the 12 STs analysed were dynamic websites, representing 58% of the total tools. The other STs, three were available as mobile phone applications, while three used desktop apps. Moreover, 10 STs were accessible through Windows operating system, representing 83% of the total ST. None of the found STs were created by a single developer. Instead, all were developed by companies or not-for-profit organisations, which somehow indicates the complexity of developing them. Additionally, different overarching guidelines and standards were found in most STs. Indeed, only three clearly stated their overarching guidelines and standards (Circular IQ and KPMG, n.d.; IDEAL&CO Explore BV, n.d.; Sphera, n.d.).

3.1. Indicators used in ST

Indicators vary considerably across various ST. Two STs do not clearly state their environmental assessment approach (ANSYS Granta and Ellen MacArthur Foundation, n.d.; Circularise, n.d.). Applying a qualitative approach, *the circularity check* measures five indicators based on answers obtained through their questionnaire (Ecopreneur, 2022). Regarding quantitative approaches, the use of Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) techniques are prevalent. Based on these two techniques, different indicators are proposed. The *CTI tool* and *the Circular IQ platform* propose their own framework considering four categories and 11 indicators (Circular IQ and KPMG, n.d.; WBCSD *et al.*, n.d.), *The Circularity calculator* defines four key performance indicators (Pauw *et al.*, 2021; IDEAL&CO Explore BV, n.d.), *PIQET* uses the Ecoinvent database, providing up to 22 indicators, while *Idemat* and *IdematLightLCA* have predefined assessments for carbon footprint and eco-cost; *IdematLightLCA* provides the option for the end-user to include other environmental impact categories for each life cycle stage

(Marinus Meursing, 2021a; 2021b), *CE analyst* implement two indicators (KATCH_e, n.d.), while *Material Circularity Indicator (MCI)* considers eight indicators which are aggregated to produce a single score and general indicator (Ellen MacArthur Foundation, 2015a). The *MCI* has also been used in the *GaBi circularity toolkit*, which generates the *MCI* score and LCA impact categories assessment (Sphera, n.d.).

Table 14. Software tools to assess environmentally circular economy strategies and principles at the material and product level

Tool name	**Access-ibility**	**Environmental categories/ Indicators**	**Overarching guidelines/ standard**	**Organisatio n**	**Level of expertise**	**Platform support**
GaBi Circularity Toolkit	Free trial	MCI score, LCA environmental categories	ISO 14040/ 14044, PAS2050 and GHG protocol	Sphera	P	Desktop app
CTI Tool	Free trial	Four categories, Close, optimise, value and impact of the loop, 11 indicators in total	Propose the circular transition indicators framework	WBCSD, KPMG, Circular IQ	P	Dynamic webpage
The Circular IQ platform	No free trial	Same indicators described above	GRI, C2C certified, ISO 14040/14044	Circular IQ, KPMG	P	Dynamic webpage
Circularise	No free trial	Not shared on website	Not found	Circularise	P	Desktop and phone app
Circularity calculator	Free trial	Four key performance indicators for improving circularity across product generations: Circularity, value capture, recycled content, reuse index	Not found, but one conference article discusses details on how indicators are measured	IDEAL&CO Explore BV	I	Dynamic webpage
The Circularity Check	Free to use	Five indicators: Circularity design procurement & production, delivery, use, recovery and sustainability	Not found	Ecopreneur , WeSustain	P	Dynamic webpage
MI: Product Intelligence	Free trial only CE100 members	Not shared on website, but mentions a "product circularity indicator"	Not found	ANSYS Granta, Ellen MacArthur Foundation	P	Dynamic webpage
PIQET	Free trial	16 indicators, including carbon footprint, water footprint, product environmental footprint from the European Union, marine and terrestrial litter, global packaging protocol indicator, renewable content, and material circularity index.	Not found, but uses Ecoinvent database, which follows ISO14040/14044 standards	PIQET	P	Dynamic webpage

Tool name	Access-ibility	Environmental categories/ Indicators	Overarching guidelines/ standard	Organisation	Level of expertise	Platform support
CE analyst	Free to use	Carbon footprint and maximum circular value capture (MCVC)	Not found, but guideline uses EPD as LCA database which is based on ISO14040/14044/ 14025 standards	KATCH_e	I	Dynamic webpage
Idemat	Free to use	Resource depletion, Eco-toxicity, Human health, carbon footprint, eco-cost	Not found	Marinus Meursing	B	Phone app
IdematLight-LCA	Free to use	End-user can change environmental impact categories. Predefined carbon footprint and eco-cost	Not found, although it uses SimaPro databases which follow ISO 14044-14044	Marinus Meursing	P	Phone app
Material Circularity Indicator (MCI)	Free to use	Eight indicators grouped into a single indicator	Not defined in guideline, but states the importance of using BSI, ISO and GHG protocol in calculations	Ellen MacArthur Foundation	P	Spread sheet

Note: Level of expertise: P= professional, I = Intermediate, B = Beginner.

Among the most used indicators, 6 STs, representing 50% of the total, consider carbon footprint, acknowledging their interest in the mitigation of Greenhouse Gas (GHG) emissions and reducing climate change (PIQET, 2017; Marinus Meursing, 2021a; 2021b; Circular IQ and KPMG, n.d.; KATCH_e, n.d.; WBCSD *et al.*, n.d.). Moreover, 42% of the tools implement indicators related to MFA, aiming at closing loops, reducing waste and incentivising the use of the 10R strategies (Ellen MacArthur Foundation, 2015a; PIQET, 2017; IDEAL&CO Explore BV, n.d.; Sphera, n.d.; WBCSD *et al.*, n.d.).

3.2. Circular economy environmental assessment software tools: An overview

The following section discusses key findings on each of the final 12 STs considered within this paper scope. This section complements the outcomes presented on Table 1.

GaBi is an ST that can produce environmental and economic LCA. End-users define activities to analyse the scope of assessment and select LCA coefficients from a list of available databases. It can be used to address circularity from a company perspective or a material/product perspective. *The circularity toolkit* implements *GaBi* to help determine the *MCI* score and economic and environmental LCA impacts (Sphera, n.d.).

The *CTI Tool* is based on a free-to-read framework. The tool establishes circularity indicators based on material flows, water consumption, renewable energy, critical materials, recovery type, value in the loop and GHG impacts of the loop. It defines 7-steps, including defining the scope of the assessment. The end-user defines material inputs and outputs to measure circularity; It provides visual representations of results. Finally, *CTI Tool* outputs the CTI report, which comprises an analysis of the material flows in a visual representation (WBCSD *et al.*, n.d.).

The Circular IQ platform is a step-by-step program that helps gather actionable insights into the eco-impact and circularity of products. Following a 5-step process and a digital tool that generates eco-impact and circularity results through a single report. It considers LCA data, material overview circular characteristics and GHG implications of CE measures (Circular IQ and KPMG, n.d.).

Circularise is a platform to implement digital assets, using blockchain to track and share information of materials/products origins while protecting the company's confidentiality. It is oriented to end-users, so they can know where their materials came from. Furthermore, it creates a digital equivalent of a physical asset with identical recorded mass, which can be used for environmental measurement and registration (Circularise, n.d.).

The Circularity Calculator provides an MFA graphic representation. The end-user defines percentages or weights of material flows inside the system. In addition, the ST has as its output a graphic representation of material flows and results of 4 key performance indicators: circularity, value capture, recycled content, and reuse index. Although the website does not specify how the indicators are calculated, Pauw *et al.* (2021) state how the indicators are measured (IDEAL&CO Explore BV, n.d.).

The Circularity Check is a free, online scan tool with a questionnaire of about 60 questions that determines a circularity score for a specific product and/or service. It is a self-evaluation tool for companies. It provides a circularity score for a specific product and/or service as output. The outcome is a percentage that indicates how circular the product is. The higher the score, the better (Ecopreneur, 2022).

The *Material Circularity Indicator (MCI)* assigns a score between 0 and 1 to a product (or company) depending on how restorative or linear the flow of the materials is. End-user inputs the functional unit, percentages of material flows, and product lifespan. The assessment is based on comparisons against the industry average. The higher the score, the better (Ellen MacArthur Foundation, 2015a).

MI: Product Intelligence integrates MCI and complementary risk and impact indicators for products. End-user inputs the functional unit, percentages of material flows, and lifespan against the industry average. The ST outputs a circularity report defining the scenario MCI score (ANSYS Granta and Ellen MacArthur Foundation, n.d.).

PIQET is a streamlined LCA tool designed to assess the environmental impacts and resource consumption profiles of different packaging options. End-users can break down the materials used in the packaging and their recycled content. The ST uses the global Ecoinvent database to generate a report that indicates LCA results. Up to 22 indicators can be reviewed in the dynamic online report, including LCA economic and environmental categories and CE indicators such as the material circularity index (PIQET, 2017). However, their website does not provide a detailed explanation of how this is measured.

The *CE analyst* is part of a series of tools developed by Katch-e. The interactive website has several games and tools to explain how to implement CE in different stages. ST are grouped into four categories: basics, businesses, design, and assessment and communication. At the assessment and communications level, *KATCHing Carbon* provides a way to provide LCA analysis. Additionally, the *CE analyst* tool offers a way to estimate the potential environmental improvement by applying assumptions to the impact data. For *CE analyst*, end-users provide the inputs: LCA impacts for each stage, parameters of product lifetime, use intensity and impact factors for each stage between different scenarios. The *CE analyst* shows the maximum circular value capture and carbon footprint for each defined scenario (KATCH_e, n.d.).

Idemat is a user-friendly mobile phone application ST to assist in sustainable materials selection based on LCA calculations and the IDEMAT database from TU Delft University. Two indicators can be measured, carbon footprint or eco-cost. Eco-cost considers resource depletion, ecotoxicity, human health, and carbon footprint (Marinus Meursing, 2021a). Although, a detailed explanation of how these are measured and integrated was not found on their website nor mobile phone application.

Lastly, *IdematLightLCA* is another mobile phone application ST based on the LCA databases of SimaPro and TU Delft University of technology; it provides cradle-to-grave and cradle-to-cradle analyses. The ST measures resource depletion, ecotoxicity, human health, and carbon footprint as predefined indicators. The ST can also be customised to include other indicators and environmental impact categories like the ones considered in environmental product declarations (EPDs) (Marinus Meursing, 2021b).

This section presented a detailed discussion of the STs considered within this scoping review. A great variety of approaches was found confirming the confusion currently happening, and highlighting the missing framework-standard that regulates and oversees the environmental assessment of CE scenarios of materials and products. LCA and MFA were prevalent as key approaches to assess the environmental impacts of CE-defined scenarios, although an integration method considering material flows and LCA was missing. Instead, different environmental categories and indicators are implemented by each ST, sometimes with no integration method. A standardised integration method is critical to really understand which is the best environmental alternative, as current assessments are focusing on specific categories, while leaving unknown the bast majority. Moreover, this missing approach makes that results from STs are not comparable, limiting their wide application.

4. Conclusions

This paper presented a scoping review of STs available to assess the environmental performance of CE strategies and principles at the material and product level. After the screening process and STs revision, 12 STs were found relevant for this purpose. Among the STs reviewed, a great variety of environmental assessment approaches were identified, as each ST defined its own overarching framework. Material flow indicators were proposed by STs, generating MFA to close loops, reducing waste and incentivising the use of the 10R strategies. The *MCI* score was the most common indicator regarding material flows. The great variety of approaches used by the STs further highlights the confusion in the domain and underscores importance of a - currently missing - framework that oversees and regulate how to deal with the CE environmental assessment at the material and product level.

The most common practice for environmental assessment was the use of LCA, as the ISO14040 and ISO14044 standards regulate the approach to assessing the environmental impacts of the CE-defined scenario(s). Carbon footprint or GHG emissions measurement was prevalent in several tools, which confirms the interest in tackling climate change. LCA databases varied considerably across STs. GaBI and PIQET were found to have the most comprehensive LCA databases, although PIQET limit end-user access to information on how the Ecoinvent data has been used to assess environmental impacts (PIQET, 2017; Sphera, n.d.). As the list of parameters to define by the end-user is limited, the use of the ST is more user-friendly. Moreover, none of the found STs incentive the use of hybrid LCA datasets, which is the most comprehensive method (Crawford, 2011). This highlights one key limitation on current STs. LCA assumptions and method selection (process, input-output, or hybrid) can change the assessment outputs. Therefore, they are critical when presenting environmental assessment results, and should be clearly stated within STs.

Limitations of this paper are related to the search strategy implemented as only STs available in English were identified and evaluated. Additionally, the scoping review should have been complemented by a review of academic articles in databases such as Scopus and Web of Science. This was not done due to time and space limitations. Moreover, a thorough analysis of the proposed indicators would be beneficial to incentivise a common practice in all STs. This analysis will be part of a secondary scoping review by the authors, aiming to identify the key indicators for materials and products used in the construction industry.

References

ANSYS Granta and Ellen MacArthur Foundation (n.d.) *MI:Product Intelligence*. < https://www.grantadesign.com >

Arksey, H. and O'Malley, L. (2005) Scoping studies: towards a methodological framework, *International Journal of Social Research Methodology*, 8(1), 19-32.

Buyle, M., Galle, W., Debacker, W. and Audenaert, A. (2019) Consequential LCA of demountable and reusable internal wall assemblies: a case study in a Belgian context, *IOP Conference Series: Earth and Environmental Science*, 323, 012057.

Cambridge Dictionary *Program*, Cambridge University Press.

Circular IQ and KPMG (n.d.) *The Circular IQ platform*. <https://circular-iq.com/>

Circularise (n.d.) *Circularise*. <https://www.circularise.com/manufacturers>

Crawford, R. H. (2011) *Life Cycle Assessment in the Built Environment*, 1st ed., Routledge.

Ecopreneur (2022) *The Circularity Check*. <https://ecopreneur.eu/circularity-check-landing-page/>

Ellen MacArthur Foundation (2012) *Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition*.

Ellen MacArthur Foundation (2015a) *Material Circularity Indicator (MCI)*. <https://ellenmacarthurfoundation.org/material-circularity-indicator>

Ellen MacArthur Foundation (2015b) *Towards a Circular Economy: Business rationale for an accelerated transition*.

Ellen MacArthur Foundation, ARUP and McKinsey & Company (2018) *The Circular Economy Opportunity for Urban and Industrial Innovation in China*.

Favi, C., Marconi, M., Germani, M. and Mandolini, M. (2019) A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling, *Advanced Engineering Informatics*, 39, 62-79.

Ghisellini, P., Ripa, M. and Ulgiati, S. (2018) Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review, *Journal of Cleaner Production*, 178, 618-643.

Griffiths, P. and Cayzer, S. (2016) Design of Indicators for Measuring Product Performance in the Circular Economy, in, Springer International Publishing, 307-321.

Gutierrez-Bucheli, L., Reid, A. and Kidman, G. (2022) Scoping reviews: Their development and application in environmental and sustainable education research, *Environmental Education Research*, 1-29.

IDEAL&CO Explore BV (n.d.) *Circularity calculator*. <http://www.circularitycalculator.com/>

KATCH_e (n.d.) *CE analyst* <https://www.katche.eu/knowledge-platform/tools-and-training-materials/katch_e-tools/ce-analyst/>

Kirchherr, J., Reike, D. and Hekkert, M. (2017) Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, Conservation and Recycling*, 127, 221-232.

Lieder, M. and Rashid, A. (2016) Towards circular economy implementation: a comprehensive review in context of manufacturing industry, *Journal of Cleaner Production*, 115, 36-51.

Marinus Meursing (2021a) *Idemat*. <http://idematapp.com/>

Marinus Meursing (2021b) *IdematLightLCA*. <http://idematapp.com/coll-page-section/lightlca/>

Munn Z Aromataris E (2021) *JBI Manual for Evidence Synthesis*, JBI.

Muñoz, S. (2022) *PRISMA-ScR-Checklist-Circular-economy-software*. figshare <https://doi.org/10.6084/m9.figshare.21425022.v1>.

Oxford reference *Applications software*, Oxford University Press.

Pauw, I. d., Grinten, B. v. d. and Alvarez-Mendez, L. (2021) The Circularity Calculator, a tool for circular product development with Circularity and potential value capture indicators.

Pieroni, M. P. P., McAloone, T. C. and Pigosso, D. C. A. (2019) Business model innovation for circular economy and sustainability: A review of approaches, *Journal of Cleaner Production*, 215, 198-216.

PIQET (2017) *PIQET*. <https://piqet.com/>

Potting, J., Hekkert, M., Worrell, E. and Hanemaaijer, A. (2017) *Circular economy: measuring innovation in the product chain*,Planbureau voor de Leefomgeving.

PwC (2021) *Building a more circular Australia, The opportunity of transitioning to a circular economy*, 33.

Sphera (n.d.) *GaBi Circularity Toolkit*. <https://gabi.sphera.com/software/gabi-software/gabi-circularity-toolkit/>

Stephan, A., Muñoz, S., Healey, G. and Alcorn, J. (2020) Analysing material and embodied environmental flows of an Australian university — Towards a more circular economy, *Resources, Conservation and Recycling*, 155, 104632.

Su, B., Heshmati, A., Geng, Y. and Yu, X. (2013) A review of the circular economy in China: moving from rhetoric to implementation, *Journal of Cleaner Production*, 42, 215-227.

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D., Horsley, T. and Weeks, L. (2018) PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation, *Annals of Internal Medicine*, 169(7), 467-473.

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K., Colquhoun, H., Kastner, M., Levac, D., Ng, C., Sharpe, J. P., Wilson, K., Kenny, M., Warren, R., Wilson, C., Stelfox, H. T. and Straus, S. E. (2016) A scoping review on the conduct and reporting of scoping reviews, *BMC Medical Research Methodology*, 16(1), 15.

Vanhamaki, S., Medkova, K., Malamakis, A., Kontogianni, S., Marisova, E., Dellago, D. H. and Moussiopoulos, N. (2019) Bio-based circular economy in European national and regional strategies, *International Journal of Sustainable Development and Planning*, 14(1), 31-43.

WBCSD, KPMG and Circular IQ (n.d.) *CTI Tool*. <https://ctitool.com/>

Zhai, J. (2020) *BIM-based Building Circularity Assessment from the Early Design Stages*, Eindhoven University of Technology.

Comparison of embodied greenhouse gas emissions data from environmental product declarations and the EPiC database: implications for material selection

Robert H. Crawford[1] and André Stephan[2]

[1] The University of Melbourne, Melbourne, Australia
rhcr@unimelb.edu.au, ORCID-0000-0002-0189-3221[1]
[2] Université Catholique de Louvain, Louvain-la-Neuve, Belgium
andre.stephan@uclouvain.be, ORCID-0000-0001-9538-3830[2]

Abstract: Architects and other construction industry professionals are increasingly seeking to reduce the embodied greenhouse gas (GHG) emissions of construction projects. To support this goal, reliable and comprehensive data is needed on material performance. There are various sources of this data currently being used, including Environmental Product Declarations (EPDs), and material life cycle inventory (LCI) databases, such as the Environmental Performance in Construction (EPiC) Database. Many LCI databases rely on manufacturer-specific data (common also with EPDs) but suffer from inherent data gaps. The EPiC Database is unique as it uses macro-economic input-output data, as part of a hybrid approach, to fill the gaps in LCI and EPD data to ensure comprehensive supply chain coverage. Due to this, data can vary considerably between EPDs and the EPiC Database. However, no study has compared these two data sources. The aim of this study was to compare the embodied GHG emissions coefficients provided by EPDs and the EPiC Database and assess the effect on material selection decisions. EPDs for Australian ready-mix concrete products were analysed and compared to hybrid GHG emissions coefficients for equivalent products within EPiC. It was shown that while hybrid coefficients are generally always higher than coefficients from EPDs, the overall trend between products was relatively consistent. On average, EPD coefficients represent 78% of the equivalent hybrid coefficient, ranging from 38 to 115%, highlighting the incompleteness associated with EPD data. The large variability in GHG emissions coefficients between EPD products of similar type means that product specific EPD data may not provide any more guidance to material selection than what the generic EPiC product data provides. EPiC data may provide very useful initial guidance for material selection, while comparison of materials based on EPDs from different manufacturers may be misleading, also questioning the compliance of EPDs with the requirements of the international standard EN 15804.

Keywords: Embodied greenhouse gas emissions; environmental product declaration; EPiC Database; hybrid life cycle assessment.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 177–188.*

1. Introduction

The contribution of construction projects to global environmental issues is well documented and significant. Buildings alone account for around 37% of global greenhouse gas (GHG) emissions and 36% of global energy demand (UNEP, 2021). Historically, efforts to improve the environmental performance of construction projects have focused on increasing the operational efficiency of buildings, through passive design, improvements to the thermal envelope, and integration of energy efficient appliances and systems (Karimpour *et al.*, 2014). While significant reductions in operational-related GHG emissions have been achieved within the built environment, these have been largely offset by an increasing demand for built assets due to a growing global population (GlobalABC *et al.*, 2019, p. 15). This has also further exacerbated the demand for materials, increasing material embodied GHG emissions. Only recently has reducing these embodied GHG emissions become a key priority for the construction industry.

To ensure embodied GHG emissions reductions are being achieved, material selection decisions must rely on robust, comprehensive data on a material's embodied GHG emissions. Historically, in Australia, this data has been difficult to access, limited to a small range of materials, or based on incomplete coverage of the material's supply chain (Crawford *et al.*, 2020). In recent years, data providers have attempted to address some of these issues. Environmental Product Declarations, known as EPDs, have emerged to provide data on the environmental performance of a much broader range of materials and products. Databases containing embodied GHG emissions coefficients for materials are also becoming more accessible and covering a growing variety of materials.

Despite the growing prevalence of embodied GHG emissions data for construction materials, this data continues to suffer from a range of limitations (see Section 2.3). For example, EPD data can be collated based on an approach that results in inconsistent and incomplete coverage of a material's supply chain, thus underestimating the related GHG emissions. Hybrid data (such as that contained within the Environmental Performance in Construction (EPiC) Database (Crawford *et al.*, 2019)) is designed to fill these data gaps but can suffer from a lack of representativeness for specific materials (see Section 2.2). Material specifiers are often confused by the difference in values that different data sources provide, and how and at what point the data can best be used. Considering the discrepancies between existing sources of data and potentially different material selection implications, it is important to understand the extent of difference between the values in commonly used data sources, the reasons for these differences, and the potential effect of relying on a data source over another for material selection decisions.

Therefore, the aim of this study was to compare the embodied greenhouse gas emissions coefficients provided by EPDs and the EPiC Database and assess the effect on material selection decisions.

2. Environmental data for materials

2.1. Key drivers

Understanding the implications of the use of different construction materials on the environment is of increasing importance and interest, globally. This is particularly pertinent in the context of climate change and the critical urgency to reduce global greenhouse gas emissions (IPCC, 2018). Construction materials are produced as part of a series of stages that involve harvesting or extracting raw materials from the earth, processing these raw materials, and transforming the processed raw materials into construction materials through various manufacturing processes. For most materials, each of these stages relies on the use of fossil fuels as an energy input. The resultant GHG emissions from the production and use of this energy is attributed to each unit of material that is produced, and commonly known as a material's embodied GHG emissions. For some materials, such as concrete and timber, additional GHG emissions that are not related to the use of fossil fuels are also released due to the harvesting or manufacturing processes. These also form part of the embodied GHG emissions of these materials. In addition, indirect processes, such as insurance, advertising, food production and others, also contribute to embodied GHG emissions of construction materials.

The embodied GHG emissions of materials have been acknowledged and studied for many decades (Azari and Abbasabadi, 2018). However, the construction industry has only recently considered it a serious issue to be addressed. The World Green Building Council has established targets for reducing the embodied GHG emissions of buildings – by 40% by 2030 and 100% by 2050 (Adams *et al.*, 2019). Australia's 2021 National Standard of Competency for Architects (NSCA) requires architects to 'demonstrate an understanding of whole life carbon implications of procurement methods, materials, components and construction systems' (PC10) and 'be able to assess embodied carbon implications of materials, components, construction systems and supply chains (including transport) to achieve net zero whole life carbon when developing design concepts' (PC35) (AACA, 2021). To support this strengthened focus on embodied GHG emissions, numerous countries have implemented policies to reduce these emissions, as outlined in part by Skillington *et al.* (2022), which will likely become more prevalent in the future.

To support these ambitious targets and mandates, decision-makers will require detailed embodied GHG emissions data for a broad range of construction materials and products. Robust, comprehensive, comparable, transparent data will help support decisions around material and product selection, leading to reductions in embodied GHG emissions. The next section discusses the various sources of this data and some of the pros and cons associated with their use.

2.2. Source of environmental data

Embodied GHG emissions data for construction materials and products can be sourced directly from the organisations involved in the various mining, processing, and manufacturing stages of a material. While this data, known as process data, is considered to be more specific (Suh *et al.*, 2004), collecting it on a project-by-project basis can be time-consuming and costly. As this data rarely changes from project to project, it can be collated less regularly and reused across projects. This data is often collected and reported in the development of LCI databases or EPDs.

Process data sources

The most comprehensive source of process data for Australian produced materials is the Australian Life Cycle Inventory Database (AusLCI) (ALCAS, 2019). Information on the quantity of various greenhouse gases associated with the different stages of a material's production are provided, which when combined and converted to carbon dioxide equivalent, provide a total embodied GHG emissions coefficient for a material in kg CO_2e/unit. The data is highly disaggregated and transparent, so it is possible to identify emissions hotspots across the material supply chain. To improve accessibility to environmental data, databases of process-based coefficients have been produced (e.g., Lawson (1996)). These coefficients are easily multiplied by the quantity of specific materials within a construction project to provide an estimation of its total environmental flows.

EPDs are usually produced by life cycle assessment consultants on behalf of product manufacturers. EPDs disclose a range of environmental data associated with a product, often including embodied GHG emissions. The published EPD is less transparent and detailed than traditional LCI data. It generally cannot be used to identify emissions hotspots, other than specific life cycle stages. EPDs for construction products are generally produced in accordance with EN 15804 (CEN, 2019). The two main sources for EPDs of Australian products is EPD Australasia (EPD Australasia, 2022) and Global GreenTag (GGTI, 2022).

Other data sources

Other types and sources of embodied GHG emissions data are also available. These have typically been developed to address truncation issues that exist with process data, where many smaller goods, and services-based processes are excluded due to the complexity of the supply chain (Lenzen and Dey, 2000; Majeau-Bettez *et al.*, 2011). Input-output data, based on macro-economic transactions between sectors, is available within the IELab (Wiedmann, 2017) and can be used to provide a top-down and more comprehensive assessment of a material's embodied GHG emissions, yet with reduced reliability and relevance to specific products (Lenzen, 2000). Hybrid data combines process and input-output data, maximising the use of process data, where available, and filling any remaining data gaps with input-output data. The earliest database of hybrid environmental flow coefficients (embodied energy and carbon) for Australia was produced by Tucker *et al.* (1996, Appendix C). Since then, further hybrid databases have been published, including that of Treloar and Crawford (2003), Crawford and Treloar (2010), Crawford (2018), and Wiedmann *et al.* (2019). The most recent hybrid data is contained in the EPiC Database (Crawford *et al.*, 2019). The EPiC Database is a database of hybrid coefficients for construction materials, compiled using a combination of Australian and international process data and Australian input-output data. It covers flows of energy, water and GHG emissions for over 280 common construction materials. Further details can be found in Crawford *et al.* (2022).

2.3. Previous studies

Multiple studies have compared the embodied GHG emissions of construction materials based on their data source (e.g. Martínez-Rocamora *et al.* (2016), Emami *et al.* (2019)). In their comparison of ecoinvent 3.1 with the GaBi database Martínez-Rocamora *et al.* (2016) found significant discrepancies for materials such as aluminium (the ecoinvent embodied GHG emissions coefficient being more than 10 times that of GaBi). At the same time, the authors found similar figures for the embodied GHG emissions coefficient of concrete (0.112 kg CO_2e/kg for ecoinvent and 0.118 kg CO_2/kg for GaBi). This demonstrates potentially significant variations in the embodied GHG emissions coefficient for the same material between established databases. When comparing the GaBi and ecoinvent databases as applied to buildings in Finland, Emami *et al.* (2019) identified relatively small differences when it comes to GHG emissions at the building level (-16% to +13%). This observation holds true when comparing at the construction assembly level, except for 'frame and roof structure' which varied by more than 30%. As such, using different databases to quantify the embodied GHG emissions of construction projects might lead to variable emissions intensities for given materials. Depending on the number of different materials within a project, these differences can either balance each other out or accumulate to result in marked differences in total embodied GHG emissions.

Similarly, other studies have compared generic data contained within databases to those of EPDs (inter alia Lasvaux *et al.* (2015), Häfliger *et al.* (2017), and Emami *et al.* (2019)). Lasvaux *et al.* (2015) collected data from 266 EPDs across 28 material categories and compared the embodied GHG emissions coefficients with ecoinvent 2.1 (as well as other indicators). They found significant variations between EPDs and ecoinvent data for specific materials, e.g., fibreglass insulation +40% or cellulose fibre -65%, on average. This variability is also highlighted by Emami *et al.* (2019) who found that embodied GHG emissions for the same material can vary by a factor of more than 100 when using different EPDs. Variations between EPDs can be due to different energy mixes, recycled content, and modelling assumptions. Häfliger *et al.* (2017) also observe a potentially significant difference between embodied GHG emissions of particular material groups when obtained from EPDs, as compared to ecoinvent.

These studies demonstrate the significant variations of embodied GHG emissions coefficients for the same product when using different EPDs, or different databases. This can be due to a range of factors, including geographic coverage, data age, modelling assumptions, and system boundary coverage. Yet, to date there are no studies comparing EPDs with hybrid embodied GHG emissions coefficients. Given that hybrid life cycle inventory approaches have comprehensive system boundaries, it is anticipated that the difference between EPDs and hybrid coefficients will be even more significant than with the process databases compared previously.

3. Research approach

This section describes the approach used to compare EPD and hybrid embodied GHG emissions coefficients. The number of materials available for comparison is quite large considering that over 280 material variations exist in the EPiC Database and the Australasian EPD database contains 129 EPDs, with 116 of these construction-related products. These EPDs also contain a varying number of material variations for each producer. Given the potential large number of comparisons possible, the scope of this initial study is focused only on ready-mix concrete produced in Australia. While a broader comparison across materials contained within the EPiC Database may be conducted in the future, this initial focus on concrete is supported by the significant contribution of concrete to global GHG emissions (with cement alone accounting for 7% of global CO_2 emissions (IEA, 2018)).

3.1. Data

EPiC Database hybrid coefficients

The current EPiC Database contains 15 concrete mix variations. This includes General Purpose (GP) concrete for five strength grades – 20, 25, 32, 40, and 50 MPa. It also includes mix designs using 30% fly ash (FA) as a cement replacement for each strength grade and 30% ground granulated blast furnace slag (GGBFS) as a cement replacement for each strength grade. In addition to these, and as part of this research, hybrid coefficients for an additional 57 concrete mixes were calculated, as per the process outlined in Crawford *et al.* (2022). This involved creating additional concrete mixes for strength grades of 65, 80 and 100 MPa, based on a standard GP blend, 30% fly ash as a cement replacement, and 30% GGBFS as a cement replacement for each strength grade. In addition, coefficients were calculated for higher proportions of fly ash and GGBFS replacement (i.e., 40%, 50% and 60%) for each strength grade. The concrete mix variations considered in this study are summarised in Table 1. The embodied GHG emissions coefficients are provided as a single figure (in kg CO_2-e/m^3).

As the Path Exchange approach used to compile the hybrid coefficients provides a systemically complete coverage of the concrete product system boundary, this data covers the emissions associated with the production of each concrete mix across its entire supply chain. This is a unique feature of the use of input-output data and contrasts with the process data used to compile the EPDs, as described below.

Table 15: Hybrid concrete data summary.

Data source	No. of products	Grades (MPa)	Variations	System boundary
EPiC Database[1]	72	20, 25, 32, 40, 50, 65, 80, 100	GP; Fly ash SCM: 30%, 40%, 50%, 60%; GGBFS SCM: 30%, 40%, 50%, 60%	A1-A3[2] complete coverage

[1] Crawford et al. (2019), [2] as per CEN (2019); SCM = supplementary cementitious material

Environmental Product Declarations

Concrete mix EPD data was sourced from the Australasian EPD database, located at epd-australasia.com. Available products were filtered within the 'Building and construction products' category to include only 'Concrete and concrete elements'. Of the 44 EPDs available, only EPDs including 'pre-mix' or 'ready-mix' concrete produced in Australia were selected, excluding precast, masonry, reinforcement, and non-Australian products. This resulted in 16 individual EPDs across 6 manufacturers (Table 2). These EPDs contained multiple products, often replicated across each state. Products with no equivalent EPiC product were excluded (e.g., fly ash/GGBFS blends), as were products where the mix could not be reliably identified. Some regional or project-specific variations were also excluded. Further detail on the specific products included in the analysis, including their embodied GHG emissions coefficient, geographical scope, international standard compliance, life cycle stage coverage, and the equivalent EPiC product is provided in Crawford and Stephan (2022). While most EPDs cover only stages A1-A3 (as per CEN (2019)), only the GHG emissions associated with these stages of the concrete mixes were included, to ensure a consistent basis for comparison with the hybrid data. GHG emissions data was extracted from each EPD for the equivalent grades of concrete covered by the EPiC Database (see Table 1). These values are typically categorised under the Global Warming Potential (GWP) impact category, in kg CO_2-e/m^3 of concrete. These values were then collated and grouped according to the strength grade (i.e., 20 to 100 MPa) and mix design (i.e., GP, FA, GGBFS).

Table 2: Environmental product declaration concrete data summary.

Data source	EPDs	Companies	Products
EPD Australasia[1]	16	6	374 (GP: 117, FA: 117, GGBFS: 140)

[1] EPD Australasia (2022)

3.2. The effect of data source on material selection

This section describes the approach used to assess the implications of using EPD or hybrid data on material selection decisions. This is achieved by comparing EPD and hybrid coefficients for the same product as well as across products. The analysis assumes that the aim of material selection is to reduce the embodied GHG emissions associated with the use of concrete. The rank of EPiC products from high to low GHG emissions was compared to the general trend in GHG emissions for EPD products across the concrete variations. Also, as there are multiple EPD coefficients for similar products, GHG emissions coefficients were compared between concrete product variations for identical strength grades to determine whether the choice to use EPD and hybrid data, and the source of EPD data used, changes the preferred concrete product for minimising GHG emissions.

4. Results

This section presents the results of the comparison between EPD and hybrid embodied GHG coefficients for a range of concrete mixes used in Australia. Of the 72 concrete mix products available in EPiC, only 45 of these were able to be matched with concrete mixes covered by current Australian EPDs. The products in EPiC for which no equivalent EPD data was available included all mixes with 60% fly ash or GGBFS, as well as 100 MPa concrete with either fly ash or GGBFS. For the 45 concrete mixes in EPiC, in most cases there were multiple comparable products identified across the 16 relevant EPDs.

Figures 1 to 3 show the hybrid coefficient for each of the 45 concrete mixes in comparison to identified equivalent products from Australian EPDs. This comparison has been separated into standard GP mixes (Figure 1), mixes with fly ash as a SCM (Figure 2), and mixes with GGBFS as a SCM (Figure 3).

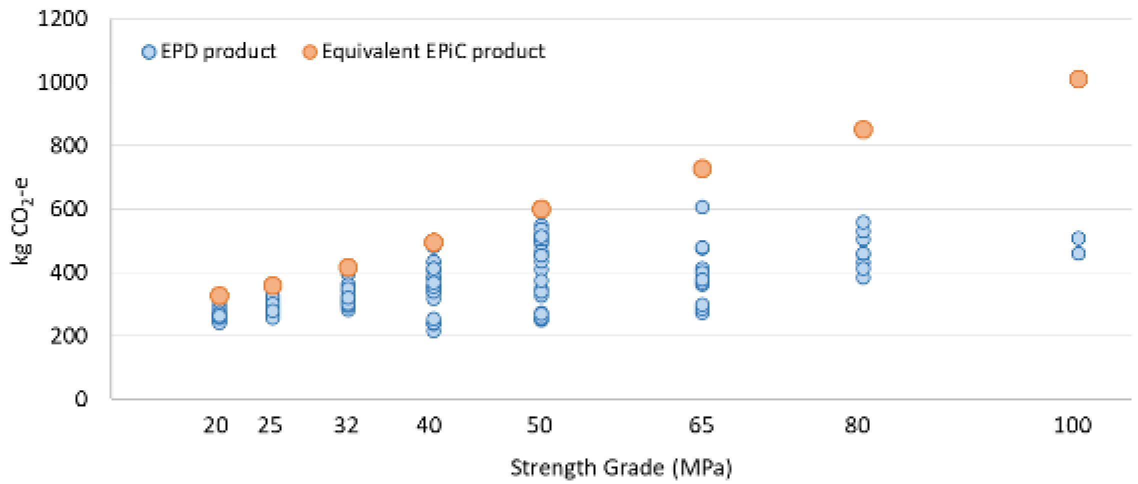


Figure 28: Comparison of EPD and hybrid embodied GHG emissions coefficients for standard GP concrete.

Figure 1 shows a relatively linear relationship between embodied GHG emission coefficients in EPiC and concrete grade. There is a similar relationship for the EPD coefficients, although not as pronounced. Hybrid coefficients are higher than all equivalent EPD coefficients, with EPD coefficients ranging from 38 to 97% of the hybrid coefficient. While there are fewer EPD coefficients published for 65 to 100 MPa concrete, the largest difference between EPD and hybrid coefficients can be seen for these products. The large spread of coefficients across EPDs mean that a higher-grade concrete may be preferred for reducing emissions, depending on the EPD products being compared. For example, the GHG emission coefficients for several 65 MPa GP concrete products are lower than most of the coefficients for lower grade concrete products, which is counter-intuitive considering the higher cement content.

Based on hybrid data, Figure 2 shows a decrease in embodied GHG emissions as a result of an increase in the proportion of fly ash used. Cement replacement with fly ash at 30% results in a GHG emissions reduction of 22 to 25% compared to standard GP concrete, a reduction of 31 to 33% for 40% cement replacement, and 38 to 42% for 50% cement replacement. Other than one case where the EPD coefficient is higher than the hybrid coefficient (as the EPD product with 20% fly ash is assumed to be equivalent to the 30% fly ash EPiC product), hybrid coefficients are up to 64% higher than equivalent EPD coefficients.

Based on hybrid data, Figure 3 shows a decrease in embodied GHG emissions as a result of an increase in the proportion of GGBFS used. Cement replacement with GGBFS at 30% results in a GHG emissions reduction of 18 to 21% compared to standard GP concrete, a reduction of 25 to 28% for 40% cement replacement and 32 to 35% reduction with 50% cement replacement. Other than five cases where the EPD coefficient is higher than the hybrid coefficient, hybrid coefficients are up to 67% higher than equivalent EPD coefficients.

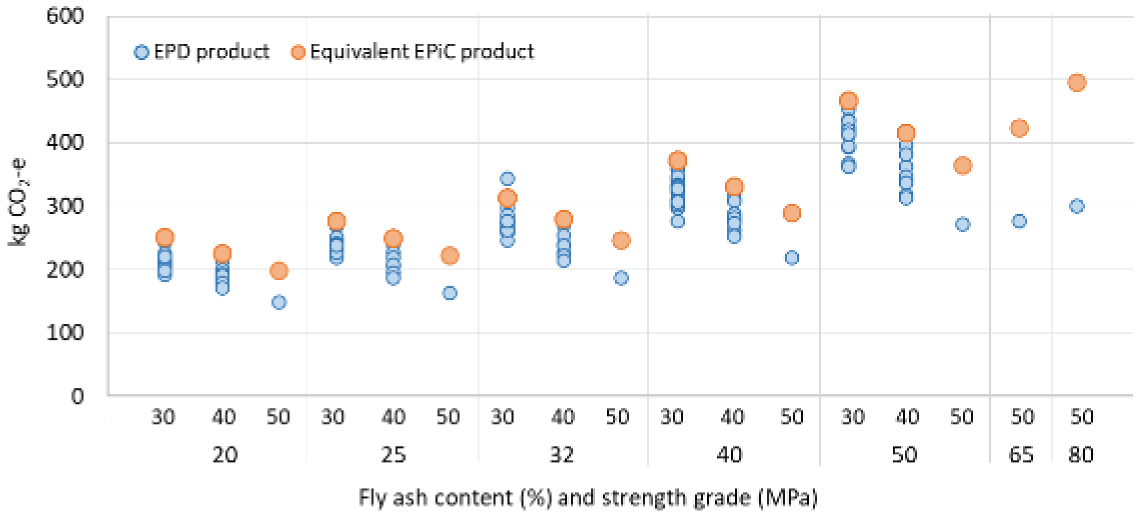


Figure 2: Comparison of EPD and hybrid embodied GHG emissions coefficients for concrete mixes with fly ash.

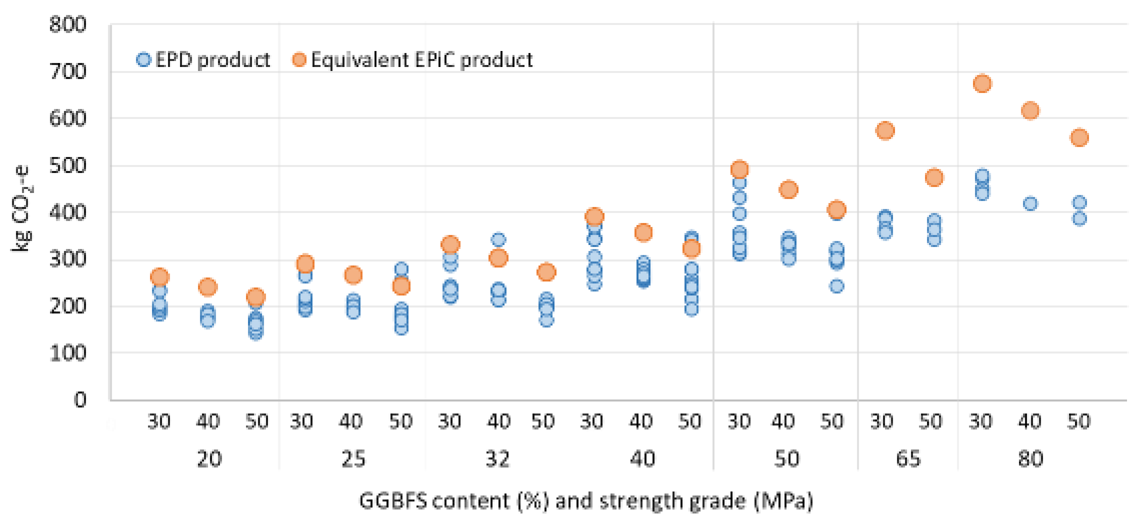


Figure 3: Comparison of EPD and hybrid embodied GHG emissions coefficients for concrete mixes with GGBFS.

While the variation in EPD coefficients is wide across all product types, there is also a clear downward trend in GHG emissions with an increase in SCM use. Hybrid data shows a greater reduction in GHG emissions for fly ash replacement, whereas EPD data tends to show a slightly greater reduction for GGBFS replacement. This may be due to how the GHG emissions of these two products are allocated. Interestingly, EPD data shows that many of the products with higher SCM content often have a higher GHG emissions coefficient than products with a lower SCM content, and as such, selecting a product with higher SCM content may not necessarily be a clear choice for minimising GHG emissions.

5. Discussion

This section discusses the results of the study as well as the broader implications of the choice of data on material selection decisions. The comparison of EPD and EPiC embodied GHG emissions data for a broad range of concrete products shows considerable variability between data sources as well as across EPD coefficients for similar products. Some of the key reasons for variability in GHG emissions data includes the source of base data used to quantify GHG emissions, system boundary completeness, different manufacturing processes and efficiencies, allocation of GHG emissions for specific raw materials such as GGBFS and fly ash, emissions intensity of regional fuel sources, and fuel mix of production processes.

The embodied GHG emissions coefficients contained within EPiC for concrete products are based on Australian and international process data as well as Australian input-output data to fill any process data gaps. The average coverage of the concrete supply chain by process data is 83%, ranging from 72 to 90%, which is high compared to the average of 43% for all products contained within the EPiC Database. This means that input-output data, including the cost variable used to translate from a financial to physical functional unit, has limited influence on the embodied GHG emissions coefficients. While the process data can be traced back to individual producers, the breadth of producers used to compile the generic process data used in the hybrid coefficients is much more limited than is available across the range of producer specific EPDs. However, despite claims that manufacturer specific EPDs are more reliable than generic process data contained in databases such as AusLCI or ecoinvent, this study has identified that all concrete EPDs analysed rely heavily on generic process data from such sources. None of the EPDs analysed rely solely on primary process data meaning that their reliability may be compromised, and for the supply chain activities covered by this generic data, is no more reliable than the data used within EPiC. EN 15804 requires that only 'processes the producer of the specific product has influence over' must be calculated using specific (i.e., non-generic) data. In a supply chain as complex as that of concrete, this can be a very limited range of processes, meaning that generic data can easily represent a large majority of the data used within an EPD. In addition, EN 15804 allows for processes to be excluded completely if their total amounts to no more than 5% of the energy usage and mass of the product. However, as this study shows, EPD coefficients are on average 22% below those of the equivalent hybrid coefficients, meaning that more than 5% of processes are excluded. On average, EPD coefficients are 78% of the equivalent hybrid coefficient, ranging from 38% to 115%, and 57% of them are more than 20% lower, with only 9 (0.02%) higher. This highlights the incompleteness associated with EPD coefficients.

The study identified that EPD GHG emissions coefficients for identical products may differ between states/manufacturing plants, even for the same manufacturer, which corroborates the findings of Lasvaux *et al.* (2015), Häfliger *et al.* (2017), and Emami *et al.* (2019). This shows that when using EPD data to select a concrete product with the lowest possible GHG emissions, the decision may not be as intuitive as previously thought. Although there appears to be a general correlation between increased proportions of fly ash and GGBFS and total GHG emissions reduction, there are instances where an increase in SCM content increases the GHG emissions, even for the same manufacturer. Some of these products can even have higher GHG emissions than equivalent strength grade GP concrete products. Where EPD coefficients for some products are substantially lower than equivalent products from other EPDs/manufacturers, this is more than likely due to exclusion of supply chain processes and associated emissions or use of different generic data sources, rather than substantially better performance. However, further research is needed to analyse specific EPDs and manufacturer's production processes and supply chains.

The study shows that while the trend in emissions between product types is generally consistent regardless of whether EPD or hybrid data is used, material specifiers typically consider a more limited range of specific products than considered here. This may mean that trends identified here may not be evident across a smaller selection of EPDs and as such may lead to different choices. Importantly, where an absolute value for the environmental performance of a material or project is required, the use of EPD coefficients will most often result in an underestimation of the total GHG emissions.

5.1. Limitations

While this study considers a substantial proportion of the ready-mix concrete products available in Australia, it only compares the performance of products covered within existing EPDs published through EPD Australasia. Other EPDs may be available, as well as many other ready-mix products where an EPD has not yet been published or may be published in the future. While EPDs have a 5-year validity period, there are new EPDs being published regularly. This means that production improvements that reduce GHG emissions may be more rapidly represented in EPD data than in the EPiC Database, which is less regularly updated. Some assumptions needed to correlate products within EPDs with EPiC Database products may also vary the findings, albeit slightly. Comparisons of other products, especially where process data accounts for a smaller proportion of the hybrid coefficient, is also needed as this will provide a more reliable comparison between the two data sources.

6. Conclusion

The aim of this study was to compare the embodied GHG emissions coefficients provided by EPDs and the EPiC Database and assess the effect on material selection decisions. EPDs for ready-mix concrete products available in Australia were analysed and compared to hybrid GHG emissions coefficients for equivalent products within EPiC. It was shown that while hybrid coefficients are generally always higher than coefficients from EPDs, the overall trend between products was relatively consistent – higher emissions for higher strength grades, and lower emissions for higher cement replacement rates.

Despite this, the study also found considerable variability in EPD coefficients for comparable products – ranging from 38 to 115% of the hybrid coefficient. This may be due to different manufacturing processes and efficiencies but is also likely to be a result of variability in the data source and supply chain coverage of EPD data. While Australia, like other developed economies, has seen the rapid expansion in the availability and use of EPDs in recent years, the considerable variability in the coefficients provided, even between equivalent products, suggests that we should not put blind faith in their use. EPD data may not provide any more guidance to material selection than what EPiC provides and may in fact increase confusion among material specifiers that are not familiar with the reasons for variations between EPD coefficients. This study highlights that by comparing data from EPDs for concrete with the comprehensive coefficients provided within the EPiC Database, showing the 22% average data truncation, these EPDs may not comply with the requirements of the international standard EN 15804.

The large variability in GHG emissions coefficients between EPD products of similar type means that product selection may be problematic and may not always lead to an intuitive choice. Further in-depth analysis of EPD data is needed to determine the reasons for such high variability in coefficients. This will help support product specifiers and improve emissions reductions in the construction sector. It appears that EPiC data may provide very useful initial guidance for material selection. It is highly likely that EPD data currently available may be misleading given the variation in system boundary coverage, data source and quality, making comparison between EPDs from different manufacturers unreliable.

Further research is needed to consider a broader range of materials and the influence of data source on the environmental benefits of the choice of construction materials and products. With a rapidly growing reliance on EPDs, an assessment of their reliability for material selection decision-making is critical, including an in-depth analysis of the comparison between international standard requirements for EPDs (as per EN 15804), the claims made in published EPDs regarding supply chain coverage and other aspects, and the degree to which EPDs comply with these.

References

AACA (2021) *National Standard of Competency for Architects 2021*, V1.0, Architects Accreditation Council of Australia, Sydney.

Adams, M., Burrows, V. and Richardson, S. (2019) *Bringing embodied carbon upfront*, World Green Building Council, London.

ALCAS (2019) The Australian National Life Cycle Inventory Database (AusLCI), Australian Life Cycle Assessment Society, Melbourne, Australia.

Azari, R. and Abbasabadi, N. (2018) Embodied energy of buildings: A review of data, methods, challenges, and research trends *Energy and Buildings*, 168, 225-235.

CEN (2019) *EN 15804:2012+A2:2019: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*, European Committee for Standardization, Brussels.

Crawford, R. H. (2018) Database of environmental flow coefficients for construction materials, The University of Melbourne, Melbourne. DOI: doi.org/10.26188/5b7c83f3dc239.

Crawford, R. H. and Stephan, A. (2022) Australian ready-mix concrete EPD data summary, The University of Melbourne, Melbourne. DOI: doi.org/10.26188/20353314.v2.

Crawford, R. H., Stephan, A. and Prideaux, F. (2019) Environmental Performance in Construction (EPiC) Database, The University of Melbourne, Melbourne. DOI: doi.org/10.26188/5dc228ef98c5a.

Crawford, R. H., Stephan, A. and Prideaux, F. (2020) EPiC: Introducing a database of hybrid environmental flow coefficients for construction materials *IOP Conference Series: Earth and Environmental Science*, 588, 042052.

Crawford, R. H., Stephan, A. and Prideaux, F. (2022) The EPiC database: Hybrid embodied environmental flow coefficients for construction materials *Resources, Conservation and Recycling*, 180, 106058.

Crawford, R. H. and Treloar, G. J. (2010) Database of embodied energy and water values for materials, The University of Melbourne, Melbourne. DOI: doi.org/10.4225/49/588eeeeda28af.

Emami, N., Heinonen, J., Marteinsson, B., Säynäjoki, A., Junnonen, J.-M., Laine, J. and Junnila, S. (2019) A life cycle assessment of two residential buildings using two different LCA database-software combinations: recognizing uniformities and inconsistencies *Buildings*, 9(1).

EPD Australasia (2022) *Australasian EPD programme: EPD database,* https://epd-australasia.com.

GGTI (2022) *EPD program*, Global GreenTag International, www.globalgreentag.com/epd-program.

GlobalABC, IEA and UNEP (2019) *2019 Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector*, Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme.

Häfliger, I.-F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M. R. M. and Habert, G. (2017) Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials *Journal of Cleaner Production*, 156, 805-816.

IEA (2018) *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, International Energy Agency, Paris.

IPCC (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, World Meteorological Organization, Geneva, Switzerland.

Karimpour, M., Belusko, M., Xing, K. and Bruno, F. (2014) Minimising the life cycle energy of buildings: Review and analysis *Building and Environment*, 73, 106-114.

Lasvaux, S., Habert, G., Peuportier, B. and Chevalier, J. (2015) Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies *The International Journal of Life Cycle Assessment*, 20(11), 1473-1490.

Lawson, W. R. (1996) *Building Materials, Energy and the Environment: Towards Ecologically Sustainable Development*, The Royal Australian Institute of Architects, Red Hill, 135p.

Lenzen, M. (2000) Errors in conventional and input-output-based life cycle inventories *Journal of Industrial Ecology*, 4(4), 127-148.

Lenzen, M. and Dey, C. J. (2000) Truncation error in embodied energy analyses of basic iron and steel products *Energy*, 25(6), 577-585.

Majeau-Bettez, G., Strømman, A. H. and Hertwich, E. G. (2011) Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues *Environmental Science & Technology*, 45(23), 10170-10177.

Martínez-Rocamora, A., Solís-Guzmán, J. and Marrero, M. (2016) LCA databases focused on construction materials: A review *Renewable and Sustainable Energy Reviews*, 58, 565-573.

Skillington, K., Crawford, R. H., Warren-Myers, G. and Davidson, K. (2022) A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings *Energy Policy*, 168, 112920.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J. and Norris, G. (2004) System boundary selection in life cycle inventories *Environmental Science and Technology*, 38(3), 657-664.

Treloar, G. J. and Crawford, R. H. (2003) Hybrid Material Energy Intensity Database, Deakin University, Geelong.

Tucker, S. N., Salomonsson, G. D., Ambrose, M. D., Treloar, G. J., Hunter, B., Edwards, P. J., Stewart, P. J., Anton, S. and Crutchley, G. (1996) *Development of Analytical Models for Evaluating Energy Embodied in Construction*, Report prepared for the Energy Research and Development Corporation (DBCE DOC 96/84M), CSIRO Building, Construction and Engineering, Melbourne, 56p.

UNEP (2021) *2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*, United Nations Environment Programme, Nairobi.

Wiedmann, T. (2017) An input–output virtual laboratory in practice – survey of uptake, usage and applications of the first operational IELab *Economic Systems Research*, 29(2), 296-312.

Wiedmann, T., Teh, S. H. and Yu, M. (2019) *ICM Database: Integrated Carbon Metrics Embodied Carbon Life Cycle Inventory Database*, UNSW Sydney.

Creating resilience through empowering Self-Build Strategies in a Myanmar refugee camp

Myint San Aung[1] and Annabel Pretty[2]

[1,2] School of Architecture,Unitec Te Pūkenga, Auckland, New Zealand
myintsan98@gmail.com[1], apretty@unitec.ac.nz[2], ORCID-0000-0001-7004-0356[1],
ORCID-0000-0001-6786-301X[2]

Abstract: Currently, around 82 million people are displaced globally, and refugees are among the most vulnerable and in need of support. Around 1.1 million refugees from Myanmar are situated in large refugee camps between Myanmar, Thailand and Bangladesh, many living in such conditions for up to 30 years. Long-term design solutions are needed to solve the refugee crisis in Myanmar, and architecture has the solution for creating meaningful place-making for the refugees who are still trapped in these camps. Through a comprehensive vernacular design approach and a holistic solution, architecture can help mitigate the quality of life of refugees. The design project will be approached with the mindset of refugees' involvement and allowing them to create their own set of rules and use their own skill sets. Alongside this, a vernacular traditional construction system will be developed to adapt to those skill sets and be appropriate to environmental conditions. The goal is to achieve an architectural solution that provides a better living environment and enhances the prospects of refugees' lives. As well as re-imagining current camps to create a resilient and self-sufficient community where one feels a sense of belonging and can express, educate and prepare themselves for the future.

Keywords: Bamboo, Traditional Construction, Refugee Communities, Myanmar

1. Introduction

We are living in a pivotal period in history. Today's world is witnessing an unprecedented number of people being forcibly displaced on a global scale. The United Nations High Commissioner for Refugees (UNHCR) estimated that global forced displacement will have surpassed 80 million by mid-2020. There are nearly 26.3 million refugees among them, with nearly half of them under the age of 18. Currently, Syria has 6.6 million refugees, Venezuela has 3.7 million, Afghanistan has 2.7 million, South Sudan has 2.2 million, and Myanmar has 1.1 million refugees (UNHCR, 2022) Many have been denied citizenship and do not have access to fundamental human rights. Since economic crises, labour demands, urbanisation, entrenched poverty, and political instability have forced people to seek refuge outside their home countries, providing essential social and educational services has become an urgent concern. Many of the

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 189–198.*

refugees live in large humanitarian areas known as temporary shelters/refugee camps. Refugees are housed in over 1,000 separate camps globally, predominantly in Central and Eastern Africa, the Middle East, and Central Asia (UNHCR, 2022) These places are seen as where lives are saved and where other organisations oversee all aspects of the refugees' lives. They are also portrayed as places of suffering and sorrow. These three representations of refugee camps are not mutually exclusive; instead, they often coexist or accompany one another.

The focus of this research will be on Myanmar refugees from Central Asia. Myanmar, formerly known as Burma, was not always in a state of political strife—beginning with thousand years of monarchy with respected kings and queens with golden palaces. It came to an end in 1885 with the invasion of the British East India Company, which marked the end of the monarchy and transformed the country into a British colony. Following a brief Japanese occupation during WWII, Myanmar was retaken by the Allies and granted independence in 1948. The period of freedom lasted from 1948 to 1962, when the military, led by General Ne Win, seized control of Myanmar in a coup. Till today, the country has been subjected to the longest military dictatorship in modern history. With the ongoing violence, the recent military coup in 2021, and human rights violations, one can be sure that the number of refugees fleeing from Myanmar to neighbouring countries will keep increasing.

Refugees are among those who are vulnerable and in need of aid—this research intends to provide and support refugees' needs through architecture, better their acculturation in the refugee camp, and improve their prospects after leaving the refugee camp. In addition, the research will aim to promote self-reliance and a community-based approach, with a comprehensive understanding of the community, and examine the condition of various communities from the standpoints of ages, genders, cultures, and religions, as well as develop support and assistance responses to the population. The project will be located in Thailand Mae Chan Sub-district, Umphang District, Tak Province. Conventional building methods and concepts learned from the vernacular architecture of Myanmar, and Southeast Asian countries will be used to enhance cultural resilience and develop appropriate architectural designs for the refugee community.

The project aims to enhance the prospects of refugees' lives by re-imagining current refugee camps to create a resilient and self-sufficient community, by promoting the use of indigenous building techniques to produce vernacular architecture. The topic of sustainability is also an essential component of the study, assisting and unifying the local communities. As a result, the initiative aims to create an effective social support system. This study intends to be contextually aware and engage in conversation with the current informal settlement, which will be discussed using local materials and familiar architectural styles.

2. State of Knowledge

The topic has received considerable attention, and the literary research spans guidelines produced by international organisations and more erudite overviews by theoreticians, which are interrogated and discussed to inform solutions for self-sufficient refugee camps for Myanmar refugees. Design approaches focusing on humanitarian design concerns such as self-reliance, refugee integration, and alternatives to camp are analysed and explored to inform ideas for a self-sufficient refugee camp. Furthermore, the concepts of providing more than just basic needs for refugees and the notions of social infrastructure and spaces for empowerment through research into vernacular architecture are interrogated and discussed to inform solutions for a way in which architecture empowers and enhances the prospect of refugee life.

In *Handbook for Emergencies*, (UNHCR, 2007) the emergency preparedness and response section of the UNHCR states that refugees are often seen as vulnerable and helpless recipients of foreign assistance in times of crisis. In the immediate future, aid workers' strategy establishes a trend of dependency. (UNHCR, 2007, p. 8) Therefore, the UNHCR began encouraging a self-reliance model and the notion that refugees should be involved from the start of an emergency. Refugees should be motivated to support themselves by using their expertise and tools. It states the importance of having a clear view of the population, assessing the various communities' conditions from age, gender, and cultural standpoint, and coordinating security and assistance responses for the community as a critical element in an adequate response. It also posits the importance of working with refugees through a community-based approach and promoting self-reliance from the start will have better effectiveness and will be significantly enhanced. Such an approach will allow the refugees to maintain their sense of dignity and purpose, encourage self-reliance and help avoid dependency.(UNHCR, 2007, p. 8)

Much of the professional and research literature on camps emphasises the influence of power and dependence. In *From Camp To City: Refugee Camps of The Western Sahara* (Herz, 2013), the editor Manuel Herz, an architect and an urban researcher on humanitarian architecture, introduces the notion of the refugee camp in the context of urbanism and architecture. Herz expresses how refugee camps are creating normality within the abnormal situation of "refugee-ness." Herz appoints that a plethora of scientific and technological literature demonstrates that camps are often sites of danger and risk, where relief is seen as dangerous, and refugees are trapped in an infinite loop of waiting. Herz argues that it is necessary to rethink this simplistic relationship of diametrical opposites, the city as a place of transparency and opportunity. The camp as a location of utter power needs to be reviewed. (Herz, 2013, p. 490) If we consider the starting point and prevailing view of the relationship between the city and camp as one antithesis, we will approach this question from two perspectives. Is the city a place of openness? Moreover, can the camp only be seen as a site of dependency?

3. Methodology

Research through Literature—Literature reviews have helped develop a strong understanding of Myanmar refugees and community-based solutions. The need for spaces of empowerment in refugee camps was an important discovery. Regenerative architecture and environmental principles methods have also been thoroughly researched to establish the best approaches.

Architecture and Precedents— Comprehensive knowledge of the conventional vernacular has been acquired to help understand the refugee context, local building materials, and traditional practices. The vernacular architectures of Myanmar, Thailand, and Southeast Asia have been closely observed alongside other vernacular architectures. In addition, an examination of selected precedents that incorporate community/context-based architecture, humanitarian architecture, and regenerative architecture also aims to contribute to a greater understanding of how architecture can empower and enhance the prospect of camp life.

Research through Experience—Personal experience and familiarity with the camp aid in understanding the research's cultural, historical, and contextual relationships. Due to the inability to access the site, the project relies on internet resources, personal photographs, and camp memories. Experience-based research is a valuable resource for better understanding the project's design specifications.

Research through Design— The design process begins with the design intent, which is backed by research and contextual criteria. Drawing and model-making experiments are then used to investigate architectural relationships. The various design solutions are then evaluated in relation to the project brief in order to get the best possible result.

4. Current Refugee Camp Models Around the World

Currently, there are millions of people who live in refugee camps. Refugee camps are also often defined as temporary shelters. The camps are created to respond to specific emergencies. Due to long-term conflicts and geopolitical factors, there is a lack of plausible durable solutions for refugees. Most refugee camps become long term despite their temporary solutions.(Amorós Elorduy, 2021) Many refugees find themselves staying in refugee camps for years, if not decades. As refugee camps grow, they represent a hazard to refugees and the people around them. It is a reality that the humanitarian system/host government assemblage is still based on this paradigm, partly owing to global politics and socio-economic reasons and partly due to assumptions based on inadequate and biased information. (Amorós Elorduy, 2021, p. 13)

These camps are sites of humanitarian assistance, conflict, political action, and everyday life. These camps are a transitional solution that turned long-term problem. These camps suffer from limited, biased geographically and disciplinary and inconsistent information, insufficient to build sturdy and contextualised frameworks to develop appropriate policies. Being understudied affects the lesser-known camps, such as those on the Thailand-Myanmar border and the Bangladesh- Myanmar border.

For decades, refugee camps have been examined from a structuralist or a humanitarian perspective. Both narratives have generalised and simplified the 'camp,' the 'refugee,' and 'education' into easily managed concepts. As a result, the camps are envisioned as efficient strategies for movement management, epidemic prevention, food distribution, and temporary shelter. Furthermore, camp spaces have been regarded as non-places, limbo, and transitory, with the built environment and issues such as child development and daily life being overlooked. (Amorós Elorduy, 2021, p. 3)

Regarding refugees' rights, refugees are not granted civil rights or allowed to own real estate. The host nation provides the refugee camps privileges that are generally associated with public places, the freedom of assembly, free expression, or political agency. Refugees are given temporary shelter and safety from harm, but they are denied the same rights as the host nation's civilian population. As non-state actors, humanitarian organisations such as the UNHCR and NGOs cannot guarantee the rights of refugees as well. (Herz, 2013, p. 488) Temporary shelters/camps are viewed as the opposite of urban living. Many academics and institutions characterised the camps as sites of isolation and total control. Some people think of them as locations where others oversee the situation and where refugees are alike, and they cannot make decisions about their own lives. Instead of empowering and exchanging ideas, camps are viewed as dependency and confinement. (Amorós Elorduy, 2021, p. 4)

5. Refugee Settlements Between Thai-Myanmar Borders

People from Myanmar have been fleeing war and violence to seek asylum in Thailand and neighbouring countries since the 1960s. As a result, Myanmar has the world's fifth-highest number of refugees. It is also home to the most significant number of displaced and non-displaced stateless people in Southeast Asia. According to the United Nations, the number of Myanmar who have been forcefully displaced or rendered stateless has gradually increased from 900,000 in 2014 to 1.96 million in 2020. There are currently nine official refugee camps spread along the Thai-Myanmar border, housing over 92,000 refugees in April 2021. (UNHCR, 2022) In addition, 900,000 Rohingya refugees have fled into Bangladesh's refugee camp, which has grown to become the world's largest refugee camp. Some of the Thai-Myanmar border camps are more than 30 to 40 years old, with most refugees never leaving the settlements. These camps are cut off from society due to government controls, inaccessible terrain, language barriers, and political power. (Demirdjian, 2020, p. 70)

6. Current Refugee Typology

There are three main prevalent ideas about refugee camps in today's time. Refugee camps are viewed as humanitarian sanctuaries where lives are saved. It is also a place of control where other institutions supervise all elements of the refugees' lives. Finally, they are portrayed as places of poverty and suffering. These three perspectives of refugee camps do not exclude one another. (Herz, 2013, p. 10) Spatial and temporal disjunction define refugee situations. As a result, refugee camps inhabit various uncertain political, social, legal, economic, and emotional situations. In terms of geography, they do not exist. They are only a stone's throw from the border, but they are entirely cut off from their homeland and far from home. Fences, inaccessible land, linguistic barriers, political boundaries, and government limitations separate them from the host society.

To seek genuine alternative camps, practitioners must offer genuine alternatives to camps that do not rely on isolating and physically confining migrants. Nerea Amorós Elorduy, an architect and researcher assisting refugees with expertise in East Africa, urges the humanitarian system/host government coalition to consider prohibiting the physical confinement of refugees in enclosed and isolated places, planned camps, settlements, and special economic zones. In *Architecture as a Way of Seeing and Learning* (Amorós Elorduy, 2021), Elorduy provides evidence that long-term camps could work as alternative urban centres in terms of architectural and urban growth, with a body in charge of its urban and architectural development, with a holistic perspective as a whole. Elorduy's finding shows that this could be done by sharing power and responsibilities among refugees, their immediate local hosts, and local authorities. (Amorós Elorduy, 2021, p. 14)However, this does not mean help to the vulnerable or foreign assistance should be stopped. Instead, power relations should shift, as they do in urban settlements across the world.

7. Site Selection and Climate

The Nupo Temporary Shelter is situated in Umphang District, approximately ten kilometres from the Thai-Myanmar border and 228 kilometres from Mae Sot, the closest major city to the Nupo temporary shelter. It has a land area of 158 acres (0.64 sq. km). The temporary shelter was built in 1997 to house refugees fleeing offensive attacks in Myanmar. It is Tak Province's smallest and most remote temporary shelter. Because it is a remote location, the design will adapt to the requirements of refugees in a self-sufficient manner. Nupo has 9,462 verified people of concern to UNHCR as of the end of June 2021. (UNHCR, 2022) The camp consists of around 82 per cent ethnic Karen/Kayin and around 6 per cent Burman, and a significant Muslim community. Nupo is inside the humid tropical climate zone. Therefore, the area has warm temperatures, which do not vary much between day and night, heavy precipitation, and rich vegetation. In the dry season, the temperature in the region can exceed 30 degrees Celsius, with an average low of 26 degrees Celsius. In the cool season, the temperature in the region has an average low of 17 and a high of 26 degrees Celsius. A year-round average temperature of 18°C and more than 180 cm of precipitation are typical in this hot and humid region.

8. Vernacular Architecture of Myanmar and Southeast Asia

Southeast Asian architecture has advanced over time; however, there are still gaps in contemporary discussion regarding Southeast Asian regional studies. The work of Southeast Asian architects tends to emphasise spatial features while ignoring the link between cultural landscape and vernacular architecture, notably the interaction between social and spatial components of built forms. Southeast Asian houses have three formal characteristics: piles, walls, and roofs. Another distinguishing feature is the indigenous beliefs of the Southeast Asian people in the practices of magic and spirit worship. People from these regions worship natural spirits who live in rivers, forests, and mountains; this tradition extends to dwellings. A house can be split into three sections: the roof, the living space, and the foundations. This divide is thought to encapsulate and represent the theological hierarchy of the gods, people (who live under the gods), and animals (who live beneath the humans). (Ju, 2017) There are over 350 ethnic groups around Southeast Asia, and most with their language, culture, and religious beliefs.

9. Brief and Programmes

The brief and programmes for this research are driven by the guidelines provided by UNHCR for planning and designing refugee camps, the research findings from literature and precedent research, and the researcher's resident experience in the Nupo Temporary Shelter. The long-term strategies and the urgent need to consider refugees' daily experiences discovered within the literary research to promote a self-sustaining living-working village (alternative to a camp) with the involvement of all parties.

10. The Bamboo Modular House

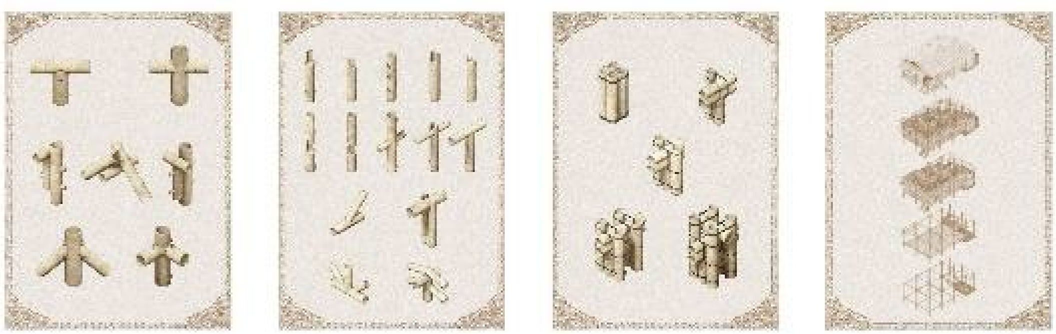


Figure 1: Bamboo connections and stages of bamboo house construction (Myint San Aung,2021)

Bamboo plantations will be the primary source of building materials for the various components. This is because it is a flexible, readily available, low-cost, durable, renewable, and sustainable resource. Bamboo is also an excellent material for designing a system that can be disassembled and reused—combining bamboo construction and vernacular building design guarantees that the beauty of the local setting is balanced. The houses are constructed of natural materials such as bamboo, sticks, leaves, and thatch roofs. Using natural materials decreases the structure's carbon footprint, enhancing the occupants' well-being. Furthermore, these materials are easily disassembled and recyclable towards the end of their lifetimes.

11. Housing Cluster Master Plan Design Concepts

The Grid—Refugee camps worldwide are designed to house as many displaced people as possible in a convenient location. This design concept generated a vast grid system, frequently perceived as unnatural and working against a natural setting, resulting in the loss of the village community's features.
Natural: In Myanmar, communities are frequently built along the main road, resulting in a long, narrow village that often only extends two ways. This can lead to a loss of belonging to a group, a decline in trust, and a sense of both natural and perceived security among households. Natural and Cluster—following the flow of the street and forming cluster micro-communities would aid in creating a resilient community whose success is measured collectively rather than individually. These microclusters would have areas to invest in based on their requirements and the needs of the whole cluster community.

Figure 2: Bamboo housing cluster design concept (Myint San Aung,2021)

Figure 3: Visualisation of cluster housing typology system (Myint San Aung, 2021)

12. Master Plan

The cluster housing typology system has been selected for this research project. Of the various options, it is best aligned with the developed brief, particularly the needs of refugees. Additional modules to the house, such as a bedroom, bathroom, kitchen, and others, can be installed. Spaces such as vegetable gardens, livestock housing, patios, and water sources can be set up between the houses and in the cluster's shared courtyard, which also minimises fire outbreaks. Therefore, a sense of belonging and security within the cluster can be achieved. It allows individuals or families to have control over their living environment. It can have several thresholds between houses but can regulate which thresholds are for private use and public use. This also is great for air ventilation between the houses. It is also possible to plant trees between housing developments and clusters in order to rehabilitate degraded land—a healthier way of living for both people and the planet.

As refugees go through various phases of life, a culturally appropriate floor arrangement with a flexible interior will help meet their needs. The floor plan may alter over time to meet the homeowner's needs. Flexible shared spaces provide a variety of activities for various users throughout the day. Because of the simplicity of design, diverse modular building typologies that best meet unique user requirements can be quickly established. The homes also provide optimum ventilation capacity through stack effect and appropriate window placement, assuring occupant comfort. A bamboo wall would not offer soundproof walls; nevertheless, the dwelling typologies' cluster structure provides a significant distance between each home, ensuring seclusion between each household.

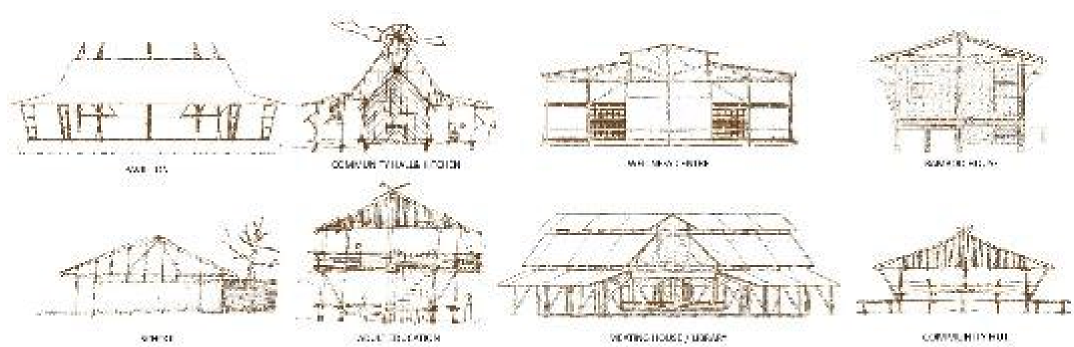


Figure 4: Proposed building typologies (Myint San Aung,2021)

A new Community Centre is also designed to satisfy the demands and desires of users—encompassing a school, adult education, workshops, community gardens, wellness, a library, a town hall, multipurpose pavilions, and a market area. These programmes are critical for refugees because they feel that information, education, and work opportunities are crucial for self-sufficiency and overall resilience. The new buildings are site-specific in terms of climatic design and multifunctional usage. The community centre is designed to be used and accessible by as many people as possible, regardless of age, gender, or ethnicity. It is a place to stay, chat, meditate, educate, study, play, create, grow, live, shop, sell and rest. The primary goal of constructing the master plan was to centralise all community activities and programmes in one area while providing access to the outside camp population. As a result, the community centre was built next to the main road. The existence of an active community centre near the main road would increase foot traffic and economic prospects for the camp and inspire the local Thai population and passing tourists to join in community activities. As a result, a self-sufficient framework for addressing alienation and building resilience is possible. This design choice is based on a literature review on alternatives to camps and the necessity for integration with the camp's external population, which would provide new possibilities, employment, and economic interchange between the local and refugee communities. Cultivating and harvesting bamboo within the microenvironment is also introduced as a self-sufficient method of resource production; this model is ideal for the refugee population to maintain community resilience and independence; UNHCR endorses this concept. (UNHCR, 2007)

13. Conclusion

Figure 5: Visualisation of proposed alternative to camp (Myint San Aung, 2021)

Because of the unknown element of how long refugees may have to stay in these camps, the concepts deemed pertinent to this enquiry include the necessity to address refugee camps as a long-term reality. Other relevant principles included prohibiting refugees' physical confinement in enclosed and isolated places; planning for a more integrated environment with access to education for all ages, providing eco-economic and work opportunities, and employing a self-resilience model that is, involving refugees from the beginning and allowing refugees to take charge of their livelihood.

The project employs Myanmar and Southeast Asian vernacular architecture's inherent aesthetic, which is driven by cultural and religious beliefs and uses natural materials obtained within its location, in order for the proposed architecture to be grounded, mature, confident, and clear and expresses rich cultural integrity imbued with compassion, dignity, and an innate knowledge of climate and customs. Understanding this regional context-based architecture was a critical first step in determining the most appropriate design for the people who live in these surroundings.

Compared to the current Nupo Temporary Shelter housing model, which uses a grid system, the new modular housing cluster concept is safer, simpler, and faster to build. Users may create unique places based on their interests and finances, thanks to the communal courtyard and open areas between the dwellings. The proposed modular housing cluster will allow variable spacing between the households, allowing tenants to build where they like while providing an adequate fire buffer between dwellers. When individuals actively participate in creating the environments they inhabit, a more wonderful sense of place and community arises.

In summary, the research seeks to provide a community-based refugee camp experience that includes the building and occupation of vernacular architecture to help address alienation and build resilience. Self-resilience measures can lessen refugees' vulnerability and their long-term need for humanitarian assistance. Furthermore, vernacular architecture may be employed to produce a self-sufficient model while also connecting individuals to a location and fostering a feeling of pride and ownership within the refugee population. This investigation aimed to respond to the refugees on the Thai-Myanmar border. The architectural interventions aimed to lift refugee spirits and determination through a community-based approach with a self-sufficient framework to overcome alienation and build resilience. Simply designing a house would not solve any of society's problems. One must collaborate with the local communities, governments, social workers, and research practitioners to address these issues.

References

Amorós Elorduy, N. (2021) *Architecture as a Way of Seeing and Learning: The Built Environment as an added Educator in East African Refugee camps*. Design Res. London: UCL Press.

Bogic, M., Njoku, A. and Priebe, S. (2015) 'Long-Term Mental Health of War-Refugees: a Systematic Literature Review', *BMC International Health and Human Rights*, 15(1), p. 29. doi: 10.1186/s12914-015-0064-9.

Ching, F. and Juroszek, S. P. (2010) *Design Drawing*. 2nd ed.. Edited by S. P. Juroszek. Hoboken, N.J.: Hoboken, N.J. : John Wiley & Sons.

Correia, M., Dipasquale, L. and Mecca, S. (2014) *VerSus: Heritage for Tomorrow Vernacular Knowledge for Sustainable Architecture*. Edited by M. Correia, L. Dipasquale, and S. Mecca. Firenze University Press.

de la Chaux, M., Haugh, H. and Greenwood, R. (2017) 'Organising Refugee Camps: "Respected Space" and "Listening Posts"', *Academy of Management Discoveries*. Academy of Management, 4(2), pp. 155–179.

Demirdjian, L. (2020) *Education, Refugees, and Asylum Seekers*. London: Bloomsbury Academic 2020.

DePillis, L., Saluja, K. and Lu, D. (2015) 'A Visual Guide 75 years of Major Refugee Crises Around the World', *The Washington Post*. Available at: https://www.washingtonpost.com/graphics/world/historical-migrant-crisis/ (Accessed: 11 June 2022).

Herz, M. (2013) *From Camp to City: Refugee Camps of the Western Sahara*. Zürich, Switzerland: Lars Muller Publishers.

Humanity, A. for (2006) *Design Like You Give a Damn : Architectural Responses to Humanitarian Crises*. New York, NY: New York, NY : Metropolis Books.

Ju, S. R. (2017) 'Southeast Asian Houses : Expanding Tradition'. Irvine, CA: Seoul Selection.

Meyer, S. *et al.* (2013) 'The Nature and Impact of Chronic Stressors on Refugee Children in Ban Mai Nai Soi Camp, Thailand', *Global Public Health*. Taylor & Francis, 8(9), pp. 1027–1047. doi: 10.1080/17441692.2013.811531.

Oranratmanee, R. (2018) 'Vernacular Houses of the Shan in Myanmar in the Southeast Asian context.', *Vernacular Architecture*. Routledge, 49(1), pp. 99–120. doi: 10.1080/03055477.2018.1524217.

Ramírez Carpeño, E. and Isabelle Feldman, H. (2015) 'Childhood and Education in Thailand-Burma/Myanmar Border Refugees Camps', *Global Studies of Childhood*. SAGE Publications, 5(4), pp. 414–424. doi: 10.1177/2043610615612951.

Rashid, M. and Ara, D. R. (2015) 'Modernity in Tradition: Reflections on Building Design and Technology in the Asian Vernacular', *Frontiers of Architectural Research*, 4(1), pp. 46–55. doi: 10.1016/j.foar.2014.11.001.

UNHCR (2005) *Handbook for Self-Reliance*, *Handbook for Self-Reliance*. Geneva: United Nations High Commissioner for Refugees.

UNHCR (2007) *Handbook for Emergencies*. Geneva: United Nations High Commissioner for Refugees.

UNHCR (2022) *UNHCR - Refugee Statistics*, *UNHCR - The UN Refugee Agency*. Available at: https://www.unhcr.org/refugee-statistics/ (Accessed: 18 June 2022).

Van Uffelen, C. (2014) *Bamboo Architecture & Design*. 1 edition., *Bamboo Architecture and Design*. 1 edition. Salenstein: Braun.

Data quality assurance in Environmental Product Declaration Electronic Database: An integrated Clark-Wilson Model, machine learning and blockchain conceptual framework

Oludolapo Ibrahim Olanrewaju[1], Wallace Imoudu Enegbuma[2] and Michael Donn[3]

[1, 2,3] Wellington School of Architecture, Victoria University of Wellington, New Zealand
{oludolapo.olanrewaju[1], wallace.enegbuma[2], michael.donn[3]}@vuw.ac.nz
ORCID-0000-0003-0034-6864[1], ORCID- 0000-0002-2455-4759[2], ORCID-0000-0002-4716-4286[3]

Abstract: Construction materials environmental product declaration (EPD) is becoming an essential data source for whole building life cycle assessment (WBLCA). In recent years, EPD programme operators have begun to digitalise the existing EPDs into a more useful data format through an electronic database. Therefore, it is essential to ensure the quality of EPD inserted in this electronic database in order to produce a reliable WBLCA. This paper aims to develop a conceptual framework for data quality assurance (DQA) in the EPD electronic database. The paper methodology is divided into two phases. Firstly, existing works of literature were examined to reveal the methods or technologies that can support DQA in an electronic database. Secondly, ten EPDs were reviewed to ascertain the data structure of existing EPDs, which will be used to determine the data to be extracted in the EPD electronic database. The information generated was used to develop a conceptual framework for a DQA embedded database design for construction materials EPD. The paper revealed that the Clark-Wilson model, blockchain and machine learning could enhance DQA in EPD electronic database. These findings have direct implications for the development of future electronic databases for EPDs. Future studies would leverage this conceptual framework to develop a working prototype for the EPD electronic database.

Keywords: Clark-Wilson model, Data Quality Assurance, Blockchain, Environmental Product Declaration.

1. Introduction

Buildings have contributed substantially to environmental emissions by consuming nearly 50% of raw materials, 16% of water and 71% of electricity (Oduyemi *et al.*, 2017). Hong *et al.* (2015) affirmed that buildings contribute around 25% to global CO_2 emissions, with an estimated annual increase of 2.7%. This high degree of resource usage in forms such as energy, water, forest use and raw materials has prompted stakeholders to develop a keen interest in sustainable development with the view to limit the impacts of buildings on the environment (Hussin et al., 2013; Zhang et al., 2019). As a result, stakeholders there have

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 199–208.*

explored sustainability assessment tools such as whole building life cycle assessment (WBLCA), green building rating tools (e.g. Leadership in Energy and Environmental Design [LEED], Building Research Establishment Environmental Assessment Method [BREEAM], Deutsche Gesellschaft für Nachhaltiges Bauen eV [DGNB] and Green Star), among others to assess the environmental impact of buildings on the environment prior to construction. This includes using data from different sources to measure the impact of construction materials on the environment. Particularly, the material aspect of green building rating tools will benefit hugely from technology adoption because the construction industry is mostly faced with a lack of information regarding construction materials and their supply chain (Shojaei *et al.*, 2019). In addition, Van Ooteghem and Xu (2012) also revealed a large variation in life cycle inventory (LCI) data of building materials as one of the fundamental problems of LCA studies in the construction industry.

Many of the existing studies on LCA in the construction industry have focused on the comparative assessment of LCA of different construction materials (Pargana et al., 2014), decision-making tools for LCA (Zanghelini et al., 2018), LCA of heritage buildings (Opher et al., 2021), BIM and LCA (Lee et al., 2015; Najjar et al., 2017; Horn et al., 2020; Naneva et al., 2020; Xue et al., 2021). Although Politi *et al.* (2018) studied the link between LCA and sustainability rating tools (LEED, BREEAM, DGNB and Green Star) with the view to identify the unique characteristics of LCA captured in notable sustainability rating tools. The study revealed that undefined boundaries, lack of adequate information and transparency, and lack of uniformity in the LCA rating process as the critical issues with the LCA framework of sustainability rating tools. EPD as a source of data for WBLCA has been introduced as a method to simplify LCA calculations. However, studies have reported some issues of data quality and transparency in construction EPDs (Gelowitz and McArthur, 2016; Waldman *et al.*, 2020). Furthermore, limited works have been done in the area of improving data traceability, transparency and reliability of EPD for WBLCA. This affects the WBLCA since the process is heavily dependent on the reliability of input data. Therefore, this study introduces a conceptual framework based on Clark-Wilson model, machine learning and blockchain that can enhance the quality of data uploaded to the EPD database.

2. EPD for Life Cycle Assessment

EPD has grown to be one of the largest sources of construction materials LCA data that is acceptable in many developed countries and used in assessing the sustainability of a building for decision-making (Strazza *et al.*, 2016; Arellano-Vazquez *et al.*, 2020; Palumbo *et al.*, 2020). The major purpose of EPD is to provide a quantified environmental impact of a product in an sorganised manner (Bovea et al., 2014). Almeida *et al.* (2013) used EPD environmental data for LCA of ceramic tiles and concluded that EPD could act as a tool for communicating the environmental impacts of products. Strazza et al. (2016) demonstrated empirically using two scenarios that LCA based on EPD data is also consistent with the conventional approach of collecting environmental impact data. Strazza *et al.* (2010) viewed LCA as an environmental management tool capable of communicating environmental information through an EPD. Palumbo et al. (2020) collected the EPD of concrete from ten different sources to determine the average environmental impact values that can be used at the design stage for LCA calculations. It was revealed the EPD is a reliable source of LCA data. AzariJafari et al. (2021) proposed a probabilistic LCA comparative approach for construction materials. It was found that there is a small difference between the EPD-based and conventional approaches, i.e. direct calculation based on generic databases without using an EPD. The summary of some relevant literature on LCA and EPD with their key findings is presented in Table 1. Overall, Table 1.2 shows that EPD is a valuable tool that can be used to communicate the sustainability of construction materials. EPD needs adequate improvement to guarantee the quality of data in it.

Table 1: Summary of Relevant Studies on EPD Data for LCA

S/N	Source	Study Type	Product	Impacts	Key Findings
1	AzariJafari et al. (2021)	Empirical	Concrete	GWP	The difference between EPD and the conventional approach based on the use of generic or average data is negligible. The study also provides important criteria for robust EPD comparison.
2	Palumbo et al. (2020)	Empirical	Concrete	GWP, AP, EP, POCP, ODP, ADP	EPD is a reliable source of data for LCA. The use of EPD for a different level of detail of BIM is not directly feasible.
3	Strazza et al. (2016)	Empirical	Bottled water	GWP, POCP, EP, AP	LCA based on EPD data is consistent with the conventional approach data based on a generic database.
4	Bovea et al. (2014)	Theoretical	-	GWP, AP, EP, POCP, ODP, ADP, E, EC	EPD can act as a verifiable source of environmental impact data. It can also be incorporated into the procurement process to select sustainable materials/products.
5	Almeida et al. (2013)	Empirical	Ceramic tiles	GWP, AP, EP, POCP, ODP, ADP, E	EPD can be an important tool for reporting the environmental impacts of a product.
6	Strazza et al. (2010)	Empirical	Cement	GWP, AP, EP, POCP, ODP, ADP, E, EC	LCA can communicate environmental impact information through an EPD.

Note: GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, POCP = Photochemical Ozone Create Potential, ODP = Ozone Layer Depletion, ADP = Abiotic Depletion, HTP = Human Toxic Potential, E = Energy and EC = Electricity Consumption

3. Construction EPD review

To identify the data that can be extracted from an EPD, ten different EPDs of construction materials were carefully reviewed. The summary of their components and corresponding EPD is presented in Table 2. The materials EPD reviewed were principally steel, concrete, tiles and timber. All the EPDs have EPD registration information (*ERI*), product composition (*PC*), scope declaration/boundary (*SD/B*), functional unit (*FU*) and life cycle impact assessment indicator (*LCIAI*), while 90% have resource indicator (*RI*) and wastes and other outputs (*WAO*) and 30% have end of life parameters (*ELP*). None of the reviewed EPDs has "used stage parameters" (*USP*). This is because the materials selected for the review do not have use stage parameters.

Based on Table 2, the data from an EPD can be classified into two categories which include:

1. Non-lifecycle data (EPD registration information [ERI], product composition [PC], scope declaration/boundary [SD/B], and functional unit [FU]); and
2. Life cycle data (life cycle impact assessment indicator [LCIAI], resource indicator [RI], wastes and other outputs [WAO], use stage parameters [USP], and end of life parameters [ELP]).

They are briefly explained as follows:

- **EPD registration information:** this consists of all information about the EPD, contact information and product category rules.
- **Product composition:** this includes a list of all the raw materials and respective quantities that are used in producing the construction material.
- **Scope declaration/boundary:** the scope of the EPD is covered here. It clearly shows the coverage of the EPD based on the building life cycle as indicated in BS EN 15978:2011.
- **Functional unit:** this is a critical component of every LCA. It is a measure of the function of the system under study. It also provides a reference point for the inputs and outputs of the system.
- **Life cycle impact assessment indicator:** this includes a range of life cycle impacts such as global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential, ozone layer depletion, abiotic depletion, and human toxic potential.
- **Resource indicator:** this shows the resources that are used at each stage of the material life cycle. Examples include; Renewable primary energy as an energy carrier, Renewable primary energy as material utilisation, Total use of renewable primary energy resources, Non-renewable primary energy as an energy carrier, Non-renewable primary energy as material utilisation, Total use of non-renewable primary energy resources, Use of secondary material, Use of renewable secondary fuels, Use of non-renewable secondary fuels, and Use of net freshwater.
- **Wastes and other outputs:** this contains relevant constants for waste at the corresponding stage of the building life cycle. Examples include: Hazardous waste indicators; Non-hazardous waste disposed; Radioactive waste disposed; Components for re-use; Materials for recycling; Materials for energy recovery, Exported electrical energy; and Exported thermal energy.
- **Use stage parameters:** this includes some constants that can be attributed to the usage of the product/material.
- **End of life parameters:** this contains relevant constants that can be used to facilitate the end-of-life calculations, such as the amount/percentage of recycling.

Table 2: Summary of Component Review of Selected Construction Materials EPD

S/N	Source	Product	EPD Program	Scope	NLCD				LCD				
					ERI	PC/TD	SD/B	FU	LCIAI	RI	WAO	USP	ELP
1	Porcelanosa	Porcelanosa STONKER façade tiles	Global GreenTag	Australia	✓	✓	✓	✓	✓	×	×	×	×
2	New-Zealand-Steel	COLORSTEEL® Endura®	EPD Australasia	New Zealand	✓	✓	✓	✓	✓	✓	✓	×	✓
3	Allied-Concrete	Ready-mixed concrete using Holcim supplied cement	The International EPD® System	New Zealand	✓	✓	✓	✓	✓	✓	✓	×	×
4	Firth	Ready-mixed concrete	The International EPD® System	New Zealand	✓	✓	✓	✓	✓	✓	✓	×	×
5	Interface-Europe-Manufacturing	Modular carpet tiles	Institut Bauen und Umwelt e.V	Germany	✓	✓	✓	✓	✓	✓	✓	×	×
6	Wood-for-Good	Sawn timber	BRE Global	United Kingdom	✓	✓	✓	✓	✓	✓	✓	×	✓
7	Abodo	Wood	EPD Australasia	New Zealand	✓	✓	✓	✓	✓	✓	✓	×	✓
8	VitrA-Karo-San	Porcelain Tile	EDP Turkey (The International EPD® System)	Global	✓	✓	✓	✓	✓	✓	✓	×	×
9	Pamesa-Cerámica	Ceramic tiles, porcelain tiles	AENOR GlobalEPD	Spain	✓	✓	✓	✓	✓	✓	✓	×	×
10	Rockfon	Ceiling tiles	Institut Bauen und Umwelt e.V	Denmark	✓	✓	✓	✓	✓	✓	✓	×	×

Note: ERI = EPD registration information, PC/TD = product composition/technical data, SD/B = scope declaration/boundary, FU = functional unit, LCIAI = life cycle impact assessment indicator, RI = resource indicator, WAO = wastes and other outputs, USP = use stage parameters, ELP = end of life parameters, NLCD = non-life cycle data, LCD = life cycle data

4. Conceptual framework for DQA-enabled EPD electronic database

The conceptual DQA-enabled EPD electronic database was based on three notable concepts: the Clark-Wilson model, machine learning, and blockchain. These technologies were embedded in the EPD database development. Clark-Wilson model (Tesfamicael *et al.*, 2021) and machine learning algorithm for data validation (Alyami and Almutairi, 2022) were incorporated to ensure the data transmitted to the blockchain are reliable.

4.1. DQA by machine learning algorithm

Various machine learning algorithms such as K-Nearest Neighbor (KNN), Linear regression, Logistic regression, genetic algorithm (GA), Decision tree, SVM algorithm, artificial neural networks (ANN), Naive Bayes algorithm, K-means, Random forest algorithm, among others have been applied to ensure data quality assurance. Jalaei and Mohammadi (2020) used the K Nearest Neighbour (KNN) algorithm to predict missing credits based on previously-rated building data. Lim *et al.* (2018) used the GA to predict the building envelop overall thermal transfer value (OTTV). The study demonstrated that GA helps to improve the accuracy of predictions and reliability. In the same vein, Yu *et al.* (2015) utilised GA to optimise the accuracy of ANN predictions for energy efficiency and thermal comfort in building design. Given the success of machine learning applications in previous studies for improving data quality, machine learning would be implemented in the electronic database to identify patterns in the data extracted from existing EPD with the view to ascertaining correctness range and help minimise human errors while uploading EPD data to the electronic database.

4.2. DQA by Clark-Wilson model

Clark-Wilson model has been applied to improve the quality of blockchain-enabled electronic databases (Tesfamicael et al., 2021; Xu et al., 2022). The model will be used to enforce access control in the blockchain database. Clark and Wilson argued that information integrity is more valuable than its confidentiality. The clark-Wilson model is an application-level model for guaranteeing the integrity of commercial data within application systems (Anderson, 2001). Clark-Wilson model divides the data in a system into constrained data items (CDI) and unconstrained items (UDI). The integrity model is applied to CDI, while none is applied to UDI. The data items (CDI and UDI) are subjected to two processes, including the integrity verification procedure (IVP) and the transformation procedure (TP). IVP ensures that the data is in a valid state while TP changes the data from one state to another. The integrity of data items is only maintained when it is modified by the TP. Integrity enforcement systems will normally require all TP to be logged with the view to provide an audit trail of data item changes. Furthermore, Clark and Wilson noted that there is a need to have integrity monitoring (certification rules) and preserving rules (enforcement rules) in order to ensure the integrity of data systems. User inputs for construction EPD that have been validated through the machine learning model is sent through the Clark-Wilson model layer for quality assurance of the data. CDI for construction EPD data is then sent to the blockchain network for storage which provides a unique hash that can be used to track the entire data used in preparing the EPD and their sources.

4.3. DQA by blockchain

Blockchain has been used to solve complex problems in different industries such as transport, financial, education, logistics, health, insurance, retail, agriculture and energy (Ali *et al.*, 2018; Rathee *et al.*, 2019;

Yu and He, 2019; Tseng *et al.*, 2020). Blockchain is capable of enhancing construction materials supply chain sustainability through proactive traceability and information sharing (Wang et al., 2020). Zhang *et al.* (2020) developed a framework to support the implementation of blockchain technology in the life cycle assessment of materials. The framework combined Blockchain, IoT, and big data analytics and visualisation. This shows that blockchain can help guarantee the traceability and authenticity of construction material's environmental impact data which is essential while assessing the environmental impacts of buildings. Furthermore, Wang et al. (2020) expressed that blockchain offers advantages, including information sharing, traceability, transparency, and security. Due to the benefits of blockchain, it will be applied to protect and as well ensure the traceability of EPD data. This will enable the users of EPD data know the source of each and every data used in the EPD preparation which is incorporated into WBLCA calculations.

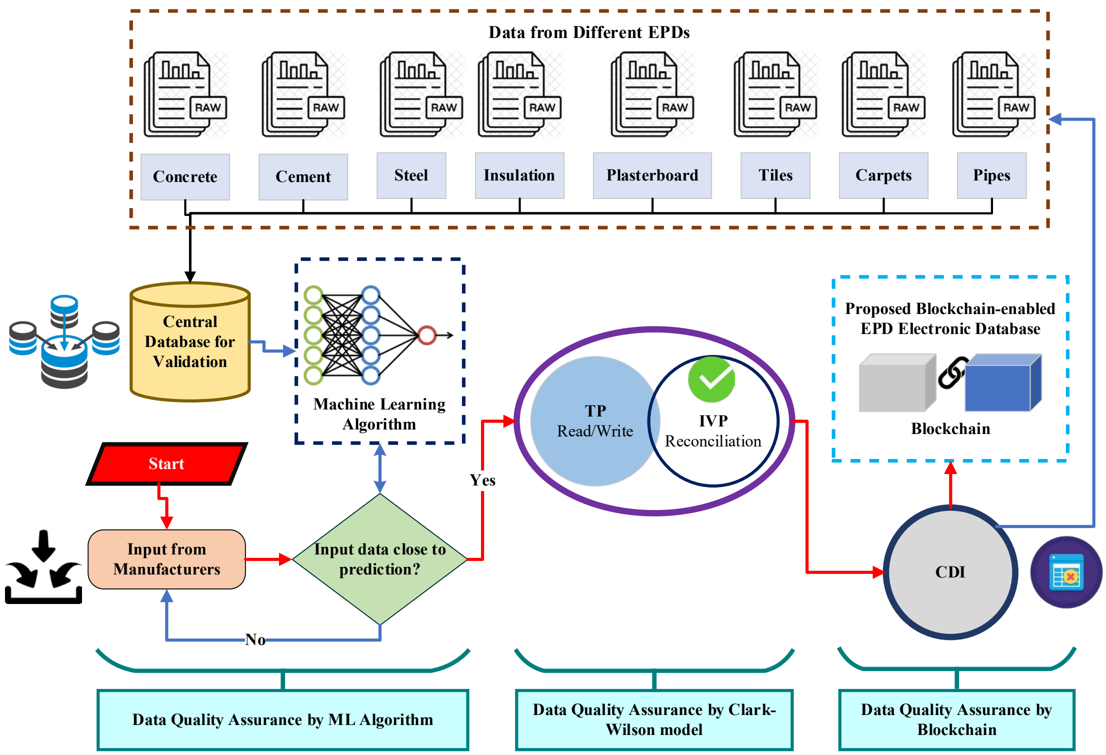


Figure 1: Conceptual framework for three-level DQA-enabled EPD electronic database

5. Conclusions and recommendations for future research

EPD is a valuable source of data for WBLCA, and the quality of data used in this process affects the overall reliability of building sustainability assessment. This paper proposed that the Clark-Wilson model, machine learning and blockchain could be valuable tools in ensuring data quality in an EPD database.

This paper introduced a conceptual framework that can be incorporated into the future development of an electronic database for EPD with a DQA-enabled module. The framework highlights how the construction industry could leverage the power of machine learning and blockchain to ensure the quality of data in the EPD electronic database. This conceptual framework would form a theoretical base for prototype development. The findings of this paper are useful for key stakeholders of the construction industry, including government regulatory bodies, as it provides a unique method to assure the quality of data in such a way that the data can be tracked to its original source, which helps improve the reliability of WBLCA results. When developed fully, the database can be integrated with a building information model to extract quantities and calculate the environmental impact of a construction project at the design stage. Therefore, it would facilitate well-informed sustainable decision-making.

Despite the contribution of this paper, it still have some limitations, which include the limited number of construction EPDs reviewed (n = 10) and the lack of real-time implementation of the DQA-enabled framework. Future studies would develop a real-time prototype of the DQA-enabled electronic database and as well review diverse EPDs from different EPD operators with the view to improve the data structure of construction EPDs.

Acknowledgements

This work is part of a PhD research project supported by a Wellington Doctoral Scholarship from Victoria University Wellington, New Zealand. The authors gratefully acknowledge Victoria University Wellington for their support. The authors also thank all the reviewers who invested their valuable time in reviewing the paper.

References

Ali, M. S., Vecchio, M., Pincheira, M., Dolui, K., Antonelli, F. and Rehmani, M. H. (2018) Applications of blockchains in the Internet of Things: A comprehensive survey, *IEEE Communications Surveys & Tutorials*, 21(2), 1676-1717.

Almeida, M., Demertzi, M., Dias, A. C. and Arroja, L. (2013) Environmental product declaration: for ceramic tile, *Energy for Sustainability, Coimbra*.

Alyami, F. and Almutairi, S. (2022) Implementing Integrity Assurance System for Big Data, *Wireless Personal Communications*, 122(3), 2585-2601.

Anderson, R. (2001) *Security engineering: a guide to building dependable distributed systems*, ed., John Wiley & Sons.

Arellano-Vazquez, D. A., Moreschi, L., Del Borghi, A., Gallo, M., Islas Valverde, G., Mayorga Rojas, M., Romero-Salazar, L. and Arteaga-Arcos, J. C. (2020) Use of EPD System for Designing New Building Materials: The Case Study of a Bio-Based Thermal Insulation Panel from the Pineapple Industry By-Product, *Sustainability (Switzerland)*, 12(17), 6864.

AzariJafari, H., Guest, G., Kirchain, R., Gregory, J. and Amor, B. (2021) Towards comparable environmental product declarations of construction materials: Insights from a probabilistic comparative LCA approach, *Building and Environment*, 190, 107542.

Bovea, M., Ibáñez-Forés, V. and Agustí-Juan, I. (2014) Environmental product declaration (EPD) labelling of construction and building materials, in, *Eco-efficient Construction and Building Materials*, Elsevier, 125-150.

Gelowitz, M. D. C. and McArthur, J. J. (2016) Investigating the Effect of Environmental Product Declaration Adoption in LEED® on the Construction Industry: A Case Study, *Procedia Engineering*, 145, 58-65.

Goglio, P., Williams, A. G., Balta-Ozkan, N., Harris, N. R., Williamson, P., Huisingh, D., Zhang, Z. and Tavoni, M. (2020) Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes, *Journal of Cleaner Production*, 244, 118896.

Hong, J., Shen, G. Q., Feng, Y., Lau, W. S.-t. and Mao, C. (2015) Greenhouse gas emissions during the construction phase of a building: a case study in China, *Journal of Cleaner Production*, 103, 249-259.

Horn, R., Ebertshäuser, S., Di Bari, R., Jorgji, O., Traunspurger, R. and Both, P. v. (2020) The BIM2LCA Approach: An Industry Foundation Classes (IFC)-Based Interface to Integrate Life Cycle Assessment in Integral Planning, *Sustainability (Switzerland)*, 12(16).

Hussin, J. M., Rahman, I. A. and Memon, A. H. (2013) The way forward in sustainable construction: issues and challenges, *International Journal of Advances in Applied Sciences*, 2(1), 15-24.

Jalaei, F. and Mohammadi, S. (2020) An integrated BIM-LEED application to automate sustainable design assessment framework at the conceptual stage of building projects, *Sustainable Cities and Society*, 53.

Lee, S., Tae, S., Roh, S. and Kim, T. (2015) Green template for life cycle assessment of buildings based on building information modeling: Focus on embodied environmental impact, *Sustainability (Switzerland)*, 7(12), 16498-16512.

Lim, Y. W., Majid, H. A., Samah, A. A., Ahmad, M. H., Ossen, D. R., Harun, M. F. and Shahsavari, F. (2018) Bim and genetic algorithm optimisation for sustainable building envelope design, *International Journal of Sustainable Development and Planning*, 13(1), 151-159.

Najjar, M., Figueiredo, K., Palumbo, M. and Haddad, A. (2017) Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building, *Journal of Building Engineering*, 14, 115-126.

Naneva, A., Bonanomi, M., Hollberg, A., Habert, G. and Hall, D. (2020) Integrated BIM-based LCA for the entire building process using an existing structure for cost estimation in the Swiss context, *Sustainability (Switzerland)*, 12(9).

Oduyemi, O., Okoroh, M. I. and Fajana, O. S. (2017) The application and barriers of BIM in sustainable building design, *Journal of Facilities Management*, 15(1), 15-34.

Opher, T., Duhamel, M., Posen, I. D., Panesar, D. K., Brugmann, R., Roy, A., Zizzo, R., Sequeira, L., Anvari, A. and MacLean, H. L. (2021) Life cycle GHG assessment of a building restoration: Case study of a heritage industrial building in Toronto, Canada, *Journal of Cleaner Production*, 279, 123819.

Palumbo, E., Soust-Verdaguer, B., Llatas, C. and Traverso, M. (2020) How to obtain accurate environmental impacts at early design stages in BIM when using environmental product declaration. A method to support decision-making, *Sustainability (Switzerland)*, 12(17), 6927.

Pargana, N., Pinheiro, M. D., Silvestre, J. D. and de Brito, J. (2014) Comparative environmental life cycle assessment of thermal insulation materials of buildings, *Energy and Buildings*, 82, 466-481.

Politi, S., Antonini, E. and Wilkinson, S. J. (2018) *Overview of building LCA from the sustainability rating tools perspective*,ZEMCH 2018 international conference, Melbourne, Australia, 237-250.

Rathee, G., Sharma, A., Iqbal, R., Aloqaily, M., Jaglan, N. and Kumar, R. (2019) A blockchain framework for securing connected and autonomous vehicles, *Sensors*, 19(14), 3165.

Shojaei, A., Wang, J. and Fenner, A. (2019) Exploring the feasibility of blockchain technology as an infrastructure for improving built asset sustainability, *Built Environment Project and Asset Management*, 10(2), 184-199.

Strazza, C., Del Borghi, A., Blengini, G. A. and Gallo, M. (2010) Definition of the methodology for a Sector EPD (Environmental Product Declaration): case study of the average Italian cement, *The International Journal of Life Cycle Assessment*, 15(6), 540-548.

Strazza, C., Del Borghi, A., Magrassi, F. and Gallo, M. (2016) Using environmental product declaration as source of data for life cycle assessment: a case study, *Journal of Cleaner Production*, 112, 333-342.

Tesfamicael, A. D., Liu, V., Mckague, M. and Caelli, W. (2021) An Architecture to Facilitate Security Assurance and Legal Compliance for Call Auditing in the Wholesale Electricity Market, *IEEE Access*, 9, 146437-146453.

Tseng, L., Wong, L., Otoum, S., Aloqaily, M. and Othman, J. B. (2020) Blockchain for managing heterogeneous internet of things: A perspective architecture, *IEEE network*, 34(1), 16-23.

Van Ooteghem, K. and Xu, L. (2012) The life-cycle assessment of a single-storey retail building in Canada, *Building and Environment*, 49, 212-226.

Waldman, B., Huang, M. and Simonen, K. (2020) Embodied carbon in construction materials: a framework for quantifying data quality in EPDs, *Buildings and Cities*, 1(1).

Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X. and Xiao, Q. (2020) Blockchain-based framework for improving supply chain traceability and information sharing in precast construction, *Automation in Construction*, 111, 103063.

Xu, D., Wang, W., Zhu, L., Zhao, J., Wu, F. and Gao, J. (2022) CL-BC: A Secure Data Storage Model for Social Networks, *Security and Communication Networks*, 2022.

Xue, K., Uzzal Hossain, M., Liu, M., Ma, M., Zhang, Y., Hu, M., Chen, X. and Cao, G. (2021) Bim integrated lca for promoting circular economy towards sustainable construction: An analytical review, *Sustainability (Switzerland)*, 13(3), 1-21.

Yu, F. R. and He, Y. (2019) A service-oriented blockchain system with virtualization, *Trans. Blockchain Technol. Appl.*, 1(1), 1-10.

Yu, W., Li, B., Jia, H., Zhang, M. and Wang, D. (2015) Application of multi-objective genetic algorithm to senergy efficiency and thermal comfort in building design, *Energy and Buildings*, 88, 135-143.

Zanghelini, G. M., Cherubini, E. and Soares, S. R. (2018) How multi-criteria decision analysis (MCDA) is aiding life cycle assessment (LCA) in results interpretation, *Journal of Cleaner Production*, 172, 609-622.

Zhang, A., Zhong, R. Y., Farooque, M., Kang, K. and Venkatesh, V. (2020) Blockchain-based life cycle assessment: An implementation framework and system architecture, *Resources, Conservation and Recycling*, 152, 104512.

Zhang, J., Li, H., Olanipekun, A. O. and Bai, L. (2019) A successful delivery process of green buildings: the project owners' view, motivation and commitment, *Renewable Energy*, 138, 651-658.

Designing for extreme weather impacts on buildings

Christopher A. Jensen[1] and Roberto Petruzzi[2]

[1,2] University of Melbourne, Melbourne, Australia
{cjensen[1], rpetruzzi[2]}@unimelb.edu.au

Abstract: In line with climate projections, extreme weather events have increased in Australian cities both in number and severity. Such events include heavy rainfall along the east coast, cyclone events along the north-west coastline and in far north Queensland, bushfires in the southeast and heatwaves across the continent. Current scientific modelling provides medium to high confidence that the effects of climate change will exacerbate these events even further. Much of the impact of these events is on private dwellings, in many cases in coastal, rural, or remote regions. Contemporary residential built environmental sustainability design in Australia commonly employs mitigation strategies seeking to reduce the potential impacts of long-term climate change, with regular reference to predictions of increased temperatures and sea level rise. However, extreme weather events are occurring now, and regulations and voluntary rating tools should be proactively addressing these critical issues. Despite extensive work on preparedness for extreme weather by researchers and Governments, practical design guidance is minimal with adaptation strategies relying on generic regulations and standards creating challenges for providing appropriate, cost-effective solutions specific to each different project location. This research reviews the regulatory and voluntary mechanisms currently in place in Australia that address extreme weather and highlights the gaps in design guidance and site-specific adaptation strategies to reduce impact of extreme weather on Australian houses

Keywords: Extreme Weather; Climate Change; Building Design; Mitigation; Adaptation.

1. Introduction

There is no shortage of literature covering issues related to the impact of the built environment on climate change often considered in line with the Intergovernmental Panel for Climate Change (IPCC) predictions for temperature and sea level rise (De Wilde, 2014). 'Building resilience' is the term often referred to when considering the impact of climate change, including mitigation against further climate change from human activities, and adaptation to reducing the immediate risks that exist due to historical emissions and/or failure to achieve mitigation targets (Swart & Raes, 2015). Extreme weather represents the most detrimental impact on buildings and poses a significant safety risk, most often affecting residential dwellings, in coastal, rural or remote regions (Kornhuber et al., 2019). Alarmingly, it is generally accepted that extreme weather events will continue to increase (Climate Council 2016). For the purposes of this research, we adopt the IPCC (2012) definition that extreme weather is "an occurrence of a value of a

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 209–218.*

weather or climate variable beyond a threshold that lies near the end of the range of observations for the variable" (Field, Barros, Stocker, & Dahe, 2012), although it is noted that other terms are sometimes used including; severe events, rare events, extreme events, or high impact events (Stephenson, Diaz, Murnane, & society, 2008). Figure 1 below categorises extreme weather as the environmental outcome of climate change with the most significant impact on buildings and the built environment, summarized as building and system thermal management, and damage resulting from rain, wind and flood.

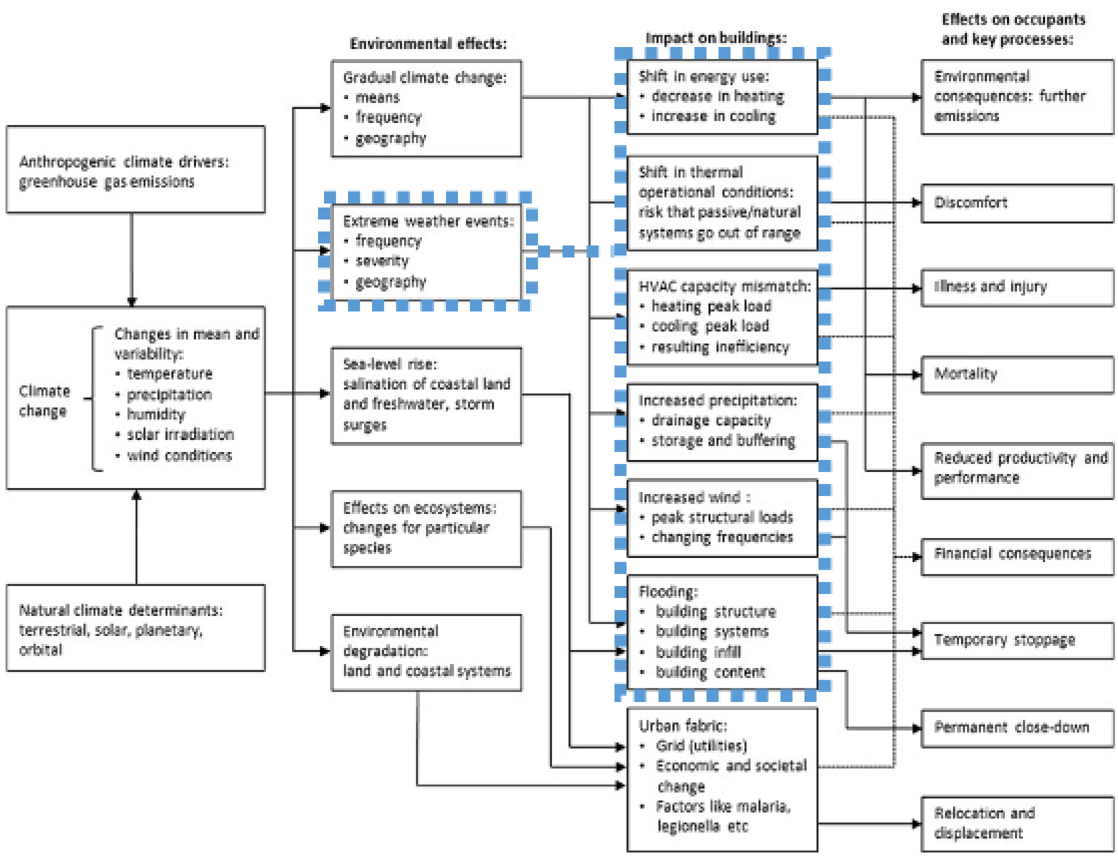


Figure 29: Schematic overview of climate change impact on buildings showing impacts of extreme weather events (highlighted) (de Wilde & Coley, 2012).

The IPCC provides the following summary of anticipated increases in extreme weather with the likelihood of its occurrence (Table 1) (IPCC, 2022).

Table 16: IPCC Regional Summary for Australasia (IPCC, 2022)

IPCC summary - Extreme weather regional observational changes - Australasia	
Australian **land areas have warmed** by around 1.4°C and New Zealand land areas by around 1.1°C between ~1910 and 2020	very high confidence
Heat extremes have increased, cold extremes have decreased, and these trends are projected to continue	high confidence
Relative **sea level rose at a rate higher than the global average** in recent decades; sandy shorelines have retreated in many locations; relative sea level rise is projected to continue in the 21st century and beyond, contributing to increased coastal flooding and shoreline retreat along sandy coasts throughout Australasia	high confidence
Frequency of **extreme fire** weather days has increased, and the fire season has become longer since 1950 at many locations (medium confidence). The intensity, frequency and duration of fire weather events are projected to increase throughout Australia (high confidence) and New Zealand	medium / high confidence
Heavy rainfall and river floods are projected to increase	medium confidence

1.1. The Australian extreme weather experience

The Australian experience closely matches the IPCC predictions. The trend of extreme weather has been demonstrated to impact all of Australia, with each region experiencing their own specific challenges (Australian Actuaries, 2022).

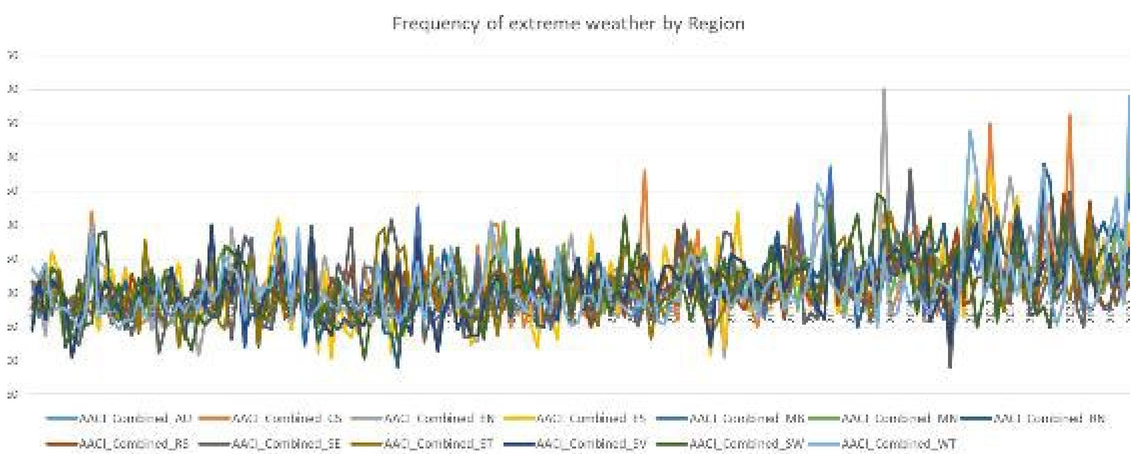


Figure 1: New modelling suggests that by 2030 one in every 25 properties nationally could be without cover due to increasing extreme weather events (Climate Council, 2022)

In addition to the positive trend in extreme weather frequency, the outliers are of particular importance - some of the which are memorable events representing key points in a long-term trend of worsening extreme weather since the 1970s.

- In 1974 Cyclone Tracy caused 65 deaths and damaged 70 percent of Darwin homes. More recently, cyclones Vance (1999), Larry (2006) and Yasi (2011) showed that updated regulations and standards have resulted in much less building damage and consequent loss of life (ACCC, 2018).
- In 2009 Victorian heatwave that began on the 27 January with daytime temperatures topping 43°C across 3 days, with night-time minimums of above 25°C (Jensen, Bartak, Petruzzi, & He, 2020). Understandably, the 2009 heatwaves coincided with catastrophic bushfires in Victoria.
- In March 2020 Black Summer fires burnt almost 19 million hectares, destroyed over 3,000 houses, and killed 33 people (Filkov, Ngo, Matthews, Telfer, & Penman, 2020)..
- On the 4th January 2020, Penrith (New South Wales) was officially the hottest place on Earth at 48.9°C. (BoM, 2020).
- The recent Queensland floods between 2021 – 2022 resulted in four rainfall and flooding events that had major impacts on infrastructure and on the wider community. Across the period, 66 of Queensland's 77 LGAs were activated for funding assistance under the Commonwealth Disaster Recovery Funding Arrangements (DRFA) following nine significant natural disaster events. (Queensland Reconstruction Authority, 2022).

These events have generated predictions that by 2030 one in every 25 properties across Australia will be considered 'high risk', meaning they will be uninsurable due to the annual damage costs from extreme weather and climate change, while one in 11 will reach 'medium risk' classification which will put them at risk of being underinsured (The Climate Council 2022). The two year period between 2019 – 2020 resulted in the insurance industry paying out more than $7 billion in claims on natural disasters alone (Insurance Council of Australia, 2022). The outcome of these events has resulted in the need for building design to account for insurance risks (Jensen & Yule, 2022), unlike more established climate change mitigation design focused advice and strategies, which do not lead to disaster resulting in claims.

2. Methodology

In order to understand the existing minimum requirements for extreme weather adaptation, the Case Study method is used. According to Eisenhardt (1989), the case study research method represents an inductive approach and one that allows the in-depth study of individual cases, which will provide a detailed understanding that would not be possible using more cross-sectional methods. It can include data from direct observation and systematic interviewing as well as from public and private archives. Any fact relevant to the stream of events describing the phenomenon is a potential datum in a case study, since context is important (Leonard-Barton, 1990). For this research, the National Construction Code (NCC) and the Green Building Council of Australia (GBCA) best practice assessment system - Greenstar Homes, have been selected for case study analysis with a focus on class 1 residential buildings. These tools together, represent the industry's "carrot" and "stick" tools for building design, thus together providing a complete picture of currently available extreme weather design guidance.

3. Results

3.1. Case Study 1 – The National Construction Code (NCC incorporating Australian Standards)

The National Construction Code (NCC) contains the minimum technical design and construction provisions that must be followed in Australia when designing and constructing buildings. This includes several referenced Australian Standards developed by Standards Australia which become a requirement when they are incorporated into the NCC. The main purpose of the NCC is human safety, but it also mandates the minimum requirements for health, amenity, accessibility, and energy efficiency. As Australia's primary statutory document for the construction of buildings and safety, it is logical that the current and predicted extreme weather events impacting buildings and their occupants be addressed in its provisions. To this end, the Australian Building Codes Board (ABCB) teamed up with the United States, Canada, and New Zealand to evaluate changes to better address the risks associated with extreme weather events. In 2014 the ABCB produced a discussion paper titled "Resilience of Buildings to Extreme Weather Events" (Australian Building Codes Board, 2014) which identified that the NCC must contain appropriate standards for building and plumbing systems to be sufficiently resilient in the face of natural hazards affected by extreme weather events. Despite this work, 8 years later there are still only a handful of provisions that touch on a few of the extreme weather events associated with a changing climate with a clear focus on life safety. New measures, such as the Bushfire Assessment Level (BAL) ratings demonstrate collaboration with planning and building, but with no evidence of a relationship with the insurance industry as identified as an area of key importance. The NCC design standards, discussion paper and guidance for extreme weather address cyclone, flood, bushfire, as the priority risks.

Part 3.0 Structural Provisions - Cyclone

The NCC and Australian Standards related to construction in cyclone areas are spread across a number of documents, as follows:

- Section 3 (various parts) National Construction Code; Volume 2: Building Code of Australia
- AS/NZS 1170.2 Structural design actions Part 2: Wind actions.
- AS 4055 Wind Loads for Housing.
- AS 1684.3 Residential timber-framed construction – Cyclonic areas.
- HB 132.2 Structural upgrading of older homes – Part 2: Cyclone areas.

Australia has a long history of damaging cyclones resulting in updated regulations and standards have resulted in much less building damage and consequent loss of life (ACCC, 2018). Although cyclones are geographically specific and defined by known cyclone regions, adaptation strategies for cyclone are relatively uniform, with a focus on structural integrity and roof material durability. Limited building design guidance is provided by these documents although it is noted that when considering cyclone adaptation, design choices play a relatively small role and are less site specific.

Part 3.10.3 Flooding

The primary NCC and Australian Standards related to construction in flood areas are as follows:

- Section 3.10.3 National Construction Code; Volume 2: Building Code of Australia
- Building Practice Note FH-01: Building in flood hazard areas (Victoria specific) (June 2022)

The limited guidance for flood in the NCC refers to floor heights and minimum freeboard (heigh above maximum flood level), with the flood heights defined through planning controls by the relevant local authority (e.g. Council). In Victoria, the Planning Provisions define special building overlay (SBO) zones to identify land in urban areas liable to inundation by overland flows from the urban drainage system as determined in consultation with, the floodplain management authority and usually based on the 100 year average recurrence interval (ARI) flood. From a design perspective, compliance can be achieved by simply ensuring the dwelling floor level is at or above the minimum specified freeboard.

Part 3.10.5 Bushfire

The primary NCC and Australian Standards related to construction in bushfire are as follows:

- AS3959
- NASH Standard – Steel Framed Construction in Bushfire Areas.

In comparison to cyclone and flood, bushfire standards provide valuable adaptation design strategies addressing materials and site issues. A residential building within a designated bushfire prone area or in the bushfire management overlay requires compliance primarily with Australian Standard AS3959 -which defines the Bushfire Assessment Level (BAL) methodology. The application of a BAL rating is based on the bushfire management overlay, which is determined by the relevant state authorities; in Victoria this is the Department of Environment, Land, Water and Planning (DELWP). As per flood and cyclone requirements of the NCC, dwelling resilience to bushfire is focused on life preservation and not dwelling retention. Location specific non-mandatory guidance requirements relate to practical minimum requirements specific to the risk level and include material choices, window shutters, but are often focused on planning, land management and access for emergence response (Gonzalez-Mathiesen & March, 2018)

3.2. Case Study 2 - Green Building Council of Australia – Green Star Homes

Several voluntary sustainability certification schemes are available in Australia, however most of them catered for the commercial sector with only a few applicable to residential dwellings. One of those is Green Star Homes which was released in 2021 by the Green Building Council of Australia (GBCA) and is specially targeted to Class 1 buildings developed by volume home builders (GBCA 2021). The tool adopts similar key principles to its commercial equivalent, Green Star Buildings, and aims to support the development of highly efficient, fossil fuel free dwellings. Unlike other Green Star tools, Green Star homes does not result in a star rating. The tool assesses developments under three key categories: Positive, Healthy and Resilient. Several design and construction criteria must be met to achieve certification. Positive criteria include typical mitigation considerations such as thermal performance, window systems, Airtightness, hot water, energy efficient appliances renewable energy, and a home users guide. Healthy criteria include air quality, moisture management, light quality and material toxicity. Resilient criteria include water use, heat resilience and resilience essentials.
Individual credits in all categories are either:

- *Mandatory*: requires a response in both the checklist and home design in line with the requirements outlined below.
- *Optional*: may or may not apply to the project or may be a measure that is not considered for the particular home. Project teams are only required to respond in the question to provide

information to the GBCA as to why it was or was not included. This allows GBCA to better understand industry responses and barriers to uptake of resilience measures.

According to the Green Star Homes technical manual, a resilient home is one that has reduced its exposure to natural hazard risks and has undertaken proactive measures that not only improve the sustainability performance of the home, but also its ability to withstand extreme weather events and natural disasters – thus protecting the home and the health of its occupants. To be certified, each project must complete a Resilience Checklist with the intent of demonstrating how the home has been designed to respond to climate change risks. The checklist is practically focused on managing water use for resource reduction, heat resilience, including reduced temperatures through urban heat island mitigation, and resilience essentials which is defined as being better adapted to climate risks. Despite the resilience category name, some of these criteria such as reduced water use, and minimization of the urban heat island are climate change mitigation strategies. All Green Star homes must meet the Resilience Checklist which contains both mandatory and non-mandatory criteria, under the categories of extreme heat, extreme rainfall and flooding, extreme storm, sea level rise, drought, bushfire, community connection resilience. Table 2 shows the mandatory criteria in the resilient category of the Green Star Homes tool.

Table 17: Mandatory requirements of the GBCA GreenStar homes Resilient category

<table>
<tr><td colspan="2">Extreme Heat Mandatory Criteria</td></tr>
<tr><td>Thermal comfort in extreme heat</td><td>under the resilience checklist category include one or more of the following features in order to demonstrate that the home is resilient to extreme heat:
• ceiling fans,
• eaves/awnings,
• adjustable blinds,
• shutters,
• louvres, or
• other shade or heat resistant measures.</td></tr>
<tr><td>Outdoor services</td><td>Outdoor services such as heating, ventilation and cooling systems, hot-water heaters must be positioned in areas of shade. This reduces the risk of failure due to exposure and increases efficiency.</td></tr>
<tr><td colspan="2">Extreme storms Mandatory Criteria</td></tr>
<tr><td>Storm-resistant fastening</td><td>The project team must demonstrate that storm resistant fasteners are rated or specified to respond to wind loads in compliance with either:
• AS4055-2012 Wind loads for Housing (use for all homes)
• AS/NZS 1170.2:2011 Structural design actions. Part 2: Wind actions (for use in homes above two storeys, large floor areas and/or unusual shapes)</td></tr>
<tr><td colspan="2">Community Connection and Resilience Mandatory Criteria</td></tr>
<tr><td>Home User Guide emergency response</td><td>The Home User Guide must include information around emergency services, response or other support services during extreme events such as floods, storms or bushfire. This includes site maps outlining access routes, designated assembly points and other community emergency information.</td></tr>
<tr><td>Electric vehicle charging</td><td>The project team must provide the following to the home to enable future provision of electric vehicle charging. Space for EV charging unit, Dedicated a/c circuit, Cable routing. Switchboard capacity</td></tr>
</table>

Flooding, sea level, drought and bushfire criteria are all optional in the checklist, providing practical but general targets to manage such events. The resilient category criteria are a productive step towards designing for extreme weather, but as yet, the tool is only available for volume builders which therefore limits the relevance to the individual projects that are more likely to be built in coastal, rural and remote regions.

4. Discussion

This research shows that the provision of guidance for designers addressing extreme weather adaptation is fragmented geographically, and in most cases non-specific to individual projects designs or site-specific constraints with application determined by local planning authorities. Cyclone performance requirements and bushfire BAL ratings provide more comprehensive criteria, with the BAL bushfire ratings specifically addressing site specific concerns related to vegetation, as well as design and material choices specific to the dwelling design. The extended period since the ABCB's 2014 extreme weather resilience publication indicates the ABCB's reluctance to introduce adaptation strategies as a minimum standard in the absence of a clear threat to human safety. Increased frequency and severity of extreme weather events indicate that standards are required to increase, and this can most be expected by priority for flood protection, not due to life safety but due to cost as well as insurance risk and premium rises. It is also now likely that geographical planning data is reconsidered to account for the new extent of areas affected.

Climate change mitigation strategies are well understood assist designers address energy and resource efficiency, low energy design to achieve thermal comfort, and ecological considerations such as vegetation and water savings. This type of design is widely available through practical guidance, relevant regulation, including tools to assist in the design for net-zero energy outcomes (NatHERS, Passivehouse, Green Star etc) and more recently embodied energy. Building design for extreme weather adaptation is significantly less developed than for climate change mitigation and this now needs to change. Designers need to have access to adaptation strategies, understand local authority zoning as well as site and building specific solutions. Green Star homes has begun to address these deficiencies with requirements for minimum performance as part of the resilience component of the assessment methodology. As one of the first rating systems to be introduced for class 1 residential dwellings, this tool is required to navigate the challenges of adoption, and potential resistance, by volume home builders to whom it is targeted. Despite these challenges it is a positive step towards addressing adaptation strategies for residential buildings across Australia such as cyclone bracing for all dwellings.

5. Conclusion

Regulatory and voluntary rating tools are beginning to address the unique challenges of extreme weather resilience, generally focused on structural integrity to withstand cyclone, bushfire and flood events through regulatory codes with the goal of human safety. Newer, best practice approaches provide limited design guidance such as GBCA's new Greenstar Homes tool. These approaches are a positive step for an industry that is otherwise lacking in design advice for extreme weather adaptation. Despite these small advances, application of the regulations and tools is subject to planning overlays defines by local Government authorities that rely on historical data such as 1 in 100 average rainfall intensity (ARI) that no longer matches the extremities of the climate that we see today. Further work is required by all industry member to advance adaptation design knowledge. Limitations of this research include the desktop nature of the research, suggesting that a broader study incorporating case studies would be appropriate for future research.

References

ABCB, 2014, Resilience of Buildings to Extreme Weather Events, Australian Building Code Board

ACCC. (2018). Northern Australia Insurance Inquiry First Interim Report. Retrieved from Australian Actuaries. (2022). Climate Index. Retrieved from (https://actuaries.asn.au/microsites/climate-index/data)

Australian Actuaries. (2022). Climate Index. Retrieved from (https://actuaries.asn.au/microsites/climate-index/data)

BoM. (2020). Special Climate Statement 73—extreme heat and fire weather in December 2019 and January 2020. Retrieved from

BoM, & Csiro. (2020). State of the Climate 2020. In: Commonwealth of Australia.

Climate Council 2016, Cranking Up the Intensity: Climate Change and Extreme Weather Events, Climate Council of Australia, Sydney

Climate Council 2022, Uninsurable Nation: Australia's Most Climate-Vulnerable Places, Climate Council of Australia, Sydney

De Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. Automation in Construction, 41, 40-49.

de Wilde, P., & Coley, D. (2012). The implications of a changing climate for buildings. Building and environment, 55, 1-7. doi:https://doi.org/10.1016/j.buildenv.2012.03.014

Eisenhardt, K. M. (1989). Building theories from case study research. Academy of Management Review, 14(4), 532-550.

Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (2012). Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change: Cambridge University Press.

Filkov, A. I., Ngo, T., Matthews, S., Telfer, S., & Penman, T. D. (2020). Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. Paper presented at the Journal of Safety Science and Resilience.

GBCA (2021), Design and construction of new homes, GBCA, https://new.gbca.org.au/green-star/rating-system/homes/

Gonzalez-Mathiesen, C., & March, A. (2018). Establishing Design Principles for Wildfire Resilient Urban Planning. Planning Practice & Research, 33(2), 97-119. doi:10.1080/02697459.2018.1429787

Insurance Council of Australia. (2022). Issues in focus: Built Environment. Retrieved from https://insurancecouncil.com.au/issues-in-focus/built-environment/

IPCC (2022). Regional Fact Sheet - Australasia. Sixth Assessment Report. Retrieved from https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Australasia.pdfJ

Jensen, C. A., Bartak, E., Petruzzi, R., & He, S. (2020). Impact of curtainwall facades on apartment overheating. Paper presented at the The 54th International Conference of the Architectural Science Association (ANZAScA)

Jensen, C. A., & Yule, J. (2022). Response strategies used to mitigate the effect of extreme weather on rural and remote housing in Australia. In IOP Conference Series: Materials Science and Engineering (Vol. 1218, No. 1, p. 012049). IOP Publishing.

Kornhuber, K., Osprey, S., Coumou, D., Petri, S., Petoukhov, V., Rahmstorf, S., & Gray, L. J. E. R. L. (2019). Extreme weather events in early summer 2018 connected by a recurrent hemispheric wave-7 pattern. 14(5), 054002.

Leonard-Barton, D. (1990). A Dual Methodology for Case Studies: Synergistic Use of a Longitudinal Single Site with Replicated Multiple Sites. Organization Science, 1(3), 248-266.

Queensland Reconstruction Authority. (2022). State Recovery and Resilience Plan 2022–24. (DOC/22/19293 GD 0701).

Stephenson, D. B., Diaz, H., Murnane, R. J. C. e., & society. (2008). Definition, diagnosis, and origin of extreme weather and climate events. 340, 11-23.

Swart, R., & Raes, F. (2015). Making integration of adaptation and mitigation work: mainstreaming into sustainable development policies? In Integrating climate change actions into local development (pp. 288-303): Routledge.

Developing a methodology to assess potential overheating of houses in Darwin

Terence Williamson[1], Siti Aisyah Damiati[2] and Veronica Soebarto[3]

The School Architecture and Built Environment, The University of Adelaide, Adelaide, Australia
{terence.williamson [1], sitiaisyah.damiati [2], veronica.soebarto [3]}@adelaide.edu.au

Abstract: The inability of the home environment to avoid overheating can result in discomfort and may have adverse effects on occupants' health and wellbeing. Overheating is defined as the extent to which a space exceeds an upper threshold of an acceptable thermal condition. Although identified as a potential issue, assessing a house design for overheating is not required by the National Construction Code. This paper will present a novel methodology to assess overheating in the Darwin region based on extensive house monitoring of 58 dwellings over extended periods with over 7400 comfort assessments provided by 103 householders. The methodology characterises the overheating performance of houses operating as either Free-Running (FR) or Naturally Ventilated (NV) based on the adaptive comfort characteristics of the occupants. The estimation of effective temperature (ET*) is adopted as the index to assess the degree of overheating. This methodology is proposed to be used for the Nationwide House Energy Rating Scheme (NatHERS) for the Darwin region.

Keywords: House overheating, Darwin, energy efficiency assessment.

1. Introduction

The Nationwide House Energy Rating Scheme (NatHERS), that provides a rating on a scale of 0-10 based on a computer simulation of a proposed new or renovated dwelling, is one method of demonstrating compliance with the energy-efficiency provisions of the National Construction Code (NCC) (NatHERS, 2022). The NatHERS rating is based on the estimation of heating and/or cooling loads calculated by the software program Chenath.

A recent report by Chen and Ren (2021) calls attention to the issue of the overheating of buildings assessed with NatHERS even when a high rating is achieved. Overheating of a house may arise on two fronts. First, a house that is assumed or expected to use cooling appliances but being operated in a Free Running (FR) mode. Such a house may experience an indoor environment with temperatures that exceed comfort (and/or health) limits when the cooling appliances are not in use. It is well-understood that the ability (or inability) of the home environment to ameliorate extreme heat conditions can result in discomfort and may have adverse effects on the occupants' health and wellbeing (Bi, et al., 2011). This may arise because of energy supply disruptions (particularly in summer) that cause cooling to be

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 219–229.*

inoperable, and/or those with limited disposable incomes are unable (or unwilling) to operate cooling devices.

Second, a house may also be designed with the intention to operate to the satisfaction of the occupants without cooling appliances being installed, thereby significantly reducing energy use. These houses, particularly in hot climates, rely on Natural Ventilation (NV) and maybe air movement via fans to maintain acceptable conditions. In warmer climates these houses provide satisfactory thermal environments because their design employs the judicious use of materials, shading and glazing elements, etc, and promotes air movement by natural ventilation or by fans. In the Northern Territory, NV designed houses are sometimes referred as "Troppo" designs (Goad, 2005). The reality is, however, that the majority of "Troppo" houses built at the present time are likely to include some provision for air-conditioning, often only in the bedrooms. These and the FR houses are described as operating in mixed-mode (MM).

Overheating is defined as the extent that a space (room, zone, *etc*) is estimated to exceed an acceptable condition. Generally, overheating is considered to occur when the room temperature, defined in terms of an effective temperature (*ET**) exceeds some defined upper threshold. This upper threshold is variously defined. In reality, the safe threshold temperatures can vary with occupant characteristics, such as health and age, and other factors such as activity (e.g., sleeping) together with social/cultural norms like the level of clothing (Nicol, et al., 2012)

The aim of this paper is to present a novel methodology to assess potential overheating in the Darwin region that would apply to houses operating either in Free-Running (FR) or Naturally Ventilated (NV) modes. It is expected that the application of the methodology will be adopted in the NatHERS software engine, Chenath. The methodology proposed is based on evidence collected during two research projects that together involved the detailed performance monitoring of 58 houses (and apartments) over extended periods in the Darwin area with over 7400 comfort assessments provided by 103 householders.

2. Data Collection Projects

Daniel (2016) monitored twenty households (designed to be naturally ventilated) located in Darwin, from June 2013 to May 2014. Temperature, humidity and air movement were recorded hourly in a living room and bedroom. During this 11-month period of the study the residents 18 years old and above were invited to complete daily a thermal comfort survey that consisted of three widely used subjective measures of thermal comfort that included; sensation 1=Cold to 7=Hot (ASHRAE, 2013); preference 1=Cooler, 2=No change, 3=Warmer (McIntyre, 1982) and; comfort 1=Very uncomfortable to 6=Very comfortable (Brager *et al*, 1993). The survey also asked the respondents to report their clothing level, activity, and window, fan and artificial heating/cooling operation. Households were invited to participate in the study because the occupants operated their dwellings as partially or solely in naturally ventilated (NV) mode. Comfort vote assessments (N=2415) were collected, mostly in living rooms.

During the period March 2020 to February 2021, Damiati (2022), conducted a similar monitoring exercise in Darwin and surrounding areas, that included a total of 30 houses and 8 apartments in the Palmerston, Howard Springs and Wagait Beach areas. All households except one had at least one air-conditioning unit installed and were generally managed in mix-mode (MM) operation, that is, either with AC cooling only or with fans and natural ventilation alone, or with AC cooling and fans running at the same time. Temperature, humidity and air movement were recorded half-hourly in a living room and bedroom. AC operation was monitored via a temperature recording in the AC outlet. Householders were also asked to complete comfort vote assessments (similar to Daniel, 2016), if possible, daily. Nearly 5000 valid thermal assessments were collected, 63% in living rooms and 37% in bedrooms.

During each study, detailed co-incident BOM data were obtained from the station closest to the house to describe the weather conditions during the monitoring periods. The mean monthly outdoor temperature can be calculated from this data. The 2013/14 study applies essentially to naturally ventilated houses (NV), while the 2020/21 data applies to houses in mixed mode operation (MM), that include periods of free-running (FR) operation.

3. The Concept of Effective Temperature

Existing "comfort" limits in the Chenath simulations that determine the application of cooling are defined by loci of effective temperature (*ET*).* *ET** is defined as the dry bulb temperature of a uniform sea level environment at 50% relative humidity (RH) which is thermally equivalent to the actual environment and therefore should evoke the same thermal response (ASHRAE, 2013). The calculation of *ET** is based on a two-node model of human physiology that incorporates dry bulb and radiant temperatures, humidity, air velocity as well as clothing level and metabolic rate (Gagge, et al., 1971). *ET** is a more comprehensive measure of comfort compared to, say, operative temperature alone. Thermal acceptability expressed as discomfort has also been shown to be closely related to *ET** as seen in Figure 1 (Gagge, et al., 1971; Gagge, et al., 1973). The term "discomfort" as introduced by Gagge, et al. applies particularly to warm-humid environments such as occur in Darwin, where the regulation of body temperature is accomplished by the evaporation of regulatory sweat on skin surface. They also developed an index of discomfort, DISC, that is described verbally as: comfortable and pleasant (0), slightly uncomfortable but acceptable (1), uncomfortable and unpleasant (2), very uncomfortable (3), limited tolerance (4), and intolerable (5). *ET** therefore provides a suitable index to assess the extent of overheating in terms of the deterioration in comfort conditions. The data collected during the two Darwin studies means that *ET** can be calculated at each "comfort" vote, in living rooms, and for the 2020/21 study also in bedrooms.

4. Chenath Validation

The assessment of a proposed dwelling to evaluate the extent of possible overheating using Chenath computer simulation relies on one important issue – that, with sufficient accuracy, the complex virtual model reliably approaches the reality of behaviour.

Detailed validation/calibration of the Chenath engine was assessed for three styles of houses in Darwin – a lightweight elevated house, a heavyweight slab-on-ground house and an apartment (to be reported elsewhere) showed that the Coefficient of Variation of the Root Mean Square Error CV(RMSE), that gives a good indication of a model's ability to predict the measured data, was in each case less than 5% in both living rooms and bedrooms of the assessed houses. A CV(RMSE) less than 10% is considered sufficiently accurate for the purposes of simulating hourly performance of a building (IPMVP Committee, 2010, p34).

5. Metric of Overheating

A metric for the degree of overheating for a given space (zone/room) within a building can be computed for each hour *i* of an assessment period as,

$$DD_i = ET^*_i - (CET + Acceptable\ Range) - CEV_i, \qquad \text{Eq (1)}$$

Where,

DD_i – Degree of overheating/discomfort – degree hour

ET^*_i - Effective temperature estimated for space at each hour *i* from Chenath output, calculated using computer code developed by the Center for the Built Environment (CBE), University of California Berkeley (Tartarini, et al., 2020) (°C)

CET – The base acceptable adaptive comfort effective temperature at still air conditions (°C)

Acceptable Range - Determined by % deviation from maximum acceptable conditions (°C)

CEV_i - Cooling Effect of Ventilation (°C) at each hour *i* to be calculated in Chenath engine, based on modelling of room design and air movement effectiveness (see below)

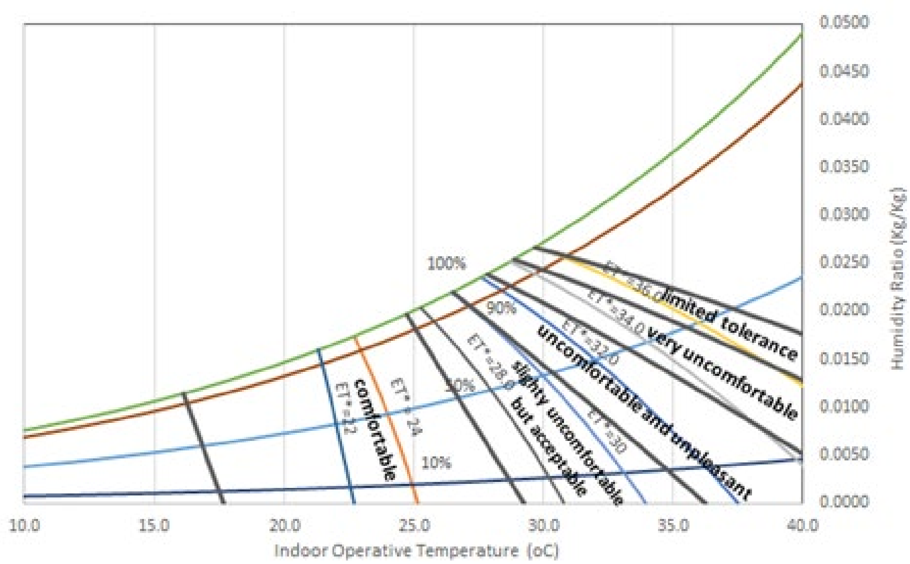


Figure 1: Limits of discomfort, on DISC scale, living rooms (Vel =0.4m/s, Met=1.5, clo=0.38)
Note: On this psychrometric chart the dark lines designate the boundaries between the discomfort categories. Loci of constant *ET** are also shown.

From Eq(1) the maximum acceptable condition can be seen as (*CET + Acceptable Range + CEV)*. DD_i can be evaluated at each hour for each zone/room and aggregated into a suitable index to represent the overall performance of a house, for example, assumed occupied hours each month or throughout the whole year.

6. The Apparent Cooling Effect of Air Speed - *CEV*

The Chenath software incorporates a formulation to account for the "cooling" effect of increased air speed developed by Steve Szokolay (Szokolay, 2000). This formula is,

$$CEV = 6.0 \times Ve - 1.6 \times Ve^2 \qquad \text{Eq (2)}$$

Where,

Ve is the effective air speed, that is, the actual air speed minus 0.2 (v – 0.2 m/s)

Szokolay derived his formulation by examining a number of studies that had correlated the perceived cooling effect with air speed. Szokolay suggested that his formulation is likely to be "slightly conservative". The Szokolay formulation is applicable to a maximum air speed of 2 m/sec.

6.1. The Darwin Data

ASHRAE Standard 55, Appendix D (2020) sets out a method for determining the apparent cooling effect of air at elevated air speeds. Figure 2 shows this method applied to calculate the cooling effect (*CEV*) of air speeds above 0.2 m/sec calculated in terms of *ΔET** for living room conditions measured in the Daniels 2013/14 and Damiati 2020/21 studies during natural ventilation periods (i.e. no AC operating).

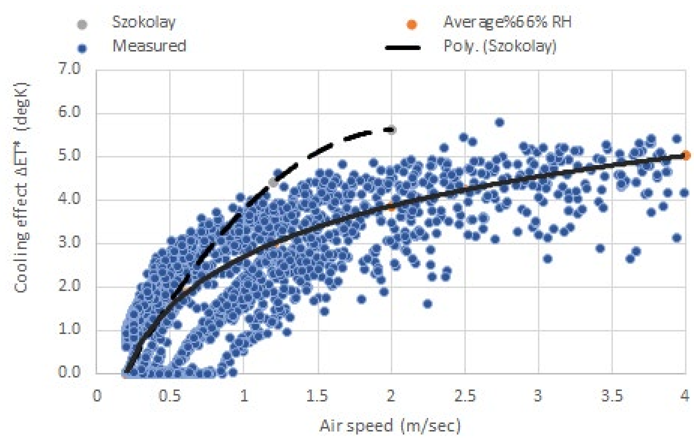


Figure 2: Air speed and apparent cooling effect – Living room

Combined Stepwise regression is used to fit a logarithmic expression to this data as shown in Eq (3) (R2=0.67, p<0.05)

$$CEV_{ET*} = 1.67\ ln(asp) + 3.97 - 0.02RH\% \qquad \textit{Eq (3)}$$

Where,

asp is air speed m/sec, limited to a maximum of 4 m/sec.

RH% is relative humidity

Figure 2 also shows this expression calculated with the average measured RH in living rooms (66%). This expression, Eq(3), is also compared with the Szokolay formula (dashed line) for air speeds up to 2 m/sec.

7. Calculation of *CET* - Thermal comfort effective temperature

Data collected during each Darwin project allows an estimation of occupant based adaptive thermal comfort - in this climate using *ET** as the dependent variable (incorporating humidity as well as dry bulb temperature). Many studies have found that the calculated neutral temperature, especially in non-air-conditioned spaces, does not correspond to a preferred temperature. The method described by Williamson and Daniel (2020), accounts for this discrepancy and therefore is employed to derive an acceptable temperature expressed in terms of *ET**. From the two studies adaptive models are derived from all votes in living rooms and bedrooms.

For the 2020/21 study, living room (MM),

$$T_{AccET*} = 0.49 \times T_{outmm} + 15.32 , \quad R2 = 0.82, p < 0.0 \qquad \text{Eq (4)}$$

and bedrooms (MM),

$$T_{AccET*} = 0.12 \times T_{outmm} + 24.72 , \quad R2 = 0.26, p < 0.05 \qquad \text{Eq (5)}$$

Where T_{AccET*} is the neutral or preferred indoor temperature, and T_{outmm} is the outdoor mean monthly temperature.

The 2013/14 study (living room only) (NV) yielded the relationship,

$$T_{AccET*} = 0.74 \times T_{outmm} \times 7.98 , \quad R2 = 0.98, p < 0.01 \qquad \text{Eq (6)}$$

These formulae do not explicitly include the air speed in the room when each comfort vote was recorded, but is included to the extent that different air speeds will affect the thermal sensation vote. The mean air speed measured in the living rooms for the 2 studies combined (outliers removed) was 0.59 m/sec (SD 0.72).

7.1 Setting *CET* at still air conditions

As described by Ren and Chen (2018) the righthand side of the Chenath "comfort" zone for a location, represented on a psychrometric chart, (the AC trigger point) is calculated in the software code from the ASHRAE adaptive comfort model, assuming still air conditions, plus 2.5K (dead band), justified as corresponding to 90% acceptability for NV buildings (de Dear and Brager, 1997) and for "simplicity" by using the mean temperature in January. For NatHERS climate01 (Darwin) the AC trigger is *ET** 29.0ºC. This value does not currently change in the simulations throughout the year.

Since few jurisdictions have sufficient data to develop location specific adaptive models (equivalent to Eqs (5,6 &7), and to allow for a future more general application, the ASHRAE model has been adopted and "nudged" to match the experimentally derived models adjusted to still air conditions according to the following steps so that,

$$T_{AccET*} = T_n + dT + dV \qquad \textit{Eq (7)}$$

Where,

T_{AccET*} is the derived adaptive temperature from Eq (4,5,&6), calculated for each month in turn,

T_n is the ASHRAE adaptive comfort temperature calculated from the monthly mean outdoor temperature,

$$T_n = 0.31 \times T_{outmm} + 17.8 \qquad \textit{Eq (8)}$$

dT is an adjustment factor that minimizes the difference (the average residual) between the experimentally derived adaptive models, Eqs (4, 5 & 6) and the ASHRAE model, such that $CET = T_n + dT$. dV is the cooling effect adjustment determined from the average air speed of measured data. As the overheating assessment methodology will consider the comfort benefit of air movement derived from the *CEV* calculation, the experimentally derived Darwin T_{AccET*} Eqs (4, 5, & 6) must be "adjusted" to represent comfort thresholds at still air conditions as described below.

Step 1. Determine dV

The derived adaptive models, *Eq (4, 5 & 6)* are standardized to still air conditions by subtracting the cooling effect of the actual average air movement measured during monitoring (dV*)*.

Step 2. Determine dT

In each case dT is determined to minimize the residual between $T_{AccET_*} - dV$ and $T_n + dT$

For MM operation, living rooms, becomes,

$$CET = 0.31 \times T_{outmm} + 17.8 + 0.80 \qquad \text{Eq (9)}$$

$T_{AccET_*} - dV$ and $T_n + dT$ together with monthly average recorded temperatures are shown in Figure 3 for MM operation living rooms (LR).

Table 1: Calculated cooling effect for various monitored conditions

Room	**Living Room (LR)**		**Bedroom (BR)**	
Mode	Ave Air speed m/s	*dV*, Cooling effect (K)	Ave Air speed m/s	*dV,* Cooling effect (K)
MM	0.59	1.85	0.4 (estimated)	1.15
NV	0.50	1.57	0.50 (estimated)	1.57

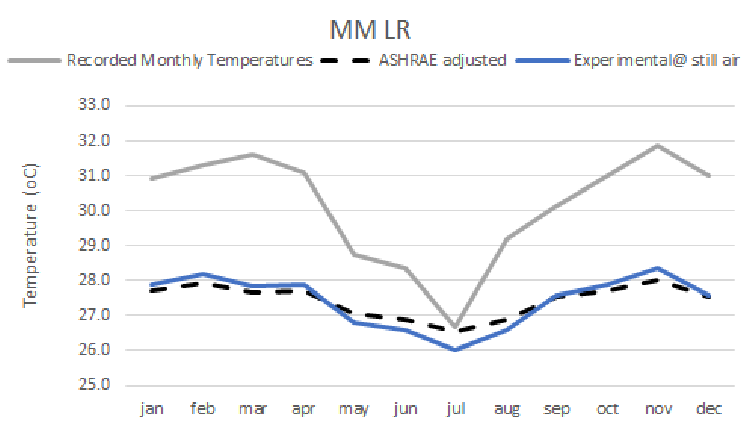


Figure 3: Comparison of mixed mode (MM) living room: recorded monthly average indoor temperatures in Darwin houses; proposed *CET* (neutral temperature according to adjusted ASHRAE adaptive model ($T_n + dT$) and recorded Darwin housing occupant ('experimental') preferred temperature adjusted to be equivalent to still air conditions ($T_{AccET*} - dV$).

In a similar way CET can be determined for MM operation bedrooms,

$$CET = 0.31 \times T_{outmm} + 17.8 + 0.32 \qquad \text{Eq (10)}$$

And for NV operation living rooms (and bedrooms),

$$CET = 0.31 \times T_{outmm} + 17.8 + 0.62 \qquad \text{Eq (11)}$$

The Darwin research project (2013/14) did not record comfort votes and conditions in NV bedrooms so the living room situation Eq (11) is assumed to apply.

7.2 Thermal Acceptability

The derived *CET* models above Eqs (9, 10 & 11) represent conditions that the maximum number of people would deem acceptable in the particular situation. In the 2013/14 study in the living room, 21.1% of participants voted 'very uncomfortable', 'uncomfortable' or 'slightly uncomfortable' on a 6-point comfort scale. The 2020/21 study did not ask this question but rather sought a response on a 5-point satisfaction scale. In the living room 28.0% (N=2668) of participants responded they were 'very dissatisfied', 'dissatisfied' or 'partially satisfied' with the conditions prevailing in the room when AC was not operating. In bedrooms this number was 24.8% (N=1188). Figure 4 shows the percentage of acceptable votes from the Darwin research with the inside temperature (calculated *ET**) binned at 0.5K intervals (blue dots) in living rooms. Also shown is a weighted quadratic expression fitted to this data (black dashed line). The Figure shows that for the living rooms of the 2020//21 study maximum acceptability (95%) occurs at 29.4°C. Ninety percent of votes occur between 27.1°C and 31.7°C, that is a width of 4.6K (or half width 2.3K) and the corresponding values at the 80%ile level are 25.4°C and 33.4°C that is a width of 8.0K (half width 4.0K).

By a similar approach the percentage of acceptable votes from the Darwin research was also determined for bedrooms. In this case the maximum acceptable votes (93.5%) occur at 28.2°C, with the 90%ile between 26.6°C and 29.8°C, a width of 3.3K (half width 1.65K) and the 80%ile between 25.0°C and 31.4°C a width of 6.4K (half width 3.2K).

On the DISC discomfort scale, as shown in Table 4, the 90%ile level of acceptability in bedrooms would correspond approximately to the lower range of the category "slightly uncomfortable but acceptable", while the 80%ile level of acceptability would correspond to approximately the upper level of the category "slightly uncomfortable but acceptable". In comparison to responses to the point-in-time survey question "*How satisfied are you with the temperature in this room?*", overall, 75.1% of occupants indicated 'very satisfied' or 'satisfied' satisfied' at a mean *ET** 29.3°C. It seems that Darwin householders, with no AC operating, are more satisfied in bedrooms when the situation is slightly cooler than the (80%ile acceptance) upper level of DISC band "slightly uncomfortable but acceptable" would suggest.

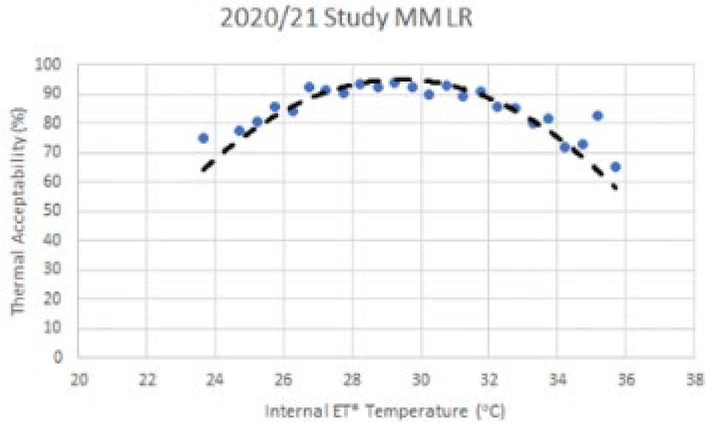


Figure 4: % Acceptable temperatures (ET*), Living rooms MM (N=2473, R2=0.84, p<0.01)

Table 3 and 4 set out the *acceptable ranges* for living room and bedrooms that would apply to Eq (1) above for two categories of acceptable stringency (90% and 80%) and the corresponding "discomfort" levels derived from Figure 1.

Table 3 Acceptable Ranges – MM Operation Living Rooms

Darwin Comfort Votes	**Approximate DISC Scale Comfort Category**	**Acceptable Temperature Range (K)**
90%ile acceptability	Lower 'Level Uncomfortable and unpleasant'	2.3
80%ile acceptability	Upper 'Uncomfortable and unpleasant'	4.0

Table 4 Acceptable Ranges – MM Operation Bedrooms

Darwin Comfort Votes	**Approximate DISC Scale Comfort Category**	**Acceptable Temperature Range (K)**
90%ile acceptability	Mid 'slightly uncomfortable but acceptable'	1.7
80%ile acceptability	Upper 'slightly uncomfortable but acceptable'	3.2

Similarly for NV houses from the 2013/14 study the maximum acceptability (96.2%) is at an internal temperature *ET** of 28.7°C, with the 90%ile between 26.1°C and 31.2°C, a width of 5.1K (half width 2.6K) and the 80%ile between 24.5°C and 32.8°C, a width 8.3K (half width 4.15K).

Table 5 Acceptable Ranges – NV Operation Living Rooms

Darwin Comfort Votes	**Approximate DISC Scale Comfort Category**	**Acceptable Temperature Range (K)**
90%ile acceptability	Lower 'Uncomfortable and unpleasant'	2.6
80%ile acceptability	Upper 'Uncomfortable and unpleasant'	4.2

It would appear, at least according to the DISC scale, occupants of NV houses in their living rooms, accept similar levels of discomfort compared to occupants in houses of MM operation. This observation is also borne out by comparing Eqs (9 & 11).

8. Summary

This paper has set out an evidence-based methodology, by which overheating of houses in the Darwin region may be assessed. A module added to the NatHERS/Chenath simulation engine would provide this assessment, calculating *ET** at each hour and comparing this to a chosen level of acceptability for room uses and mode of operation as shown in Table 6 below. The appropriate level of acceptability is essentially a political decision, yet to be finalised. It is noted however that ASHRAE Standard 55 (2020) recommends 80% acceptability limits be used for typical applications while the 90% acceptability limits are advised to be used only when a higher standard of thermal comfort is desired.

Table 6: Calculation of Overheating (Degree of Discomfort) for modes of operation, rooms at 2 levels of acceptability

Operation	Room	Acceptability	Degree (Hours) of Discomfort (DD_i)
MM	LR	90%	$ET * -(0.31 \times Toutmm + 20.9) - CEV$
MM	LR	80%	$ET * -(0.31 \times Toutmm + 22.6) - CEV$
MM	BR	90%	$ET * -(0.31 \times Toutmm + 19.8) - CEV$
MM	BR	80%	$ET * -(0.31 \times Toutmm + 21.3) - CEV$
NV	LR	90%	$ET * -(0.31 \times Toutmm + 21.0) - CEV$
NV	LR	80%	$ET * -(0.31 \times Toutmm + 22.6) - CEV$
NV	BR*	90%	$ET * -(0.31 \times Toutmm + 20.4) - CEV$
NV	BR*	80%	$ET * -(0.31 \times Toutmm + 21.8) - CEV$

* The Darwin research project (2013/14) did not record comfort votes in NV bedrooms. The NV living room results are adjusted by the difference between the MM living room and bedroom results, to derive the NV bedroom equation.

These formulae can be compared to the approach given by CIBSE TM52 (2013) *The limits of thermal comfort: avoiding overheating in European buildings*. Both approaches establish very similar overheating threshold criteria. CIBSE recommends building assessments against two overheating limits,

1) For living rooms, kitchens and bedrooms: the number of hours during which ΔT is greater than or equal to one degree (K) of a defined threshold temperature during the warmer months should not be more than 3% of occupied hours.
2) For bedrooms only: the operative temperature in the bedroom from 10 pm to 7 am should not exceed 26°C for more than 1% of annual hours.

Similar limits or a rating scheme could therefore be developed for Darwin conditions. Assessing the possibility for overheating would provide valuable information for designers and householders on the performance of a house and potentially promote more passive designs. This work is ongoing.

Acknowledgements

The authors wish to acknowledge the 108 Darwin residents who assisted with these projects and Johanna Kieboom, Senior Engineer, NT Department of Infrastructure, Planning and Logistics for her most helpful comments and suggestions. The advice and assistance provided by Dr Dong Chen, CSIRO is also acknowledged. CSIRO provided top-up support for the Daniel (2016) study as well as a full PhD scholarship and top-up support for the Damiati (2022) study.

References

Bi, P.; Williams, S.; Loughnan, M.; Lloyd, G.; Hansen, A.; Kjellstrom, T.; Dear, K.; Saniotis, A. (2011) The effects of extreme heat on human mortality and morbidity in Australia: Implications for Public Health. *Asia Pac. J. Public Health*, *23(Supp 2)*, 27S-36S.

Damiati, S, A. (2022) Investigation on occupant thermal comfort and behaviour in dwellings In hot and humid climate, PhD Thesis (in progress), The University of Adelaide.

ASHRAE (2020). Thermal Environmental Conditions for Human Occupancy, ASHRAE Standard 55–2020. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Peachtree Corners, GA.

ASHRAE. (2021). *ASHRAE Handbook – Fundamentals*, American Society of Heating Refrigerating and Air-Conditioning Engineers, Peachtree Corners, GA.

Chen, D., & Ren, Z. (2021). *Rating methodology for naturally-ventilated residential buildings in Australia – Stage 2*. S. Report for Australian Government Department of Industry, Energy and & Resources, CSIRO, Melbourne.

CIBSE. (2013) *TM52. The limits of thermal comfort: avoiding overheating in European Buildings*. The Chartered Institution of Building Services Engineers, London.

Daniel, L. (2016). Thermal Mavericks in Australia: A Study of Occupant Preferences in Dwellings of Atypical Construction, PhD Thesis, The University of Adelaide.

Gagge, A. P., Nishi, Y., & Gonzalez, R. R. (1973). Standard Effective Temperature - A Single Temperature Index of Temperature Sensation and Thermal Discomfort Proceedings of CIB W45 Commission, BRE, London.

Gagge, A. P., Stolwijk, J. A. J., & Nishi, Y. (1971). An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatory Response. *ASHRAE Transactions*, *77*(Part 1), 247-262.

Goad, P. (2005) *Troppo: Architecture for the Top End*, 2nd Ed, Pesaro Architectural Monographs, Balmain, NSW.

IPMVP Committee (2010) *International Performance Measure and Verification Protocol: Concepts and Options for Determining Energy and Water Savings, Vol 1*, Technical Report, Efficiency Valuation Organization, Washington, DC.

NatHERS (2022) *Home energy star ratings*, https://www.nathers.gov.au/owners-and-builders/home-energy-star-ratings , accessed 20/6/2022.

Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive Thermal Comfort: Principles and Practice*. Routledge, UK.

Ren, Z., & Chen, D. (2018). Modelling study of the impact of thermal comfort criteria on housing energy use in Australia. *Applied Energy*, *210*, 152-166. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.10.110

Szokolay, S. V. (2000). Dilemmas of Warm-Humid Climate house Design: Heavy vs. Lightweight + Cooling Effect of Air Movement. Paper presented at the Proc. PLEA 2000, Cambridge, UK.

Tartarini, F., Schiavon, S., Cheung, T., & Hoyt, T. (2020). *CBE Thermal Comfort Tool : online tool for thermal comfort calculations and visualizations. SoftwareX 12, 100563.* In (Version 2.3.2) https://doi.org/10.1016/j.softx.2020.100563

Williamson, T., & Daniel, L. (2020). A new adaptive thermal comfort model for homes in temperate climates of Australia. *Energy and Buildings*, *210*, 109728. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.109728

Developing a prefabricated timber and straw-bale wall panel for Aotearoa New Zealand

Min Hall[1]

[1] *Unitec Institute of Technology, Auckland, Aotearoa New Zealand*
mhall2@unitec.ac.nz [1], *ORCID*-0000-0001-8374-5179[1]

Abstract: Making greater use of materials that sequester carbon, like timber and straw, is one way of reducing carbon emissions in the construction industry. In Aotearoa New Zealand building with straw bales has been perceived as a fringe technique, undertaken mostly in rural locations and often by owner-builders. For the past twenty years, however, and in the face of escalating climate change, practitioners have looked to prefabrication to advance the process of building with straw. Prefabricated timber and straw-bale wall panels have been developed in Europe, the United Kingdom, North America and Australia. They have been used to construct stand-alone houses, medium density housing, schools and medium scale commercial projects. This paper reports on Project Pātūtū, a research project aiming to develop a straw-bale panel system suitable for use in Aotearoa. International examples have been investigated before designing six panel options. Scale model panels were built and analysed in terms of their suitability for both community participation in the construction process and mainstream commercial construction. A small house was designed using the panels and analysed in terms of compliance with building regulations and the practicalities of construction

Keywords: Prefabrication; straw-bale; low carbon.

1. Introduction

Carbon emissions from the construction industry are estimated at 39% of the worldwide total, and in Aotearoa New Zealand, the figure is 20% (NZGBC, 2022). The Building Research Association of New Zealand, suggests a number of ways to mitigate these, including adopting “solutions and tools for designing and constructing buildings with a long useful life and low embodied carbon over their life cycle” (BRANZ, 2022). Making greater use of low carbon materials, those that sequester carbon, is therefore an important way of achieving this. Timber is the most widely used low carbon building material and is the predominant structural element used in Aotearoa. Straw, a by-product of the cereal grain industry, is also a low carbon material; but until now its use for building has been limited to the fringes of conventional construction, occurring mostly in rural locations and often involving owner-builders.

Farmers in Aotearoa are adept at growing grain and therefore straw, but despite changes in arable farming methods over the past ten years, where more straw is being ploughed back into the soil, at least

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 230–239.*

20% of it is still considered waste and is often burned in the field. Estimates show that there is sufficient excess straw available to produce timber and straw wall panels for over 2,000 stand-alone houses annually (Hall, 2019).

This paper explores the potential of this wasted material by outlining progress to date on Project Pātūtū, a research project begun in 2019, which looks to develop a sustainable prefabricated timber and straw-bale wall panel system. It also looks to address the current housing crisis by asking how such a system could be suitable for papakāinga and other group housing projects where community sweat equity has the potential to reduce costs. International precedents have been investigated and analysed in terms of their suitability for the geography and climate of Aotearoa, the existing regulatory system, the makeup of the construction industry, and the potential for community involvement. Six panel types were designed and prototypes at one-third scale were built. After analysis one of these was developed further and integrated into the design of a compact two-bedroom house.

The paper concludes with a discussion about the next steps, including carbon footprinting and hygrothermal analysis, and the challenges to be faced when introducing a building technology traditionally regarded as unsophisticated into a conservative construction industry and marketplace.

2. Background

Although building with straw and grasses is common in many forms of traditional vernacular architecture, using straw bales is comparatively new. Ever since baling machines were invented towards the end of the nineteenth century, straw bales have been used for construction. Houses over one hundred years old are still being used in the USA and France, and their history is documented in Steen et al's *The Straw Bale House* (Bainbridge, 1994). Straw fell out of favour during the twentieth century, but in the 1980s some looked to it again in response to the increasingly evident environmental crisis. By the turn of the century, a global straw-building network emerged. A rundown of this more recent history is provided in Barbara Jones' *Building with Straw Bales* (2015), and Gernot Minke and Benjamin Krick's *Straw Bale Construction Manual* (2020).

The first straw-bale house in Aotearoa was completed in Marlborough in 1995, and by 2010 there were 34 in the Nelson/Tasman region alone (Hall, 2012). Although no official record has been kept, it is generally accepted within the close-knit straw-bale building network that there are now several hundred scattered throughout the country. Over the past 30 years construction techniques have developed. Generally, straw-bale walls are constructed insitu with an integral timber frame taking the majority of the roof loads. Hybrid systems, where some of the load is taken by the straw-bale walls, have also been developed, and some builders have used a tilt up method where the straw-bale walls are built flat on a concrete slab and then lifted to the vertical. To date, most straw-bale houses have plaster finishes inside and out, but these have changed from being cement-based plaster on wire mesh, used in the 1990s, to predominantly external lime and internal earth plasters applied directly on to the bale surface or with a fibreglass mesh. Plastering is time-consuming, and along with weather constraints, often makes onsite straw-bale construction a slow process. This has led some practitioners to look to offsite prefabrication.

Prefabrication means panels can be built in a controlled environment whatever the weather. Scaffolding is not required: panels are constructed on horizontal surfaces, which also makes plastering easier. In Aotearoa, Sol Design of Geraldine have experimented with prefabricating walls for a small building in a nearby shed and then transporting them to the building platform (Forsyth et al, 2014). Other builders are experimenting with prefabrication but, at the time of writing, no fully developed systems are in operation. Internationally, however, there are a number of successful systems where prefabricated wall panels are constructed off-site and transported to site. Project Pātūtū aims to contribute to the development of such a system for Aotearoa by looking first to examples from North America, Europe, the United Kingdom and Australia.

3. Existing prefabricated timber and straw bale systems

3.1. Introduction

In *Essential Prefab Straw Bale Construction,* Chris Magwood outlines his own experience with straw-bale building in Ontario, Canada including prefabrication of walls (Magwood, 2016). He has developed a methodology for designing prefabricated systems, identifying some of the key decisions to be made: panel size, the structural frame make up, materials for interior and exterior finishes, bale orientation, panel to panel fixings, integrating services, accommodating openings, and panel to foundation and roof connections. This methodology is also useful when analysing existing systems.

A number of prefabricated timber and straw-bale systems have been developed internationally, the most well-known being ModCell® from the UK and Ecococon from Lithuania. These two systems along with Rainbow Ecosystem from Ukraine, Situps from Australia, and Gryphon from the USA have been studied and analysed to inform the development of a system suited specifically to Aotearoa.

3.2. ModCell®

The ModCell® Core panel comprises an engineered timber frame with straw bale infill. Panel sizes and thicknesses vary but are generally whole wall components up to 4m wide. They are made to suit specific designs. The perimeter frames are full depth glulaminated elements with vertical timber I-beams within, separating vertically stacked straw bales. Panels leave the factory fully closed in with sheathing boards inside and out, ready to receive their chosen finish on site; or with final finishes pre-installed (Modcell, 2022).

3.3. Rainbow Ecosystem

The Rainbow Ecosystem factory in Ukraine manufactures narrower width panels, 1200mm, using sawn timber frames and then combines them within the factory to create full walls, complete with windows. These are finished inside and out with lime or clay plasters before being transported to site (Rainbow, 2018).

3.4. Ecococon

Ecococon panels are generally smaller than ModCell®, ranging in width from 800mm to 3m. Frames are sawn timber and, rather than using bales, the straw is compressed into each frame using a patented system. Panels arrive on site with both straw surfaces exposed or protected by a wrap and can be either plastered on to the straw or lined with a variety of sheathing boards inside and out (Ecococon, 2022).

3.5. Situps

Situps is the brainchild of John and Susan Glassford, pioneering straw-bale builders in Australia. The panels use a full depth plywood frame and range in size from 600 to 900mm wide and up to 3m high. They are designed to be handled by two people but are generally lifted off the truck with a tractor or other small-scale lifting equipment. Situps panels arrive with both straw surfaces exposed ready for finishing on site (Glassford, 2022).

3.6. Gryphon

The Gryphon panel is being developed by New Frameworks in Vermont, USA. The panels are 600mm, 900mm and 1200mm wide and are constructed in a modest scaled workshop using a simple purpose-built steel-framed jig to compress vertically stacked straw bales into sawn timber frames. Panels are partially finished in the factory with an Intello wrap to the interior, and plywood and battens to the exterior. Final finishing is completed on site using dry systems (New Frameworks, 2022).

Table 1: Features of five prefabricated timber and strawbale wall panel systems

System	Panel width (mm)	Frame material	Wet or dry finish	Factory finishing interior	Factory finishing exterior	Specialised factory equipment	Bale orientation
ModCell®	limited only by truck capacity	engineered timber	either	optional	optional	yes	vertical
Rainbow	limited only by truck capacity	sawn timber	wet	yes	yes	yes	horizontal
Ecococon	800-3000	sawn timber	either	no	no	yes	NA
Situps	600-900	plywood	either	no	no	somewhat	horizontal
Gryphon	600-1200	sawn timber	dry	no	no	somewhat	vertical

3.7 Summary

Table 1 summarises the attributes of each system. All use the enclosing timber frames as the main structural element for taking vertical loads, whether that be engineered timber as for Modcell, plywood as per Situps or sawn timber with some plywood for Ecococon, Rainbow and Gryphon. The internal timber I-beams in the Modcell panels also take some of the load, thus permitting larger width panels to be made. Rainbow make their large wall panels by joining smaller ones together in the factory.

Chris Magwood identifies the choice of wet or dry processes for finishing as being the first decision to make. Wet systems include lime or earthen plasters and dry systems: plywood, gypsum plaster board, and wood fibreboard. Wet systems are less common for prefab because of the increased weight they add to the panel, complications with joining panels on site, and their increased vulnerability to damage during transport. Although it is still possible to use plaster finishes for all the systems, Rainbow is the only company to actively promote it. Their panels leave the factory pre-finished inside and out, the other systems involve varying levels of onsite finishing.

Modcell began operating out of ‘flying factories,’ using existing farm or industrial buildings located no more than 20Km from the building site, but the panels are large and over time permanent manufacturing facilities have been created. Rainbow and Ecococon have made considerable investment and built bespoke machinery to manufacture their panels, particularly with regard to compressing the straw or straw bales into the timber frames.

The desktop study of these five systems, along with Magwood's analysis, helped identify some key factors to consider when developing a wall panel for Aotearoa: size of panel, scale of manufacturing operation, structural components, internal and external finishes, and bale orientation.

4. Developing the Pātūtū Panel

4.1. Objectives

Project Pātūtū has clear objectives which influenced decision-making around developing the panel. Firstly, there needs to be a clear pathway to satisfying specific clauses of the New Zealand Building Code (NZBC): B Stability, C Protection from fire, E Moisture, and H Energy Efficiency (MBIE, 2022). The panel design also needs to take account of the availability of materials and skills, public perception, embodied CO_2 emissions, and the scale of operation. The latter is important when considering a commercial or community-led enterprise.

4.2. Prototype designs

Following the analysis of existing systems, three panels were designed in 2019. Consideration of the NZBC requirements and public perception influenced decision-making specifically with regard to exterior cladding. To avoid being limited to a direct plaster finish to the exterior, it was decided to include a ventilated cavity for all panel options. This allows a broad range of material finishes to be considered depending on the context and availability of materials. The cavity also makes satisfying Clause E2 External Moisture straightforward.

Table 2: Details of six panel designs using timber and straw bales

Panel	Panel width (mm)	Frame material	Bale orientation
C-2019	2000	Sawn timber and plywood	horizontal
IC - 2019	2400	Sawn timber, plywood, engineered timber	vertical
LVL-2019	1000	Engineered timber	horizontal
C-2021	2000	Sawn timber and plywood	horizontal
GR-2021	1000	Sawn timber and plywood	horizontal
Pātūtū-2022	1200	Sawn timber and plywood	horizontal

Table 2 provides details of the three initial designs and three subsequent iterations. The C panel built on ideas developed by Ryan Pringle in his thesis *Straw into Gold*, where timber C sections constructed from framing timber and plywood form the frame for 2.0m wide panels (2017). The IC panel combines the C exterior frame with internal I-joist posts, as used in the Modcell Core panel, with six rows of bales stacked vertically to create panels 2.4m wide. The LVL panel uses engineered timber for the entire frame, much like the earlier Modcell panels, with one stack of horizontally laid bales creating a 1.0m wide panel.

The next stage involved constructing one-third scale models of the panels; one-third because of the availability of small straw bales from local garden centres which at 150mm wide, 120mm high and 300mm long, happen to be one-third the size of a typical straw bale: 450mm wide, 350mm high, 900mm long. The first models were constructed in 2019 during Resource Matters, an elective course within the Bachelor of Architectural Studies programme at Unitec Institute of Technology. A team of fourteen students and two lecturers constructed seven C panels and assembled these into a small one-third scale structure which became the centrepiece of their *Straw into Gold* exhibit at BuildNZ, the largest trade show in Aotearoa. The panels were prefinished with earthen plasters inside, recycled softboard to the exterior under a ventilated cavity, and a combination of plywood and profiled metal cladding completing the exterior (Figure 1)

After a one-year hiatus caused by the global pandemic, the project was picked up again in 2021. The C-panel was modified to reduce thermal breaks identified during construction of the *Straw into Gold* model, and the GR panel was designed based on the Gryphon panel. One-third scale models were built, focusing on the structure rather than the finish (Figure 2). The key differences between the GR panel and the C panel are the reduced size, fully framed sides rather than C sections and locating the cross ties on the exterior. The final iteration, the Pātūtū panel (Figure 3), is based on the GR panel but with the straw bales stacked on their edge, reducing the wall thickness by 100mm.

Figure 1: 'Straw into Gold' model 2019.

Figure 2: One-third scale models L to R: GR -2021, C – 2021, IC – 2019, LVL – 2019

4.3. Pātūtū panel

The design of the Pātūtū Panel integrates learning from the precedent study and the earlier designs. Other considerations were availability of skills and materials, and the NZBC requirements. Size was determined by considering bale lengths, 800-1100mm, which result in panels 900-1200mm wide; a useful range when looking to use off-the-shelf sheathing products. Light timber framing, the most widely used construction method in Aotearoa, has been adapted to suit bale sizes. Essentially this means that double 90 x 45 studs are located at each end of the bale, separated by spacers to suit the bale thickness. Strips of wool blanket insulation are proposed for filling the gaps between framing members as shown in Figure 3.

The intention of the first iteration of the Pātūtū Panel was to integrate it into the design of a small house which could then be analysed in terms of its structural and hygrothermal performance. To that end a standard width of 1200mm was chosen with a maximum height of 2820mm (6 bales).

4.4. Pātūtū house design

The best way of assessing how the Pātūtū wall system complies with the NZBC was to design a house using the panels. A simple rectangular house was designed using 1200mm wide by 2820mm high (6 bales) panels, see Figure 4. A timber foundation and sub-floor system was chosen along with a simple prefabricated single pitch roof truss system, deep enough to allow generous ceiling insulation. Internal finishes include earth plaster, gib board to service areas, and plywood ceilings throughout. Exterior finishes include vertical timber cladding and profiled metal roofing.

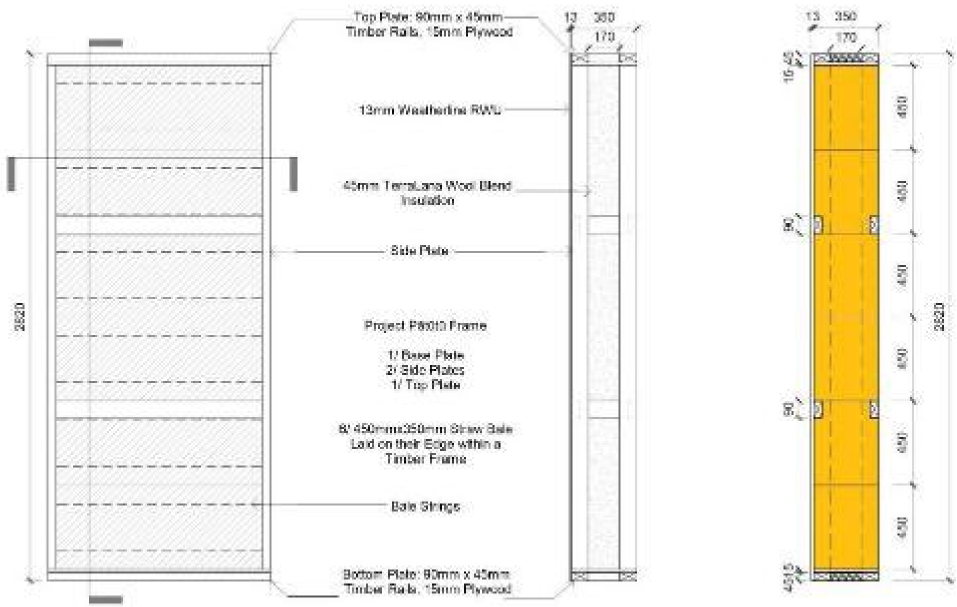


Figure 3: Pātūtū Panel: elevations and section

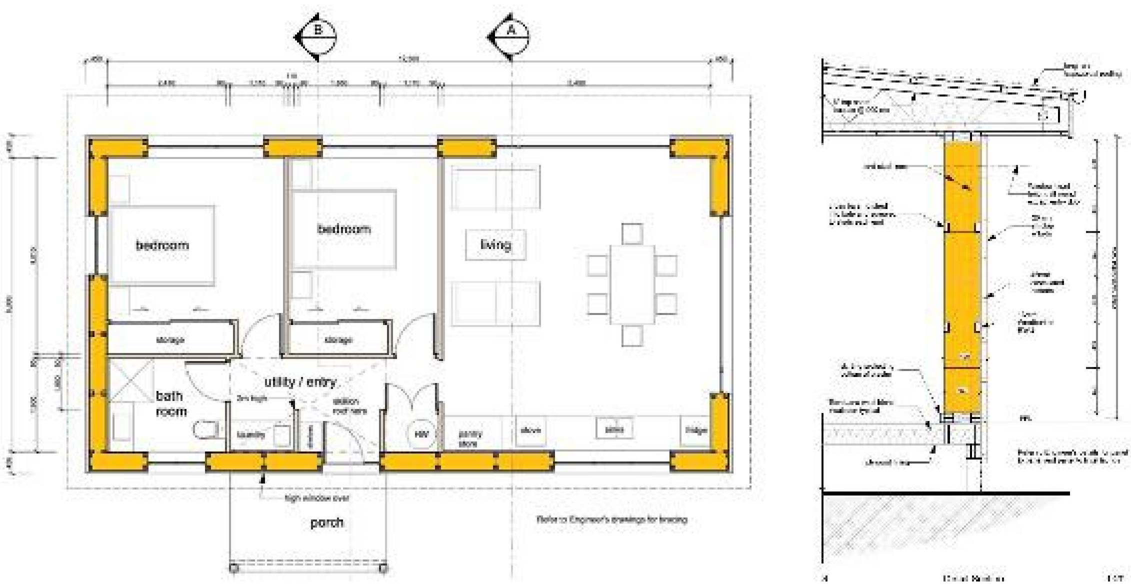


Figure 4. Pātūtū House: floorplan and section

A structural analysis was carried out by engineer David Reid of Lignum Structural. His analysis assumed the house was located in the most demanding wind and seismic zones covered by Clause B1 of the NZBC, and found the house would perform well. Part of his analysis included specifying panel to panel, panel to lintel, panel to foundation and panel to roof structure fixings.

Detailed design of the external envelope was carried out with satisfying Clause E2 in mind. Going forward, the next stages of the analysis will include a hygrothermal forecast, life cycle analysis, and accumulating existing data for fire and thermal resistance to satisfy clauses C and H respectively.

5. Discussion

One of the key reasons for looking to prefabrication is to speed up the build by reducing time on site. However, unlike traditional insitu straw builds where the main structural framework and roof are constructed before the straw bales arrive on site, prefabricated wall panels need to be assembled before the roof can go on. The existing systems studied either use wraps, which are part of the finished system, or temporary tarpaulins to protect the panels for this stage of construction. Either way, it is important that the roof goes on as soon as possible.

Keeping the panel size small enough to be handled by up to four people or small-scale lifting equipment was important when factoring in the potential for community engagement in the process. Panel size is also affected by the size of straw bales, except where straw is compressed directly into the timber frame, as for Ecococon. At this stage of Project Pātūtū, both larger scale commercial and community production options are still being considered. Therefore, the panel size has been limited to 1.2m wide to suit possible bale lengths and readily available sheathing products. Smaller panels permit greater flexibility for design regarding window and door openings, and they can also be joined to make bigger panels before leaving the factory, as in the Rainbow Ecosystem.

Building the one-third scale models was an important part of the panel development, and they have been extremely useful for demonstration purposes. However, there are limitations. While it is easy enough to use one-third scale timber and straw bale elements, this is not the case with fixings, particularly the gauge of screws. In most cases timber elements were slightly larger than a straight one-third scale in order to accommodate the ‘oversized’ screws. This aside, even at one-third scale the impossibility of compressing straw bales into the prebuilt frames without the frames bowing in the middle became obvious. Magwood identified a number of strategies to address this, using timber cross-ties located either centrally in the wall or on the exterior, both require notching of bales to get a snug fit (2016). Mock-ups of mid-wall and exterior cross-members were tried; it was easier to get a tight fit with the latter. Ecococon use centrally located cross-ties, suggesting it is easier to use this system when the straw is being compressed directly into the frames rather than using bales.

One of the aims of Project Pātūtū is to use homegrown materials. This is easy to achieve with regard to timber and straw bale, but where it was not possible to find products using raw materials from Aotearoa, home manufactured products have been preferred over imported ones. For instance, there is a lack of locally produced insulative sheet linings like those used for Modcell, Ecococon and Gryphon. It is a sad truth that globalisation has seen the demise of locally manufactured goods using locally sourced raw materials. Despite having an abundance of raw wood fibre, manufacture of low-density wood fibreboard in Aotearoa ceased in 2007 (Isaac, 2008). Since then, the only available product is imported from Germany. The only viable options for sheathing materials manufactured in Aotearoa are paper-faced gypsum fibre board (known as gib board) using imported gypsum, and plywood and medium density fibreboard (MDF) which both use homegrown timber. Given the sheathing material also needs to provide lateral bracing, the two options being considered are gib board or plywood. At this stage of the project both options are still being considered, the final material to be determined after hygrothermal analysis of the complete wall sandwich has been carried out.

The decision to incorporate a ventilated cavity means that it is easy to comply with Clause E2 and also to 'normalise' the appearance of straw-bale construction by enabling the use of a variety of commonly used cladding materials. Straw-bale houses can sit alongside those built using conventional construction and appear no different. Superficial maybe, but considering appearance is an important first step towards countering negativity towards a fringe construction technique.

One drawback to building in straw has been the complicated and often difficult building consent process where applicants must show how their proposals satisfy the NZBC. Anecdotal evidence suggests however, that the informative appendix on straw-bale construction in the recently updated New Zealand standard, *NZS4299: 2020, Earth buildings not requiring specific engineering design* is already making the process easier for both applicants and the building consenting officers processing those applications (SNZ, 2020). This bodes well for Project Pātūtū.

Designing a small house using the Pātūtū panels was an opportunity to engage with methods of satisfying the relevant clauses of the NZBC. Although standard timber framing elements are proposed their spacing does not comply with NZS:3604, an acceptable solution for Clause B1. The structural analysis carried out by Lignum Structural, however utilised the verification methodology in B1 to show that it was a straightforward exercise to comply. Similarly, the proposed timber elements comply with B2 Durability.

There has been no testing for fire or thermal resistance of straw-bale walls in Aotearoa but results from overseas testing have been used successfully for building consent applications for insitu builds to demonstrate compliance with the NZBC. Internationally, Modcell, Rainbow and Ecococon have had their systems tested for fire and thermal resistance, while Situps and Gryphon use laboratory test results by others to prove the rating of their panels. This latter approach is also intended for Project Pātūtū although it would be useful to carry out testing for both fire and thermal resistance in the future.

6. Conclusion

The importance of addressing the unsustainable carbon footprint of both the agricultural and construction sectors in Aotearoa cannot be overstated. Making greater use of locally grown and, in the case of straw, underutilised carbon sequestering materials for construction has the potential to reduce the footprints of both. But in order to do this at the scale necessary to make a significant impact, more efficient construction methodologies, like off-site prefabrication, will be required.

This paper set out to document progress to date on Project Pātūtū which explores the potential of straw as a component of a sustainable prefabricated wall panel system. Four key objectives have been explored: using homegrown materials, suitability for community-led projects, meeting the requirements of the NZBC, and strategies for countering public perception of straw-bale construction. The most difficult objective to satisfy is using entirely homegrown materials and a compromise has been made to include materials that are at least manufactured in Aotearoa. Panel sizes have been kept small so that small scale production is possible and expensive infrastructure is not required. This is also important when considering community-led projects. International precedents demonstrate how prefabricated timber and straw panels have been used successfully and that houses constructed with them can appear no different than those constructed using more conventional methods. Like the precedents, Pātūtū panels incorporate a ventilated cavity, meaning that not only can any number of cladding materials be used but it is also easy to comply with Clause E2 of the NZBC. Similarly, light timber framing, the most widely used structural system in Aotearoa, was adapted to accommodate straw bales and analysis shows it complies with Clause B1. Although the project is yet to be concluded, there is a clear pathway for satisfying other relevant clauses. If consenting is easier, if straw-bale houses can 'fit in', and if public attention can be focused towards the environmental benefits, then carbon sequestering straw-bale construction, at scale, could become a reality.

Acknowledgements

This research would not be possible without the support of Unitec Institute of Technology staff and students, or the generosity of the team at New Frameworks in Vermont, and John Glassford in New South Wales. I am also indebted to Lignum Structural, Fineline Architecture, Martin Ulenberg, and members of the Global Straw Bale Network (GSBN) who continue to share their knowledge.

References

Bainbridge, D., Steen, A. and Steen, B. (1994), *The Straw Bale House,* Chelsea Green Publishing, Vermont.

BRANZ, (2022), https://www.branz.co.nz/sustainable-building/climate-change/ (accessed 12th June 2022).

Ecococon Ltd. (2022), https://ecococon.eu/, (accessed 20th March, 2022)

Forsyth, B., Hall, M. and Johnston, S. (2014) *Is there a place for natural building in New Zealand's conventional housing market?* https://unitec.researchbank.ac.nz/bitstream/handle/10652/4145/1410_Min_Hall.pdf?sequence=1&isAllowed=y (accessed 29th June, 2022)

Glassford, J. (2022) https://glassford.com.au/main/sit-up-example/ (accessed 27th June, 2022)

Hall, M. (2012) *Earth and straw bale: an investigation of their performance and potential as building materials in New Zealand*, M.Arch thesis, Architecture, Victoria University of Wellington, Wellington.

Hall, M. (2019) Counting straw: the capacity of New Zealand's grain growing sector to supply straw for construction in A. Agrawal and R. Gupta(ed) *Revisiting the Role of Architecture for Surviving Development (*53rd International Conference of the Architectural Science Association (ANZASCA), pp1-10.

Isaac, N. (2008) *Wall linings* in *BUILD* April/May, Wellington, 86-7.

Jones, B. (2015), *Building with Straw Bales,* Green Books, England.

Magwood, C. (2016), *Essential Prefab Strawbale Construction*, New Society Publishers, Canada.

MBIE https://www.building.govt.nz/building-code-compliance/building-code-and-handbooks/ (Accessed 10th July 2022)

Minke, G. and Krick, B. (2020), *Straw Bale Construction Manual,* Birkhauser, Basel.

Modcell®, (2022), http://www.modcell.com ,(accessed 20th June, 2022)

Standards New Zealand. (2020) *NZS 4299:2020 Earth buildings not requiring specific engineering design.* Wellington, NZ, Standards New Zealand.

New Frameworks, (2022), https://newframeworks.com/ (accessed 12 June, 2022)

NZGBC, (2022), https://www.nzgbc.org.nz/climate-change-and-building-pollution (accessed 12th June, 2022).

Pringle, R. (2017), *Straw into gold*, MARCP thesis, Architecture, Unitec Institute of Technology, Auckland.

Rainbow Ecosystem, (2018), https://rainbowecosystem.com/en/ (accessed 22nd June 2022).

Development of a novel method to establish the hygrothermal water vapour resistance factor of construction materials for moisture management design of buildings

Toba Samuel Olaoye[1] and Mark Dewsbury[2]

[1, 2] Architecture and Design, University of Tasmania, Inveresk, Launceston 7250, Australia
{toba.olaoye[1], mark.dewsbury[2]} @utas.edu.au,
ORCID-0000-0003-2773-9043[1], ORCID-0000-0002-3607-3637[2]

Abstract: For nearly a century, it has been acknowledged that the nexus of envelope design, material choices and interior conditioning patterns can lead to surface and interstitial mould and condensation. Both of which affect building durability and occupant health. In Australia, the development of hygrothermal building regulations has been deferred based slow, which has resulted manufacturers reticence to obtain and publish construction material hygrothermal properties, such that high quality hygrothermal simulations can occur. This paper reports the results of the research completed to develop a novel methodology for acquiring high-quality water vapour diffusion resistivity data for input into hygrothermal simulation software. The method involves establishing a new hygrothermal laboratory, international round robin validation of the new laboratory and the design of a new experimental methodology to quantify relative humidity dependent water vapour diffusion resistivity properties for construction materials. Construction material relative humidity dependent hygrothermal boundary curves were established, using a new harmonic adjustment method. Hygrothermal simulations were then completed using single point and multivariable relative humidity water vapour diffusion resistivity values. The results show that there are significant differences in simulated moisture accumulation and the mould growth risk between hygrothermal simulations using single point and multi-point water vapour diffusion resistivity values.

Keywords: hygrothermal simulation; gravimetric measurement; water vapour diffusion resistivity; hygrothermal boundary curve; pliable membranes.

1. Introduction

The aim of this research was to investigate the most appropriate method for measuring the water vapour diffusion resistivity properties for common construction materials. The catalyst being the need to assist and guide policy and regulatory development for condensation and mould in new energy efficient buildings. As Australia leaps toward its net zero target by 2050, or earlier, there is a significant impetus to require new buildings to be increasingly energy efficient. However, for nearly a century, it has been

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 240–251.*

acknowledged that the nexus of envelope design, material choices and interior conditioning patterns can lead to surface and interstitial mould and condensation, both of which affect building durability and occupant health (Babbitt, 1939; Glaser, 1958; Fedorczak-Cisak *et al.*, 2022). The potential for a building to have a net zero energy use is largely determined by the envelope design, materials and components used, and the quality of construction (Hens, 2017). Additionally the actual energy performance can be very strongly influenced by external weather conditions, water vapour pressure and occupant behaviour (Thomas and Rosenow, 2020). This is an important matter when considering moisture management and energy efficiency in buildings, which brings us to the building physics field of hygrothermal calculation and simulation. The quantification of construction material hygrothermal properties, such that high quality hygrothermal simulations can occur is an international priority. Many other developed nations have longstanding and ongoing hygrothermal regulatory frameworks. In Australia, the development of hygrothermal building regulations has been deferred based on the legislative requirement to prove market failure. Sadly, due to the international experiences (Dyer, 2019), the insurance industry has classed building defects from mould and moisture as a design and construction flaw and not an event. In Australia, this has led to a lack of economic data to prove market failure. Even though there is an international standard (European Committee for Standardisation, 2007), and nation specific standards (DIN 4108-2, 2013; British Standard, 2016) and guidelines (ANSI/ASHRAE, 2016), leading researchers are questioning the water vapour diffusion resistivity quantification method, that is more than fifty years old, and no longer sufficient to provide suitable data for the modern transient hygrothermal simulation of contemporary energy efficient buildings (Feng and Janssen, 2016; Richter and Staněk, 2016; López *et al.*, 2017; Olaoye *et al.*, 2022). A material used in the construction of a building envelope experiences significant variations in temperature, relative humidity, and rain. Understanding a materials physical response to moisture (relative humidity) and how it may affect water vapour diffusion resistivity properties is critical, such that hygrothermal simulation better reflects the real, (and measured), conditions within building envelopes (Feng *et al.*, 2015; Olaoye *et al.*, 2021c). Therefore, the development of an appropriate methodology to quantify any relative humidity dependence for water vapour diffusion resistivity properties is required, as the current international single point test method does not explore this variability. The current single point test method involves a single temperature of 23°C and relative humidity of 50%, to quantify the material’s water vapour diffusion resistivity (ASTM, 2010; International Standard Organization, 2016). This in turn will lead to a biased calculation of water vapour diffusion and moisture accumulation within the simulated envelope system.

The current test method is based on the principle of water vapour diffusion from an area with higher partial pressure to an area with lower partial pressure (Olaoye *et al.*, 2021c). If the relative humidity condition is varied, the vapour pressure values on either side of the material become variable, which may significantly change the water vapour diffusion properties. Subject to the construction material properties, changes in moisture may also affect other physical properties and durability. In this research, the water vapour diffusion measurements were completed using the wet-cup and dry-cup test methods with a precisely controlled hygrothermal testing room. This created partial pressure differences between to solution in the test cups and the test room, which caused water vapour diffusion to occur (Olaoye *et al.*, 2021b). This paper reports the results of research completed to develop a novel methodology for acquiring high-quality relative humidity dependant construction material water vapour diffusion resistivity values for input to hygrothermal modelling software.

2. Material and methods

The methodology for this research followed the principle of an empirical research which included setting up a laboratory, obtaining water vapour diffusion resistivity values for the selected construction materials under different relative humidity conditions, and the use of the measured data as inputs for transient hygrothermal simulation, as shown in Figure 1

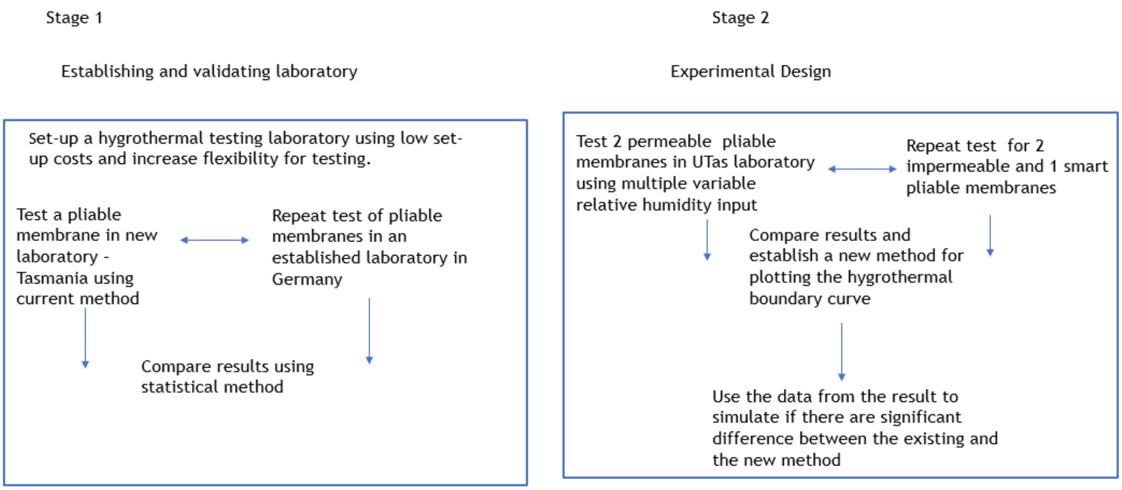


Figure 1: A schematic summary of the research design and methodology

2.1. Establishing a hygrothermal testing room

Internationally, there are two approaches that can be used to obtain construction material water vapour diffusion resistivity, namely, using a ready-made climatic cabinet with predefined programme, or using a conditioned test room. A climatic cabinet is often quite small, thus limiting both the sample sizes and the number of samples that can be tested. Additionally, the cabinet may have significant limitations on temperature and relative humidity conditions it may provide. It has been identified that measurement errors may occur due to opening and closing of the cabinet during weighing. For example, this research followed the international practice requiring the simultaneous testing of five samples of a material via both the wet-cup and dry-cup methods. A review of methods used at other research organizations, like the Fraunhofer Institute of Building Physics', identified the use of hygrothermal testing rooms, which was adopted for this research. The use of the testing room also allowed the weighing of samples to 0.001 grams to occur within the conditioned space. The details of the establishment and operation of the laboratory has been previously reported (Olaoye *et al.*, 2021a). The environmental controls established for the test room would allow for the measurement of water vapour diffusion resistivity properties through the wet-cup and dry-cup samples under different temperature and relative humidity conditions.

2.2. Multivariable relative humidity laboratory measurement of the water vapour resistivity properties of the five pliable membranes.

The second stage of this research involved design of the temperature and relative humidity conditions within the test room. The review of existing methodologies and the concerns raised about the limitations and adequacy of the single-point test method for water vapour diffusion resistivity quantification led this research to explore how the construction material properties may change when subjected to different relative humidity conditions. The water vapour diffusion properties for most construction materials that are used for hygrothermal simulation purposes is normally based on data from single-point measurement with single point hygrothermal boundary line.

To understand if the behavior of construction material's water vapour diffusion resistivity properties changed subject to the relative humidity, required the establishment of multi-variable climate testing parameters as shown in table 1. This table was developed based on consideration of different climatic conditions that may be experienced by elements used in the external envelope of Australian low-rise buildings, that are located between a ventilated cavity and an interior lining material. Due to time constraints, this research only investigated the combination of a constant temperature of 23°C, but four different relative humidity conditions.

To establish if this method provided significantly different relative humidity dependent water vapour diffusion resistivity results, five commonly available pliable membrane products were assessed. If the method did provide different water vapour diffusion resistivity results, future research could consider other environmental conditions and other construction materials. The prioritisation of analysing materials used as an exterior weather resistive control layer, the pliable membrane, was based on existing knowledge from the literature regarding the importance of water vapour diffusion properties of this component within the external envelope.

Table 1: Different scenarios and boundary conditions for dynamic testing of the water vapour diffusion resistivity of construction materials

Stage of research	Multivariable temperature and relative humidity conditions			
Future research	13°C, 35% RH	13°C, 50% RH	13°C, 65% RH	13°C, 80% RH
Future research	18°C, 35% RH	18°C, 50% RH	18°C, 65% RH	18°C, 80% RH
This research	23°C, 35% RH	23°C, 50% RH (ASTM, 2010; ISO, 2016)	23°C, 65% RH	23°C, 80% RH
Future research	30°C, 35% RH	30°C, 50% RH	30°C, 65% RH	30°C, 80% RH

The pliable membranes that were selected included two types of vapour permeable membrane (AS4200 Class 3-4), two types of vapour impermeable membranes (AS4200 Class 1) and one type of "smart" membrane, which has been documented to have different water vapour diffusion resistivity characteristics under different relative humidity conditions. All five products were from different manufacturers, are available in Australia and are installed on NCC Class 1 and Class 2 low-rise residential buildings. The vapour impermeable products had similar polymer characteristics and were coated with aluminium foil on the surface of one side. The smart membrane was a polyethylene copolymer product.

The gravimetric measurement began immediately a set of five specimens of each material were assembled for a particular test, as per the procedure discussed above. Given that the temperature inside the cup and outside the cup, is the same, partial vapour pressure differential was achieved by the difference between the conditioned room relative humidity and the wet or dry substrate within each test dish, causing water vapour diffusion through each test specimen. The amount of water vapour diffusion was established by periodically measuring the weight of the cup assembly. The water vapour resistivity properties for each specimen tested was then calculated using the mathematical equations provided by the ISO 12572 and the water vapour diffusion resistivity boundary graphs were plotted (International Standard Organization, 2016).

2.3. Hygrothermal modelling of single and multi-point relative humidity dependent water vapour resistivity of five pliable membranes

The last stage of this activity was to establish whether there is a significant difference in the results from a transient hygrothermal simulation that used a single-point water vapour diffusion resistivity value or multi-point water vapour diffusion resistivity values, that were obtained from the detailed measurements as discussed above. In this activity, a clay masonry veneer wall system was selected, as approximately 60% of new low-rise residential buildings adopt this external wall system. The stage of the research established two users defined transient hygrothermal simulation models, namely:

- CR 1 which simulated the timber-framed clay masonry veneer wall with the five different pliable membranes using the single-point value for vapour diffusion resistance factor, and
- CR 2 which simulated the timber-framed clay masonry veneer wall with the five different pliable membranes using the harmonic balanced multipoint values for vapour diffusion resistance factor.

This study adopted a 366 m^3, three-bedroom detached building with a standard air exchange rate of 0.2 ACH, which represents the minimum air supply of 30 m^3/h per person for hygienic supply of air rate recommended by DIN 1946-6 (DIN, 2019). Adopting the international trend, simulations were completed for a period of 10 years, to enable a more detailed analysis and understanding of hygrothermal performance of the wall assembly.

The transient hygrothermal simulations were completed using the WUFI Pro 6.5 software for heat and moisture calculations, and the WUFI VTT post processing software for mould growth calculations. Sixty simulations were completed in three different climates and in a northern and a western orientation. Internationally, the equatorial orientation is seen as the lowest risk, whilst the western and non-equatorial orientation are understood to provide the highest risk for mould growth and/or moisture accumulation within the building envelope. The three climates selected for this research were:

- Darwin—Australia's most northern capital city, located in a hot and humid climate, with no hourly rain data (tropical savannah; Köppen climate classification—Aw)
- Sydney—Australia's most populous city, with a temperate climate and no hourly rain data (humid subtropical; Köppen climate classification—Cfa), and
- Holzkirchen—southern Germany, a humid temperate, but cooler climate with rain and climate data that include values for hourly rainfall (oceanic/marine west coast climate; Köppen climate classification—Cfb).

The interior temperature conditions for the hygrothermal and bio-hygrothermal simulation applied the heating and cooling thermostat set points from the Nationwide House Energy Rating Scheme (NatHERS). The interior relative humidity conditions for the hygrothermal and bio-hygrothermal simulation applied the principles from ASHRAE standard (ANSI/ASHRAE, 2016). Also, the international expectation is that water vapour load for the indoor relative humidity is kept below 70% for at least 80% of the hours in a year but in contrast Australia has no requirement for relative humidity control in new housing.

3. Results and Discussion

3.1. Results of water vapour diffusion resistivity measurements

The relative humidity and their vapour pressure differences, which represent the targeted boundary condition from the four test periods of the experiment are shown in Table 2. In each of the experiments, the relative humidity in the hygrothermal test room was carefully controlled between 35.0% to 36.9%, with an average of 36% in the first test period. In the second test period, the relative humidity was maintained between 49.8.% to 50.8%, with the average humidity of 50.4%. The relative humidity was maintained between 64.5% to 65.2%, with an average relative humidity of 65.12% in the third test period. During the fourth test period the relative humidity was maintained between 77.84% to 83.2% with an average relative humidity of 80.29%.

Table 2: Boundary conditions for each test period

Experimental period	Temperature (°C)	Relative humidity (dry side) (%)	Relative humidity (wet side) (%)	Water vapour pressure difference ΔP(Pa)
1 dry-test	23	3	35	898
1 wet-test	23	35	93	1628
2 dry-test	23	3	50	1319.8
2 wet-test	23	50	93	1207.25
3 dry-test	23	3	93	1740.74
3 wet-test	23	65	93	786.12
4 dry-test	23	3	80	2161.83
4 wet-test	23	80	93	364.99

Table 3 shows the results of the water vapour diffusion resistance factors for the five pliable membranes. As mentioned earlier, specimen A and B are permeable membranes, and they belong to class 3 and 4 in the Australia AS4200 vapour classifications, while specimen C, D and E are vapour barrier, and they belong to class 1 and 2(AS/NZS, 2017). Figure 2 shows the hygrothermal boundary curves for specimens A and B after harmonic adjustment and given that their water vapour diffusion resistance factors are very low, they are open to the water vapour diffusion processes. Figure 3 shows the graph of the hygrothermal boundary curves for specimen C, D and E after harmonic adjustment. Interestingly these three membranes behave differently subject to the relative humidity. Specimen C, which is classed as a smart membrane, has a moderately high water vapour diffusion resistance factor, much higher than either specimen A or B.

Table 3: Summary of resistance factor µ and diffusion air layer thickness from gravimetric quantification

	RH%	Dry test resistance factor µ	Wet test resistance factor µ	Dry test S_D (m)	Wet test S_D (m)
Sample A	35	88.88	95.8	0.0724	0.078
	50	96.01	64.04	0.0772	0.052
	65	69.05	78.11	0.0551	0.062
	80	66.17	90.37	0.051	0.073
Sample B	35	457	490.83	0.2113	0.2248
	50	599.6	365.9	0.2842	0.1744
	65	448.2	375.9	0.2128	0.1616
	80	432.5	408	0.1993	0.1874
Sample C	35	189398	13043	46.21	3.4
	50	94895	7180	23.25	2.5
	65	64499	7640	16.04	2.37
	80	10005	6918	2.72	1.98
Sample D	35	222099	120265	49.5	26.82
	50	139160	210033	31.4	48.99
	65	265273	223063	59.9	50.44
	80	388586	91312	87.7	20.27
Sample E	35	383221	304191	116.4	97.5
	50	530781	71909	160.8	23.07
	65	472951	90899	144.6	30.9
	80	378743	47612	114.9	15.2

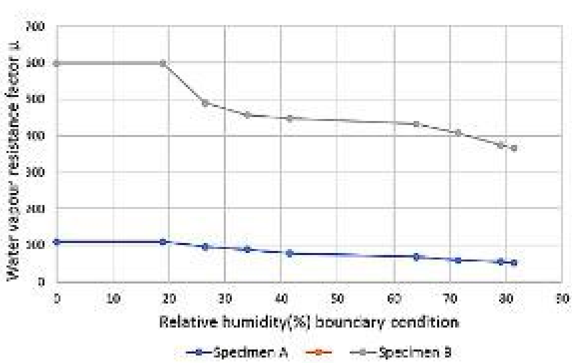


Figure 2: Plot of resistance factor against relative humidity boundary conditions after harmonic adjustment for specimen A and B

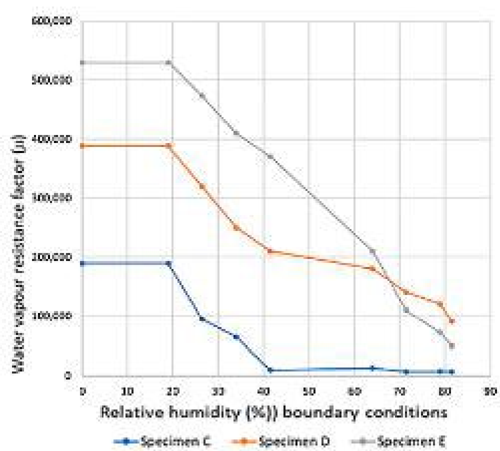


Figure 3: Plot of resistance factor against relative humidity boundary conditions after harmonic adjustment for specimen C, D, and E

Figure 4 shows the boundary curves for the five pliable membranes with single point relative humidity water vapour resistance factor as applied within the transient hygrothermal simulation software. To plot the boundary curves for CR 2, required a mathematical method when applying the multiple measured water vapour diffusion resistivity properties under different relative humidity conditions. To plot the graph a mathematical boundary curve method using the mean harmonic adjustment approach was used (Olaoye *et al.*, 2021c). The mean harmonic adjustment enables the µ-values to vary continuously along the cross section of the material, from the highest resistance factor to the minimum resistance factor in varying relative humidity, using the combination of wet and dry cup test results from the gravimetric measurement discussed above. Figure 5 shows the boundary curves plotted as applied within the transient hygrothermal simulation software, after the harmonic mean adjustment was applied to the five pliable membranes that were measured within this research. The horizontal water vapour diffusion resistance factors remain unchanged between 0% and 20% RH, and between 85% and 100% RH due to gravimetric measurements not being taken within these conditions.

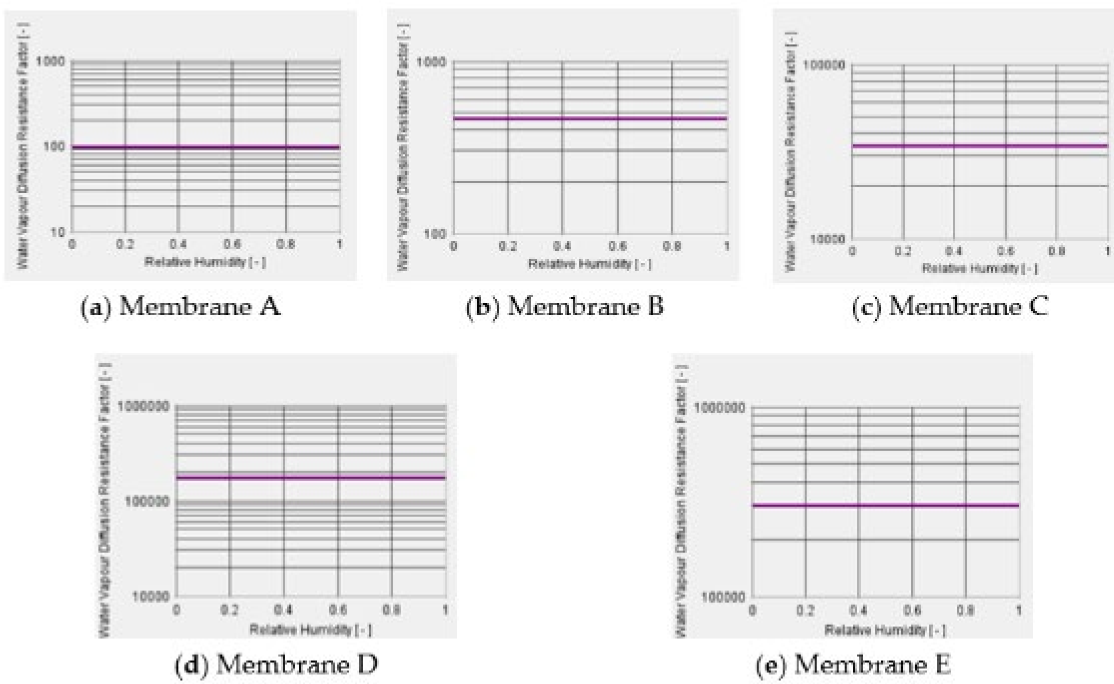


Figure 4: Single-point water vapour diffusion resistance factor graphs for the five tested membranes.

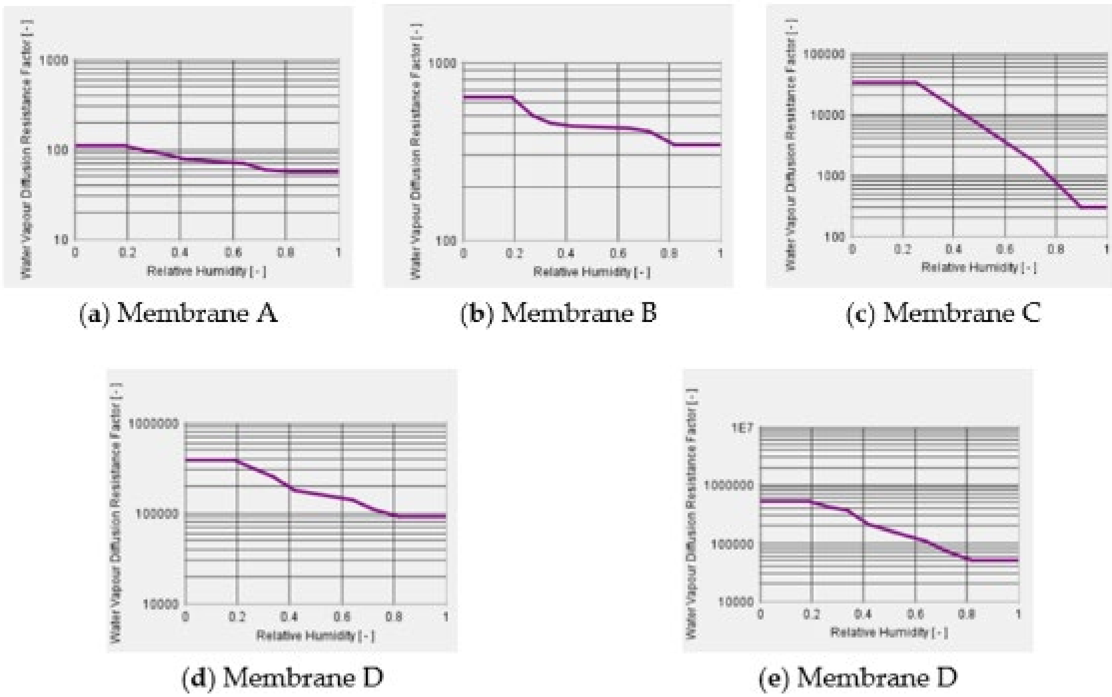


Figure 5: Multivariable vapour diffusion resistance factor graphs for five tested membranes.

3.2. Results from the transient hygrothermal simulations

The results for the risk of moisture accumulation from the hygrothermal simulations that did not include precipitation data showed no discernible difference between pliable membranes that included single-point and multipoint water vapour diffusion resistance values. The results for the risk of moisture accumulation from the hygrothermal simulations that included precipitation data showed discernible differences between pliable membranes that included single-point and multipoint water vapour diffusion resistance values.

The results of the Mould Growth Index simulations that did not include precipitation data showed discernible differences between pliable membranes that included single-point and multipoint water vapour diffusion resistance values, as shown in Figure 6a and 6b. The results of the Mould Growth Index simulations that included precipitation data showed significantly discernible differences between pliable membranes that included single-point and multipoint water vapour diffusion resistance values as shown in Figure 7a and 7b.

Table 6 shows a summary of the results from the 60 bio-hygrothermal simulations undertaken for this research. This table highlights whether the simulation results were the same or different subject to climate type and orientation and whether the water vapour diffusion resistivity values of the pliable membrane used the single-point or the multi-variable relative humidity water vapour diffusion resistivity values. These results show that in all but 3 of 60 bio-hygrothermal simulations, the resultant Mould Index is different. The differences between the mould growth simulations that used single point or multipoint water vapour diffusion resistance values were very significant, such that a wall system that was deemed climatically unsuitable, due to a high mould growth index became climatically suitable, resulting into a no risk for mould growth.

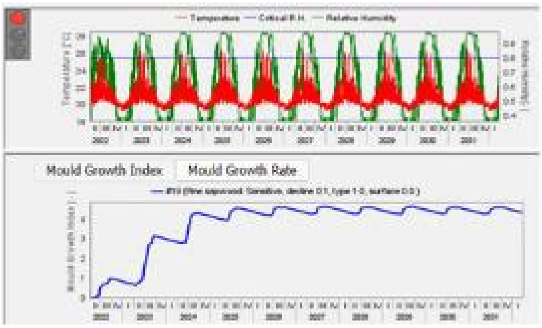


Figure 6a: Mould growth index graph for the wall assembly with single point resistivity value of membrane C in west orientation of Holzkirchen climate

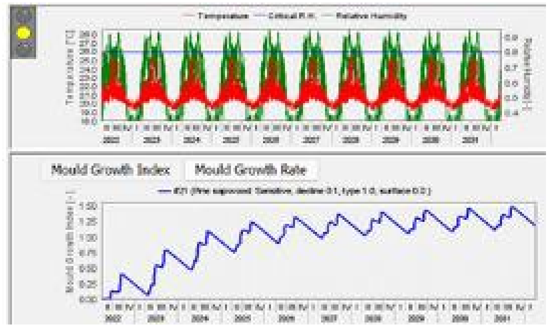


Figure 6b: Mould growth index graph for the wall assembly with multipoint resistivity value of membrane C in west orientation of Holzkirchen climate

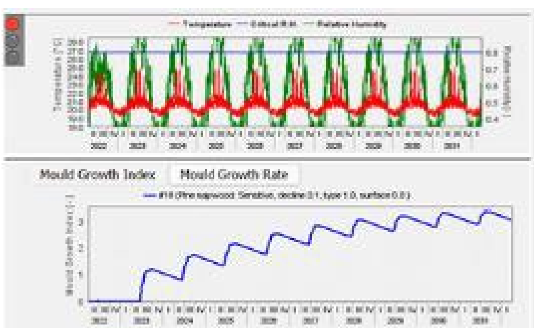


Figure 7a: Mould growth index graph for the wall assembly with single point resistivity value of membrane C in north orientation of Holzkirchen climate

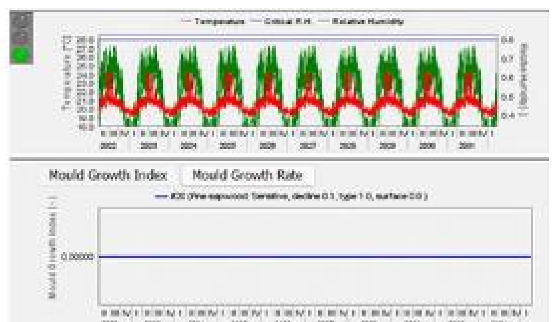


Figure 7b: Mould growth index graph for the wall assembly with multipoint resistivity value of membrane C in north orientation of Holzkirchen climate

Table 6. Ratio of bio-hygrothermal Mould Index results that changed when a multipoint water vapour diffusion resistance was applied.

Location	Koppen Climate Classification	Northern Orientation	Western Orientation
Darwin	Aw	3 of 5	5 of 5
Sydney	Cfa	4 of 5	5 of 5
Holzkirchen	Cfb	5 of 5	5 of 5

4. Conclusion and recommendations

This research has established that the current single-point water vapour diffusion resistivity test method as prescribed by ASTM E 96m, and ISO 12572 is inadequate for quantifying the water vapour diffusion resistivity properties of construction materials used in the external envelope of buildings .This research recommends a more accurate methodology for acquiring water vapour diffusion resistivity values, as input to long-term transient hygrothermal modelling for an external envelope systems. Secondly, the use of multipoint (or relative humidity dependent water vapour diffusion resistance values) in hygrothermal and bio-hygrothermal simulations provided significantly different results to simulations that use only a single-point water vapour diffusion resistance value. Within this context, all materials that are used within the external envelope of a building should be evaluated to obtain relative humidity-dependent water vapour diffusion resistance properties. These new values should then be incorporated within international hygrothermal simulation material databases.

Acknowledgements

This research acknowledges the commonwealth Scientific Industrial Research organization (CSIRO) which co-funded this project.

References

ANSI/ASHRAE (2016) *Criteria for moisture-control design analysis in buildings. In ASHRAE Standard 160*, ASHARE, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, USA, .

AS/NZS (2017) *Pliable building membranes and underlays*,AS/NZS 4200:1, SAI Global Limited and Standards New Zealand,, Council of Standards Australia.

ASTM (2010) *Standard Test Methods for Water Vapor Transmission of Materials*, in A. International (ed.),E96/E96M, ASTM, West Conshohocken, PA, America.

Babbitt, J. D. (1939) The difussion of water vapour through various building materials, *Canadian Journal of Research*, 17(Sec A number 2), 15-32.

British Standard (2016) *BS 5250-Code of practice for control of condensation in buildings*,Londres: BSI.

DIN 4108-2 (2013) *Thermal protection and energy economy in buildings -Part 2: Minimum requirements to thermal insulation*.

DIN, E. (2019) *DIN 1946-6,*,Ventilation and air conditioning - Part 6: Ventilation for residential buildings - General requirements, requirements for design, construction, commissioning and handover as well as maintenance.

Dyer, P. (2019) *The story of New Zealand's leaky buildings disaster*, ed., David Bateman Limited.

European Committee for Standardisation (2007) *EN ISO 10456 Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values*.

Fedorczak-Cisak, M., Bomberg, M., Yarbrough, D. W., Lingo, L. E. and Romanska-Zapala, A. (2022) Position Paper Introducing a Sustainable, Universal Approach to Retrofitting Residential Buildings, *Buildings*, 12(6), 846.

Feng, C. and Janssen, H. (2016) Hygric properties of porous building materials (II): Analysis of temperature influence, *Building and Environment*, 99, 107-118.

Feng, C., Janssen, H., Feng, Y. and Meng, Q. (2015) Hygric properties of porous building materials: Analysis of measurement repeatability and reproducibility, *Building and Environment*, 85, 160-172.

Glaser, H. (1958) Temperatur und Dampfdruckverlauf in einer homogene Wand bei Feuchteausscheidung, *Kältetechnik*, 6, 174-181.

Hens, H. S. (2017) *Building physics-heat, air and moisture: fundamentals and engineering methods with examples and exercises*, ed., John Wiley & Sons.

International Standard Organization (2016) *Hygrothermal performance of building materials and products - Determination of water vapour transmission properties - Cup method ISO 12572*,EVS-EN ISO 12572:2016, López, O., Torres, I., Guimarães, A. S., Delgado, J. M. P. Q. and de Freitas, V. P. (2017) Inter-laboratory variability results of porous building materials hygrothermal properties, *Construction and Building Materials*, 156, 412-423.

Olaoye, T. S., Dewsbury, M. and Kunzel, H. (2021a) A Method for Establishing a Hygrothermally Controlled Test Room for Measuring the Water Vapor Resistivity Characteristics of Construction Materials, *Energies*, 14(1), 4.

Olaoye, T. S., Dewsbury, M. and Künzel, H. (2021b) Empirical Investigation of the Hygrothermal Diffusion Properties of Permeable Building Membranes Subjected to Variable Relative Humidity Condition, *Energies*, 14(13), 4053.

Olaoye, T. S., Dewsbury, M. and Künzel, H. (2021c) Laboratory Measurement and Boundary Conditions for the Water Vapour Resistivity Properties of Typical Australian Impermeable and Smart Pliable Membranes, *Buildings*, 11(11), 509.

Olaoye, T. S., Dewsbury, M., Wallis, L. and Küenzel, H. (2022) Hygrothermal Modelling of the Differences between Single versus Variable Relative Humidity Vapour Diffusion Resistivity Properties of Pliable Membranes, *CivilEng*, 3(3), 687-716.

Richter, J. and Staněk, K. (2016) Measurements of Water Vapour Permeability – Tightness of Fibreglass Cups and Different Sealants and Comparison of μ-value of Gypsum Plaster Boards, *Procedia Engineering*, 151, 277-283.

Thomas, S. and Rosenow, J. (2020) Drivers of increasing energy consumption in Europe and policy implications, *Energy Policy*, 137, 111108.

Drivers for adaptive behavior in Human-Building Interaction: measuring the factors motivating room modifications for personal comfort

Veronica Garcia-Hansen[1], Francisca Rodriguez[2] Debra Cushing[3] and Glenda Caldwell[4]

[1, 2, 3, 4] Queensland University of Technology, Brisbane, Australia
{v.garciahansen[1], f2.leonard[2], debra.cushing[3]. g.caldwell[4]}@qut.edu.au
ORCID-0000-0001-5934-5554[1], ORCID-0000-0001-9177-1991[2], ORCID-0000-0002-2192-0637[3], ORCID-0000-0003-0837-9310[4]

Abstract: With the ubiquity of sensors, researchers contributing to the emerging field of Human-Building Interaction (HBI) have started incorporating embedded technologies to monitor energy conservation indoors. Automated systems to increase building performance are now more common as the algorithms to predict the characteristics of the room environment increase in accuracy. And yet, energy optimisation in buildings is still not achieved as occupants modify the environment to increase personal comfort. Although researchers have proposed alternative procedures to identify personal comfort and refine predictive algorithms, the drivers that motivate or deter a person to modify their environment are unclear. As a result, architectural science endorses energy-efficient solutions that may not fully respond to occupants' requirements for indoor comfort. This study presents the findings of a semi-systematic literature review (n = 20) seeking to map recurrent questions and tools to investigate the role of perceived control of the environment on adaptive behaviours for comfort. First, we selected and contextualized four themes (demographic, psychographic, sensory/biometric, and situational) to structure the evidence base. Next, we highlighted methodological innovations proposed in the literature, namely the incorporation of work-related constructs, the use of biometric devices, and the implementation of participatory approaches to inform research inputs. Finally, we introduced a procedure for post-occupancy evaluation of shared environments using a mixed methods approach. In doing so, this paper contributes to the evaluation of energy and user outcomes as multifactorial outputs and broadens the understanding of the individual and social dimensions of personal comfort.

Keywords: Human-building interaction, personal comfort, perceived behavioral control, measurements

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 252–261.*

1. Introduction

Significant changes are occurring in the built environment because of the climate crisis. With an increase in the time spent indoors (Klepeis, 2001) and the rise in average temperatures, the built environment must be continually monitored to meet the comfort requirements of occupants (Kentwell, 2007; Martirano, 2011; Anderson et al., 2016). With the incorporation of sensing technologies and automated processes and systems (Huovila et al., 2009) traditional post-occupancy evaluation procedures (use of handheld instruments) have been simplified to minimize disruption to building occupants. Building management systems are also experiencing optimization procedures to reduce energy consumption and meet the thresholds for indoor comfort (Mashaly et al, 2021; Xiong and Yao, 2021). Although these initiatives are promising, optimizing energy use and increasing personal comfort is difficult in practice, as comfort is tied to a range of social and individual factors. To increase energy conservation and meet occupants' needs for indoor comfort, integrated systems should not only achieve thresholds from standards and design guidelines (LEED, WELL) but also account for those other variables likely to influence energy use and personal comfort.

Architects have long addressed the need to rethink the built environment so that it responds more sensibly to changing needs for usability and comfort. For example, the Ambient Intelligence (AmI) paradigm proposed that environments should incorporate ubiquitous sensing capabilities to respond to the presence of users in ways that are *personalized* (the devices know the user and the environment), *adaptive* (the devices are modified in response to the user and the environment), and *anticipatory* (the devices satisfy users' and environmental requirements with limited or unconscious mediation) (Weiser, 1991; Zelkha and Epstein, 1998; Estrin et al., 2002). To attain building responsiveness for ambient intelligence and its potential applications within the built environment (e.g., ambient assisted living), we need to better understand the range of personal, environmental, behavioural, and social factors influencing users' requirements for well-being in the post-occupancy evaluation phase. Human-building interaction (HBI) studies have insisted on this focus, emphasizing the need to integrate human values, needs, and priorities to improve occupants' interactions with such pervasive environments (Alavi et al., 2019). Although interesting new research is aimed at increasing building responsiveness for personal comfort in a changing climate (e.g., Schweiker, 2022; Coley and Kershaw, 2010), more work is needed to systematize the instruments and procedures used to evaluate those interactions. Such an approach would result in increased human-building resilience and improved occupant well-being.

Researchers have previously linked environmental stress and occupants' strain due to indoor climate conditions to physiological, behavioural, and cognitive-emotional factors (Schweiker, 2022). These factors have been tied to both familiarity with the building and the opportunities for adaptation available to users. Studies have suggested that users achieve higher levels of satisfaction through individualized opportunities for manipulating/controlling their environment, as opposed to automated systems adjusting the indoor climate (Ajzen, 1991; Steemers and Yun, 2009; Hong and Lin, 2013; Konis and Selkowitz, 2017; Biner et al., 1993; Nicol and Humphreys, 2004; Wagner et al., 2018; Bavaresco et al., 2020a). Although it can be drawn from this evidence that providing occupants with opportunities to modify the indoor climate may result in increased engagement with environmental adaptations, and as a result, increased personal comfort, the extent to which adaptive behaviours respond to cognitive, biological, social, environmental, or organizational factors has not been thoroughly examined to date. For example, it is still unclear whether decisions for personal comfort in shared environments (e.g., open-plan offices) are motivated by independent decisions with no conscious mediation or a result of consensus between the occupants (Raw et al., 2017). As a result, architects and facility managers may endorse the design of shared work environments that provide inefficient opportunities for interaction and adaptation, thus decreasing levels of engagement (Millward et al., 2007; Kim et al., 2013) and increasing reliance on automated solutions for energy efficiency and indoor comfort.

One possible reason for the limited knowledge of the drivers motivating adaptive behaviours in shared environments is the limited number of instruments to evaluate them. Although important work has reviewed quantitative/qualitative tools and approaches to investigate interactions between buildings and their users (Wagner et al., 2018), multifactorial instruments to evaluate drivers for adaptive behaviours have not been consolidated to date.

In this paper, we present the first attempt to bridge this gap in the literature. First, we revised the different approaches through which adaptive behaviours for comfort have been investigated in field studies. Using a semi-systematic review style (Snyder, 2019), we mapped recurrent questions and tools from the evidence base (n = 20) and structured them into four themes: demographic, psychographic, biometric/sensory, and situational data. Next, we assessed the prevalence of each theme within the context of Human-Building Interaction research using a critical review approach. Finally, we provided recommendations for designing instruments that address multifactorial variables in field studies. With this approach, we aim to lay the foundations of more holistic procedures to understand the drivers of occupants' behaviours in shared environments, which will assist in the efforts to increase energy conservation and human well-being through evidence-based design.

2. Methodology and methods

2.1. Definition of preliminary themes

To understand those factors likely to influence adaptive behaviours in the field, we scanned for themes that were deemed well-documented in the HBI literature, that is, having at least ten published research works on the topic over the past 5 years. This preliminary work led us to define four themes encompassing the range of questions and strategies to approach the problem: demographic data, psychographic data, sensory/biometric data, and situational data. Although not equally covered by the literature, we considered the proposed four themes appropriate to promote combinations that would assist in the multifactorial assessment of adaptive behaviours in shared environments. Future work will delve into the rationale behind these themes more thoroughly.

Demographic data is a traditional way to describe the profile of a studied population and is usually collected via online surveys in field research (Axinn et al., 2011). Despite most post-occupancy evaluation studies collecting demographic information to understand the size and components of the population sample, the approaches for collecting demographic measures are being contested to ensure that the dimensions of a population are captured in ethical and inclusive ways (Fernandez et al., 2016). Although sensitive questions are usually excluded in post-occupancy evaluation studies (e.g., religious beliefs), other questions posed to determine the thermal and photic profile of participants (e.g., body mass index, pregnancy, and menopause status) may also distress participants and lead to the omission of research data. By conducting a critical revision of the demographic questions in post-occupancy evaluation studies we aim to identify key problems leading to missing data and provide suggestions to improve the collection of profiling information.

Psychographic data is aimed at positioning people within psychological dimensions by analyzing their attitudes, needs, opinions, activities, and lifestyles (Gladwell, 1990). Although psychographic research has been traditionally used for market segmentation, its methodologies have also been widely used to identify types of users (or 'personas') in the design of user experiences (Mulder and Yaar, 2006) and, more recently, to investigate occupants' attitudes, motivations, and beliefs influencing interactions with their domestic environments (Haines and Val Mitchell, 2014). Although psychographic data can assist decision-making by specifying a limited number of user types for which to design (Pruitt and Adlin, 2010), it can also lead to biased archetypes when those characterizations are not grounded in appropriate evidence (Saffer, 2007). By critically reviewing quantitative and qualitative approaches to collect psychographic data in post-occupancy evaluation studies, we will be able to identify recurrent issues with the typification of users and present suggestions based on the most recently available research.

Sensory and biometric approaches to capture real-time data from users and their environments have only recently been incorporated in post-occupancy evaluation research. The rise of the Internet of Things (IoT) has allowed for continuous, non-invasive monitoring of space occupancy, activity, and health outcomes using standalone and/or wearable devices in different setting types (Stavropoulos et al., 2020; Zhou et al., 2021). Other approaches to generate sensory/biometric data include comprehensive profiling surveys (e.g., Bajaj et al, 2011; Horne and Ostberg, 1976), although these results will rely on participants' disposition to complete all items of a survey. By critically assessing how new sensory and biometric approaches can assist in overcoming nonresponse bias, we will be able to provide suggestions on how to document this type of data in sensible, ethical ways.

Situational or contextual data is well-documented in the post-occupancy evaluation literature to describe the spatial and temporal conditions during the evaluation period. This includes both external factors influencing indoor measures (building location or season) and internal factors influencing the perception of comfort (desk location and access to indoor climate modifiers (dimmers, on/off switches)). These variables are particularly relevant in open-plan and shared spaces, where achieving personal comfort is a challenge (Shahzad et al., 2018). By assessing the approaches to capture the different sources of situational data reported in the literature, we will be able to identify opportunities for further development based on the availability of new technologies and evaluation tools.

2.2. Definition of the evidence base

With the definition of preliminary themes, we proceeded to define the evidence base using a semi-systematic review style (Snyder, 2019). First, we conducted a search of peer-reviewed articles in Scopus considering a 20-year publication range (2002-2022). The list of terms defined to structure the literature screening included 'field', 'evaluation', 'adaptive', 'behaviour', 'perceived', 'control', 'personal', 'comfort', 'demographic', 'questionnaire', 'self-reported', 'persona', 'user', 'employee', 'biometric', 'sensory', 'wearable', 'log', 'location', and 'observation' in the article title, abstract, or keywords. This preliminary search resulted in 101 original papers. To ensure internal validity, we defined a filtering criterion based on the abstract content, excluding papers whose research focus was other than field evaluations (e.g., simulation studies). We then refined the evidence sample through a full text sift to ensure pertinence. The resulting evidence base consisted of fifty-five papers, of which twenty are reported in this study. The articles selected for review allowed for equal distribution between themes (i.e., five articles per theme) and were selected due to the best match for internal validity (i.e., all studies having reported outcomes in shared work environments).

3. Results

A categorization of the evidence base is presented in Table 1. We included five articles per theme, which were clustered to better represent the scopes and strategies in current post-occupancy evaluation research.

Table 18: Evidence base of research articles (n = 20).

Descriptor	Research work
Demographic data	Candido et al., 2019; Chen et al., 2020; Farrag et al., 2022; Indraganti & Humphreys, 2021; Thach et al., 2020
Psychographic data	Bavaresco et al., 2020a; Brager et al., 2004; Kim et al., 2016; Vellei et al., 2016; von Frankenberg, 2021
Sensory/biometric data	Hasan et al., 2016; Li et al., 2019; Liu et al., 2019; MacNaughton et al., 2017; Wagner et al., 2007
Situational data	Candido et al., 2020; Healey, 2014; Li et al., 2019; Shahzad et al., 2019; Zamani & Gum, 2019

Selected studies for the demographic theme included evaluations of the workplace indoor climate for thermal comfort, perceived productivity, and health (either stress or sick building syndrome) as output variables. Age and gender descriptors were collected in all studies, although utilizing different age brackets. Other inputs included socio-demographic (educational attainment, average monthly income), health (smoking status, BMI), and work-related factors (working hours, type of work). One study included items related to work culture (type of work, time spent in buildings, workspace arrangement, availability of individual space(s)) (Candido et al., 2019), which were instrumental to the evaluation of productivity and health as multifactorial outputs. Thus, demographic descriptors pertinent to work culture may assist the appraisal of drivers motivating adaptive behaviours for personal comfort.

Studies addressing psychographic themes in the evaluation of personal comfort are scarce. The descriptors retrieved from the selected literature sample aimed at evaluating a range of output variables, including user-centric control, energy use, productivity and health, and thermal comfort. The most recurrent psychographic descriptor addressed behavioural adaptations (changes in clothing), for which standardized questions were posed to participants (ASHRAE, 2013; ISO, 2005). Other recurrent descriptors addressed environmental adaptations, such as knowledge of controls, and beliefs of control (freedom to adapt, intention to adapt, ease to share control, perceived personalization). From the evidence base, only one study employed personalized comfort models based on user types, or 'personas' (von Frankenberg, 2021), which provided a unique opportunity to address the social dimensions of personal comfort. Thus, incorporating psychographic descriptors oriented at building 'personas' may be a key contributor to evaluate indoor comfort more effectively in shared environments.

Only a few studies within the evidence base reported the use of sensory and biometric/wearable instruments to investigate environmental conditions and personal comfort in the field. These included commercially available and built dataloggers capturing environmental (temperature, lighting, relative humidity, airspeed, acoustics) and occupancy measures that were usually contextualized with self-reported scores for comfort. One study also correlated environmental parameters with concurrent cognitive function and sick building syndrome tests (MacNaughton et al., 2017) thus expanding the scope of the use of sensors for indoor comfort. The use of biometric/wearable sensors was mostly studied in controlled conditions replicating a field setting and included the use of wristbands and thermal cameras. We believe there is abundant room for investigating the implementation of those tools in field studies, thus it is key to incorporate them in future studies, provided that all ethical and data privacy aspects are considered.

Several studies within the evidence base included situational considerations in the data collection process. Studies addressing situational descriptors considered descriptions of the physical layout and simultaneous environmental measurements at different locations within the open-plan rooms. Indoor measures were contextualized using predominantly qualitative techniques, including focused observations, space syntax, and structured interviews addressing thermal comfort, satisfaction, collaboration, and productivity. One controlled study also incorporated opportunities for real-time, instant feedback (Li et al., 2019), suggesting the potential of these interactive approaches to test occupants' evaluations of personal comfort as a function of energy and social normative information. Thus, we estimate that a combination of qualitative and interactive approaches may be a key factor in understanding the motivations behind adaptive behaviour for indoor comfort.

3.1. Proposed improvements

To contribute to the development of multifactorial approaches in post-occupancy evaluation research, we condensed typical applications and suggestions for improvement for each theme (Table 2). We anticipate that implementing those suggestions would lead to a broader understanding of the individual and social dimensions of personal comfort in shared environments moving forward.

To test the implementation of this multifactorial approach, we designed and conducted a pilot study in October 2022 in an open-plan office located in Brisbane, Australia. Before commencing the study, participants (n = 11) were asked to complete a baseline profile survey including the range of improved demographic, psychographic, and sensory/biometric factors presented in Table 2 (Demographic: organizational culture, familiarity, lifestyle; Psychographic: types of work activities, social interactions at work, contextual data; Sensory/biometric data: thermal profile, photic history). During the study, participants were requested to complete a personal environmental comfort survey twice a week (Sensory/biometric: thermal and visual comfort) and use a wristband for a week (Sensory/biometric: activity, metabolism, light exposure). Purpose-built thermal and lighting sensors were installed in participants' desks for the duration of the study (Sensory/biometric data). Concurrent focused observations regarding physical adaptations to the environment were performed by two researchers during this period (Psychographic: behavioural and environmental adaptations; Situational: interactions). To analyse the multifactorial data gathered as part of this study, we propose the use of a triangulation approach following a convergence model (Creswell and Plano Clark, 2011), which allows for combined interpretations of quantitative and qualitative data. These interim results will be then presented to end users in a focus group aimed at identifying drivers for adaptive behaviours (Situational: interactions).

Although the results of the multifactorial approach to collect and analyse complex field data will be reported elsewhere, several advantages to this approach can be anticipated here. For instance, the combination of proposed themes will result in a more thorough understanding of the phenomenon in study (Mingers, 2001), namely personal comfort at individual and social scales, and will enable discoveries motivated by the unconventional triangulation of quantitative and qualitative data in post-occupancy evaluation studies.

Table 2: Comparison of approaches for data collection

Dimension	Typical	Improved
Demographic data	-Age, gender *(Always asked)* -Health factors *(Usually asked)* -Work-related factors *(Usually asked)*	*Include other factors to help the evaluation of adaptive behaviour as multifactorial outputs, for example:* -Organizational culture -Familiarity -Lifestyle
Psychographic data	*Rarely asked. When asked typically focuses on:* -Behavioral adaptations (clothing) at an individual level -Environmental adaptations (physical): knowledge and beliefs of control at an individual level	*Include other data that indicate potential conflicts between occupants to help the evaluation of social drivers for adaptive behaviour (creating 'personas'), for example:* -Types of work activities -Social interactions at work -Contextual data
Sensory/biometric data	*Sensory: Rarely included. Contextualized with self-reported scores for thermal and visual comfort but also cognitive function. When included typically includes:* -Standalone environmental devices -Occupancy sensors Sensory data correlated *Biometric: Rarely included, mostly in controlled conditions. When included usually consists of:* -Wristbands (metabolism, physical activity) -Thermal cameras (skin temperature)	*Sensory: Include other self-reported questions to help the evaluation of adaptive behaviours as multifactorial outputs, for example:* -Thermal profile -Photic history -Productivity -Attention restoration *Biometric: Include with special consideration of data privacy.*
Situational data	*Usually included, when included environmental measures are typically contextualized with:* -Focused observations -Individual interviews -Self-reported surveys	*Include opportunities for feedback and follow-ups from occupants, including:* -Focus group: interactions -Real-time, open feedback

4. Concluding remarks

This paper has presented four themes that encompassed the range of questions and strategies to approach adaptive behaviours for personal comfort.

Through a critical revision of the demographic, psychographic, sensory/biometric, and situational approaches used to collect and generate the data in the field, we observed new streams of research worth considering in the future. For example, the implementation of multifactorial approaches will expand the scope of post-occupancy evaluation studies, leading to indoor spaces that better respond to the range of energy efficiency, comfort, productivity, and satisfaction requirements. Methodological innovations including the addition of work-related constructs, the use of biometric devices, and the implementation of participatory approaches to contextualising the findings were also proposed and tested in an exploratory field study. Although we have only covered a limited number of research articles in this paper, future iterations will develop the proposed themes and approaches, aiming to lay the foundations of a refined framework to investigate building responsiveness for human well-being.

References

Ajzen, I. (1991). The theory of planned behavior. *Organizational behavior and human decision processes, 50*(2), 179-211.

Alavi, H. S., Churchill, E. F., Wiberg, M., Lalanne, D., Dalsgaard, P., Fatah gen Schieck, A., & Rogers, Y. (2019). Introduction to human-building interaction (hbi) interfacing hci with architecture and urban design. *ACM Transactions on Computer-Human Interaction (TOCHI), 26*(2), 1-10.

Anderson, T. R., Hawkins, E., & Jones, P. D. (2016). CO2, the greenhouse effect and global warming: from the pioneering work of Arrhenius and Callendar to today's Earth System Models. *Endeavour, 40*(3), 178-187.

ASHRAE (2013). ANSI/ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy*, Atlanta, Ga. 2013.

Australian Building Codes Board (2010) *Building Code of Australia Class 2 to Class 9 Buildings, Volume 1*.

Axinn, W. G., Link, C. F., & Groves, R. M. (2011). Responsive survey design, demographic data collection, and models of demographic behavior. *Demography, 48*(3), 1127-1149.

Bajaj, A., Rosner, B., Lockley, S. W., & Schernhammer, E. S. (2011). Validation of a light questionnaire with real-life photopic illuminance measurements: the Harvard Light Exposure Assessment questionnaire. *Cancer Epidemiology and Prevention Biomarkers, 20*(7), 1341-1349.

Bavaresco, M. V., D'Oca, S., Ghisi, E., & Pisello, A. L. (2020a). Assessing underlying effects on the choices of adaptive behaviours in offices through an interdisciplinary framework. *Building and Environment, 181*, 107086.

Biner, P. M., Butler, D. L., Lovegrove, T. E., & Burns, R. L. (1993). Windowlessness in the workplace: A reexamination of the compensation hypothesis. *Environment and Behavior, 25*(2), 205-227.

Brager, G., Paliaga, G., & De Dear, R. (2004). Operable windows, personal control and occupant comfort, ASHRAE *Transactions 110*(2)

Candido, C., Chakraborty, P., & Tjondronegoro, D. (2019). The rise of office design in high-performance, open-plan environments. *Buildings, 9*(4), 100.

Candido, C., Marzban, S., Haddad, S., Mackey, M., & Loder, A. (2020). Designing healthy workspaces: results from Australian certified open-plan offices. *Facilities, Vol. 39 No. 5/6*, 411-433.

Chen, C. F., Yilmaz, S., Pisello, A. L., De Simone, M., Kim, A., Hong, T., ... & Zhu, Y. (2020). The impacts of building characteristics, social psychological and cultural factors on indoor environment quality productivity belief. *Building and Environment, 185*, 107189.

Coley, D., & Kershaw, T. (2010). Changes in internal temperatures within the built environment as a response to a changing climate. *Building and Environment, 45*(1), 89-93.

Creswell, J.W. & Plano Clark, V.L. (2011) *Designing and Conducting Mixed Methods Research*. 2nd Edition, Sage Publications, Los Angeles.

Estrin, D., Culler, D., Pister, K., & Sukhatme, G. (2002). Connecting the physical world with pervasive networks. *IEEE pervasive computing, 1*(1), 59-69.

Farrag, N., Abou El-Ela, M. A., & Ezzeldin, S. (2022). Sick building syndrome and office space design in Cairo, Egypt. *Indoor and Built Environment, 31*(2), 568-577.

Fernandez T, Godwin A, Doyle J, Verdin D, Boone H. (2016) *More comprehensive and inclusive approaches to demographic data collection*. In *School of Engineering Education Graduate Student Series*. Lafayette: West.

Gladwell, N. (1990). A psychographic and sociodemographic analysis of state park inn users. *Journal of Travel Research, 26*, 15-20.

Hasan, M. H., Alsaleem, F., & Rafaie, M. (2016). Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation. *Building and Environment, 110*, 173-183.

Healey, K. (2014). Measurement and interpretation of thermal comfort in a highly adaptive mixed-mode building. *Architectural Science Review, 57*(3), 207-214.

Hong, T., & Lin, H. W. (2013). *Occupant behavior: impact on energy use of private offices (No. LBNL-6128E).* Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States).

Horne, J. A., & Östberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International journal of chronobiology, 4,* 97–110.

Huovila, P., Ala-Juusela, M., Melchert, L., Pouffary, S., Cheng, C. C., Ürge-Vorsatz, D., ... & Graham, P. (2009). *Buildings and climate change: Summary for decision-makers.* Paris, France: United Nations Environment Programme - Sustainable Buildings and Climate Change Initiative.

Indraganti, M., & Humphreys, M. A. (2021). A comparative study of gender differences in thermal comfort and environmental satisfaction in air-conditioned offices in Qatar, India, and Japan. *Building and Environment, 206,* 108297.

ISO, E. (2005). ISO 7730 Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. *Management, 3*(7–10), 605-615.

Kentwell, A. (2007). Climate change adaptation issues for planners. *Australian Planner, 44*(3), 20-21.

Kim, J., Candido, C., Thomas, L., & de Dear, R. (2016). Desk ownership in the workplace: The effect of non-territorial working on employee workplace satisfaction, perceived productivity and health. *Building and Environment, 103*, 203-214.

Kim, J., de Dear, R., Candido, C., Zhang, H., & Arens, E. (2013). Gender differences in office occupant perception of indoor environmental quality (IEQ). *Building and Environment, 70,* 245-256.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., ... & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Science & Environmental Epidemiology, 11(3), 231-252.

Konis, K. & Selkowitz, S. (2017). Validating Performance from the Perspective of End Users. In: Konis, K., Selkowitz, S. *Effective Daylighting with High-Performance Facades*. Green Energy and Technology. Springer

Li, Z., Loveday, D., & Demian, P. (2019). Feedback messaging, thermal comfort and usage of office-based personal comfort systems. *Energy and Buildings, 205,* 109514.

Li, D., Menassa, C. C., & Kamat, V. R. (2019). Robust non-intrusive interpretation of occupant thermal comfort in built environments with low-cost networked thermal cameras. *Applied energy, 251,* 113336.

Liu, S., Schiavon, S., Das, H. P., Jin, M., & Spanos, C. J. (2019). Personal thermal comfort models with wearable sensors. *Building and Environment, 162,* 106281.

Martirano, L. (2011). A smart lighting control to save energy. In: *IEEE 6th international conference on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS), Prague, Czech Republic, IEEE, September 15, 2011; Vol. 1,* pp.13200–138.

MacNaughton, P., Satish, U., Laurent, J. G. C., Flanigan, S., Vallarino, J., Coull, B., ... & Allen, J. G. (2017). The impact of working in a green certified building on cognitive function and health. *Building and Environment, 114,* 178-186.

Mashaly, I. A., Garcia-Hansen, V., Cholette, M. E., & Isoardi, G. (2021). A daylight-oriented multi-objective optimisation of complex fenestration systems. *Building and Environment, 197,* 107828.

Millward, L. J., Haslam, S. A., & Postmes, T. (2007). Putting employees in their place: The impact of hot desking on organizational and team identification. *Organization Science, 18*(4), 547-559.

Mingers, J. (2001). Combining IS research methods: towards a pluralist methodology. *Information systems research, 12(3)*, 240-259.

Mulder, S., & Yaar, Z. (2006). *The user is always right: A practical guide to creating and using personas for the web*. New Riders.

Nicol, J. F., & Humphreys, M. A. (2004). A stochastic approach to thermal comfort-occupant behavior and energy use in buildings/discussion. *ASHRAE transactions, 110,* 554.

Pruitt, J., & Adlin, T. (2010). *The persona lifecycle: keeping people in mind throughout product design*. Elsevier.

Raw, G. J., Littleford, C., & Clery, L. (2017). Saving energy with a better indoor environment. *Architectural Science Review, 60*(3), 239-248.

Roskams, M., & Haynes, B. (2019). Predictive analytics in facilities management: A pilot study for predicting environmental comfort using wireless sensors. *Journal of Facilities Management, Vol. 17 No. 4,* 356-370.

Saffer, D. (2007). *Designing for interaction: Creating smart applications and clever devices.* Berkeley, CA: New Rid

Schweiker, M. (2022) Rethinking resilient thermal comfort within the context of human-building resilience. In: Nicol, F., Rijal, H.B., & Roaf, S. (Eds.) *Routledge Handbook of Resilient Thermal Comfort*: 23-38.

Shahzad, S., Calautit, J. K., Calautit, K., Hughes, B., & Aquino, A. I. (2018). Advanced personal comfort system (APCS) for the workplace: A review and case study. *Energy and Buildings, 173,* 689-709.

Shahzad, S., Calautit, J. K., Hughes, B. R., Satish, B. K., & Rijal, H. B. (2019). Patterns of thermal preference and Visual Thermal Landscaping model in the workplace. *Applied Energy, 255,* 113674.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of business research, 104,* 333-339.

Stavropoulos, T. G., Papastergiou, A., Mpaltadoros, L., Nikolopoulos, S., & Kompatsiaris, I. (2020). IoT wearable sensors and devices in elderly care: a literature review. *Sensors, 20*(10), 2826.

Steemers, K., & Yun, G. Y. (2009). Household energy consumption: a study of the role of occupants. *Building Research & Information, 37*(5-6), 625-637.

Thach, T. Q., Mahirah, D., Sauter, C., Roberts, A. C., Dunleavy, G., Nazeha, N., ... & Car, J. (2020). Associations of perceived indoor environmental quality with stress in the workplace. *Indoor Air, 30*(6), 1166-1177.

Xiong, L., & Yao, Y. (2021). Study on an adaptive thermal comfort model with K-nearest-neighbors (KNN) algorithm. *Building and Environment, 202,* 108026.

Vellei, M., Natarajan, S., Biri, B., Padget, J., & Walker, I. (2016). The effect of real-time context-aware feedback on occupants' heating behaviour and thermal adaptation. *Energy and Buildings, 123,* 179-191.

von Frankenberg, N. (2021). Towards Resolving Thermal Comfort Conflicts in Shared Spaces. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems,* 1-5.

Wagner, A., Gossauer, E., Moosmann, C., Gropp, T., & Leonhart, R. (2007). Thermal comfort and workplace occupant satisfaction—Results of field studies in German low energy office buildings. *Energy and buildings, 39*(7), 758-769.

Wagner, A., O'Brien, W., & Dong, B. (2018). *Exploring occupant behavior in buildings: methods and challenges.* Charm, Switzerland: Springer International.

Weiser, M. (1991). The Computer for the 21st Century. *Scientific american, 265*(3), 94-105.

Zamani, Z. & Gum, D. (2019). Activity-based flexible office: Exploring the fit between physical environment qualities and user needs impacting satisfaction, communication, collaboration and productivity. *Journal of Corporate Real Estate, Vol. 21 No. 3,* 234-253.

Zelkha, E., Epstein, B. (1998) From devices to ambient intelligence. In: *Digital Living Room Conference*. Laguna Niguel, California.

Zhou, Y., Hua, Y., & Liu, J. (2021). Study workplace space occupancy: a review of measures and technologies. *Journal of Facilities Management, Vol. 20 No. 3,* 350-368.

Electricity demand analysis for solar PV houses: Polyvalent heat pumps coupled with water storage tanks

Zheng Wang[1], Mark B. Luther[2], Peter Horan[3], Jane Matthews[4] and Chunlu Liu[5]

[1, 2, 3, 4, 5] *Deakin University, Geelong, Australia*
{wangzheng[1], mark.luther[2], peter.horan[3], jane.matthews[4], chunlu.liu[5]}@deakin.edu.au
ORCID-0000-0002-8468-5937[1], ORCID- 0000-0002-9677-7636[2], ORCID-0000-0002-0514-8501[3], ORCID- 0000-0003-3367-9278[4]

Abstract: As a result of the increasing adoption of rooftop solar photovoltaic (PV) systems in homes and the mismatch between peak residential load and peak harvested solar energy, a considerable percentage of harvested energy fails to be consumed in homes, resulting in low PV self-consumption. This is further compounded by recent rules and limits, which control how much of the excess PV power can be exported back to the electrical grid and may also force some available solar energy to remain unharvested. To address these issues, a combined system is proposed in which a polyvalent heat pump coupled with water storage tanks produces and stores hot and cold water by using PV power for heating, cooling, and domestic hot water use. Annual hourly thermal loads for heating and cooling of a typical Australian house located in Geelong, Victoria, are determined using TRNSYS. The house's annual hourly electricity consumption is calculated based on energy data, measured with a smart meter, and harvested solar energy, measured with a PV system controller. Results show that by working with relevant setpoint temperatures of water tanks and control strategies of the polyvalent heat pump, the proposed combined system reduced the annual grid energy demand by about 28%. In addition, the PV self-consumption and self-sufficiency were increased to 31.39% and 64.57%, respectively. This study demonstrated that this proposed combined system could effectively increase the PV self-consumption and self-sufficiency and reduce the grid electricity use of the house, thus reducing the burden on the electrical network.

Keywords: Solar PV; self-consumption; heat pump; water storage tanks.

1. Introduction

Growing concern over the energy crisis and climate change has highlighted the necessity of reducing global energy use and greenhouse gas (GHG) emissions. The building sector, especially residential buildings, is of great importance in terms of these two issues. In the European Union, the residential sector is responsible for over 25% of total final energy consumption (Bee *et al.*, 2018) and 20% of GHG emissions (Rinaldi *et al.*, 2021). Similarly, in Australia, approximately 93% of total energy consumption is supplied by

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 262–272.*

fossil fuels, and the residential sector represents about 11% of Australian total final energy consumption (Department of Industry Science Energy and Resources, 2021). Building operation, including space heating, cooling, and domestic hot water (DHW) heating, accounts for 63% of total energy use in Australian households (Energy Rating, 2014). The Australian Government has ratified the Kyoto Protocol, committing to achieve 40% of the 2000 level of GHG emissions by 2050 (Bahadori *et al.*, 2013). In such cases, the transition towards the decarbonization of the energy sector requires the adoption of environmentally friendly technologies, such as heat pumps, and the installation of renewable energy generation systems, such as solar photovoltaic (PV) systems.

The heat pump, a well-established technology, is now a promising approach to reducing residential energy use and GHG emissions, thereby achieving a decarbonized energy future due to its high system performance (Hirmiz *et al.*, 2019). It was reported that 20 million heat pumps were in use worldwide in 2016, and this number is expected to expand to over 250 million in 2050, covering 27 % of global heating demand (International Renewable Energy Agency, 2019). Rooftop solar PV systems are already installed on more than 30% of Australian homes, with a total installed capacity of over 11 Gigawatt (Australian Renewable Energy Agency, 2022). However, the PV self-consumption, measuring the percentage of total PV generation consumed locally, is relatively low due to the mismatch between the PV generation and household electricity consumption (Wang *et al.*, 2021). When connecting heat pumps with water storage tanks to PV systems, the PV self-consumption and self-sufficiency can be increased by consuming locally generated electricity to produce and store energy for heating and cooling (Pena-Bello *et al.*, 2021). In this context, PV self-sufficiency refers to the proportion of the house load met by PV generation (Langer and Volling, 2020).

Many studies have been conducted to analyse the performance of using heat pumps coupled with water storage tanks in PV houses. For example, Battaglia *et al.* (2017) investigated the potential of heat pumps in combination with water storage tanks and batteries to increase PV self-consumption. They discovered that installing an 800 L water tank and an 8-kWh battery could compensate for more than 40% of the electricity consumption for DHW production and house loads. However, the assessment was mainly based on the simulation results and only considered the conditions of space heating and DHW in houses. Also, Bee *et al.* (2019) analysed the performance of an air source heat pump plus PV systems based heating and cooling system in two different houses in nine different European climates. Again, this study only considers the use of a heat pump for space heating and cooling. Li *et al.* (2021) analyzed the effectiveness of integrating solar PV, a heat pump, and water storage tanks in reducing the house's grid energy demand and increasing PV self-consumption. The authors found that by integrating a 5 kW solar PV system, the annual grid electricity demand of the house was reduced by approximately 76% compared to a conventional system without water storage tanks. In addition, the use of water storage tanks increased PV self-consumption from 27% to 56%. However, the heat pump used in the paper can only operate in heating only or cooling only mode.

This work is distinct because a polyvalent heat pump is used, and the hot and cold water produced by the heat pump is used for space heating, cooling, and DHW in houses. Conventional heat pumps can offer heating-only or cooling-only modes, but they can not offer both simultaneous heating and cooling operation. As such, the idea of considering both thermodynamic outputs of heat pumps, namely, heating on the condenser side and cooling on the evaporator side, leads to a co-generation system, implying that both heating and cooling processes are achieved from the same energy input. This type of heat pump can be called a polyvalent or 3-in-1 heat pump. This implies that both heating and cooling can be achieved for a specific time simultaneously, or the heat pump can deliver only heating or only cooling.

Therefore, this work investigates how a polyvalent heat pump coupled with water storage tanks can increase PV self-consumption and reduce grid electricity demand for a solar PV house. Also, sensitivity analyses will be conducted to investigate the most critical factors affecting PV self-consumption and the grid electricity demand of the case study house with a polyvalent heat pump plus water storage tanks. Section two describes the proposed combined system, and the control strategies are explained in Section three. Section four introduces a case study house and its energy data collection, as well as the explanation of two scenarios. The grid electricity demand and PV self-consumption of two scenarios are presented and compared in section five. Section six presents the sensitivity analyses. Section seven concludes this research work.

2. Proposed electricity, heating, cooling & DHW system for solar PV houses

The energy flows of the proposed residential electricity, heating, cooling and DHW system is shown in Figure 1. An inverter converts the PV-generated electricity into alternating current, which is then supplied to household appliances for consumption or used to operate a heat pump to produce hot and cold water. The hot water produced by the heat pump and stored in the hot water tank can be used for DHW or space heating. Similarly, the cold water produced by the heat pump and stored in the cold water tank can be used for space cooling. If there is excess PV-generated electricity after meeting the electrical demand of home appliances and storing heating and cooling energy in the two water tanks, it will be exported to the grid. If the PV-generated electricity cannot meet the electrical demand of the heat pump and home appliances, the shortfall will be met by importing the electricity from the grid.

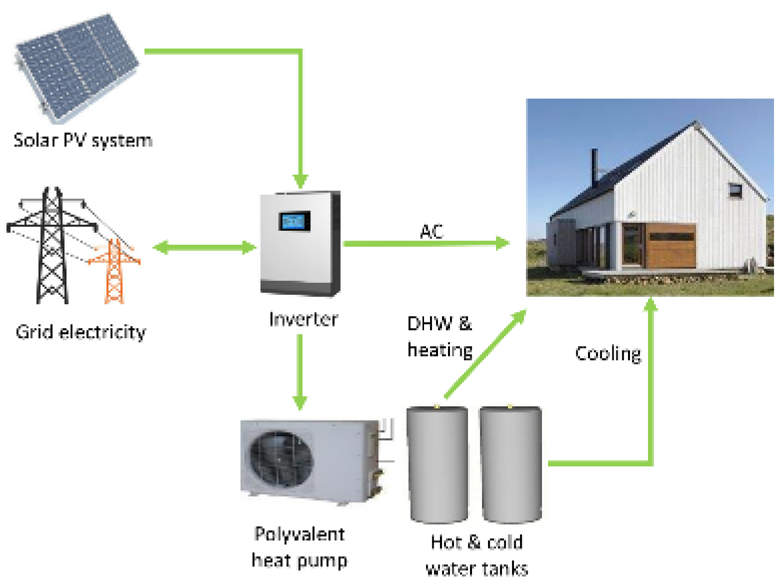


Figure 30. Energy flows of grid-connected solar PV houses with heat pump and water storage tanks

3. Control strategies for operating the proposed combined system

The heat pump is one of the most important components in this proposed combined system because it produces the hot and cold water for heating, cooling, and DHW use. Again, a polyvalent heat pump is used in this study, and it can offer three modes: heating only, cooling only, and both heating and cooling. It is important to note that when the polyvalent heat pump initially operates in both heating and cooling mode, it works as a water-to-water heat pump system to produce both hot and cold water. Eventually, when the water temperature in one of the tanks reaches the preset point, the polyvalent heat pump automatically switches to an air-to-water or a water-to-air heat pump system to continue to heat the hot water or cool the cold water. Then, the polyvalent heat pump will stop its operation when the water temperature in the second tank reaches the preset point. The coefficient of performance (COP) of the polyvalent heat pump is assumed to be a constant value in all three modes in this paper.

In addition, the operation of the polyvalent heat pump is controlled by the seasonal schedule, the temperatures of two water tanks as well as the availability of PV-generated electricity. First, cold water is only produced by the polyvalent heat pump under the summer schedule, and the arrival of the summer schedule refers to a house having a cooling load during the following week. Noteably, considering daily DHW needs, the polyvalent heat pump prioritizes operating in both heating and cooling mode under the summer schedule, producing hot and cold water simultaneously. Under the non-summer schedule, the polyvalent heat pump operates in heating only mode to produce hot water. Second, regarding the setpoint temperatures of two water tanks, it is assumed that hot water can be heated up to 65°C by the polyvalent heat pump, and hot water will not be used for heating or DHW when its temperature is lower than 40°C. Once the hot water temperature falls below 55°C, the polyvalent heat pump will start to heat the water to 60°C regardless of the availability of PV-generated electricity. If there is excess PV-generated electricity at the hot water temperature of 60°C, the polyvalent heat pump will continue its operation to heat the hot water up to 65°C. Similarly, the cold water is assumed to be cooled down to a minimum of 5°C, and the cold water will not be used for cooling when its temperature is higher than 25°C. When the cold water temperature is higher than 15°C, the polyvalent heat pump will start to cool the water down to 10°C regardless of the availability of PV-generated electricity. Again, under the summer schedule, the polyvalent heat pump can operate in both heating and cooling mode, producing both hot and cold water from the same energy input. If there is excess PV-generated electricity at the cold water temperature of 10°C, the polyvalent heat pump will continue its operation to cool the cold water down to 5°C and heat the hot water to 65°C. Finally, when the water temperatures in the two water tanks reach their thermostat temperature setting, the polyvalent heat pump will stop its operation, and the excess PV-generated electricity will be exported to the grid. The setpoint temperatures of the two water tanks can be found in Table 1. The control strategy for this proposed combined system is developed and run in Visual Basic for Applications.

Table 19. Setpoint temperatures of the two water tanks

	Hot water tank	Cold water tank
Thermostat temperature setting	65°C	5°C
Dead band temperature setting	55°C & 60 °C	15°C & 10°C
Minimum or maximum use temperature	40°C	25°C

4. Case study house and scenario description

4.1. Electrical and thermal energy data acquisition from a case study house

A grid-connected solar PV house in Geelong, Victoria, is used as the case study house. The house was completed late in 2016. A gas ducted system provides space heating; cooling is achieved through natural ventilation, and a gas-boosted solar hot water system provides DHW. A smart meter was installed in 2013, measuring the amount of electricity imported from and exported into the grid on a half-hour basis. This house is now equipped with a 10 kW solar PV system, and the PV-generated electricity is recorded by a PV system controller every fifteen minutes. The grid and PV-generated electricity are the electrical energy sources for this case study house. Again, the imported and exported energy is measured using a smart meter, and PV-generated electricity is measured using a PV system controller. Therefore, the electrical energy loads of the house can be calculated using equation 1:

$$E_h = E_s + E_i - E_e \tag{1}$$

Where:

E_h= house electricity consumption; E_s= PV-generated electricity; E_i= imported electricity from the grid; E_e= exported electricity to the grid.

Because heating is provided by a gas-ducted system, and cooling by natural ventilation, and DHW by a gas-boosted solar hot water system, this calculated E_h reflects the unique electricity use pattern of the house. Due to the limitation of measuring the electricity consumption by the fan used for space heating, this calculated house electricity consumption is considered to be the base electrical load of this case study house.

The annul hourly thermal demand for house heating and cooling is obtained through the Transient Systems Simulation (TRNSYS) program. The operating schedule and temperature setting of house heating and cooling are shown in Table 2. Then, by using the same house model, the electricity required to conditioning the house to the same temperatures using air conditioning system is simulated in TRNSYS as well.

Table 20.Operating schedule of the air conditioning system and temperature setting of different rooms

	Bedrooms and associated spaces	Living areas and associated spaces
Operating schedule	21:00 – 7:00 occupied 7:00 – 21:00 unoccupied	21:00 – 7:00 unoccupied 7:00 – 21:00 occupied
Temperature setting in summer	25°C when occupied 30°C when unoccupied	25°C when occupied 30°C when unoccupied
Temperature setting in winter	20°C when occupied 15°C when unoccupied	20°C when occupied 15°C when unoccupied

Since the hourly DHW loads for this house is difficult to measure, the DHW demands of a second house has been used as a proxy. The two houses are separated by 4.2 km, and the weather conditions at both locations are therefore similar. The DHW demand of the second house is provided by a heat pump water heater, its hourly electricity consumption is measured by a smart power meter, and the COP of the heat pump water heater is approximately 4. Therefore, the hourly thermal demand of DHW can be calculated based on the electricity consumption and the COP of the heat pump water heater.

4.2. Scenario description

The purpose of this work is to investigate the impact of combining a heat pump with water storage tanks on the grid and PV energy use of a case study house. PV self-consumption and self-sufficiency can be calculated using equations 2 and 3, respectively.

$$SC = \frac{PV_{sc}}{PV_{total}} \tag{2}$$

$$SS = \frac{PV_{sc}}{L_{total}} \tag{3}$$

Where:

SC = self-consumption; SS = self-sufficiency; PV_{SC}= the amount of PV energy consumed; PV_{total}= total PV generation; L_{total}= total electrical load of the house.

Two system configurations and operation scenarios are designed to compare grid energy demand and PV self-consumption rates. Because this case study house has a 10 kW solar PV system already installed on the roof, the scenario design for this paper is based on a 10 kW PV system. Therefore, scenario 1 refers to the house with a 10 kW solar PV system, an air conditioning system for heating and cooling, and an instantaneous heat pump water heater for providing DHW. Scenario 2 refers to the house with a 10 kW solar PV system and a polyvalent heat pump coupled with two water tanks, and the stored hot and cold water is used for DHW, heating, and cooling. The output capacity of the polyvalent heat pump is calculated based on the peak hourly heating and cooling load. The input power of the polyvalent heat pump can be calculated by dividing the output capacity by the COP value. The sizes of the two tanks are calculated using the peak daily heating and cooling load, and the two water tanks are assumed to be fully charged at the initial stage. The capacities of relevant systems in two scenarios are included in Table 3.

Table 21. System configuration and sizing of two scenarios

Scenarios	Air conditioning capacity (kW)		Heat pump water heater capacity (kW)	Polyvalent heat pump capacity		PV system (kW)	Water Tanks (L)	
	Heating	Cooling		COP	Power input (kW)		Hot tank	Cold tank
Scenario 1	11.5	11.5	3.6	-	-	10	-	-
Scenario 2	-	-	-	4	2.6	10	2600	2000

5. Energy consumption performance of the two scenarios

In order to investigate how a polyvalent heat pump coupled with water storage tanks can increase the PV self-consumption of the case study house and reduce its grid electricity demand, the annual grid demand, PV self-consumption, and PV self-sufficiency for two scenarios are plotted in Figure 2. It can be observed that the annual grid energy demand for the two scenarios are 3445 kWh and 2474 kWh, respectively, which indicates that using a polyvalent heat pump coupled with water storage tanks reduces the annual grid electricity demand by 28%. In addition, the PV self-consumption, which measures the proportion of total PV-generated electricity consumed locally, increases from 24.14% in scenario 1 to 31.39% in scenario 2. Furthermore, the PV self-sufficiency, which measures the proportion of house electrical load met by PV-generated electricity, increases from 50.16% in scenario 1 to 64.57% in scenario 2. The significant variations in these values can be attributed to two factors: first, the polyvalent heat pump plus water storage tanks consume more PV power and store it as thermal energy than instantaneous electrical equipment such as air conditioning system and the heat pump water heater; and second, when PV power is unavailable, the thermal energy stored in two water tanks can be used for heating, cooling and DHW by the house, reducing the grid electricity consumption of the house.

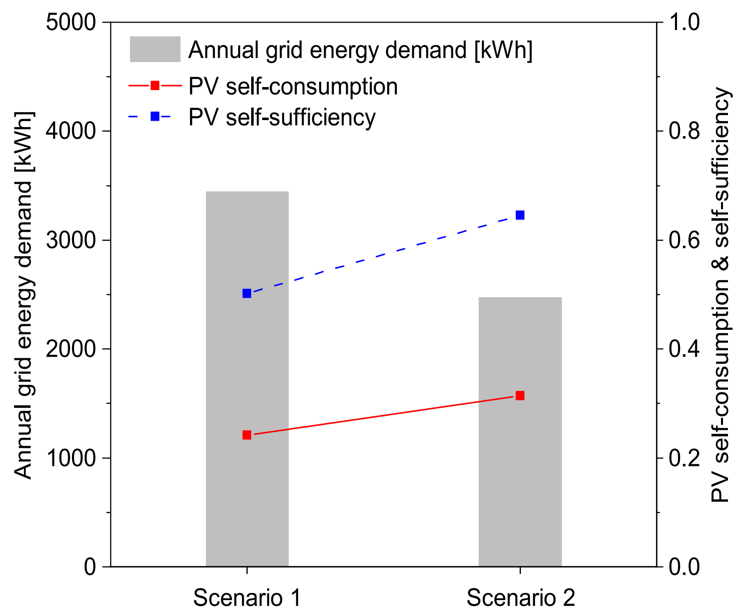


Figure 31. The impact of a polyvalent heat pump coupled with water storage tanks on annual grid electricity demand, PV self-consumption and PV self-sufficiency

To further investigate the impact of using a polyvalent heat pump in combination with water storage tanks on the annual consumption of PV-generated electricity and grid electricity, the monthly energy imports from and exports to the grid for both scenarios are plotted in Figure 3.

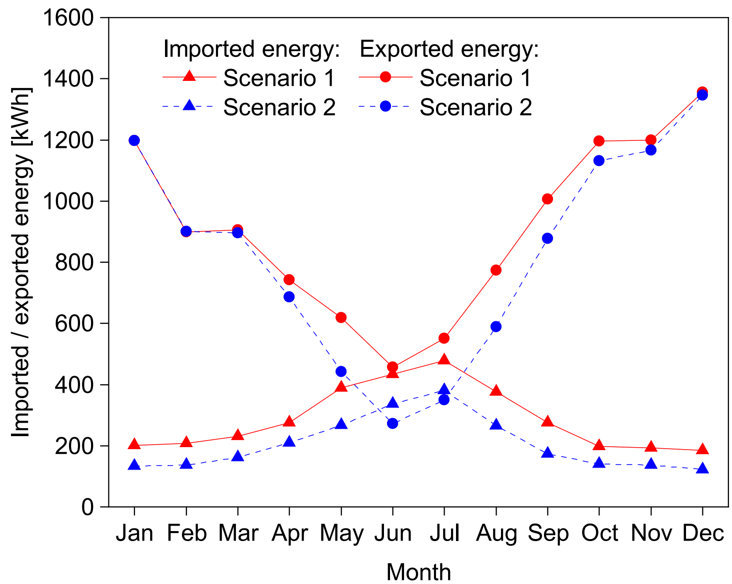


Figure 32. Monthly imported and exported energy

It can be seen that the amount of exported energy is almost the same for both scenarios during the summer schedule from January to March and from November to December, but the amount of imported energy in scenario 1 is higher than in scenario 2 in these months, This is mainly due to the fact that in the summer period, the polyvalent heat pump in scenario 2 can produce and store hot water in simultaneous heating and cooling mode while producing the cold water needed for cooling. In contrast, since there is no storage tank in scenario 1, the instantaneous heat pump water heater only consumes grid electricity and produces hot water at night when there is a demand for hot water and no PV generation. In addition, it can be observed that the amount of exported and imported energy in scenario 2 is much lower than in scenario 1 during the non-summer schedule from April to October. This is due to the fact that in the non-summer schedule, there are only heating and DHW loads, which mostly occur at night, and the polyvalent heat pump in scenario 2 consumes PV-generated electricity during the day to produce hot water and store it in the hot water tank, offsetting some of the grid electricity consumed by the instantaneous air conditioners and heat pump water heater in scenario 1 during the night.

To demonstrate the effect of using polyvalent heat pumps combined with water storage tanks on grid demand reduction from different perspectives, the annual hourly distribution of various grid electricity demands was calculated for two scenarios, and the results are shown in Figure 4. It can be discovered that the number of hours with zero grid electricity demand rises from 3436 in scenario 1 to 3646 in scenario 2. In addition, the maximum number of hours of non-zero grid electricity demand occurs between 0.3 and 0.6 kW in scenario 1, while this maximum falls between 0 and 0.3 kW in scenario 2. This is because some hours that fall in the range of 0.3 to 1.5 kW in scenario 1 are substantially shifted to between 0 and 0.3 kW in scenario 2. As a result, it can be argued that the use of the polyvalent heat pump combined with water storage tanks can successfully decrease the home's grid electricity demand and ultimately reduce the burden on the electricity network.

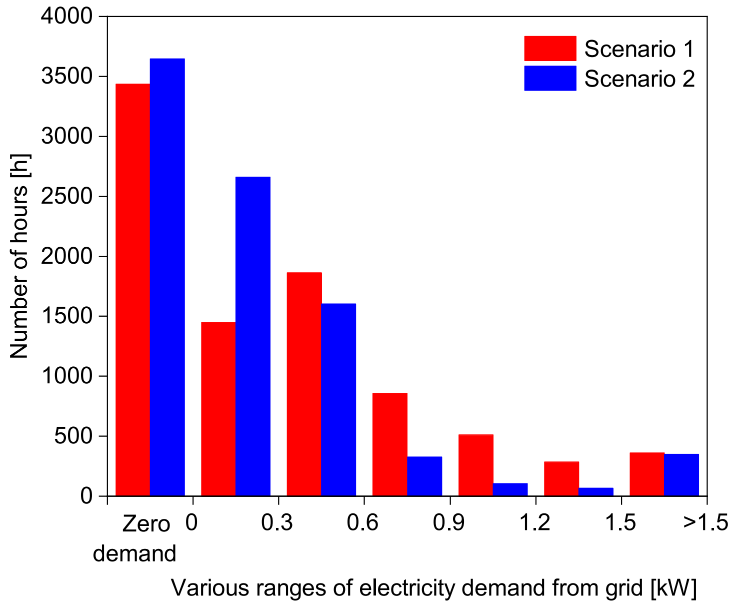


Figure 33. The annual hourly distribution of the various grid electricity demand from the grid

6. Sensitivity analysis of different factors on PV self-consumption and grid energy demand

This work aims to investigate the impact of using a polyvalent heat pump in combination with water storage tanks on PV self-consumption and grid electricity demand of houses. The factors that can affect these two parameters include the sizes of cold and hot water tanks, the size of the solar PV system as well as the COP and the input power of the polyvalent heat pump. Therefore, a sensitivity analysis has been conducted to evaluate the influence of different factors on the PV self-consumption and the grid energy demand. The values of each of the above parameters are increased or decreased by 10%, 20%, and 30%, respectively, based on the original values in Table 3 to calculate the PV self-consumption and house grid energy demand. Only one factor's value is changed in each calculation keeping the other factors' values as their original values, and the results are shown in Figure 5.

It is obvious from Figure 5-a that the PV system size has a largest impact on the PV self-consumption. This is because the change in PV system size can directly change the amount of PV-generated electricity. In addition, the heat pump COP is the second parameter that most affects PV self-consumption, since an increase in the heat pump COP indicates an increase in the heating or cooling efficiency of the heat pump, thus reducing its power consumption at the same thermal output.

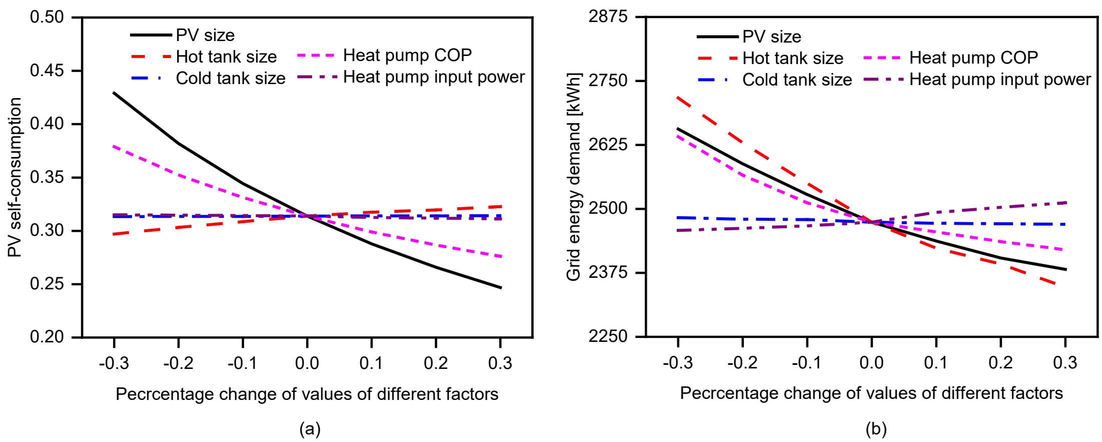


Figure 34. The influence of different parameters on (a) PV self-consumption and (b) grid energy demand

From Figure 5-b, we can see that the size of the hot water tank has the greatest impact on the grid energy demand of the case study house. The reasons are as follows: most of the heating or DHW load occurs during periods when there is little or no solar radiation, and second, as the hot water tank size decreases, less hot water is stored, so the water temperature in the hot water tank drops at a faster rate. Due to the control strategy for operating the polyvalent heat pump, once the hot water temperature falls below 55°C, the polyvalent heat pump will start heating the water to 60°C, even if there is no PV-generated electricity. As a result, the grid energy demand will increase.

7. Conclusion

This work proposes a combined system in which a polyvalent heat pump, in combination with water storage tanks, produces and stores hot and cold water for heating, cooling, and DHW by consuming PV-generated electricity. Results show that after determining the setpoint temperatures of water tanks and the control strategies for operating the polyvalent heat pump, this combined system can increase the self-consumption and self-sufficiency of the 10 kW PV system to 31.39% and 64.57%, respectively. Additionally, grid energy demand is reduced by 28%, from 3445 kWh in scenario 1 to 2474 kWh in scenario 2.

A sensitivity analysis has also been conducted to investigate the most critical factors affecting PV self-consumption and the grid electricity demand of the case study house using a polyvalent heat pump plus water storage tanks. Results show that the PV system size has the largest impact on PV self-consumption, and the grid energy consumption of the house is most influenced by the size of the hot water tank. However, there are beneficial limits to the sizing of the water storage tanks. In this case study, it is realized that sizing up to a 30% increase (from the size applied) may still benefit the grid energy saving. This is an important outcome of the research, as illustrated in Figure 5.

At this point in the study, electrical battery storage was not implemented. It is highly expected that future studies will indicate significant grid energy savings from battery storage, increasing PV self-consumption and self-sufficiency. Finally, considering that the control strategies for running the proposed combined system were developed in Excel Visual Basic for Applications, in future studies, a more accurate analysis will be performed in TRNSYS utilizing shorter time intervals.

References

Australian Renewable Energy Agency (2022) *Solar energy*. Available from: <https://arena.gov.au/renewable-energy/solar/> (accessed 5 May).

Bahadori, A., Nwaoha, C., Zendehboudi, S. and Zahedi, G. (2013) An overview of renewable energy potential and utilisation inAustralia, *Renewable and Sustainable Energy Reviews*, 21, 582-589.

Battaglia, M., Haberl, R., Bamberger, E. and Haller, M. (2017) Increased self-consumption and grid flexibility of PV and heat pump systems with thermal and electrical storage, *Energy Procedia*, 135, 358-366.

Bee, E., Prada, A. and Baggio, P. (2018) Demand-side management of air-source heat pump and photovoltaic systems for heating applications in the italian context, *Environments*, 5(12), 132.

Bee, E., Prada, A., Baggio, P. and Psimopoulos, E. (2019) Air-source heat pump and photovoltaic systems for residential heating and cooling: Potential of self-consumption in different European climates, *Building Simulation*, 12(3), 453-463.

Department of Industry Science Energy and Resources (2021) *Australian Energy Update*, Canberra.

Energy Rating (2014) *Space heating and cooling*. Available from: Energy Rating
<http://www.energyrating.gov.au/products/space-heating-and-cooling> (accessed 7 June 2021).

Hirmiz, R., Teamah, H., Lightstone, M. and Cotton, J. (2019) Performance of heat pump integrated phase change material thermal storage for electric load shifting in building demand side management, *Energy and Buildings*, 190, 103-118.

International Renewable Energy Agency (2019) *Global energy transformation: the remap transition pathway*, International Renewable Energy Agency (IRENA).

Langer, L. and Volling, T. (2020) An optimal home energy management system for modulating heat pumps and photovoltaic systems, *Applied Energy*, 278.

Li, Y., Mojiri, A., Rosengarten, G. and Stanley, C. (2021) Residential demand-side management using integrated solar-powered heat pump and thermal storage, *Energy and Buildings*, 250, 111234.

Pena-Bello, A., Schuetz, P., Berger, M., Worlitschek, J., Patel, M. K. and Parra, D. (2021) Decarbonizing heat with PV-coupled heat pumps supported by electricity and heat storage: Impacts and trade-offs for prosumers and the grid, *Energy Conversion and Management*, 240, 114220.

Rinaldi, A., Soini, M. C., Streicher, K., Patel, M. K. and Parra, D. (2021) Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation, *Applied Energy*, 282, 116110.

Wang, Z., Luther, M. B., Amirkhani, M., Liu, C. and Horan, P. (2021) State of the art on heat pumps for residential buildings, *Buildings*, 11(8), 350.

Embodied greenhouse gas emissions of structural systems for tall buildings: is there a premium for plan irregularity?

James Helal[1], Alireza Mehdipanah[2], André Stephan[3], Elisa Lumantarna[4] and Robert H. Crawford[5]

[1,4,5]The University of Melbourne, Melbourne, Australia,
{james.helal[1], elu[4], rhcr[5]}unimelb.edu.au,
ORCID-0000-0002-8211-1454[1], ORCID-0000-0002-2854-856[4], ORCID-0000-0002-0189-3221[5]
[2]WSP Australia, Melbourne, Australia,
alireza.mehdipanah@wsp.com, ORCID-0000-0003-0162-1098[2]
[3]Université Catholique de Louvain, Louvain-la-Neuve, Belgium
andre.stephan@uclouvain.be, ORCID-0000-0001-9538-3830[3]

Abstract: In mitigating the effects of climate change, life cycle assessment (LCA) has been proposed as a design tool to facilitate the choice of structural typologies, materials and floor plan layouts for tall buildings. Existing studies that use LCA to compare alternative structural systems for tall buildings adopt regular floor plans, whereby their centres of mass, stiffness and strength coincide throughout the building height. Thus, existing comparative LCA studies of structural systems exclude torsionally unbalanced tall buildings. The aim of this paper is to demonstrate the detrimental influence of plan irregularity on the embodied greenhouse gas emissions (EGHGE) of structural systems for tall buildings. This influence is evaluated using three finite element models of structural systems with varying degrees of plan irregularity for a 15-storey building scenario. The eccentric placement of shear walls is amplified across the alternative structural designs for each scenario, yet the materials and typology are kept constant to isolate the influence of plan irregularity on the EGHGE of the structural systems. All three structural systems comprise reinforced concrete shear walls and a moment-resisting frame that consists of band beams, columns and one-way slabs. A hybrid life cycle inventory analysis method is used to quantify the EGHGE of the structural systems. The findings of this study provide an initial estimation of the EGHGE premium for plan irregularity and confirm the need to reduce and eliminate these irregularities in the aim of minimising the EGHGE of structural systems for tall buildings.

Keywords: embodied environmental flows; high-rise; premium for height; structural systems.

1. Introduction

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), buildings were responsible for 21% of global greenhouse gas (GHG) emissions for the year 2019 (Masson-Delmotte et al., 2021). During that period, embodied GHG emissions (EGHGE), which are involved in the extraction of raw materials, manufacturing of building materials, and construction of buildings,

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 273–283.*

contributed 18% of the global GHG emissions for buildings (Masson-Delmotte et al., 2021). Thus, urgent changes are needed in the construction of buildings to meet short term mitigation goals for climate change and other environmental effects.

Regulations and current attempts to improve the environmental performance of buildings have principally focused on operational GHG emissions (OGHGE), which are associated with the ongoing uses of buildings such as lighting, ventilation, heating, cooling and other operational demands. However, studies have revealed that the growing significance of embodied environmental flows in buildings is often underestimated (Dixit, 2017). Moreover, improvements in the operational efficiency of buildings are often achieved using assemblies of high EGHGE such as thermal insulation and advanced façade systems. Therefore, as the operational energy efficiency of buildings improves and their OGHGE decreases (Röck et al., 2020), EGHGE will progressively form a higher proportion of the life cycle GHG emissions of buildings. Indeed, it is predicted that EGHGE will represent 50% of the entire GHG footprint of new construction between 2020 and 2050 (Adams, Burrows, & Richardson, 2019).

The increasing rate of world population growth and urbanisation have seen an accelerating trend in the construction of tall buildings aimed at increasing population density near employment opportunities. From 2000 to 2021, the total number of buildings taller than 200 m increased by 550%, globally (CTBUH, 2021). The number of tall buildings is expected to continue to grow as a solution to the challenges of urbanisation and as a means of establishing more compact cities that are attributed with less car dependency, better public transport services and better health outcomes. This could exacerbate existing problems like pollution and GHG emissions, but it could equally be an opportunity to develop more resource-efficient cities for the future.

The construction of tall buildings generates high spatial and temporal concentrations of GHG emissions, a phenomenon described by Säynäjoki, Heinonen, and Junnila (2012) as a 'carbon spike'. These 'carbon spikes' are further exacerbated in the case of tall buildings that can have up to 60% more EE per gross floor area (GFA) than low rise buildings (Helal, 2022; Trabucco, Wood, Vassart, Popa, & Davies, 2015; Treloar, Fay, Ilozor, & Love, 2001). This increase in resource use with increasing building height is defined by Khan (1967) as the premium-for-height and is mainly due to the cumulative effect of wind and earthquake loads on the structural systems of tall buildings. This has major implications for the environmental performance of tall buildings since the EGHGE of structural systems represents the greatest portion of the life cycle EGHGE of tall buildings (Zhao & Haojia, 2015).

In practice, the structural design of tall buildings begins with selecting preliminary member sizes and proceeds by iteration to meet strength, stability and serviceability design requirements until an acceptable design solution is reached. However, this iterative approach does not guarantee that the final design uses the least amount of structural materials and yields the least amount of EGHGE. To overcome this shortcoming, several studies have used a comparative life cycle assessment (LCA) approach to examine equivalent structural systems for tall buildings. Their results demonstrate the importance of the choice of structural typology, materials and floor plan layouts in the reduction of EGHGE. Despite their contribution, existing studies that use LCA to compare alternative structural systems for tall buildings adopt symmetrical and regular floor plans, whereby their centres of mass, stiffness and strength coincide throughout the building height. Thus, existing comparative LCA studies of structural systems exclude torsionally unbalanced tall buildings, which are abundant in cities. Therefore, in response to the increasing environmental effects of urbanisation and climate change, the influence of plan irregularity on the EGHGE of structural systems for tall buildings must be explored to minimise potential effects on the environment.

1.1. Aim and scope

The aim of this paper is to demonstrate the influence of plan irregularity on the embodied greenhouse gas emissions (EGHGE) of structural systems for tall buildings.

Structural systems of tall buildings are designed to perform their intended functions throughout their design working life with minimum maintenance and structural repair being necessary. As such, the operational flows of structural systems are considered by this study to be negligible and thus outside the scope of work. Moreover, the end-of-life GHG emissions for structural systems were also not considered due to their relative insignificance, representing approximately 1% of the total life cycle GHG emissions of buildings (Trabucco et al., 2015; Winistorfer, Chen, Lippke, & Stevens, 2007). End-of-life GHG emissions were also not considered due to the uncertain and unpredictable nature of deconstruction and demolition processes decades into the future. According to the European Standard EN 15978:2011, the life cycle of a building can be divided into four stages: product stage, construction stage, use stage and end-of-life stage (European Committee for Standardization, 2011). The scope of this work encompasses the initial EGHGE of structural systems for tall buildings associated with the product stage, also called cradle-to-gate.

1.2. Notions and definitions

1.2.1. Tall buildings

Among multiple possible definitions, this work adopts the definition for tall buildings proposed by Stafford Smith and Coull (1991) coupled with a minimum height criteria as set by Emporis Standards (2018) for a high-rise building. As such, this work defines a tall building as a building whose height is at least 35 metres and whose structural design is significantly influenced, because of its height, by lateral forces due to wind or earthquake actions.

1.2.2. Irregularity

For near-optimum structural performance, the following characteristics are generally desirable in the structural design of tall buildings: continuous load paths, equal floor heights, and symmetrical floor plans with identical resistance to lateral loads on both orthogonal axes (Taranath, 2017). Structural engineers typically refer to a building that has these desirable characteristics as a regular building. Irregularities, as defined by deviations from desirable structural characteristics, tend to create abrupt changes in the strength and/or stiffness of structural members that may results in an adverse concentration of stresses. Plan irregularity, which is the focus of this paper, is defined as the result of eccentricity between the centres of mass and stiffness of floor plans (Taranath, 2017). This eccentricity typically originates from the lack of symmetry in the configuration of shear walls, which may lead to the development of torsional forces and stress concentrations. Figure 1 illustrates an example of plan irregularity, which is characteristic of the proposed 60-storey One Victoria building in Melbourne, Australia.

2. Exclusion of torsionally unbalanced buildings in the comparative life cycle assessment of structural systems for tall buildings

A total of 10 comparative life cycle assessment (LCA) studies of structural systems for tall buildings have been identified in the existing literature. The case study tall buildings analysed in these studies range in height from 15 to 120 storeys and are designed to be built in Australia, South Korea, Italy and China. The identified studies assess a range of structural systems for tall buildings including rigid frame, braced frame, shear wall, outrigger and belt, and diagrid. The identified studies also consider reinforced concrete, steel and composite as alternative structural materials.

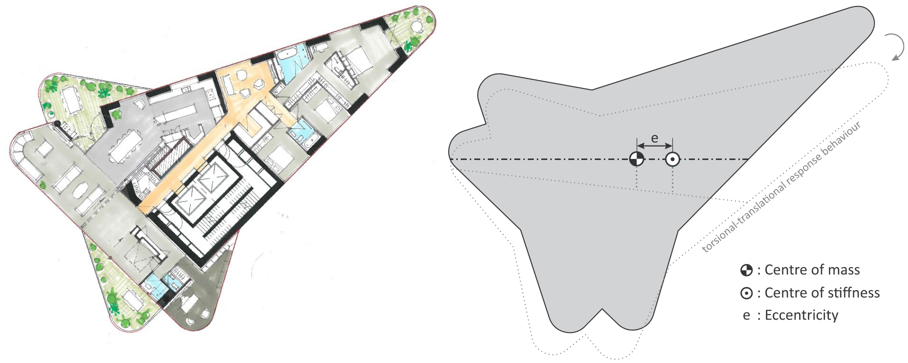


Figure 1: Example of plan irregularity in the 60-storey One Victoria building, Melbourne, Australia (CTBUH, 2021)

As seen in Table 1, existing studies that use LCA to compare alternative structural systems for tall buildings adopt regular plans, whereby their centres of mass, stiffness and strength coincide throughout the building height. Thus, existing comparative LCA studies of structural systems exclude torsionally unbalanced tall buildings.

Table 1: Existing studies that use life cycle assessment to compare alternative structural systems for tall buildings

Study	**Storeys**	**Structural typology**	**Structural materials**	**Plan irregularity**
Cho, Kim, Hong, and Kim (2012)	30	Braced frame, Outrigger and Belt	Steel	-
Foraboschi, Mercanzin, and Trabucco (2014)	20, 30, 40, 50, 60, 70	Shear wall	RC, Composite	-
Zhao and Haojia (2015)	70	Shear wall, Outrigger and Belt	RC, Composite	-
Moussavi Nadoushani and Akbarnezhad (2015)	5, 10, 15	Rigid frame, Braced frame, Shear wall	RC, Steel	-
Trabucco et al. (2015)	60, 120	Shear wall, Diagrid	RC, Composite, Steel	-
Tae, Baek, and Shin (2011)	35	Shear wall	RC (various grades)	-

Study	Storeys	Structural typology	Structural materials	Plan irregularity
Mavrokapnidis, Mitropoulou, and Lagaros (2019)	64	Braced tube, Tube in tube, Diagrid, Outrigger and Belt	RC, Steel	-
Helal, Stephan, and Crawford (2020a)	10, 20, 30, 40, 50	Shear wall	RC, Steel	-
Helal, Stephan, and Crawford (2020b)	5, 10, 15, 20, 25, 30, 50	Shear wall	RC	-
Helal (2022)	5, 10, 20, 30, 40, 50, 60, 70, 80	Shear wall, Outrigger and belt, Braced tube	RC, Steel	-
This study	15	Shear wall	RC	✓

Thus, the influence of plan irregularity on the EGHGE of structural systems for tall buildings is unexplored in the literature. Faced with the immense challenges of climate change, all means of structural optimisation based on EGHGE must be understood to better inform the architectural and structural design decision making process.

3. Method

Parametric modelling is adopted to assess the relationship between plan irregularity and the EGHGE of structural systems for tall buildings. This method of modelling is presented in Section 3.1. Due to the complex process of structural design for tall buildings, which involves equations with millions of unknowns, finite element modelling and analysis is used to ensure that structural systems are structurally adequate and meet the required performance criteria. The method of finite element modelling and analysis is presented in Section 3.2. The method of quantifying plan irregularity is presented in Section 3.3. The material quantities, which are derived and extracted from the finite element models, are then converted to embodied greenhouse gas emissions (EGHGE) using the Path Exchange (PXC) hybrid life cycle inventory method, as presented in Section 3.4.

3.1. Finite element modelling and analysis of structural systems

To assess the influence of plan irregularity on the EGHGE of structural systems for tall buildings, three finite element models were constructed for a 15-storey commercial building scenario with varying degrees of plan irregularity. Figure 2 presents the floor plan drawings of the three models and illustrates the alternative adopted placements of shear walls.

The finite element models are designed for permanent loads (i.e. self-weight of the structural elements), super-imposed dead loads of 1.0 kPa (for a typical floor) and 0.5 kPa (for the roof level), and imposed loads of 3.0 kPa (for a typical floor) and 0.25 kPa (for the roof level). In compliance with Australian standards for the structural design of commercial buildings, the adopted building parameters and structural design loads for wind and earthquake actions, along with the structural drawings and the detailed calculations of structural material quantities and associated embodied greenhouse gas emissions, are presented as supplementary information at: https://doi.org/10.26188/20218871. The commercial software ETABS (Computers and Structures Inc., 2018) is used for the finite element modelling and analysis of tall buildings. Widely regarded as one of the most reliable and powerful structural analysis and design software for multi-storey buildings, ETABS has been used for the design and analysis of some of the most complex and iconic tall buildings in the world, including Burj Khalifa, the tallest building in the world as of 2022 (CTBUH, 2021).

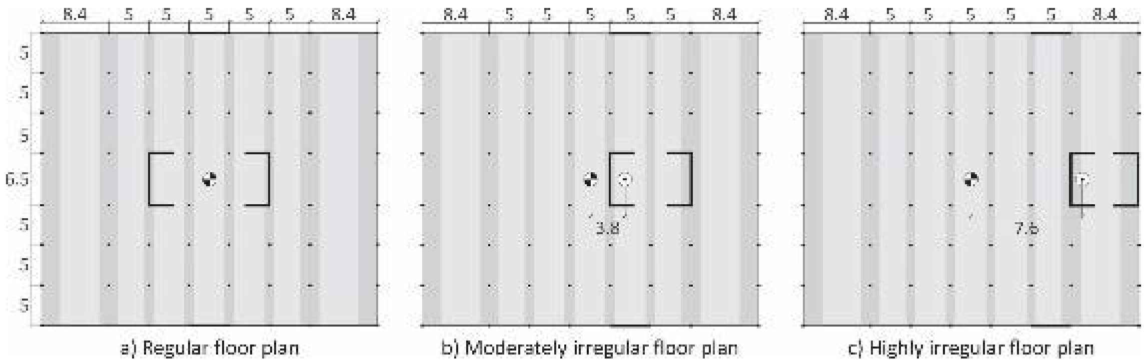


Figure 2: Floor plan schematic drawings of the building models. Note: all measurements are in metres

As seen in Figure 2, the eccentric placement of shear walls is amplified across the alternative structural designs, yet a range of material and geometric properties are kept constant. A 32 MPa reinforced concrete is selected for the design of the band beams and the one-way slabs whereas a 40 MPa reinforced concrete is selected for the design of the columns and shear walls. A rectangular floor plan is adopted with a width of 41.6 m and a depth of 36 m along with column span length ranging from 5 m to 8.4 m. An inter-storey height of 4.2 m is adopted for the first and second floors, while a height of 3.2 m is adopted for other storeys. These material and geometric properties and their values were selected based on best and common practices in the design and construction of tall buildings.

3.2. Quantifying the plan irregularity of structural systems

In principle, structural systems are continuous systems that have an infinite number of degrees of freedom that specify the position or configuration of a building model. However, to analytically analyse the structural behaviour of buildings, conceptual idealisation and simplifying assumptions are needed to reduce the number of degrees of freedom to a discrete number and in some cases, to just a single degree of freedom. By applying Newton's second law of motion, the structural response of a single-storey structural system with plan irregularity can be conveniently described with the following equations for translational motion (Eq. 1) and rotational motion (Eq. 2):

$$m\ddot{x} + k(x + e\theta) = 0 \qquad \textit{Eq. 1}$$

Where m = mass of the building in kg; x = translational deflection of the centre of mass of the floor plan in m; $\ddot{x}$ = second derivative of the translational deflection profile; k = translational stiffness in N/m;

e = eccentricity as measured by the distance between the centres of mass and the stiffness in m; and ϑ = rotational deflection of the floor plan in radians.

$$mr^2\ddot{\theta} + k(x + e\theta)e + k_t\theta = 0 \qquad \textit{Eq. 2}$$

Where r = mass-radius of gyration of the building in m; $\ddot{\theta}$ = second derivative of the rotational deflection profile; and k_t = torsional stiffness in N/radians.

By solving these equations of motion simultaneously, the displacement time-history of an arbitrary point within a single-storey structural system can be expressed in terms of the structure's eccentricity, mass-radius of gyration, floor plan geometric dimensions, and torsional and translational stiffness values. This paper uses the generalised force method (GFM) of analysis to idealise and convert a multi-storey structural system with plan irregularity to an equivalent single-storey structural system whose dynamic response (i.e., seismic displacement demand and shear force profile) is governed by the equations of motion presented earlier. Developed by Lam, Wilson, and Lumantarna (2016), and later enhanced by Mehdipanah (2018), the GFM has been shown to be a highly accurate method of estimating the structural response of multi-storey buildings with plan-irregularity while incorporating the effects of higher modes of vibrations for tall buildings. By applying the GFM, a range of building parameters and modal characteristics can be calculated including plan irregularity (e_r), which is defined as the ratio of eccentricity to mass-radius of gyration (i.e., e/r). Table 2 represents the magnitudes of eccentricity, mass-radius of gyration and the resulting plan irregularity for the three building models.

Table 2: Eccentricity, mass-radius of gyration and plan irregularity of the building models

Building model	**Eccentricity (e) (m)**	**Mass-radius of gyration (r) (m)**	**Plan irregularity (e_r) (unitless)**
Regular floor plan	0	0	0
Moderately irregular floor plan	3.816	16.02	0.24
Highly irregular floor plan	7.583	16.02	0.47

To better understand these values of plan irregularity, it is beneficial to compare them to the maximum theoretical plan irregularity of the building models, which occurs when the centre of stiffness is located at the furthest point away from the centre of mass (i.e., maximum eccentricity). This unrealistic hypothetical scenario would yield a maximum theoretical plan irregularity of 1.72. Thus, the moderately irregular and highly irregular building models have plan irregularities that are approximately 14% and 28% of the maximum theoretical plan irregularity, respectively.

3.3. Quantifying the embodied greenhouse gas emissions of structural systems

Due to its comprehensiveness and relevance to Australian construction materials, this paper uses the Environmental Performance in Construction (EPiC) database of embodied environmental flow coefficients compiled by Crawford, Stephan, and Prideaux (2019) using the PXC method for hybridisation. The initial embodied GHG emissions of the structural systems are calculated using the following equation:

$$EGHGE/NFA_{SS} = \sum_{m=1}^{M} \left(Q_{m,SS} \times EGHGEC_m\right) / \, NFA$$

Where $EGHGE/NFA_{SS}$ = embodied greenhouse gas emissions of structural system SS per Net Floor Area (NFA) in $kgCO_2$-e/m^2; $Q_{m,SS}$ = quantity of material m in structural system SS (e.g. steel in kg/m^2); and $EGHGEC_m$ = embodied GHG emissions coefficient of material m (e.g. 2.90 $kgCO_2$-e/kg for hot-rolled steel and 0.17 $kgCO_2$-e/kg for 32 MPa concrete).

4. Results

The material quantities of all three finite element models were extracted, converted to embodied GHG emissions (EGHGE) and normalised per net floor area (NFA) to enable better comparisons. The resulting EGHGE/NFA values for each structural system are presented in Table 3. As seen in Table 3, the eccentric placement of shear walls in the structural systems with irregular floor plans resulted in a slight increase in EGHGE/NFA compared to the regular building model. These increases in EGHGE/NFA were relatively low at 1% and 3% for the structural systems with the moderately irregular floor plan and the highly irregular floor plan models, respectively. This result translates to an increase of approximately 36,000 $kgCO_2$-e and 104,000 $kgCO_2$-e for the moderately and highly irregular building models, respectively. In the case of the highly irregular model, the increase in EGHGE is equivalent to the annual GHG emissions of more than six average Australian citizens (Crippa et al., 2019).

Table 3: Embodied greenhouse gas emissions (EGHGE) per net floor area (NFA) of the structural systems

Model	**Total EGHGE/NFA ($kgCO_2$-e/m^2)**	**Relative change to regular model**
Regular floor plan	163	-
Moderately irregular floor plan	165	+1%
Highly irregular floor plan	168	+3%

An analysis of the EGHGE of the building models per structural element type shows that the eccentric placement of shear walls significantly influences the EGHGE of columns due to the required increases in both column sizes and steel reinforcement. Other structural element types (i.e., shear walls, slabs and beams) were relatively uninfluenced by plan irregularity. Table 4 shows the increase in the EGHGE of columns across the three different structural systems.

Table 4: Embodied greenhouse gas emissions (EGHGE) of the columns across the building models

Model	**EGHGE of columns ($kgCO_2$-e)**	**Relative change to regular model**
Regular floor plan	393,050	-
Moderately irregular floor plan	457,051	+16%
Highly irregular floor plan	485,182	+23%

To better understand the influence of plan irregularity on the EGHGE of structural systems, Figure 5 demonstrates the increase in EGHGE/NFA as a function of the magnitude of plan irregularity, as measured by the ratio of eccentricity to mass-radius of gyration. The results depicted in Figure 2 show that the relationship between EGHGE/NFA and plan irregularity does not have a constant rate of change. Instead, a growth in the rate of change is observed whereby as the plan irregularity of the structural system increases, the percent change in the EGHGE/NFA of the structural system increases.

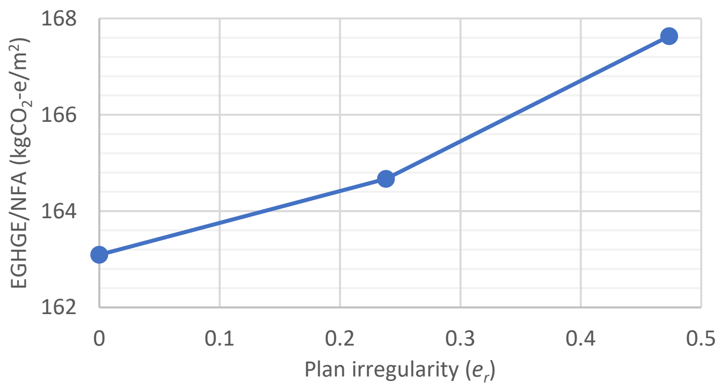


Figure 2: Influence of plan irregularity on the embodied greenhouse gas emissions of structural systems. Note: vertical axis begins at 162 $kgCO_2$-e/m^2

5. Discussion and conclusion

This study assessed and quantified the detrimental influence of plan irregularity on the EGHGE of structural systems for tall buildings using three structural systems parametrically designed and analysed using finite element modelling. The study demonstrates that increasing the plan irregularity of tall buildings can significantly increase the EGHGE of columns, by up to 23%, resulting in an overall increase of up to 3% in the EGHGE of the entire structural system. In comparison, existing comparative LCA studies of structural systems exclude torsionally unbalanced tall buildings.

The influence of plan irregularity on the EGHGE of structural systems for a 15-storey building scenario was found to be relatively small. However, this influence is postulated to exponentially increase with building height. This is largely due to the compounding influence of wind loads and earthquake loads on the structural behaviour and the resulting material requirements of tall buildings, a phenomenon described by Khan (1967) as the 'premium for height'. This is particularly problematic for tall buildings since the embodied environmental flows of their structural systems have been shown to represent the greatest portion of their total life cycle embodied environmental flows (Zhao & Haojia, 2015). Further research could investigate the influence of plan irregularity on tall buildings of different heights, floor plan geometries, structural materials and structural typologies.

This study suffers from several limitations. Firstly, this study assessed the influence of plan irregularity on 15-storey buildings with reinforced concrete shear walls and a moment-resisting frame that consists of band beams, columns and one-way slabs. Thus, the findings of this study are restricted to these structural materials and typologies. Secondly, this study relies on Australian hybrid data for calculating

EGHGE, which are specific to the economic situation and energy mix of Australia. Despite the geographic specificity in the adopted material coefficients for EGHGE, the resulting material quantities, which were derived from the constructed finite element models, are still relevant.

Thus, tall buildings are not only characterised by a premium for height. Rather, this work established that tall buildings are also characterised by an EGHGE premium for plan irregularity. The complex interrelationships between these various premiums require a paradigm shift towards design frameworks that integrate the assessment of EGHGE into the structural design of tall buildings. This will ultimately contribute to reducing the environmental effects of buildings.

References

Adams, M., Burrows, V., & Richardson, S. J. W. G. B. C., London. (2019). Bringing embodied carbon upfront.

Cho, Y. S., Kim, J. H., Hong, S. U., & Kim, Y. (2012). LCA application in the optimum design of high rise steel structures. *Renewable and Sustainable Energy Reviews, 16*(5), 3146-3153. doi:https://doi.org/10.1016/j.rser.2012.01.076

Computers and Structures Inc. (2018). ETABS. Retrieved from https://www.csiamerica.com/products/etabs/releases#17-17.0.0

Crawford, R. H., Stephan, A., & Prideaux, F. (2019). *Environmental Performance in Construction (EPiC) Database*. Melbourne: The University of Melbourne.

Crippa, M., Oreggioni, G., Guizzardi, D., Muntean, M., Schaaf, E., Lo Vullo, E., et al. (2019). Fossil CO_2 and GHG emissions of all world countries - 2019 Report, EUR 29849 EN. In. Luxembourg: Publications Office of the European Union.

CTBUH. (2021). The Skyscraper Center. Retrieved from https://www.skyscrapercenter.com/

Dixit, M. K. (2017). Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renewable and Sustainable Energy Reviews, 79*, 390-413. doi:https://doi.org/10.1016/j.rser.2017.05.051

Emporis Standards. (2018). High-rise Building (ESN 18727). Retrieved from https://www.emporis.com/building/standard/3/high-rise-building

European Committee for Standardization. (2011). *EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*: BSI Standards.

Foraboschi, P., Mercanzin, M., & Trabucco, D. (2014). Sustainable structural design of tall buildings based on embodied energy. *Energy and Buildings, 68*(Part A), 254-269. doi:https://doi.org/10.1016/j.enbuild.2013.09.003

Helal, J. (2022). *Towards a comprehensive framework for integrating embodied environmental flow assessment into the structural design of tall buildings.* (Doctor of Philosophy), University of Melbourne, Melbourne, Australia.

Helal, J., Stephan, A., & Crawford, R. H. (2020a). The influence of life cycle inventory approaches on the choice of structural systems to reduce the embodied greenhouse gas emissions of tall buildings. *IOP Conference Series: Earth and Environmental Science, 588*, 032028. doi:10.1088/1755-1315/588/3/032028

Helal, J., Stephan, A., & Crawford, R. H. (2020b). The influence of structural design methods on the embodied greenhouse gas emissions of structural systems for tall buildings. *Structures, 24*, 650-665. doi:https://doi.org/10.1016/j.istruc.2020.01.026

Khan, F. R. (1967). *Current trends in concrete high-rise buildings*. Paper presented at the Symposium on Tall Buildings with Particular Reference to Shear Wall Structures, Southampton, England. http://ebookcentral.proquest.com/lib/unimelb/detail.action?docID=1677275.

Lam, N. T. K., Wilson, J. L., & Lumantarna, E. (2016). Simplified elastic design checks for torsionally balanced and unbalanced low-medium rise buildings in lower seismicity regions. *Earthquake and Structures, 11*(5), 741-777.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., et al. (2021). Climate change 2021: the physical science basis. 2.

Mavrokapnidis, D., Mitropoulou, C. C., & Lagaros, N. D. (2019). Environmental assessment of cost optimized structural systems in tall buildings. *Journal of Building Engineering, 24*, 100730. doi:https://doi.org/10.1016/j.jobe.2019.100730

Mehdipanah, A. (2018). *Buildings featuring irregularities in the gravity load carrying frames in low-to-moderate seismicity regions.* (Doctor of Philosophy), University of Melbourne, Melbourne, Australia. Available from EBSCOhost University of Melbourne's Catalogue database.

Moussavi Nadoushani, Z. S., & Akbarnezhad, A. (2015). Effects of structural system on the life cycle carbon footprint of buildings. *Energy and Buildings, 102*, 337-346. doi:https://doi.org/10.1016/j.enbuild.2015.05.044

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., et al. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy, 258*, 114107. doi:https://doi.org/10.1016/j.apenergy.2019.114107

Säynäjoki, A., Heinonen, J., & Junnila, S. (2012). A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. *Environmental Research Letters, 7*(3), 034037.

Stafford Smith, B., & Coull, A. (1991). *Tall building structures: analysis and design*: Wiley-Interscience.

Tae, S., Baek, C., & Shin, S. (2011). Life cycle CO_2 evaluation on reinforced concrete structures with high-strength concrete. *Environmental Impact Assessment Review, 31*(3), 253-260. doi:https://doi.org/10.1016/j.eiar.2010.07.002

Taranath, B. S. (2017). *Tall building design*. Boca Raton: CRC Press.

Trabucco, D., Wood, A., Vassart, O., Popa, N., & Davies, D. (2015). *Life Cycle Assessment of Tall Building Structural Systems*. Chicago, Illinois: CTBUH.

Treloar, G. J., Fay, R., Ilozor, B., & Love, P. E. D. (2001). An analysis of the embodied energy of office buildings by height. *Facilities, 19*(5/6), 204. doi:https://doi.org/10.1108/02632770110387797

Winistorfer, P., Chen, Z., Lippke, B., & Stevens, N. (2007). Energy consumption and greenhouse gas emissions related to the use, maintenance, and disposal of a residential structure. *Wood and fiber science, 37*, 128-139.

Zhao, X., & Haojia, M. A. (2015). Structural System Embodied Carbon Analysis for Super Tall Buildings. *Procedia Engineering, 118*, 215-222. doi:https://doi.org/10.1016/j.proeng.2015.08.420

Emerging collaborative design platforms and the future of architectural education and practice

Tristan Morgan[1]

[1] *Curtin University, Perth, Australia*
[1] *Aurecon Group, Australia*
[1] *Intensive Fields Lab, Perth, Australia*
[1]*tristan.morgan@curtin.edu.au, ORCID-0000-0002-7140-7428*

Abstract: In 2017, Susskind and Susskind said that the future of the professions would move beyond the comfort of routine task automation and towards transformative re-configuration with an increased focus on demystification, democratization, and decomposition. At the same time, the rise of digital 'superusers', highlights the critical role of transdisciplinarity if the design professions are to be equipped to contribute to solving complex global challenges – wicked problems – such as climate change and resource scarcity.

Collaborative digital platforms, typically accessed via web-based interfaces and enhancing, rather than replacing, existing digital toolboxes, have emerged as catalysts of this transformation, at once democratizing access to specialist knowledge, whilst also providing users with toolsets that enable them to embed their own knowledge and experience within the platforms. This is different to the neo-materialist and parametricism-driven concerns of the first and second digital turns, where the focus was often on embedding material and crowd behaviours into modelling software. A focus on user interface and experience supports demystification of professional knowledge. Non-specialists can operate the tools and extract their own insights from large spatial datasets autonomously. Such affordances indicate an emergent future where traditional professions are decomposed into their constituent parts, re-configured into platform components that are accessed on-demand by professionals.

This paper identifies a future construction industry that is increasingly systematised, enabling cross-organisational collaborative practice and discusses these emerging platforms within the context of a continuing teaching project at an urban scale, demonstrating impact on design methods and outcomes.

Keywords: Transdisciplinarity, Digital Technology, Zero Carbon, Collaboration.

1. Introduction

The transformation of architecture, engineering, and construction (AEC) industries is a significant concern of researchers and practitioners, particularly as the global community seeks to address complex global

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 284–293.*

challenges – wicked problems (Cutler and Burry, 2010) – such as climate change, to which construction contributes almost 40% of global embodied carbon emissions (Blanco *et al.*, 2021). While there is a clear imperative to reduce carbon emissions that result from construction, current building stock is estimated to double by 2050, from 223 to 415 billion square metres (Laski and Burrows, 2017).Pathways to climate change mitigation must therefore include building less by increasing renovation and adaptive reuse rates and net zero carbon as a minimum standard for all future buildings. To achieve this, designers must be supported in making better decisions about where, what, and how to build, which means improved access to critical data and associated insights to target opportunities for reuse and renovation over building new unless strictly necessary.

Concurrently, the industry has seen shifts in labour resource allocation and the emergence of a growing community of technology-driven start-ups selling digital platforms that seek to integrate into the design and delivery processes of incumbent firms (Talarico et al., 2020). This is an evolution of industry concerns emblematic of the digital turn of the 1990s and 2000s (Carpo, 2013).The focus at that time was often one of neo-materialism and parametricism, explored through digital fabrication methods – the making of objects or objectiles (Cache et al., 2011, p. 20). Modelling, whether it be of geometry or behaviours, was often at the forefront of research and application during this time (De Landa, 2002).

Since 2020, a collaboration between research and industry has delivered an urban design focused programme to master's students at Curtin University in Perth, Western Australia. As a research-driven unit, it tasks student groups to address complex issues around urban design at a large urban scale, encompassing one or several precincts. These teams must collaborate to undertake research that identifies existing strengths, opportunities, threats, and weaknesses. Designers develop proposals in response and presented for industry and stakeholder critique and response within several sessions held across the semester-long teaching period. Giraffe, an urban-design focused web-based modelling platform (Giraffe, 2022), is implemented by the author to support teams working collaboratively in a data-informed manner, enabling continual visibility of design decisions and impact between team members and groups. The platform is also used by users to visualise urban form and illustrate impact through real-time metrics.

This paper reviews the impact of integrating emerging collaborative design platforms within a teaching programme and identifies future scenarios using a 'cone of plausibility' strategic foresight methodology. These platforms are considered against a backdrop of industry transformation, enabling increasingly transdisciplinary practice (Nicolescu, 2002) , accelerated through demystification, democratisation, and decomposition. A preliminary conceptual framework for future AEC practice is proposed by the author, characterised by transdisciplinary collaborative platforms that ensure practitioners can make the best decisions possible to enable a sustainable zero carbon future.

2. Collaborative platforms

As digital and computational techniques and applications have become normalised within industry, questions of dissemination and scale have emerged. The required specialisation within practice necessitates that not every practitioner can become a specialist computational designer or software engineer (Heumann and Mullenix, 2014). The typical computational toolbox, however, is the domain of hackers, coders, and developers, making it difficult for non-experts to effectively integrate computational processes within their work. It is in this landscape that an emerging group of AEC technology start-ups operate, providing productised computational processes accessed as web-based applications. Rather than neo-materialism or parametric formalism, the focus therefore shifts towards user interfaces and user experiences (UI/UX) to ensure that specialist and computational knowledge is effectively demystified and democratised. This enables the benefits of computational thinking to be scaled across organisations and the industry.

Of these platforms, many identify a requirement to provide affordance for collaboration between designers, consultants, clients, and key stakeholders. Hypar, for instance, provides a code execution platform accessible via a browser-based interface that allows functions – code, scripts, or algorithms – to be sequenced together to automate end-to-end processes (*Hypar*). These functions are authored by experts who then share them for use and adaptation by the wider community (Figure 1).

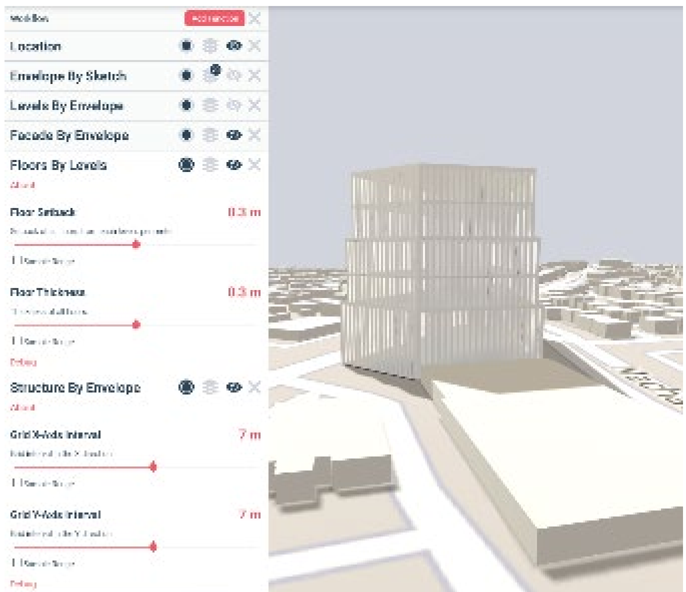


Figure 35: Hypar user interface showing stacked modular functions (*Hypar*)

In recent years there has been a shift in the way technology is deployed and leveraged within the AEC industry. A decade ago, most software was installed and executed on a local computer. It was typically licensed based on a single seat or user, and often this license was perpetual, in that ongoing costs were limited to regular version releases or maintenance plans. Currently, most software is offered as subscription only, charged monthly or annually, and many developers are charging for usage using tokens rather than sharing licenses across an organisation. At the same time, medium and large firms must purchase and maintain a wide range of different software, as well as negotiate complex interoperability requirements when collaborating with other consultants and disciplines. The most significant shift, however, is the growth of specialised tools that bring automation and intelligence to narrow yet deep slices of the design and delivery process. These tools seek to complement existing toolboxes and ecosystems, are often lightweight and relatively inexpensive, and – significantly – are delivered using web-based interfaces that are more familiar to users of Facebook and YouTube. This means no command-lines, macros, or other hallmarks of tools of AEC's first digital turn.

They have other things in common with Facebook and YouTube, as well – they are dynamic, social, and collaborative in nature. This enables new workflows where models can be easily shared with collaborators and stakeholders. Design decisions can be communicated in real-time to other parties, which supports rapid decision-making and seamless transfer of information and knowledge. In the case of a tool such as Giraffe, this means that a group of designers can work remotely alongside one-another in a synchronous manner. Not only that, but they are able to comment on decisions, and these comments are fed directly back to the original owner. This is similar to standard collaborative workflow loops of text document authoring and editing. What sets this apart, however, is that these platforms are rich three-dimensional environments that must contend with complex hierarchies of geometry assemblages. The sophisticated tagging and classification of elements ensure traceability of design decisions, real-time object ownership and transfer, and the ability to calculate the results of interactions between users in a one-to-many relationship (Figure 2).

Implementing these types of emerging platforms provides opportunities for practitioners to reconsider their workflows and technology toolkit. Rather than having to choose between limited functionality provided 'out-of-the-box' in software or building new and custom tools from scratch, they now have the choice to integrate deeply specialised tools into their workflows. This is especially important as the complexity of projects is increasing, and more specialised knowledge is required to ensure outcomes have a positive impact. Furthermore, this is exemplified in the emerging client and community expectations surrounding zero carbon buildings, which requires specific knowledge and expertise in life cycle analysis and energy simulation that is not typically part of standard professional expertise or training. Tools such as Giraffe support integrations that provide these types of analytics that embed the required expertise. In fact, one of the core integrations is carbon impact modelling that provides users with metrics on the predicted embodied carbon required for a specific proposed urban proposal, as well as guidance as to the relative impact of best practice approaches that could be implemented as the project develops. This type of insight and analysis, seamlessly integrated into the platform, ensures that such information can be shared across a project team, supporting collaborative decision making, rather than remaining solely within the domain of the expert.

Giraffe is an example of a web-based urban design platform that supports the rapid exploration of development options at the precinct and city level. Real-time feedback provides designers with insights into the environmental, economic, and social impact of their designs alongside key metrics such as floor areas and accommodation schedules. Users, designers, and software developers can extend this platform through a robust application programming interface (API) that enables connection between the platform and specialist domain expertise and intellectual property.

Other emerging platforms such as Speckle and Arkio provide multi-platform interoperability and collaborative virtual reality design experiences, respectively. Crucially, the platform's developers do not intend for them to replace existing software ecosystems or processes wholesale. They are instead focused on developing software solutions to solve specific problems through either vertical (end-to-end, single specialisation) or horizontal (discrete task across range of specialisations) scaling. As these platforms begin to integrate into existing practice models there is an opportunity to explore how this shift will alter the future of the industry through a pedagogical lens.

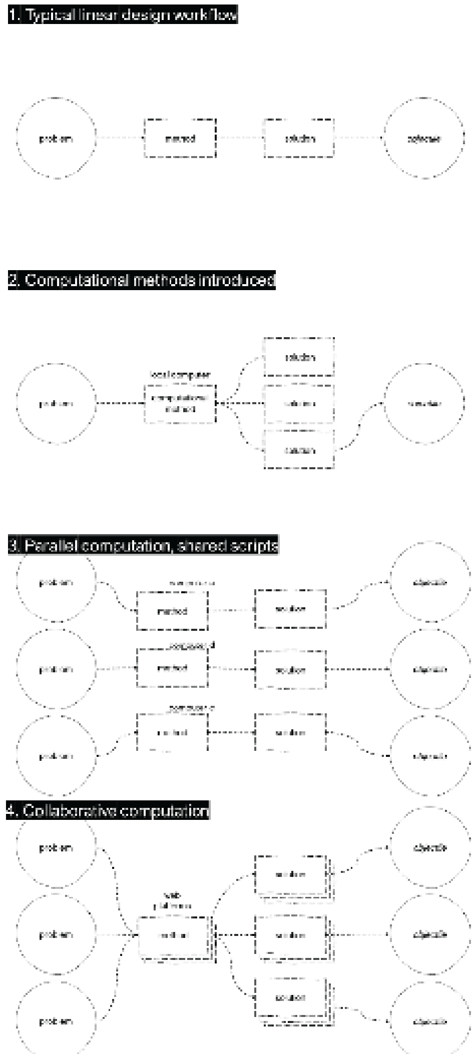


Figure 36: From traditional linear design processes to web-based collaboration workflows. (Source: Author)

3. Pedagogical applications

Giraffe has been integrated into the Urban Design unit at Curtin University, Australia, since 2020. This unit requires students to consider an existing urban condition – typically at precinct or partial city scale – and propose a speculative masterplan and urban form in response to analysis of the area's strengths, weaknesses, opportunities, and threats. In 2019 this unit was delivered entirely on-campus, with students working in groups to develop their proposals. In 2020, however, this had to adapt to rapidly changing circumstances due to the global pandemic.

Computational processes were introduced in 2019 to provide students with tools to undertake basic urban analytics and connect data and insights with automated parametric generation of urban form. Basic environmental analysis was also introduced, using Ladybug Tools, to support students in understanding environmental context and ensuring their proposals were adequately responsive. While most students are familiar with design modelling tools such as Revit, Rhino, and Sketchup, the typical approach was for each student to identify individual portions of their group's precinct, and work in isolation before combining into a single model for presentation. Beyond the obvious issues this introduces with asynchronous collaboration and interoperability, students experienced challenges with implementing computational processes and undertaking the required analysis across a group's entire area of focus.

Often, any computational approaches were applied after model combination, once most key design decisions were already made. This meant that any insights were unlikely to be critiqued and responded to through design, and the computational processes were simply used, at best, as validation for decisions made. This is a well-known challenge with applying computational processes in practice and is an ongoing concern of AEC technology start-ups such as Shapediver, which brings Grasshopper-authored scripts to the web for sharing and deployment. This approach, however, does not adequately address problems of collaboration, as each user still engages with the computational process in isolation on their local computer and local models, even if they are sharing the underlying computational processes.

Against the backdrop of an ongoing pandemic and the rapid adoption of working-from-home and virtual meetings, the collaboration challenges experienced in 2019 required an urgent response. Rather than explore ways to adapt software such as Rhino and SketchUp to support virtual collaboration, Giraffe was identified as a mature platform that was natively engineered to take advantage of the collaborative foundations of the modern web, leveraging web-mapping technology, easily invoked sharing functionality, and a robust backend API that allowed Grasshopper-authored scripts to be hosted on a remote virtual machine that could be triggered by actions undertaken by users in the Giraffe modelling interface (Figure 3).

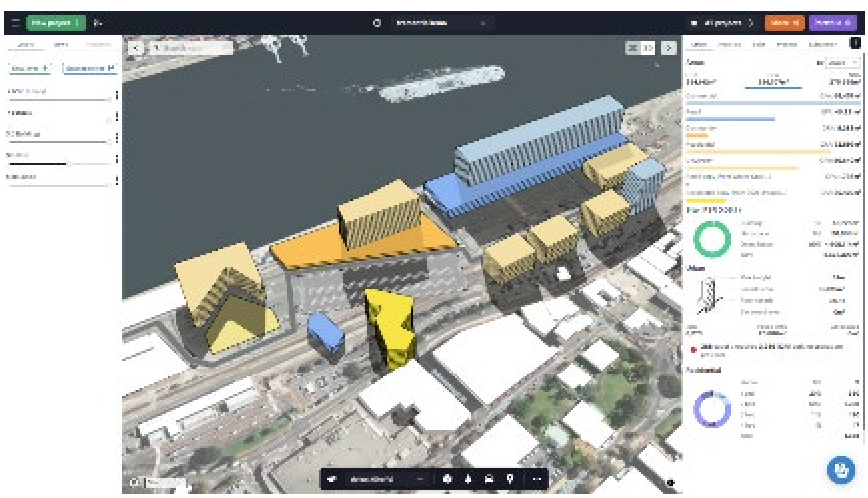


Figure 37: Screenshot of Giraffe interface (*Giraffe*, 2022)

While teaching has returned primarily to an in-person paradigm, Giraffe has remained as a key component of the students' digital toolbox. Several observations can be made as to the impact of this approach:

- When provided with real-time design metrics within the design modelling environment, students were able to quickly respond and make decisions (FIG).
- Using a collaborative web-tool allowed students and instructor to be in continual asynchronous communication, as the instructor was able to monitor model development and provide feedback outside of formal teaching periods.
- Hosting computational scripts that were accessible individually allowed students to leverage computational design without requiring them to establish an appropriate environment on their local computers. This ensures that the scripts themselves can be audited, maintained, and distributed by relevant experts with ease.
- Non-technical practitioners can easily work alongside domain experts. This allows parties to dynamically respond to respective insights, which dramatically reduces the time taken to iterate proposals and make design decisions.
- As the platform is web-based and natively collaborative, additional parties can be easily invited to examine the proposal. This allows engagement to occur beyond the limitations of a typical design studio, and aids in democratising access to key information for stakeholders.

These findings begin to suggest the emergence of new AEC practice configurations that shift beyond cross-disciplinary approaches towards those that are highly integrated and authentically transdisciplinary. We begin to observe the closing of the design-decision and iteration loop, but without pitfalls of enforced silos. Decisions are transparently made and highly traceable and invite collaboration and dialogue between parties that is enabled both asynchronously and in real-time. Additionally, the presence of integrated analyses and performance metrics continually provides designers with key information, supporting truly data-informed design approaches (Figure 4).

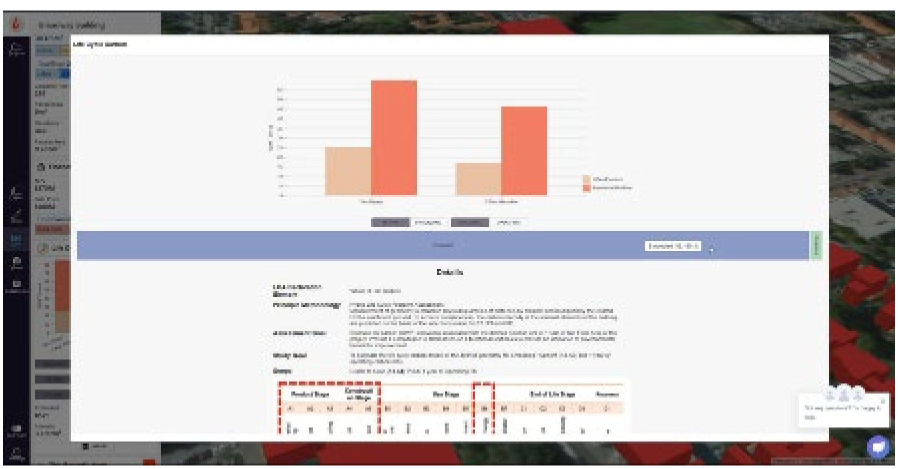


Figure 38: Screenshot of Hybrid Life Cycle Footprint Assessment in Giraffe (*Giraffe*, 2022)

4. The future of the AEC professions

It is easy to identify a shift in the AEC professions from even ten years ago. The impact of the digital turn in architecture is well understood, however the industry is currently amid a more significant shift that is characterised by complexity, integration, and an imperative to reconfigure itself in response to wicked problems that transcend traditional disciplinary boundaries. Recent research identifies that the impact of digital technology on practice models in architecture and engineering is not limited to a single sector or scale but is recognisable across the industry in its entirety (Hensel, 2016). Even smaller practices that have previously been inoculated against the requirements of digitisation of their processes must contend with the increasing complexity of project delivery within an environment that expects evidence of building performance and integration with digital twin and asset management platforms. By examining this AEC practice reconfiguration using the 'Cone of Plausibility' framework, it is possible to identify plausible future scenarios (Conway, 2022). In doing so, the industry can identify preferred future scenarios and ensure that is positioned to achieve a preferred, rather than adverse, future state (Figure 5).

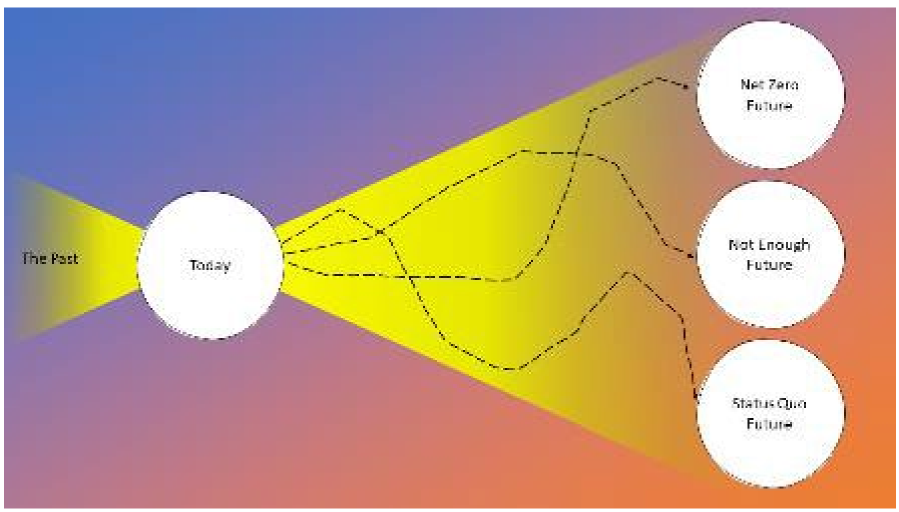


Figure 39: Cone of plausibility framework (Source: Author)

Susskind and Susskind suggest that the future of work will experience a move beyond the status-quo of routine task automation towards transformative re-configuration accelerated by demystification, democratisation, disintermediation, and decomposition (Susskind and Susskind, 2017). In AEC specifically, the move towards digital-first service models built upon BIM software ecosystems and standardised data management processes provides the backdrop for the rise of a new breed of design professional – or 'superuser' - who naturally transcends disciplinary boundaries and is as comfortable pushing technological boundaries as they are connecting other domains and disciplines. They also possess qualities to ensure effective communication, collaboration, and leadership qualities (Deutsch, 2019).

The superuser model positions such skills within existing practice models. However, to truly demystify and democratise AEC expertise, a transdisciplinary framework must emerge that connects 'superusers' with non-experts both within and beyond the industry. This also presents an opportunity to reconsider prevailing professional service business models, referred to as disintermediation, reintermediation, and decomposition by the Susskinds.

In the shadows of the second digital turn, there is also a shift away from the formal complexity and parametric exuberance of first-wave computational design, parametricism, and digital fabrication. Though this focus on 'outliers' was an important catalysing agent for development of computational techniques and applications, the wider impact of digital design technological is currently re-directing towards the 'fat middle' (Davis, 2021). In architecture this is the market sectors that are most ubiquitous, and highest impact, such as multi-family housing and commercial building. In engineering, this is less the structural gymnastics of formally complex building forms and more transformative and impactful transport, infrastructure, and resources projects.

It is within this landscape that collaborative platforms such as Giraffe become powerful agents of industry transformation, enabling a transdisciplinary approach to addressing wicked problems and complex challenges confronting society, and connecting experts and non-experts alike with greater transparency. In this scenario, superusers connect with other disciplines and stakeholders throughout a project lifecycle, and relevant domain expertise is integrated into the decision-making process at the precise time it is needed, which is typically as early as possible. This is especially critical when considering the impact that early decisions have on life cycle energy impacts, not to mention social, economic, and cultural outcomes. A plausible and preferred future, therefore, is one where domain experts and superusers leverage collaborative platforms to not only track and communicate decision-making processes and key insights, analyses, and performance metrics, but also seamlessly translate this into comprehensible information for stakeholders. This may enable increased autonomy for stakeholders to make decisions that impact their communities and environments, with immediate access to the information to guide and support their decisions. Rather than relying on the 'black-box' of expertise or software, professional knowledge is demystified and distributed democratically and equitably.

5. Conclusion

The industry is undergoing a significant shift in how it is configured due to internal factors such as the emergence of 'superusers' and computational, combined with external factors such as climate change and increasing complexity of projects and the conditions in which they are delivered. The design studio is a valuable environment for observing the impact that these factors have on design processes. From these pedagogical observations a plausible, possible future-state can be posited considering concepts of transdisciplinarity, demystification, democratisation, and disintermediation. Additionally, others have observed the return to 'the fat middle' as a focus of technological innovation in AEC, and the role in supporting this focus that emerging technology start-ups play. Collaborative platforms play a significant role in enabling these plausible, possible, and preferred futures, acting as key agents of transformation, and providing access to decision-supporting insights that are often the domain of specialists and experts.

It is important to explore these plausible futures and scenarios within a pedagogical framework, as commercial pressures often drive industry to continue to implement entrenched processes. It is often too great a risk to explore new processes, even when the result of such transformative endeavours could radically improve the outcomes and enable new commercial value streams to be discovered. As AEC start-ups continue to emerge and mature, it is imperative that industry understand the impact and opportunities they afford. Furthermore, it must be poised to integrate within existing and emerging ways of working. There is, therefore, a critical imperative to adopt increasingly transdisciplinary approaches, undertaken within the spirit of demystification and democratisation, enabling all stakeholders to exercise a degree of autonomy and contribute effectively to a future that is equitable and sustainable.

Acknowledgements

Thanks to the staff and students at Curtin University School of Design and the Built Environment.

References

Blanco, J. L., Engel, H., Imhorst, F., Ribeirinho, M. J. and Sjodin, E. (2021) *Call for action: Seizing the decarbonization opportunity in construction*, in M. Company (ed.).

Cache, B., Barrett, C. and Johnston, P. (2011) *Projectiles*, Architecture words, ed., Architectural Association, London.

Carpo, M. (ed.) (2013) *The Digital Turn in Architecture: 1992 - 2012*, AD Reader, John Wiley & Sons Ltd, West Sussex, United Kingdom.

Conway, M. (2022) *The Futures Cone*. Available from: <https://foresightpresent.foresightfutures.net/the-futures-cone/> (accessed July 15).

Cutler, T. and Burry, M. (2010) *Designing solutions to wicked problems: a manifesto for transdisciplinary research and design*, ed., RMIT University.

Davis, D. (2021) *CAD's Boring Future and Why it's Exciting*. Available from: <https://www.danieldavis.com/cads-boring-future/> (accessed 15 July).

De Landa, M. (2002) Philosophies of Design: the Case of Modeling Software, in, *Verb Processing*, ACTAR Press, Madrid.

Deutsch, R. (2019) *Superusers Design Technology Specialists and the Future of Practice*, ed., Routledge, New York : Routledge, 2019.

Giraffe (2022). Available from: Giraffe Technology Pty Ltd <https://www.giraffe.build/> (accessed July 15).

Hensel, M. N. F. (2016) The changing shape of practice : integrating research and design in architecture.

Heumann, A. and Mullenix, R. (2014) Digitally designing collaboration. Computational approaches to process, practice, and product., *ACADIA 2014 Design Agency*, edited by D. Gerber, A. Huang and J. Sanchez, USC School of Architecture, Los Angelse, California, 317 - 326.

Hypar. Available from: Hypar Inc. <https://hypar.io/> (accessed July 15).

Laski, J. and Burrows, V. (2017) *From Thousands to Billions - Coordinated Action towards 100% Net Zero Carbon Buildings By 2050*, in W. G. B. Council (ed.), World Green Building Council.

Nicolescu, B. (2002) *Manifesto of Transdisciplinarity*, ed., State University of New York Press, Albany.

Susskind, R. E. and Susskind, D. (2017) *The future of the professions : how technology will transform the work of human experts*, ed.

Talarico, G., da Rocha, D. and Nguyen, D. (2020) *aec.works*. Available from: <https://aec.works/> (accessed July 15).

Evaluating possible options for reusing borer-infested post-demolition timber in New Zealand

Lucia Graham[1] and Dr Emina Kristina Petrović[2]

[1, 2] Victoria University of Wellington, Wellington, New Zealand
grahamlucia7@gmail.com[1], emina.petrovic@vuw.ac.nz[2], ORCID-0000-0003-3446-093X[2]

Abstract: Overconsumption contributes to irreversible environmental damage. The issues arise from resource extraction, processing, and disposal. Therefore, there is an urgency to develop techniques and strategies to keep materials in the loop for longer. Reusing reclaimed building materials could be a pivotal method to reduce overall material waste and decrease the need for new extraction, looking at demolition waste as a potential reservoir for future materials. The specific focus of this paper is the investigation of the opportunities for extending the lifespan of demolition timber. Post-demolition timber is found in a range of different conditions. One consideration is whether the timber infested with wood-boring insects (borer) should be recovered. A sustainable evaluation has been made on the most suitable treatment of borer, considering toxicity and energy involved, and identifying microwaves as an effective solution. Although reusing timber post borer infestation may not apply to an extensive range of situations, this work shows that there are real possibilities for the non-toxic treatment of the issue for in-situ timber. Borer thrives in climates with high levels of humidity, and with climate change, humidity levels in New Zealand are expected to increase, which will lead to an increase in borer. It was found that more work is needed to bring the application of microwave treatment to the mainstream market. The overarching aim of this paper is to stimulate others to explore waste material proactively, as waste material will play a vital role in the sustainable development of the construction industry.

Keywords: C&D Waste, circular economy, reuse, microwaves.

1. Introduction

The construction industry is the most significant worldwide consumer of raw materials (Guerra & Leite, 2021), contributing to about half of all that is extracted from the planet's core. Construction and demolition (C&D) waste dominate 30% of landfills. Demolition waste represents more than 90% of the total C&D waste in landfill, while construction waste represents less than 10% (US EPA, 2016). However, more effort is being made to reduce construction than demolition waste because of the complexities inherent in giving demolition waste another use.

This paper investigates the environmental and social benefits of not dismissing waste material from construction and demolition. The primary focus is on opportunities for the second use of post-demolition

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 294–303.*

timber infested with borer. The paper acknowledges the disadvantages of redirecting borer-infested timber and identifies when it should not be considered for reuse. This research aims to provide insight into non-toxic treatment for borer and identifies that with climate change, humidity levels are increasing, which will lead to an increase in borer in countries with climates similar to that of New Zealand.

2. Methodology

The presented research was carried out in three stages. In the first stage, a review of C&D waste identified five currently overlooked timber waste categories; borer timber, scrap native timber shorter than 0.6 meters, broken timber, weathered timber and contaminated timber (nails, paints and plastics). Timber infested with borer was identified as a particularly challenging material for subsequent uses and therefore was selected as the focus of this research. The second stage of the study investigated through a literature review if genuinely non-toxic solutions were available to eliminate borer. Once it was clear that technology for the non-toxic removal of borer infestation did exist, the third stage investigated potential material applications through design experimentation, arriving at a more detailed understanding of the material's limitations and opportunities.

3. Stage 1: issues with construction and demolition waste

C&D waste has environmental implications when disposed of, including releasing inorganic pollutants and greenhouse gasses. The C&D industry needs a paradigm shift to the circular economy. The current waste pathway tends to be "take-make-dispose", favouring demolition, with waste already normalised as part of C&D costs, which emphasises the cost of labour but only partially captures the costs of natural degradation from the material extraction and disposal. On average, deconstruction is about 17–25% more expensive than demolition and can take 2–10 times longer to complete (Gorgolewski, 2017). However, research has found that revenue generated from deconstruction can reduce overall demolition costs by 10% (Low et al., 2020) as the process achieves an array of co-benefits (Pytel, 2018). Deconstruction is vital for a circular economy. To enable this, designers must design for deconstruction so that future materials can be taken from the current building stock, a concept called Urban Mining (Aldebei & Dombi, 2021).

The waste management hierarchy puts reduction as the top priority for waste minimisation, followed by reuse, recycling, and disposal in landfills (EPA, 2017). Whilst recycling (into new products) is an option for achieving significant diversion from landfills, it fails to provide resources for future construction and does not complete the desired waste management loop. The energy requirements for recycling are often far more significant than for reuse (Low et al., 2020). A large proportion of demolition waste sent to be recycled is being downcycled, crushed, and used as a road base or other low-value solutions (Zhang et al., 2022). The usefulness and value of these materials are therefore decreased. With the depletion of natural resources and the high impact of virgin material, existing building waste could provide much-needed resources back into the industry (Gorgolewski, 2017, pp. 43–44). The reuse of C&D waste faces numerous barriers, including lack of training and education, insufficient logistics, health and safety issues, lack of incentive, existing perception toward reused materials and the lack of a transparent resource market worldwide (Gorgolewski, 2017, p. 43).

Currently, there is more of an explicit effort to design elements so they can be reused. An excellent example is the X-Frame, 'a recoverable and reusable framing system' (XFrame, n.d). However, this is where more innovation is needed to fully explore the possibilities of urban mining (Aldebei & Dombi, 2021). To meet increasingly important carbon targets and other regulative requirements, developing better systems to use the materials extracted through demolition is essential and becomes part of a more sustainable way of engaging with building materials and their lifecycle. Therefore, the focus of this paper is to contribute to efforts to make waste-to-resource innovations that will be used for a long time and can be reused, remanufactured, or recycled — without forgetting the long-term goal of designing out waste from the start (Lysgaard Vind, 2021).

To judge the environmental value of reuse, it is essential to consider whether it is viable to reuse the material or if it would be more energy-efficient to use a new, more sustainable option. In many cases, preservation and conservation save energy by extending its use by taking advantage of the non-recoverable energy embodied in existing materials. Extending the life of materials means less energy used in demolition, less waste to landfill sites, and less energy for manufacturing new materials (Watson, 2016). Embodied energy is increasingly considered part of carbon accounting and efforts to move to zero carbon solutions. Unlike operational energy saving, the effect of embodied carbon is immediate. As operational energy emissions fall, embodied carbon will become the battleground for achieving sustainable development (Watson, 2016).

There is still a sense that cost and economic characteristics dominate many considerations. However, cost should not be the primary consideration for cutting-edge innovative insight; for true innovation to be possible, it is essential to push the envelope. The focus here is on contributing to a better-quality accounting for environmental and social impacts by evaluating if a material commonly seen as waste could become helpful.

A review of C&D waste identified five currently overlooked timber waste categories; borer timber, scrap native timber (smaller than 0.6 meters), broken timber, weathered timber and contaminated timber (nails, paints and plastics). The exploration of timber infested with borer was a particularly challenging material for reuse; therefore, it became the main research focus.

4. Stage 2: Borer and borer-infested timber

Borer-infested timber was identified as one group of C&D waste which is challenging to salvage, which is why it presented an opportunity to explore novel approaches for its potential utilisation. However, before utilising the borer-infested timber, it was deemed essential to establish if there were any genuinely non-toxic solutions to eliminate borer. This section summarises the literature review on existing treatments of borer-infested timber.

4.1. Borer

Wood borer is among the most severe forest pests (Brockerhoff, 2009). Borer is a significant issue in New Zealand's current housing stock. Borer thrives in climates with high humidity levels, and with climate change, humidity levels in New Zealand are expected to increase, which will lead to an increase in borer. For wood-boring insects to become established, there are two factors: a source of infection and a suitable host. Borer commonly attacks untreated and damp timber. There are up to seven species of borer in New Zealand. The common house borer, *Anobium Punctatum*, is the most prevalent, followed by the two-toothed longhorn borer, *Ambeobdontis Tristis*, native to New Zealand. (*Borer and Other Pests*, 2015; Clifton, 1990).

Common house borer females lay up to 100 eggs on bare timber surfaces or in old borer holes. The eggs take 4-5 weeks to hatch, and the larvae bore into the wood, where they stay for four years. They then pupate before leaving the wood, creating holes. The adults are airborne for about a month between

November and March to mate before the cycle starts again. The Two-tooth Borer can remain in the wood for 11 years before exiting in autumn. Although borer has been present in past centuries, they were not dangerous to structural elements. The amount of sapwood used was insignificant. If the borer were to attack elements with small amounts of sapwood on the edges, this would not affect the structural integrity of the components. Depending on the age of the timber, different actions are recommended on whether treatment is needed. No treatment is required for timber that pre-dates 1900 as the borer attack is probably diminishing or extinct. For timber from 1900-1939, treated based on merit, a widespread active infestation may require whole-space treatment, but small attacks could be individually treated. Post-1939 treatment of infestation is usually required (Ridout, 2000, p. 184).

Active wood-borer infestations can be recognised through the presence of sharp-edged holes with the colour of freshly cut timber. If it is a historical infestation, the timber inside the holes is dark, caused by oxidation, and the sharp edges are lost. When there is still doubt about whether the borer is still active, this can be resolved by fastening tissue paper tightly to the surface for flight season. If they are active, they will make holes in the paper (Ridout, 2000). An infestation will decline if the dampness is haltered and the timber remains dry. However, these components may need to be replaced due to structural damage (Ridout, 2000, p. 62).

4.2. Current treatments in New Zealand

There are treatments for borer-infested timber, although it often must be replaced if the timber has been severely weakened. The treatment must last longer than the lifecycle of the borer. The only long-term treatment used in New Zealand is a residual surface application of a product, including insecticides or preservatives. This treatment can only be used on bare timber, meaning that all paints and varnish must be stripped off. Airborne treatments (such as bombs, misting or fogging) will only kill the adults on the wing (November to March) and will not stop the larvae from eating away inside your timber. Furniture can be treated by fumigation or injecting the flight holes. Fumigation is not usually suitable for houses or large areas as the area needs to be completely sealed. Fumigation does not provide residual protection (Borer and Other Pests, 2015).

The treatment of borer using boron-based preservative compounds (Borates) has significant environmental and health advantages over other preservatives, with low mammalian toxicity and low environmental impact (NZFF, n.d.). Spray treatments of preservatives are successful for treating borer. Injection of insecticide into the flight holes is one of the standard treatments. Fogging treatments have been devised to reduce the quantities of preservatives used. Fogs are used where large or inaccessible spaces are treated (Ridout, 2000), although fogging treatments are not 100% effective. Museums have commonly fumigated infested objects with insecticides, which are highly toxic and affect some objects adversely. In recent years fumigation techniques have shifted to using high concentrations of carbon dioxide, which act on the insects' central nervous system. Although research has shown this method is not 100% effective. However, fumigation treatments are commercially available for portable objects (Ridout, 2000, p. 64). Fumigation is not a viable option for large-scale applications, is not 100% effective, can damage objects and uses highly toxic insecticides.

4.3. Toxicity of Current Treatments

Borates are a common chemical in borer treatment methods. Borates are inexpensive and highly effective at fighting both fungal and insect attacks. Data indicates that borates have been proven effective against all known wood-destroying organisms. There are many commercial uses, including water-softening and flame-retardant properties. Leaching is not concerned with borate-treated structural wood as long as the wood is sheltered from rain or sealed against moisture (Hadrup et al., 2021). Water is used to diffuse boron into the timber. However, this is not always appropriate for seasoned timber, where it is not desirable to increase moisture content, such as where dimensional stability is critical and where grain-raising is to be avoided in joinery products (Hadrup et al., 2021).

There has been no evidence so far of the carcinogenicity of boric acid, and the data indicates that boron-containing compounds are not genotoxic (Hadrup et al., 2021). However, Hadrup et al. (2021) found that skin exposure to boric acid can be fatal, and the toxicity effects include abdominal and local effects on the skin. Fatalities from boric acid also have occurred after oral ingestion, and weight loss and reproductive toxicity are common. It is vital to know that inhalation toxicity data are sparse, but one animal study showed reduced fetal weight after inhaling cellulose with a boric acid content of 20%.

The information on the toxicity of borates is reported as 'inconclusive' despite the recognition that the chemical itself is toxic. As with many other substances, the specifiers and consumers must decide if something should be used or avoided based on very partial information. Such patterns tend to reflect the challenges with insufficient evidence to trigger change rather than the absence of issues (Petrović, 2017).

4.4. Non-toxic solutions

Demands for chemical-free and non-insecticidal treatments for insect pests are increasing worldwide as public concern over pesticide treatments has increased (Ridout, 2000, p. 62; Yanagawa et al., 2020).

One solution is deep freezing (-20ºC) of furniture and other artifacts to destroy the infestation. However, this method is not 100% effective. The items with borer should be kept at room temperature before treatment to keep the insects active. Heating timber will also eventually kill the wood-boring insects. However, the timber may shrink and crack. This issue has been overcome for the treatment of furniture and small artifact, "a process which slowly raises the temperature to 55ºC and then lowers it again over an 18-hour cycle while maintaining a constant humidity" (Ridout, 2000, p. 64). Ridout (2000) suggests that this method is currently being adapted for use on timber buildings. However, as of 2022, there is a lack of data to judge the process in the building context. The applicability of these treatments is complex as heating must be slow and very controlled.

Both freezing and heating treatments have real disadvantages in that they require a considerable period and consequently present genuine energy demand for these treatments. They also require large enough enclosures to contain the treated objects, which can severely limit what can be effectively treated compared to the building size.

This review of the borer treatments of timber currently available in New Zealand shows that none is straightforward and without some disadvantages. Therefore, it is helpful to consider if there are any alternative approaches available internationally.

4.5. Emerging potential for microwave remedial treatment

In the last decade, a new area of consideration has emerged: microwaves as a remedial treatment for wood-boring insects. Although this treatment is not as yet commercially available, nor as yet available in New Zealand, it is showing real promise, and three studies experimented with devices outside a laboratory environment (Lluch et al., 2013; Novotny et al., 2013; Patrascu et al., 2017). Other studies investigate the biology of how the microwave works (Krajewski, 2017; Thasangkha et al., 2020; Yanagawa et al., 2020).

The first significant study of the use of microwaves to treat wood-boring insects was published in Spain in 2013. The case study was conducted on an Art Nouveau residential building erected at the beginning of the 20th century in Valencia. The timber structure was affected by both borer and termites. The researchers created a specific microwave system to use on-site, *The Dryparasite System*, which generates microwaves with a frequency of 2.45 GHz. This system works by heating the humidity inside the insect. Using microwaves, 100% efficacy is achieved in eliminating the insects (Lluch et al., 2013; Novotny et al., 2013). Microwave radiation is advantageous as it can get to less accessible locations. All studies observed that no damage was caused to the wood or the finish of the works of art, including pigments, polishes, and stains. In 2017 Romanian researchers developed *Microwood 12* to study microwave treatment for pest control in wooden objects. The equipment presented in the studies is based on an open horn for the irradiation, although this is somewhat complicated to use – the operator needs to take some precautions when using it – the operator's safety and interference with electronics. It is not recommended to experiment with this application unless the microwaves can be safely contained. Due to these issues, the devices have not been commercialised. Nevertheless, this could be an area where with additional technological development, non-toxic solutions could be achieved for borer treatment of timber, expanding the lifespan of timber.

As this review shows, microwave treatment presents a real opportunity for entirely non-toxic treatment of borer-infested timber. This finding is used as a basis for the design experimentation work in Stage 3.

5. Stage 3: Design experimentation

Once it was established that a truly non-toxic treatment of borer infestation is possible, explorations were undertaken to evaluate how to reuse or recycle post-deconstruction borer-infested timber effectively. Early investigations showed that borer-infested timber performed differently depending on the level of present infestation. Therefore, investigations were grouped based on mildly and highly infested timber.

5.1. Mildly infested timber

The experiments found that it was easy to work with very mildly infested wood (Figures 1 A&B) and that there is a real potential to extend its life effectively, but also to use the existing borer holes as functionally useful.

Figure 40: A) Section through timber post infestation. B) Mild timber infestation. (Source: Graham, 2022)

These findings developed a conceptual design to visualise the material as acoustic panelling (Figure 2). In these examples, the perforations due to the borer would enhance the acoustic performance, while the aesthetic celebrating the holes can be seen as reflective of some existing artworks. A similar approach was used by Zac Langdon-Pole, a New Zealand artist whose work often has levels of meaning, concrete and abstract, literal and symbolic, which coexist, often in tension (Leonard, n.d.). Langdon-Poles' 'Punctatum' series explores timber artifacts infested with borer, filling the holes with gold. The technique used to fill the holes with gold echo's the Japanese technique of Kintsugi or 'golden repair'. Kintsugi treats breakage and repair as part of the history of an object rather than something to disguise. (Leonard, n.d.). When observing the objects and the beauty that has come from filling the holes with gold, it is fascinating how the tiniest hole in a piece of wood could cause the furniture to lose value entirely. Langdon-Poles' work is an exciting example of giving value back to something that would otherwise be considered waste and, in some cases, cause people to be disgusted. However, from the perspective of effective reuse of timber, introducing gold would not help the natural decomposition of the material, and therefore applications were sought without introducing additional materials.

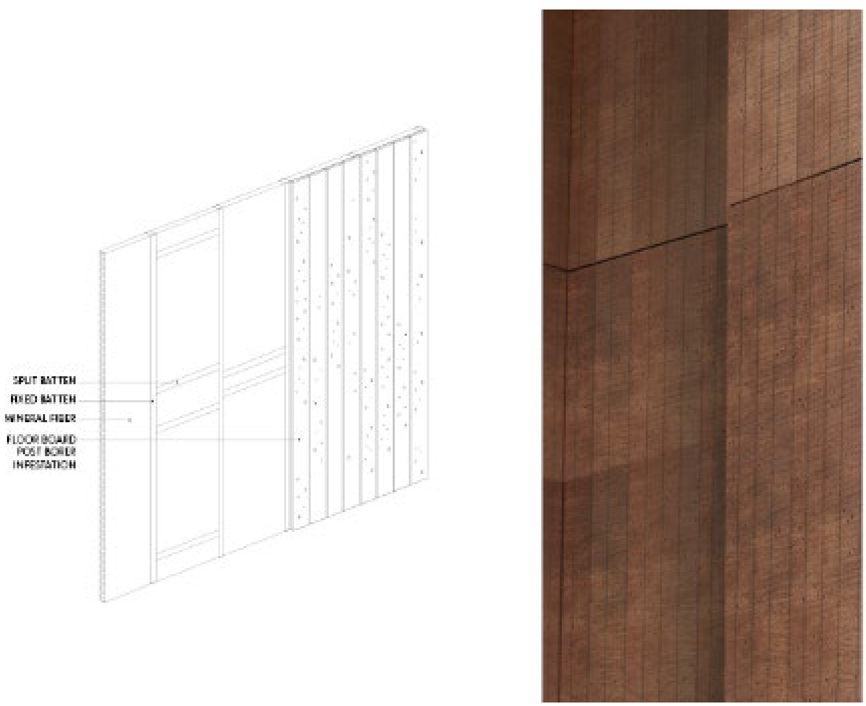


Figure 2: Conceptual application of reused borer timber as acoustic panels. (Source: Graham, 2022)

Because borer-infested timber can be seen as a 'waste in transit' towards decomposition, reasonably transient applications were considered particularly beneficial, and the interior fit-outs provide such opportunities. Building on the concept from Figure 2, a further concept was developed (Figure 3), visualising how this material could be applied to add visual value and improve the acoustic performance of an interior. The material has a brittleness, purposely designed not to be durable.

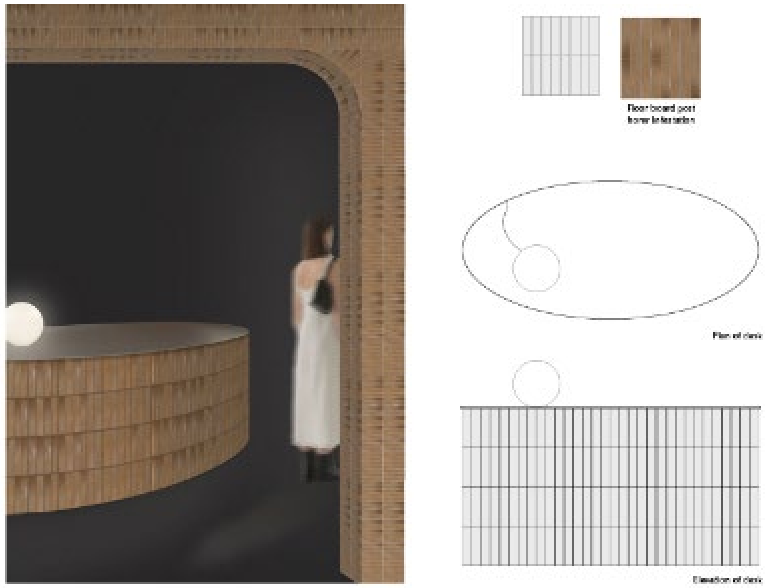


Figure 3: Conceptual application of reused borer timber as a retail desk. (Source: Graham, 2022)

5.2. Highly infested timber

On the other hand, very infested timber was challenging to work with, and in some cases, it even fell apart into dust (Figure 4A). In such cases, only the timber dust could be used in a reconstituted form, which would require binding agents, such as glues, and accepting the disappearance of the structural integrity of the timber itself. Timber with a high level of infestation but still retaining its structural integrity appears to have offered interesting aesthetic qualities (Figure 4B) due to the infestation, which could help us develop a novel understanding and appreciation for a natural, non-human ecological system capable of creating beauty through the synergies of the timber fibre structure and borer hole structure. These aesthetic qualities are seen in the art explorations that explored the subject of borer-infested timber aesthetics and their meaning. The challenge with using timber with high infestation levels is that the structural integrity is so low that resin or glue would be needed to become a useful material. This then would become waste in transit, meaning the biodegradability of the original material is lost, causing the reuse to be unsustainable.

Figure 4: A) Wood dust. B) Aesthetic qualities of borer infestations. (Source: Graham, 2022)

6. Discussion: key findings

This research investigated limitations for the possible reuse of a range of demolition timber conditions and found that borer-infested timber presented real challenges and was often overlooked. Through this research, many of the challenges observed by others were repeated. Issues with working with infested timber and sourcing non-toxic treatments are real and re-emerged as this work progressed. Issues with the structural weakness of the more infested timber are equally real and limit the possible applications.

However, these experiments show that for milder levels of borer infestation post-demolition timber, the microwave treatment could offer new opportunities for effective reuse as the timber can provide natural aesthetic qualities for short-term application. One significant limitation is that reusing timber infested with wood-boring insects may not apply to an extensive range of situations, especially if structural properties are needed. However, interior fit-outs present excellent opportunities for non-structural applications of the mildly borer-infested timber, which would also greatly support efforts towards carbon-neutral working methods. As the experiments in Figures 2 and 3 show, the borer holes can be used to provide additional advantages in this case for acoustic performance.

Therefore, this work shows that even when one of the most limited waste materials is carefully considered, additional applications can be identified. Further research would be needed before this becomes commercially viable, but the potential is evident.

7. Conclusion

This work shows practical ways to consider reusing waste material, generally seen as demolition. The research summarised an emerging area of research into the treatment of borer using microwaves, as accepting borates-based treatments are safe is not the most sustainable approach. The research found that microwave treatment could be helpful in forestry wood attacks by wood-boring insects. More work is needed on using the most effective technologies, such as microwaves, for borer treatment.

Although reusing timber infested with wood-boring insects may not apply to an extensive range of situations, a range of design experiments were undertaken to show the potential for reusing borer-infested timber in transient interior fit-outs. This is especially the case for milder infestations.

This paper aimed to stimulate others to explore waste material proactively. Many of the materials we are currently disposing of have a life that can be extended further. Sustainable design should explore material reuse, and the production of artefacts should be based on cyclical resource use.

References

Aldebei, F., & Dombi, M. (2021). Mining the Built Environment: Telling the Story of Urban Mining. *Buildings*, *11*(9), 388. https://doi.org/10.3390/buildings11090388

Borer and other pests. (2015, March 15). Consumer NZ. https://www.consumer.org.nz/articles/interior-maintenance-borer-and-other-pests

Brockerhoff, E. G. (2009). Wood Borer and Bark Beetle Risk Analysis. *SCION Next Generation Biomaterials*, 27.

Clifton, N. (1990). *New Zealand Timbers. The complete guide to exotic and indigenous woods.* GP Publications.

EPA, N. (2017). *Waste Hierarchy*. NSW Environment Protection Authority. https://www.epa.nsw.gov.au/your-environment/recycling-and-reuse/warr-strategy/the-waste-hierarchy

Gorgolewski, M. (2017). *Resource salvation: The architecture of reuse* (1st ed.). Newark: Wiley-Blackwell.

Guerra, B. C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resources, Conservation and Recycling*, *170*, 105617. https://doi.org/10.1016/j.resconrec.2021.105617

Hadrup, N., Frederiksen, M., & Sharma, A. K. (2021). Toxicity of boric acid, borax and other boron containing compounds: A review. *Regulatory Toxicology and Pharmacology*, *121*, 104873. https://doi.org/10.1016/j.yrtph.2021.104873

Krajewski, A. (2017). Wood-Boring Insect Control in Constructions by High Temperature and Microwaves. In *Wood in Civil Engineering*. IntechOpen. https://doi.org/10.5772/66094

Leonard, R. (n.d.). *Introducing Zac Langdon-Pole*. City Gallery Wellington. https://citygallery.org.nz/blog/introducing-zac-langdon-pole/

Lluch, A. M., Vegas López-Manzanares, F., Mileto, C., & Diodato, M. (2013). Microwaves as a Remedial Treatment of Wood. *Advanced Materials Research*, *778*, 620–627. https://doi.org/10.4028/www.scientific.net/AMR.778.620

Lysgaard Vind, D. (2021, July 16). *Designing for the circular economy—The Danish way*. Ellen Macarthur Foundation. https://ellenmacarthurfoundation.org/articles/designing-for-the-circular-economy-the-danish-way

Novotny, M., Skramlik, J., Suhajda, K., & Tichomirov, V. (2013). Sterilisation of Biotic Pests by Microwave Radiation. *Procedia Engineering*, *57*, 1094–1099. https://doi.org/10.1016/j.proeng.2013.04.138

NZFF. (n.d.). *NZ Farm Forestry—Pinhole borers, native*. Retrieved April 26, 2022, from https://www.nzffa.org.nz/farm-forestry-model/the-essentials/forest-health-pests-and-diseases/Pests/Platypus/pinhole-borers-native/

Patrascu, M., Radoiu, M., & Pruna, M. (2017). Microwave Treatment for Pest Control: Coleoptera Insects in Wooden Objects. Studies in Conservation, 1–8. https://doi.org/10.1080/00393630.2017.1298305

Pytel, E. (2018). Deconstruction & Building Material Reuse: A tool for local governments and economic development practitioners. Delta Institute.

Ridout, B. (2000). Timber Decay in Buildings. The conservation approach to treatment. E & FN Spon.

Thasangkha, P., Thodsdeekorapat, T., Thongsopa, C., & Kotchpradit, S. (2020). Exterminate Borer Worm by High-Frequency Electromagnetic Wave. 2020 IEEE 7th International Conference on Industrial Engineering and Applications (ICIEA), 662–666. https://doi.org/10.1109/ICIEA49774.2020.9101945

US EPA, O. (2016, March 8). Sustainable Management of Construction and Demolition Materials [Overviews and Factsheets]. https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials

Watson, M. (2016). Adaptive re-use and embodied energy. In Industrial Heritage Re-tooled: The TICCIH Guide to Industrial Heritage Conservation (pp. 136–141). Routledge.

XFrame. (n.d). XFrame. XFrame. https://xframe.com.au

Yanagawa, A., Kajiwara, A., Nakajima, H., Desmond-Le Quéméner, E., Steyer, J.-P., Lewis, V., & Mitani, T. (2020). Physical assessments of termites (Termitidae) under 2.45 GHz microwave irradiation. Scientific Reports, 10(1), 5197. https://doi.org/10.1038/s41598-020-61902-6

Extending the life: Deep energy retrofit analysis for classroom blocks in New Zealand

Ruby Crooks[1], Robyn Phipps[2], Wallace Enegbuma[3,] and Tayla Lindsay[4]

[1,2,3,4] *Victoria University of Wellington, Wellington, New Zealand*
crooksruby@myvuw.ac.nz[1], {robyn.phipps[2], wallace.enegbuma[3]}@vuw.ac.nz, taylalindsay@gmail.com[4]
ORCID-0000-0001-7273-2479[1], ORCID-0000-0003-2810-7662[2], ORCID-0000-0002-2455-4759[3]

Abstract: The New Zealand Ministry of Education owns 33,000 classrooms, many of which possess low levels of insulation and depend on openable windows for ventilation. Extending the life of existing buildings reduces the number of buildings that end up in landfills and the embodied carbon embodied in the construction of a replacement classroom. The aim of this review is to explore potential retrofit measures towards improving sustainable practices in external classroom block façade and invariably improve indoor quality for children occupying the classroom block. This study adopts a comprehensive literature review of deep energy retrofits of classrooms. The exclusion and inclusion criteria involved the use of keywords such as retrofit, energy savings, education, and lifecycle analysis. A total of 50 articles were reviewed which had a direct impact on extending the life of classroom blocks. The analysis revealed that the current pressure to plan for New Zealand's carbon targets requires a change in design thinking. This change can be provided through the retrofit of existing buildings to extend the life cycle. This will enable buildings that are present to reduce the adverse environmental impacts that they are presenting and will concurrently improve the functional ability of our domestic environment. This simultaneously provides a resource that nurtures the child whilst creating a design that will aid in meeting UN Sustainable Development Goals and will benefit future generations of children. Future research would investigate standardisation of retrofit guidelines for New Zealand classroom blocks.

Keywords: Retrofit; Education; Sustainability; Carbon Impact.

1. Introduction

There is a need to restore and utilise the architecture that is already present within our environments. Where possible extending the life of a structure whilst saving the embodied carbon required of a new build, and the incurring waste of demolition can be offered. Of the 2,100 School blocks across the Ministry of Education's portfolio, over 30 of those are existing Nelson Blocks (Ministry of Education, 2022). During the 1960s the Ministry of Education constructed a lot of schools using a limited number of standardised plans. One design that has been reproduced in all areas of NZ is called the Nelson Block (Ministry of Education, 2013). The form of the Nelson Block is an H shape plan layout with variations of the form.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 304–316.*

These blocks were built across the country with little variation despite changes in climatic region. The Nelson block is constructed with raised timber piles, timber framed walls and roof structure, single glazed joinery, and timber weatherboards. The superstructure is usually very solid but lacks any wall insulation. Roof insulation has often been added but to a low R value. The structure leaves a large area for improvement and within this review, insight can be made into what systems and alterations can be made as a solution.

As we live in an environment where the architecture and construction sector define the prospect and future for a city, it is imperative that make the shift towards sustainable practices to provide for future generations. Deep energy retrofits offer an opportunity to utilise existing resources within our educational facilities and government portfolios to integrate this architecture. A deep energy retrofit enables a structure previously in disrepair or tired an opportunity to utilise innovative technologies for vast energy savings of the architecture. Deep energy retrofits not only provide substantial energy savings but allow an opportunity to forming suitable comfort conditions for the benefit of students and teachers within educational sectors (Reiss, 2014).

Educational facilities are often sites in need of refurbishment due to their large footprint, heavy usage, and evolving requirements towards their facility (Park et al., 2021). The modernisation and repair of these buildings allows an opportunity to restore heritage to a site while providing a carbon focus for the benefit of the environment. The prospect of altering and upgrading these common type schools allows for a life cycle improvement and ensures the stylised architecture has an opportunity to be valued beyond its anticipated lifetime. In identifying the boundaries and opportunities of standardised forms of educational architecture, a solution can be formed in addressing the sustainability and carbon impact of these spaces. Currently, poor classroom design and ventilation can lead to mental health effects, illnesses, asthma-related health outcomes, fatigue and lack of productive learning due to these environments (Bluyssen, 2013).

Hence, the aim of this review is to explore potential retrofit measures towards improving sustainable practices in external classroom block façade and invariably improve indoor quality for children occupying the classroom block. The North and South perspective of the Nelson School Block is shown in Figure 1(a) and (b). To achieve this study aim, a case study analysis with a simultaneous literature review of recent studies on retrofit and extension of life of classroom blocks was adopted. Subsequently, a design solution of proposed retrofit system was simulated with key environmental criteria.

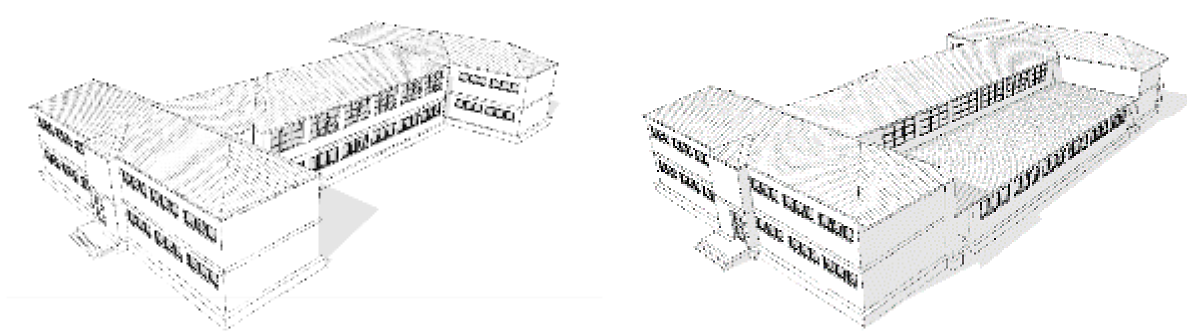


Figure 1(a) and (b): Nelson Block North and South Perspectives

2. Literature Review

2.1. Existing Literature

Literature on energy efficiency is vast and broad. The discourse spans a large network of ideas and themes that relate directly to the sustainability of architecture and of how buildings can prosper to be more efficient. This topic can be associated towards a variety of aspects, however the topic of deep energy retrofit narrows the scope and literature into a genre which can be determined through specific internal and external qualities. The idea of a deep energy retrofit reflects the theme of flexibility and the opportunity to provide and transform a space to the character that the site itself presents. This research aims to provide a base that can be utilised towards the broader field of Nelson Block Designs spanning across New Zealand. Existing literature that reflects the integrity of this research can be seen through key authors such as Bob Lloyd (2006), Yu Wang (2020) and Alexander Zhivov (2017). Their work highlights a previous integration for process and innovation into design for achievable and sustainable energy standards. Their research identified the potential for refurbishing and retaining older buildings with an efficient longer life. The central question is how can older low-rise buildings be made viable for the future through being retrofitted with a low energy design system.

The previous study provides a body of work that identifies the positive role of investigating ventilation in schools and the capacity that retrofitting systems in schools provides to the CO2 levels for the wellbeing of students (Wang, 2020). It is worth noting that CO2 is crude proxy for the occupancy and ventilation rate and sufficient air changes per hour is the ideal measure. This directly highlights the importance of a healthy internal environment and in result correlates to the opportunity of reinvigorating these existing forms of architecture to provide better facilities to the user. Lloyd (2006) presents key precedents in identifying the gaps in current architecture throughout New Zealand and how a variety of systems impact the energy standards of the buildings. His work looks closely at New Zealand case studies and how these effects are felt across New Zealand's contrasting climate conditions. Discourse highlights how important it is to utilise productive systems within a retrofit and of how the quality of the product results in a direct impact to the energy saving potential.

Zhivov et al's (2017) range of work looks specifically at the success and results of retrofitted case studies around the world and identifies key technologies that when applied together will reduce a buildings energy by 50%. He provides a guide to achieving large energy reductions and indicates the best achieved strategies to attaining a lower energy space. His broad range of work identifies successful bundle systems for how to retrofit major building renovation and of how to achieve a significant energy improvement. These previous studies all examined case studies where alternating systems can be implemented and allow insight to be made to the success and or failures of how high-performing systems can be applied to architecture within a variety of climates.

2.2. Standardised Blocks

The standardisation of educational facilities is a component to consider within the research of this paper. Designing quality learning spaces is a reference guideline from the Ministry of Education for how their portfolio of buildings can be enhanced to bring the learning spaces closer to the ministry's recommendations. The assumption within this is that the existing natural ventilation and lighting of these spaces is to an adequate level, however this will be a factor that is reconsidered within this research in order to bring the standard of thermal comfort and ventilation to an improved standard– especially in a post-pandemic learning environment (Ministry of Education, 2016).

The Nelson Two Storey Block is the standardised structure from the Ministry of Education that will be investigated within this paper as shown in Figure 2. This style of architecture was designed within the 1960's before the introduction of seismic requirements and is based on an H shaped plan layout. The design of each school varies in structure and form, however they all retain similar properties with lightweight timber framing and roofs. The blocks often consist of high windows roughly of a 1m x 3m stretching along the extended bays and contain the equivalent of six classrooms to each floor as seen in the figure below (Ministry of Education, 2022).

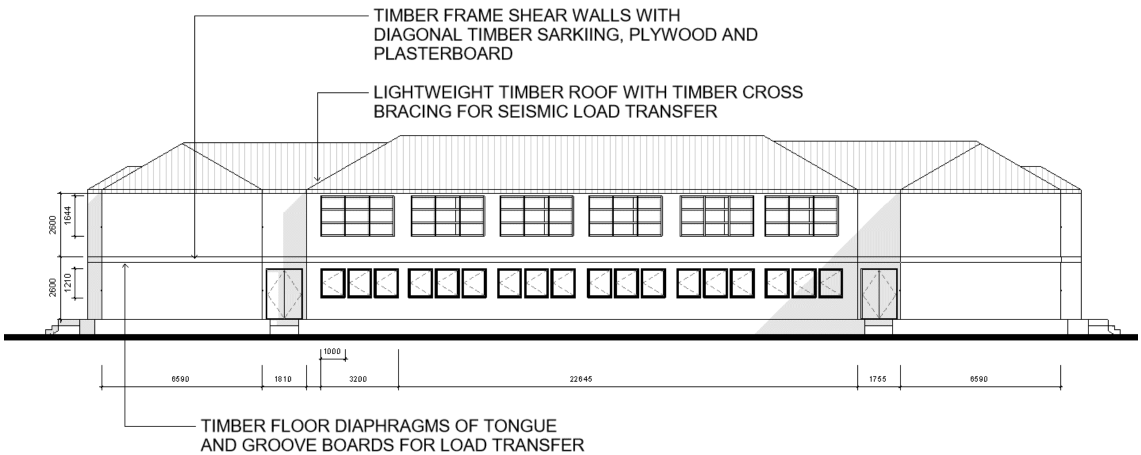


Figure 2: Nelson Block North Elevation

The Nelson block is a standardised form spanning across the country in various school portfolios. The design of the standard block provides an opportunity for a retrofit to best utilise the historic properties and style of the original site to be regenerated for use into the future. In consideration of the current design options available through the Nelson Design Features report there is a large scope in improving the thermal and energy performance that are not addressed (Ministry of Education & Aurecon New Zealand Limited, 2016). This therefore presents opportunity towards retrofitting the external structure. The lightweight structure provides a base for a successful deep energy retrofit and offers vast possibilities to not only the layout for internal spaces but the potential for an energy efficient and sustainable space to be created.

2.3. Energy in a retrofit

Energy and the improvement of sustainable practices within this paper will be a change that will happen out of necessity rather than opportunity. The foundation for this research is to aid in providing a regeneration towards the architecture of the educational sector and cited within that is the need to respond to the significant impact that results from past building stock (Zhivov & Lohse, 2017). Architecture and construction contribute towards the largest energy sector in the world. In the case where one-third of total building energy use is imputable to existing buildings it proves the necessity to provide action with the combination of existing buildings and energy use (Rabani et al., 2017).

The concept of retrofitting within this research will aid in reducing the environmental impact of these existing buildings. This will be achieved through optimising the constraints of least cost investments, greatest energy savings and the reduction of carbon emissions (Başarır et al., 2012, Rabani et al., 2017). Retrofitting a school environment is a critical aspect to recognise not only due to the large energy consumption caused by the high-performance builds but also due to the fast evolution and need for alteration to teaching and learning environments (Thi Hoai Le et al., 2021). Retrofitting provides a means to preserving the superstructure which avoids the increase of embodied carbon of a new build. It provides the ability to retain established architecture for the next generation and ensures an efficient design can take precedent towards new and developing school programs (Moazzen et al., 2020).

When considering the implications and advantages between choosing to retrofit an existing building compared to demolishing and rebuilding the structure, the potential to provide an 80% energy saving using passive systems must be considered (Moazzen et al., 2020). This increase in potential energy savings results in the architecture being advantageous and invaluable to salvage and allows the structure to be modified to achieve an ideal thermal comfort. The approach to managing the energy efficiency of an existing architecture can provide a logical approach to a passive and renewable integration towards architecture and ensures the potential to have net zero emissions by 2050 as required by the New Zealand Climate Change Response Act (2019).

Heating and cooling were the focus of this research as they make the most effective shift towards a deep energy retrofit. By improving the envelope of the building and the heating and cooling practices, an incremental change will occur within the space to the benefit of its thermal performance. Schools in New Zealand are an obvious type of building for optimising solar energy as they are typically operated between the hours of 9:00 AM to 3:00 PM which coincides with the hours of highest solar radiation levels. Retrofitted solar systems can include photovoltaic panels for converting solar energy to electricity, which in turn can be used for operation of a heat pump, or solar thermal systems for the conversion of solar radiation to heated air. Solar Air Heaters (SAH) are a a relatively easy system to retrofit on low rise buildings and effective for heating an internal environment. Their system is employed to gain useful heat energy from solar radiation in order to heat a space. Their benefits range from the natural resource that is utilised to retain the heat (Preda, 2017; Wang 2020).

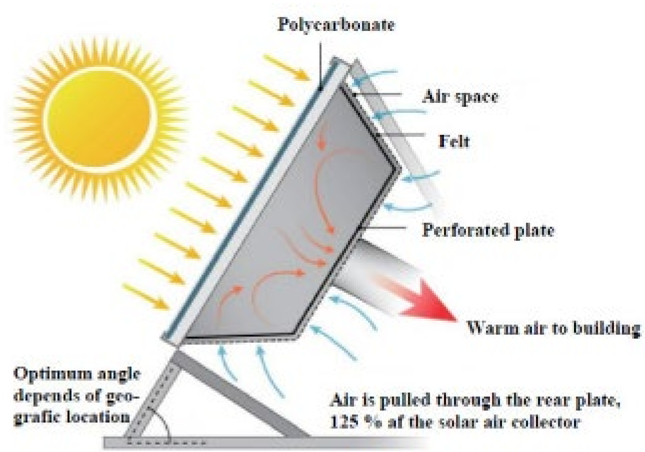


Figure 3: Solar Ventilations in Schools (SolarVenti Australia, 2022)

In the previously mentioned study by Wang (2020), it was found that classrooms fitted with a solar air heater had better indoor air quality, warmer and drier air then matched adjacent classrooms and used their existing heat pumps $2^1/_2$ times less. The integration of alternative forms of space heating and cooling within the building sector is of high importance especially when considering the vast effects of global warming. The ability to utilise systems that are reliant on natural resources is an opportunity that needs to be utilised. Solar energy provides the potential to fulfil the energy requirements of a space and when considering the efficiency of the system it offers the solution to be carried out across these standardised blocks (Audu et al., 2021)

2.4. Influence of Daylighting

Daylighting is a key concept to identify when considering the retrofit of a New Zealand school. The importance and influence that daylighting can make to an educational environment is critical towards the performance of a student. When looking at the energy savings that can be utilised by advocating for proper daylighting tools within architecture, a significant impact can be made through the reduced need for not only electric light, but cooling needs too (Heschong et al, 2002).

Daylighting is an important criterion to acknowledge as the sunlight determines and further influences comfort levels of the internal environment and therefore the energy consumption of the architecture (Li et al., 2021). Utilising the daylighting principles will allow the majority of building stock to be upgraded to satisfy present day green building standards. They present an opportunity to contribute to the building sector for years to come and when effectively retrofitted, the design measures taken to achieve the quality standard will positively impact the chosen architecture (Li et al., 2021).

Prevalent to the influence of increased daylighting, the opposition to window size and artificial lighting is also a pertinent topic. The period of the chosen Nelson Blocks as described within this review identifies the late 1960’s and 70’s as being the key time of construction. As transcribed within a review of the development of daylighting in schools, during this period, large windows and daylighting influence were negated in exchange for fluorescent lighting and small windows to mitigate screen glare and reflectivity (Barch et al., 2003). This change in schooling design resulted in the preference for air-conditioning units due to the lack of daylighting and sunlight which directly impacted on the performance and focus of the student’s health (Barch et al., 2003).

Daylighting is a critical factor to consider when informing the retrofit of an educational space. Not only for the positive impact it can make towards the student’s performance but also for the benefits that incur from a renewable and efficient source of heating and cooling. Daylighting is an imperative tool to utilise within a deep energy retrofit. Within the building sector electric lighting design can contribute towards 40% of annual building energy consumption, especially in a commercial build such as a school (Wong, 2017). The replacement, where possible, of artificial light is the most direct and efficient way of approaching daylighting in terms of passive solar energy design. Successful treatment of this system and strategy can heavily supplement the building energy consumption and can allow an improvement in the buildings performance standard.

Although daylighting systems provides a vast number of advantages towards a site, there is the necessity for balance in ensuring glare, overheating and thermal discomfort to occupants is avoided. This can be achieved through a variety of daylighting systems such as overhangs, light shelves, louvres, sun tunnels, blinds, screens, and light filters (Littlefair, 1990). Strategies that will be identified as potential proposals towards this retrofit are influenced through innovative systems that will aid in conserving energy and enhancing the building user's environment.

In retrofitting the Nelson Block design, the key focus within identifying the daylighting system will be in how the selected system can significantly reduce lighting and cooling loads for the performance of the space. Without the opportunity of a new build to alter the orientation of the site, it is imperative that the strategy will provide optimal natural daylighting into the given space and will ensure applicability of the system for the entire site (Kim & Kim, 2010, p. 256). The potential that daylighting provides towards any environment in reducing the energy consumption by artificial light is considerable (Onubogu et al., 2021). In a space that does not require evening illuminance, like the Nelson Blocks, an opportunity is provided to utilise natural systems in an attempt to aid in the United Nations sustainable development goals.

2.5. Façade Treatment and Glazing

The implementation for systems towards this retrofit span a large network of tools and considerations. For this purpose, it is necessary to limit the scope towards which systems will be addressed within the research. Windows are a wound on the thermal envelope of a building allowing up to 50% of a buildings heat to escape under single glazed environments (BRANZ & Burgess, 2008). Given the low thermal performance that single glazed windows offer, they are an obvious building element to upgrade to increase the thermal performance. Glazing and façade replacement is an initial system within the scope that will be addressed.

Façade treatment and the replacement of their design provides a key influence towards architecture. The façade acts as a barrier and system that is the initial treatment before mechanical air and ventilation come into play. Façade design within the 1960's was inefficient and acted as a major source of energy and heat loss within the architecture. The ability for this system to be replaced in order to maximise and control internal comfort is an opportunity to be utilised (Martinez & Carlson, 2014)

The importance of identifying and replacing the façade within this deep energy retrofit is due to the opportunity to utilise higher performing products and materials that will ensure an improvement in energy performance and future needs of the site. Within the changing environmental conditions and strategies for building development, façade technology can aid in providing the performance goals that existing and future buildings will be required to meet (Martinez et al., 2015).

Façade treatments are an integral factor to consider due to the ability to reduce energy consumption of a building that was designed when energy considerations were not of a high importance. The building envelope holds potential for innovation and refurbishment through the ability to utilise the system of the façade, and the sub-structure of the framing and panels (Brown & de Wilde, 2012). This replacement can accommodate for a savings of over 50% in energy reduction compared to a pre-retrofit condition when addressed within the deep energy retrofit system (Martinez & Choi, 2018).

2.6. Impacts of Ventilation on a Retrofit Space

New Zealand schools have a large opportunity to provide a comfortable and enjoyable environment for the wellbeing of students while gaining the potential to create a sustainable and regenerative retrofit prospect. The ventilation and indoor air quality of these spaces is an area that can be of great use towards altering the energy efficiency of the architecture. New Zealand classrooms often have low ventilation rates, and high carbon dioxide levels particularly within the winter months (Wang, 2020). This is especially important to acknowledge in light of COVID and the influence of air concentrations for student health.

The importance of acknowledging the ventilation and air quality within an educational environment is also of particular interest where the energy required to heat and cool a space will be impacted with the fluctuation of higher ventilation rates (Fisk, 2017).

Ventilation in classrooms is an everchanging practice where adjustments in efficiency and airtightness are constantly changing. Forming a response to a retrofit concept that allows for alteration and or change to the practice will be necessary. Providing the space with a system that delivers an increase in ventilation and decrease of indoor pollutants (Allen et al., 2016). Recent Studies done by the Ministry of Education investigated experiments for how new systems can be effective on poorly ventilated indoor environments. The study identified CO_2 levels within control rooms across a variety of test scenarios which looked at the differing systems of solar air heaters, natural ventilation versus augmented ventilation fans, air cleaners and temperature differential of window openings (Ackley & Phipps, 2022a; Phipps, 2017).

As the study was conducted within a light timber framed classroom with both high and low windows, it is viable to form a close comparison to that of the Nelson Block design. The systems utilised within one of these studies resulted in the findings that natural ventilation can provide the required Air Changes per Hour (ACH) for good ventilation assuming the openings are maintained at 2 m2. Using Augmented systems such as HEPA filter air cleaners can be supplemented when the 2m2 of openings becomes impractical due to weather conditions or thermal discomfort (Ackley & Phipps, 2022b).

A study towards this paper was completed on the Nelson Block design where a simulation model was developed using EnergyPlus, Radiance, and Insul software. This research was completed as an investigation towards how the existing Nelson Block performs in its current state and how implementing new systems can form a positive response towards the results of internal comfort and efficiency.

The design changes carried out for thermal performance included increasing the insulation and shading. For ventilation, an HVAC system was incorporated alongside increased window openings. In terms of daylighting, shading, changes to wall to window ratio (WWR), light shelves, and different glazing properties have been included. For acoustics, acoustic insulation and materials have been added, as well as removing building leakages. From this, results are gained for the performance of design recommendations for the Nelson Block. In order to work towards the goals of a zero-carbon operational building and optimum performance and wellbeing of school building occupants, the priorities for design changes are increasing WWR for passive heating and greater levels of daylighting, adding insulation (plus double glazing) for thermal performance and acoustic performance, and increasing the window openings for appropriate ACH and passive cooling. These design changes are the priorities because they address multiple design parameters in one, whilst fitting within the scope of works proposed by the Ministry of Education.

2.7. User Comfort

The fundamental part of this research will be influenced using energy modelling and simulation of an internal space. As the results that will occur from this modelling will inform the majority of work that is resolved, it is essential to consider the implications of user experience on a space outside of a simulated environment.

The considerations to a student's environment are critical when identifying how a deep energy retrofit can benefit a child's experience in a school. As students spend the majority of their educational time indoors it is crucial to ensure the classroom is ventilated and sitting at a comfortable level, which is where the modelling can be utilised as a tool (Domínguez-Amarillo et al., 2020).

With the steady increase in temperatures and the impact of climate change, it is essential to consider the internal comfort of the students in order to ensure their performance, health, cognitive processing, and engagement are a priority (Domínguez-Amarillo et al., 2020).

When positioned in a space that does not suit the comfort parameters that allow a student to perform, a loss of control and management are at the forefront (Majd et al., 2019). Indoor performance plays a crucial role in the experience of a child's education, therefore through utilising the tools available with simulation-based results, a result that ensures the highest internal comfort level can be reached.

2.8. Sustainable Implications

Benefits towards utilising this idea of a deep energy retrofit instead of a rebuild is dependent on the potential of retaining the sub-structure of a build. Within the process of demolishing a build, the waste accrued increases the embodied carbon emissions of the site through the process of deconstruction, removal, and disposal means of the materials. The carbon footprint of the building is increased and the potential for the building to be of a circular approach is diminished. This is where the deep energy retrofit comes most into play. When retrofitting a build, the substructure and therefore the highest carbon producers of the build remain intact; therefore, retaining and reducing the carbon footprint of the building when compared to a site which is demolished and replaced.

The highest embodied carbon is produced through the demolition of substructures of beams, columns and slabs at a rate of 46%, and the greatest embodied energy comes through the mechanical, electrical and plumbing services at 58% (Gonzalez et al., 2021). When architecture presents itself with the opportunity to retain these key contributors, it has to be undertaken in order to aid the efforts towards a zero-carbon future.

Waste is a factor often overlooked in its implication to the environment. The vast number of metals, oils, scraps, and plastic that are in our environment once their product life is classified as over is immense. The opportunity to recycle and avoid the environmental hazard that comes with this end of life is prominent – especially within the building and construction industry. Within this project comes to opportunity to recognise the waste accumulated by this industry and to provide an opportunity to recycle and reuse. Product life cycle assessment will aid in forecasting the impact of the selected materials and will ensure the potential to design for disassembly (DFD) in order to aid and facilitate further recycling at the end of the building's life cycle (Gonzalez et al., 2021).

3. Research Design and Methodology

The Methodology behind this project begins with research about design to inform current practices with the New Zealand context of education and the limitations that a retrofitted form will produce. It will prospect into case study analysis with a simultaneous literature review to examine the dimensions extended by this study (Ackley & Phipps, 2022a; Phipps, 2017).

Research led design will lead the secondary part of the research where the design of the retrofit system through simulation of key environments and a series of phases in connection with this research will ensue. Researching through design will form the foundation for this research where in concluding on the specified systems, a design will be ascertained (Groat & Wang, 2013).

A key focus on the improvement of current practices regarding re-design within the educational sector should aid in providing a resolution to the state of existing dilapidated schools with considerable room for improvement. Through creating boundaries for application of the research and through methodical analysis of each of the systems, a proposal can be structured as a response to the retrofit of the Nelson Blocks.

Through the analysis that was performed on a Nelson Block example; of Nayland College in Nelson, New Zealand, a summary could be concluded in consideration to design proposals, literature reviews, and environmental building simulations. With particular regard to the thermal performance, ventilation, lighting, and acoustics - EnergyPlus, Radiance and Insul were used to develop a model which tested a range of design alternatives. In order to work towards the goals of a zero-carbon operational building, optimum performance and wellbeing of school building occupants, the design changes that were summarised and in conclusion should be a focus within future research include increasing WWR for passive heating and increasing levels of daylighting, adding insulation into the walls and floor (plus double glazing) for thermal performance and acoustic performance, and increasing the window openings for appropriate ACH and passive cooling. These design changes are the priorities because they address multiple design parameters in one, whilst fitting within the scope of works proposed by MOE. Overall, the occupant comfort and performance levels will increase as a result of all of the design interventions stated, working towards a zero operational energy goal indicated through the energy balance.

4. Discussion

There are many tools and resources that can be identified when considering a deep energy retrofit, however a school presents new opportunities and considerations. In taking into account the implications for how these systems influence the performance of the standardised block, an effective resolution can be formed towards the future of New Zealand school design.

The results from the anticipated system design will implicate the performance of the build in a variety of ways. Through altering the glazing and façade solutions by selecting systems such as light shelves, translucent louvres, overhangs or low e glazing replacements, a result can be formed in terms of adjusting the daylighting and overall performance of the solar and thermal intensities as present during the course of the school year.

Going forward, each of the aspects of the walls, roof, glazing, façade and floor of the original structure will be analysed further than the initial study in order to form a comprehensive understanding of the implications towards altering each component.

The need for a deep energy retrofit will allow for any of the Nelson Blocks across the six climate zones in New Zealand to be responsive towards the changing conditions that are required for the performance of schools in the current environment. This research is necessary in order to provide an example to how you can build for existing architecture and for how architecture can be resilient for the future. In providing the opportunity to bring new life into existing buildings a strategy needs to be made in how we can best utilise the form that is existing and make it suitable for future use.

This research also provides insight into not only the retrofit of educational spaces but also provides an opportunity to utilise this knowledge and methodology towards other types of building stock. Through utilising the same strategy and technique, a system could be implemented into informing the performance of other facilities that are underperforming.
The retrofit allows possibility into what design can offer for the lifecycle of existing buildings and to how they can be redefined for use well into the future.

By considering the technological advancements and renewable sustainable systems that can be implemented into a retrofit design, a proposal can be made into altering existing property portfolios. In our preliminary results shown in Figure 4 (a) as the base model and (b) as the model with alteration, there is significant growth in energy performance to achieve a higher internal comfort rate from 10% to 77% with basic changes to the whole building envelope. The research into further analysis is currently ongoing and the final results will be presented in subsequent articles.

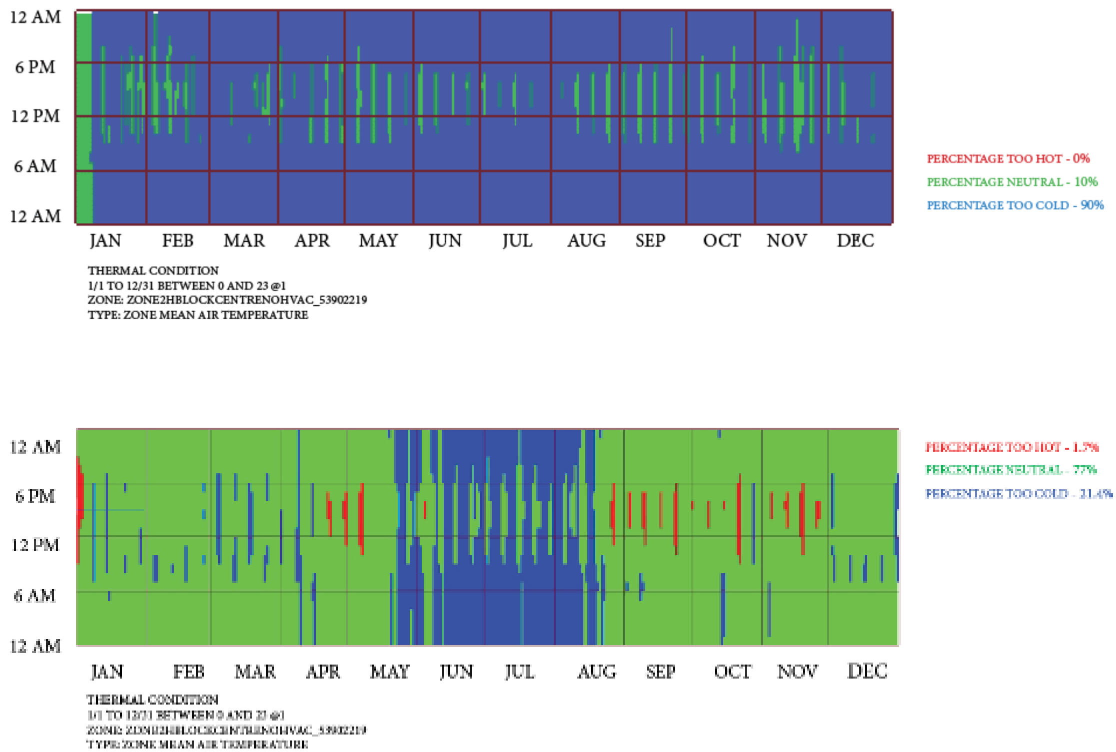


Figure 4 (a) and (b): Energy Performance Gains (Authors Preliminary Results)

5. Conclusion

Deep energy retrofits offer the opportunity for existing building stock to be reinvented and to restore its life towards the use for future generations. It allows architecture to reinstate not only the embodied energy of the original building but also the impact of the structure on carbon emissions. In an environment where every architectural move and decision causes a permanent response, utilising the resources that are already present is essential.

The standardised Nelson Block by the Ministry of Education not only provides this opportunity to reinvigorate existing buildings, but to improve the quality of comfort and learning within schools that the future generations are accustomed to. In upgrading schools and educational spaces, a tool is produced through the enhancement and increased performance of these spaces. One that provides opportunity towards the future of old building stock, and one that allows existing architecture a means to augment their estimated lifecycle.

References

Ackley, A., & Phipps, R. A. (2022a). *The Impact of Natural Ventilation During Winter on Thermal Comfort*. https://www.researchgate.net/publication/360555416.

Ackley, A., & Phipps, R. A. (2022b). *The Effectiveness of Natural Ventilation - A Case Study of a Typical New Zealand Classroom with Simulated Occupation*. https://www.researchgate.net/publication/360555339.

Allen, J. G., MacNaughton, P., Satish, U., & et al. (2016). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers. *Environmental Health Perspectives*, *124*(6), 805-812. https://doi.org/10.1289/ehp.1510037.

Audu, S. T., Utazi, D. N., & Umaru. S. (2021). *Optimization of a Solar Air Heater: A Review*. 98–107. https://www.researchgate.net/publication/359118127.

Barch, W. W., Ng, E., & Barch, H. (2003). A review of the development of daylighting in schools. *Lighting Res. Technol*, *35*, 111–125. https://doi.org/10.1191/1477153503li072oa.

Başarır, B., Basarir, B., Diri, B. S., & Diri, C. (2012). *Energy efficient retrofit methods at the building envelopes of the school buildings*. https://www.researchgate.net/publication/260066099.

Bluyssen, P. M. (2013). *Intelligent Buildings International What do we need to be able to (re)design healthy and comfortable indoor environments?* https://doi.org/10.1080/17508975.2013.866068.

BRANZ, & Burgess, J. (2008). Pitfalls of Avoiding Double Glazing. *BUILD*, 34–35. https://www.buildmagazine.org.nz/assets/PDF/Build108-34.pdf.

Brown, J., & de Wilde, P. (2012). *Integrated Performance Framework to Guide Façade Retrofit.*

Fisk, W. J. (2017). The ventilation problem in schools: literature review. *Indoor Air*, *27*, 1039–1051. https://doi.org/10.1111/ina.12403

Domínguez-Amarillo, S., Fernández-Agüera, J., Minaksi González, M., & Cuerdo-Vilches, T. (2020). *Overheating in Schools: Factors Determining Children's Perceptions of Overall Comfort Indoors*. https://doi.org/10.3390/su12145772.

Gonzalez, R. E., Stephens, M. T., Toma, C. L., Elwood, K. J., & Dowdell, D. (2021). Quantifying the embodied carbon cost from demolitions following the Canterbury Earthquakes. *NZSEE*.

Groat, L. N., & Wang, D. (2013). *Architectural Research Methods* (Second). John Wiley & Sons. https://ebookcentral.proquest.com/lib/vuw/detail.action?docID=1166322.

Heschong, L., Wright, R. L., & Okura, S. (2002). Daylighting Impacts on Human Performance in School. *Journal of the Illuminating Engineering Society*, *31*(2), 101–114. https://doi.org/10.1080/00994480.2002.10748396

Kim, J. T., & Kim, G. (2010). Overview and new developments in optical daylighting systems for building a healthy indoor environment. *Building and Environment*, *45*(2), 256–269. https://doi.org/10.1016/j.buildenv.2009.08.024

Li, Q., Zhang, L., Zhang, L., & Wu, X. (2021). Optimizing energy efficiency and thermal comfort in building green retrofit. *Energy*, *237*. https://doi.org/10.1016/J.ENERGY.2021.121509.

Littlefair, P. J., & Phd, M. A. (1990). *Innovative daylighting: Review of systems and evaluation methods*.

Majd, E., McCormack, M., Davis, M., Curriero, F., Berman, J., Connolly, F., Leaf, P., Rule, A., Green, T., Clemons-Erby, D., Gummerson, C., & Koehler, K. (2019). Indoor air quality in inner-city schools and its associations with building characteristics and environmental factors. *Environmental Research*, *170*, 83–91. https://doi.org/10.1016/J.ENVRES.2018.12.012

Martinez, A., & Carlson, A. (2014). View of State of the Art Methodology to Assess Energy Facade Retrofits (EFR). In *University of Southern California*. https://www.arcc-journal.org/index.php/repository/article/view/290/227

Martinez, A., & Choi, J. H. (2018). Analysis of energy impacts of facade-inclusive retrofit strategies, compared to system-only retrofits using regression models. *Energy and Buildings*, *158*, 261–267. https://doi.org/10.1016/j.enbuild.2017.09.093.

Martinez, A., Patterson, M., Carlson, A., & Noble, D. (2015). Fundamentals in Façade Retrofit Practice. *Procedia Engineering*, *118*, 934–941. https://doi.org/10.1016/J.PROENG.2015.08.534

Ministry of Education. (n.d.). *Project: MOE-FLS Reference Designs for Standard Classroom Upgrade Nelson Two Storey Block (Concrete Stairs) Structural Calculations: Wellington*.

Ministry of Education. (2013). *Ministry of Education Catalogue of Standard School Building Types*. www.minedu.govt.nz

Ministry of Education. (2016). *Reference Designs for Standard Classroom Upgrade NELSON TWO STOREY BLOCK Document history Revision date*.

Ministry of Education. (2022). *Property, procurement and chool transport*. https://www.education.govt.nz/school/property-and-transport/#Property.

Ministry of Education, & Aurecon New Zealand Limited. (2016). *Design Features Report - Flexible Learning Space Upgrade*.

Moazzen, N., Ashrafian, T., Yilmaz, Z., & Karagüler, M. E. (2020). A multi-criteria approach to affordable energy-efficient retrofit of primary school buildings. *Applied Energy*, *268*, 1–19. https://doi.org/10.1016/J.APENERGY.2020.115046.

Onubogu, N. O., Chong, K.-K., & Tan, M.-H. (2021). *Review Article Review of Active and Passive Daylighting Technologies for Sustainable Building*. https://doi.org/10.1155/2021/8802691.

Park, K. S., Domingo, N., Rasheed, E., Mithraratne, N., & Thi Hoai Le, A. (2021). Sustainable refurbishment for school buildings: a literature review. *International Journal of Building*, *39*(1), 5–19. https://doi.org/10.1108/IJBPA-01-2018-0009

Phipps, R. A. (2017). *Indoor Air Quality in New Zealand Homes and Schools*. www.standards.

Preda, D. (2017). *Standardization of Solar Air Heaters*. https://www.researchgate.net/publication/315747078.

Rabani, M., Madessa, H. B., & Nord, N. (2017). A state-of-art review of retrofit interventions in buildings towards nearly zero energy level. *Energy Procedia*, *134*, 317–326. https://doi.org/10.1016/J.EGYPRO.2017.09.534

Reiss, J. (2014). Energy retrofitting of school buildings to achieve plus energy and 3-litre building standards. *Energy Procedia*, *48*, 1503–1511. https://doi.org/10.1016/J.EGYPRO.2014.02.170.

SolarVenti Australia. (2022). *School & Care Facilities*. https://www.solarventi.com.au/commercial/school/.

Thi Hoai Le, A., Park, K. S., Domingo, N., Rasheed, E., & Mithraratne, N. (2021). Sustainable refurbishment for school buildings: a literature review. *International Journal of Building*, *39*(1), 5–19. https://doi.org/10.1108/IJBPA-01-2018-0009.

Wang, & Yu. (2020). *Effects of operating a solar air heater on the indoor air quality in classrooms during the winter A case study of Palmerston North primary schools*.

Wong, I. L. (2017). A review of daylighting design and implementation in buildings. *Renewable and Sustainable Energy Reviews*, *74*, 959–968. https://doi.org/10.1016/J.RSER.2017.03.061.

Zhivov, A., & Lohse, R. (2017). *Deep Energy Retrofit: A Guide to Achieving Significant Energy Use Reduction with Major Renovation Project.*

For a philosophy of good construction: a learning experience

Paola Marrone[1], and Francesco Maria Mancini[2]
[1] *University of Roma Tre, Rome, Italy*
Paola Marrone paola.marrone@uniroma3.it ORCID-Number[1]
[2] *Curtin University, Perth, Australia*
Francesco Mancini francesco.mancini@curtin.edu.au, ORCID- 0000-0001-7119-7056 [2]

Abstract:

The knowledge of construction techniques handed down its wealth of experience through manuals and codes of practice for a long time. The manuals of the past not only supported the construction through technical information but also expressed a 'philosophy' of good construction by transferring construction principles and rules into the project. The themes of good construction were enriched in the twentieth century by numerous objectives, among which the most significant are the industrialization and systematisation of building processes and the challenges of sustainability, from energy efficiency to the recycling of materials to building regeneration. In university education, however, the transmission of knowledge on construction stayed limited to lessons on the elements and construction techniques that declined in the various materials.While the recent global spread of computerization ensured the wide availability of technical information sources online, this phenomenon did not produce, per se, innovative, integrated and sustainable building solutions. The authors hypothesise that today's technical information is not ethically committed to clarifying the complex aspects of construction in sustainable terms.The proposed thesis considers architecture, like medicine, a “practice based on science and operating in a world of values” (Cosmacini, 2008).

Keywords: Architecture, Education, Learning Experience, Sustainable Construction

1. Manuals and good construction

The knowledge of construction techniques handed down its wealth of experience through manuals and codes of practice for a long time. The manuals of the past not only supported the construction through technical information but also expressed a 'philosophy' of good construction by transferring construction principles and rules into the project.

Until the recent past, the transmission of construction knowledge, especially in university education, was delegated to lessons on the elements and construction techniques in various materials such as wood, brick, stone, iron, and reinforced concrete. In the bibliography of the courses, the reference books recalled, even in the titles, the same contents of the lessons, which were very similar to the technical manuals in use. They were the main sources of knowledge, based on empirical and scientific information that made it possible to tackle the study of the fundamental problems of building construction.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 317–326.*

This tradition started with the Renaissance Architecture treaties like Palladio's four books on architecture (1570) which, building on Vitruvius' Roman text De Architectura Libri Decem, adopted a specific 'architectural philosophy' to guide the design with indications for good construction under all conditions, and thanks to this approach successfully influenced Western architecture and building literature for over three centuries. Since then, books and manuals on construction techniques have always accompanied the professional life of future designers, handing down the 'art of well-built', that is, knowledge of construction techniques, a heritage of experience and professionalism that has always been present in construction, ensuring that the design information guided the design, transferring principles and rules from theory to practice to attain high-quality buildings.

Over time, advertising has been added as the further scope of this information as an inevitable consequence of mass building production. To increase their competitiveness, building manufacturers displayed building materials and components praising their qualities, performance, and relatively inexpensive price, due to their industrial production. In America, this practice led in the early XX century to abandon the manual as a theoretical text on construction and replace it with texts rich in information that came directly from the industry world. Famous examples are the Time-saver standards for architectural design data or the Architectural Graphic Standards of the American Institute of Architects, published as a prototype in 1924 and its first edition in 1932.

2. The challenges to construction practice's knowledge transmission

The themes of good construction were enriched in the twentieth century by numerous objectives, among which the most significant are the industrialization and systematisation of building processes and the challenges of sustainability, from energy efficiency to the recycling of materials to building regeneration. In university education, however, the transmission of knowledge on construction stayed limited to lessons on the elements and construction techniques that declined in the various materials.

The growing complexity of construction and the present possibilities of accessing many sources of information, well organized and easily selectable, make it impossible to propose a design activity based on a fixed set of information. Compared to the past century, the crystallized knowledge embodied in a single manual today is no longer a sufficient source of information to design, because a vast amount of information has now become available online. Small and medium-sized professionals without the infinite resources of large professional firms are the primary users of these sources today. Notwithstanding this, we suggest that the advent of computerization and its diffusion has not led to major changes in the relationship between designers and available information. University and professional courses have not varied much, as the greatest impact of computerization on learning resources is concerned with the forms of advertising rather than high-quality and comprehensive technical information which often ended in unsuccessful attempts to replace technical manuals with web searches. Within this context, we suggest that with the development of such increasingly advanced access to data, we face a twofold problem: On the one hand, the information available online does not per se constitute knowledge; on the other, not only manuals have become obsolete, but a way of doing things consolidated over the centuries has also entered a crisis with them. A crisis that has forced architects to manage many 'specialisms' and, at the same time, to acquire and interpret an endless series of continuously updated documents, principles, and standards, which make it difficult today to access and select the essential information for choosing and designing correctly.

Empirical and theoretical experiments, conducted in a purely specialized form have added to the wealth of experiences collected in technical manuals, which demonstrates how scientific research, especially in the field of physics, has been increasingly defining useful laws and principles in the construction field. While for centuries architects dealt with the building as a whole, this approach resulted in the massive use of 'reductionist' study methodologies and applications: the simple aspects of building, have been isolated and solved separately: firstly, the loading structure, secondly the envelope and its 'thermal quality, then the interior space, the acoustics of its partition walls and so on.

In the face of a more precise understanding of some phenomena, the loss of sight of the whole building as 'context' has often led to questionable or unsuccessful choices. Further to this, the construction process changed drastically over the past thirty years, from a simple juxtaposition of a few elements to the assemblage of many diverse industrial products and components. This change necessarily involved the interaction of specialized knowledge from many disciplines in executing a building which transformed the construction into a complex operation and reduced the architect's role from master builder to design controller, leaving to project managers the takes to lead the building process. It is undeniable that such a shift towards specialization was somehow necessary, due to the unprecedented development of new materials and better environmental systems.

On the other hand, Kieran and Timberlake, (2004) argue that while the greater availability of materials, systems and component s' choice has favoured the specialization of many disciplines, it has equally increased the demand for much more complex skills for the understanding of longstanding problems. Today, architects can no longer govern such a complexity alone, hence why their education has to make them able to coordinate it.

3. The insufficient knowledge of the information currently available does not produce integrated innovative solutions

While the recent global spread of computerization ensured the wide availability of technical information sources online, this phenomenon did not produce, per se, innovative, integrated, and sustainable building solutions.

By their generalist background, architects investigate and design architectural objects as 'organisms' for human inhabitation, composed of parts that are harmonically and functionally connected. For this reason, any knowledge related to the subject of study must allow learners and practitioners to understand and control it, not as an isolated fact, but rather as an element interconnected with all the other parts.

Since the wealth of building methods are always evolving to respond to very different needs and environmental conditions, it is difficult to understand the built environment as a "system". Consequently, it is equally difficult to define the varied whole of elements that should contribute to forming the "construction system". In other words, if an architect is designing the window of a building, the goal will not be to study a theoretical and perfect object, but rather a building component that serves to illuminate a room, which regulates the ventilation, controls the acoustic and thermal insulation, resists any break-in, wind, and rain. The window component is also designed in such a way that it is not fragile and dangerous for users, allows firefighters to enter in case of danger, is durable, and easy to clean, and allows you to shield yourself and close completely. The designer, in the end, needs to consider an appropriate component cost and make it easy to assemble and beautiful, as well as compatible with the language of the building in which that window will be placed. It is evident that all these needs are not solved by studying the window as an isolated object, but only by understanding the window as an element composed of parts - such as glass, profiles, hinges, closures, seals, and so on - which must be chosen through rational criteria and, at the same time, an integrated part of the building organism. It is only when the architect considers the most direct links between these important aspects of the building design and addresses them altogether by understanding how a choice of a single element directly affects the rest, that their work does not become infinite or unproductive.

Architects are usually aware of this problem, but often they limit their study to just the architectural organism, neglecting the accurate definition of the elements that compose it and limiting their interest to their generic definitions, living to other stakeholders the task of their translation into products and components and their management. Alongside substantial technical knowledge, which is necessary to operate, it is equally important to draw attention to the cultural sphere. This “need to think” approach helps identify the possible connections between design and its real consequences on building correctness and performance which might be otherwise just guessed or supposed.

4. Architecture and technology as practice in a world of values

The authors hypothesise that today's technical information is not ethically committed to clarifying the complex aspects of construction in sustainable terms. The proposed thesis considers architecture, like medicine, a “practice based on science and operating in a world of values” (Cosmacini, 2008).

It is indisputable that there is a profound difference between architects and civil engineers in their training as well as their field of activities. While the engineering profession can be considered a 'product' of eighteenth-century science (Addis, 2007), the essence of being an architect is not tied to scientific activities in the strict sense of the term. Paraphrasing the title of a book title by Cosmacini (2008) that defines Medicine as "a practice based on science and operating in a world of values", we argue that "Architecture is not a science", but rather a practice in a world of values. This difference can also assist in clarifying the eternal confusion that exists between 'Technology' and 'Technique' in architecture, due to the lexical connection between the two terms.

The confusion concerns not only the Technology of Architecture and Technical Architecture taught in the schools of Architecture or Engineering, but all the discourses that revolve around these terms, so much so that Cosmacini believes that it is necessary to specify that 'Medical Techniques' they are closer to 'philosophy' than 'know-how'. If we accepted this interpretation, even in the field of architecture we could say that technology can be considered closer to 'philosophy', while the technique is in the strict sense of 'knowing how to do’. Of course, the reasons for this difference depend on how we approach the search for a solution to a building problem. If we feel we are experts by proving that we know how to do something, without valuing the reasons why we have reached that solution, our soul is closer to that of a specialist technician. If, on the other hand, we consider the selected solution as one of the many possibilities of our creative work, we could find ourselves closer to the soul of a designer architect. Two types of mindsets derive directly from how we teach technique or technology. The engineering training focuses on equipping the student with tools for them to transform ideas into realizations, while studies in architecture aim to generate and develop ideas. When it comes to teaching technology, many questions arise. Who is right? Or, better, which training is more useful? Is Architecture Technology a corrective to the excessively 'artistic' training of the architect? If the answer is yes, what should a technology teacher be concerned about?

If we share the architecture definition as a "science-based practice that operates in a world of values", then we answer that architecture is more than a 'science', as it also includes a philosophical vision that guides technologists; only a philosophical approach to the problem of construction for spatial inhabitation can prevent from an excessively superficial training, and orient students towards a more in-depth knowledge approach. Only using such deep knowledge will they be able to consciously operate in a 'world of values'. From this perspective, close integration between practical technique and technology knowledge in the educational field is essential for a balanced education in the technology of architecture today.

On the one hand, the architect needs practical knowledge to use the information from architectural publications, even if such information is often presented for promotional purposes rather than to inform.

On the other hand, architects must enter the merits of technical choices without passively accepting materials and technologies available on the market, as the information does not clarify and guide professionals into the complex world of modern construction.

Making this information understood and best used in the design phase is one of the main philosophical tasks of Architecture Technology, as studying and defining the possibilities and limits of knowledge is precisely the task of philosophy (Jasper, 2014). As educators involved in the training of future operators in the construction field, we developed a teaching method to process information relating to construction within a system that allows us to both analytically control construction details without losing their links with the whole.

5. A learning experience

The study we present here is based on the learning experience of second-year Architecture students in the Laboratorio di Costruzioni 1B 2021/2022 (Laboratory of Construction) at the University of Roma Tre. The unit is designed on the assumption that the technological design of construction elements relies on a complex building system whose definition, especially in terms of sustainability, today requires ethically correct information to measure the real environmental and technical performance of the design choices. For this purpose, we have set up a didactic approach that uses the design and construction history of a simple building to define its sustainable performance, linking basic concepts of construction to known construction examples.

Through the comparison of a building's design and construction history with similar architectural examples, we enabled students to understand the basic functioning of building system parts and gain an organic comprehension of the design choices that defined its building system.

A new form of organization of technological knowledge based on cognitive maps representing the parts within the whole of the 'construction' system is the basis of this approach, which enables the identification, coding, and transmitting information statements to students. In this way, the single information concerning one element of the construction is delivered making evident the connections between the elements themselves and the whole of the construction to which they belong, rather than discrete parts.

Once students learned the design characteristics of the building components, such as ground connection, structure, envelope, roof, etc., they were invited to reconsider their Design from the previous semester and apply technological solutions considering sustainability needs and objectives.

The definition of such a system has been published in a series of books Morabito, Marrone, 2010, 2014) which addresses four main themes of the 'construction' system (ground connection, vertical and horizontal structure, opaque vertical envelope, transparent vertical envelope, roofing) and provides the basic information necessary for an architect to understand the rules of detailed design and construction within a system of interrelated elements.

This approach has been used as a didactic framework providing a learning pathway for second-year students that include a scaffolded and interconnected study of each element of the construction, from the ground connection to the roof composed of five steps

Step 1. Telling the story of the construction element through examples.

Students present architectural examples of technological solutions related to the construction elements studied and the drivers that identify their needs and performances to explain the choice for their use.

Step 2. Organizing knowledge by concepts.

Students build a discourse on the aspects to consider in the design of the building element using the concept map defined to establish relationships between concepts and performance parameters.

Step 3. Moving from concepts to put into practice through construction on site.

Students demonstrate, using the selected building case study, how the design concept was translated into construction through the negotiation of technological choices on the construction site that determined the correct construction sequences.

Step 4. Applying knowledge to select the preferred solution among technical alternatives.

Students design the construction element describing the technological performance and representing the succession of the construction sequences of the individual components of the element.

Step 5. Resolving the relationships between elements of the system.

In the end, students insert the detailed solution in a section of their previous semester's building design and identify how this specific building node is to be redeveloped to resolve the interrelationships with the other elements of the construction system.

Step 1. Telling the story of the construction element through examples.

In the 'construction system’, the study of construction detail is useful to understand the reasons behind the solution of a specific building problem beginning the ascent from the particular to the general, which is essential not to lose sight of the unity of the 'construction' system. Studying construction problems by selecting architecture examples in a certain order enables students to inquire about the design problem - the performance requested by a particular node and present their findings explaining the project in response to the project demand – the services to be offered. For this purpose, students describe each example in its generality to understand the construction problems as consequential to the architectural objectives. The study of technologies entrusted to the presentation of examples of constructions or specific projects is inevitably partial, as only in specialized books, can we find an almost complete, albeit theoretical, illustration of the possible technological solutions for the architecture of constructive elements (fig. 1).

For this reason, we asked students to illustrate a constructive element as exhaustively as possible through a series of examples, comparing each alternative solution to each other, and framing problems to understand the general principles behind them. A legend of individual details is proposed to students for them to display information concerning "what" elements you are talking about, “where” and "why" of their presence and "how" The architects intend to resolve or have resolved the detail. Through the ordered structure of the legend, all students can describe the parts that compose the represented element and indicate the reasons underlying that choice using a common code, which makes the characteristics of a technical solution understandable and comparable to each other.

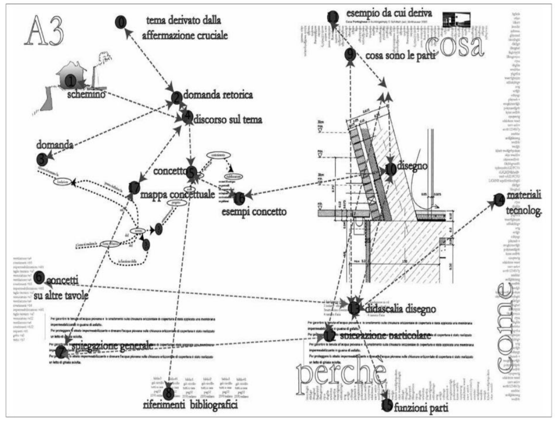


Figure 1 – Student diagram showing the connection between construction nodes

Step 2. Organizing knowledge by concepts.

The set of problems found in the various examples allows us to construct a discourse on the theme that frames the element studied in the construction system. This work derives from the application of J.D. Novak and D.B. Gowin in their book “Learning how to Learn” (1984), as developed in the aforementioned study on concept maps applied to the study of technology. For Novak and Gowin, concept maps are a form of communication and explanation, that concentrate key objects of a discourse in the concepts dealt with.

The study of each element of the construction was thus articulated using concept maps. Each set of concepts in the map identifies significant aspects of the assigned construction problem and the relationships between each component to address the technological design of each element. The desired performances were thus related to technical solutions, explaining the reasons underlying the possible adoption of different detail configurations.

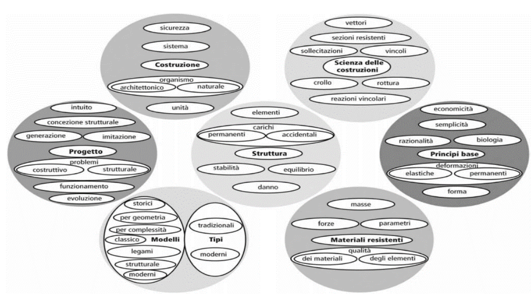


Figure 2. Organization of the structure map illustrating driving concepts.

Step 3. Moving from concepts to put into practice through construction on site.

The presentation of examples taken from the literature and the reasoned description of the various technological solutions does not yet allow students to holistically understand the performances determined by the construction needs. For this purpose, additional information about the analysed examples concerning the whole construction process is required. To address this issue, we used a real building located on campus as a reference, a teaching pavilion of the Department of Letters of the Roma Tre University, of which both the design and construction events were known. The teaching team presented the design, and the construction site of the reference building, explaining how each element of the construction and the construction sequences helped to assemble the building to perform correctly from a functional, structural and sustainable standpoint. For the theoretical treatment of each element of the construction, alongside the examples (Step 1) and the guiding concepts for its design (Step 2), the reference to a realised building played an important role, especially using the connection between components and elements to demonstrate the importance of correct design, procurement, and execution nexus to fully achieve the required building performance, locally and overall.

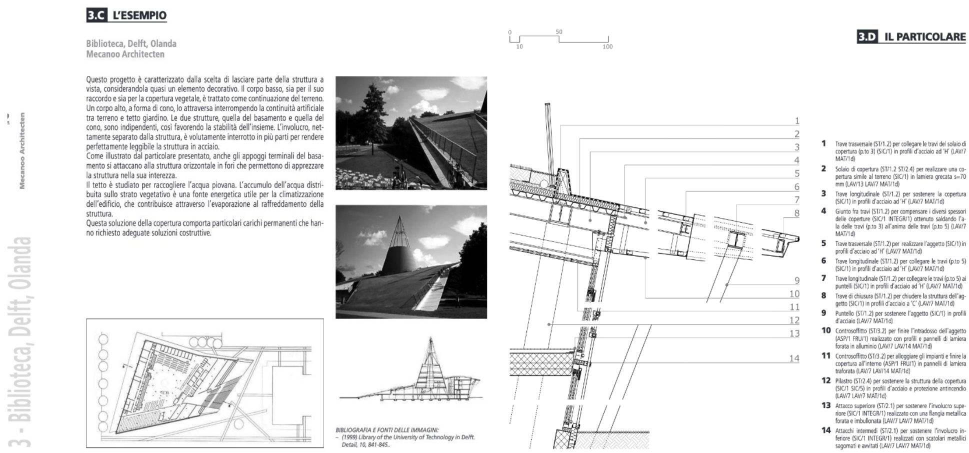


Figure 3. Students' presentation of an Architectural Example and construction detail.

Step 4. Applying knowledge to select the preferred solution among alternative technical alternatives.

Once students investigated the functioning of a construction element, the relationships between elements and performance through alternative solutions, and understood the construction process as a whole, we asked them to analyse their project developed in the Architectural Design Laboratory in the previous semester. The analysis of their building's structural design, accessibility, fire prevention and, above all, sustainability, the definition of which was limited to some general settings, aimed at putting the technical design choices made in the previous term back into play and responding to the building's fundamental needs in light of the newly acquired knowledge.

At the end of the analysis, students identified with greater awareness bettered solutions that they could not identify in the previous Design studio, such as dimensional rethinking of spaces, in plan and section; distributive reorganization; optimization of the transparent and opaque envelope based on the quality of natural lighting and protection from solar radiation; choice of structural materials and layers' definition, with a focus on circularity, low environmental impact and reduction of CO2 emissions. In this phase, students deal with a partial re-design which starts from the identification and understanding of the technical reasons for their design rather than a response to the site and brief.

Having re-defined the framework of the building requirements, students identify one or more significant sections representing their project and rebuild them element by element starting from the structure that constitutes the supporting framework. Starting from the evaluation of alternative solutions' performance, the selected solutions for the single elements of the construction system are gradually added to the structure. Only after identifying the most suitable solution, do the students draw it, initially component by component, describing the sequence of construction operations on-site step by step, then inserting it in the reference section.

Step 5. Resolving the relationships between elements of the system.

After repeating steps 1 to 4 for each element of the construction system, the section begins to be defined, but at the same time the themes of the interrelation between the different elements become evident and, above all, it becomes necessary to verify the figurative/architectural outcome of the whole, exactly as it happens in a real design process. This operation, apparently easy to perform, requires the development of a competence that goes beyond the correct application of the acquired knowledge. It involves the critical design skill to control more aspects as a whole and translate the choices into the desired architectural configuration. In this phase, students experience first-hand how their choices, sometimes *impromptu*, are challenged by needs of a different nature that require a synthesis not only through the maturation of the acquired knowledge but also the individual capacity to control and reinterpret the architectural expression of the construction.

Conclusion

In an interview published a few years ago, the philosopher Carlo Sini, addressing the problems of information interpretation, argued that the internet is only a medium for its transmission (Cannata, 2010). He convincingly asserted that information, if left to itself, generates disinformation. This apparent paradox is valid also for architects. One just needs to browse online through a 'technical' magazine in which even well-documented details of construction elements, while providing additional information to a professional's training background, lack any critical note, which would help understand the real validity of the solutions presented. The potential designer-reader is left with the task of evaluating the solutions trying to understand if they are dictated by formal needs, or if they have interesting and innovative results such that they can be reused in different constructions. The information that a cultural professional can retrieve from trade magazines is, in general, very superficial.

It is believed that nothing 'more' is needed, but this 'more' is precisely the missing information that generates disinformation. It is that kind of misinformation that leads to designing and building kitschy projects, as evidenced by the long series of poor building copies that Frank Gehry's Guggenheim Museum has generated. Instead, appropriately structured information is needed to explain the reason for certain exceptional constructions that students and technology teachers look at very carefully. It is necessary to understand what qualitative improvements the innovative ideas bring, concerning the needs of comfort, maintainability, durability, safety and sustainability, so that they can be extrapolated for future use.

The architectures presented in technical architecture magazines do not explain the constraints that led to the choice of specific solutions. Unfortunately, the information contained in commercial publishing seems to consider, for example, engineering conditioning as marginal or does not provide measured characteristics of environmental performance. Correct and exhaustive information on all aspects of an experiment would guarantee complete control by entrusting it to the figure of the architect, which has always been the antithesis of any specialism.

It is with this spirit that the teaching experience presented here was set up, in the awareness that in a technological design laboratory, technical knowledge should turn into critical skills starting from the case studies, to understand the sustainable and architectural value of possible choices between many alternatives. In other words, the attempt was precisely to move away from the logic of technical manuals, to build a philosophy capable of guiding students in choosing technological solutions and, above all, governing them as non-specialist architects.

Bibliography

Addis, B. (2007), Building: 3000 years of designing engineering and construction, Phaidon Press, New York.

American Institute of Architects (1932), Architectural Graphic Standards, Ed. John Wiley&Sons, New York. (https://www.graphicstandards.com/product-history/)

Cannata, M. (2010), "La Rete e la riscrittura dei saperi: Intervista con il filosofo Carlo Sini" MIT Technology Review Italia, No.11.

Cosmacini, G. (2008), La medicina non è una scienza, Raffaello Cortina Edizioni, Milano.

Davis, G.B. (1974), Management Information Systems: Conceptual Foundations, Structure and Development, McGraw-Hill, Inc., New York.

Giebeler, G. (2009), "Building with the context. Split identities as design concep", Detail, No.11, p.1224.

Gowin D.B. and Novak, J.D. (1984) "Learning how to Learn". Cambridge University Press 1984

Gowin D.B. and Novak, J.D. (1989), Imparando a imparare, Sei Frontiere, Torino.

Kieran, S., Timberlake, J. (2003), Refabricating Architecture: How Manufacturing Methodologies are Poised to Transform Building Construction, McGraw-Hill, New York.

Kieran, S., Timberlake, J. (2004), Refabricating Architecture. How Manufacturing Methodologies Are Poised To Transform Building Construction, McGraw-Hill, New York.

Marrone, P.; Morabito, G. (2008). La tecnologia che serve agli architetti. Come si costruisce oggi e (forse si costruirà) domani, Alinea editrice, Firenze.

Marrone, P.; Morabito, G. (2010). La tecnologia che serve agli architetti 2. L'attacco a terra, Alinea Editrice, Firenze.

Marrone, P.; Morabito, G. (2011). La tecnologia che serve agli architetti 3. La struttura, Alinea Editrice, Firenze.

Marrone, P.; Morabito, G. (2014). La tecnologia che serve agli architetti 4. L'involucro, Altralinea Edizioni, Firenze.

J.D. Novak & D.B. Gowin "Learning how to Learn". Cambridge University Press 1984

Watson, D., Crosbie, M.J. (1946), Time Saver Standards for Architectural Design: Technical Data for Professional Practice, McGraw-Hill, New York

Yeomans, David T. Early carpenters' manuals 1592-1820, Construction History, 1986, Vol. 2 (1986), pp. 13-33, The Construction History Society Stable URL: https://www.jstor.org/stable/41613617

Identifying glass for improving energy efficiency in office buildings of Addis Ababa, Ethiopia

Hawi Tilahun[1] and Avlokita Agrawal[2]

[1, 2] Indian Institute of Technology, Roorkee, India
{h_tilahun[1], avlokita[2]}@ar.iitr.ac.in

Abstract: Despite numerous international guidelines for energy-efficient practices worldwide, Ethiopia is still in its early stages. Ethiopia has many types of climates that necessitate the use of specific energy studies to guide building design. As a building envelope component, fenestration design significantly impacts total energy demand (heating, cooling, and lighting). The fenestration design determines the natural light and heat exchange between the indoor and outdoor environments. This study aims to identify the best glass type for air-conditioned office buildings in Ethiopia's humid subtropical climate and provide a scientific basis for selecting glass materials in early design decisions. The study employs a simulation-based approach for comparative analysis of glass type using total energy consumption as performance criteria. According to the study, the VT (Visual transmittance) of the glass type determines the energy performance of the glass. In this case, window glass with a high visual transmittance performs significantly better than glass with a lower VT (Visual transmittance). The U-value and SHGC (Solar heat gain coefficient) have been found to have less impact on building energy performance.

Keywords: Humid subtropical climate of Ethiopia; energy efficient building; fenestration design; glass type.

1. Introduction

The 2019 Global status reports that 40% of energy-related greenhouse gas emissions are from the construction and building sectors. Yüksek and Karadayi, (2017) discussed that energy in the modern world is a significant driver of wealth creation, economic growth, and social development.

Ethiopia is one of the rapidly urbanizing countries in East Africa. As Asres, (2021) pointed out, the energy in Ethiopia primarily comes from biomass. Ethiopia's electric grid's power generation has relied on hydropower, but there is high demand and uneven distribution between rural and urban areas. In urban areas, 87% of the population has access to electricity. In rural areas, only 5% population has access to electricity, where most of the time, the energy resource used for heating and cooking is biomass(Mondal *et al.*, 2018). Ethiopia needs a high energy supply to satisfy the need, but the demand is increasing

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 327–338.*

continuously due to infrastructure growth and lifestyle change. The emerging new building construction and design in Addis Ababa and other cities do not consider the climate type due to a lack of guidelines for energy-efficient strategies; the whole country's building design is similar despite the vast climate variation. Ethiopia has different climate types due to its location and geography, ranging from tropical in the north-eastern and south-eastern plains to temperate and cold in the highlands (*Ethiopia: When to Visit - Journeys by Design*, no date). Based on the Koppen-Geiger classification, Ethiopia has around eight climate zones. Addis Ababa has a CWB-subtropical oceanic high-land climate (humid subtropical climate) (Kottek *et al.*, 2006). In building design, fenestration design significantly impacts thermal performance. Unlike other building envelope parameters, a fenestration is an opening responsible for the visual connection, lighting, ventilation, and heat exchange. Fenestration is less resistant to heat exchange than other building envelopes (Paulos and Berardi, 2020). The thermal performance of fenestration is determined by the glass type, frames, window orientation, WWR, and material placed between layered glazing (Carmody and Northernstar 2012; Cuce and Riffat 2015).

The glass in the window is referred to as glazing, which significantly determines the window's performance. This physical property is quantified by U-Value, SHGC, and VT (Gasparella et al., 2011). According to the British Fenestration Rating Council (British Fenestration Rating Council, no date), the type of glazing material, the number of glazing layers, sizes of the cavity, inner gas, types of frame, glass coating, the number of panes, and the design significantly impact these measurements. Based on many studies, window performance is not only affected by the window glazing type but by the Window-to-wall ratio, building orientation (Alghoul, Rijabo, and Mashena, 2017), frame types (Paulos and Berardi, 2020), opening distribution, and shading (Amaral *et al.*, 2016) also. It is not comprehensive to identify energy-efficient glass without considering correlated parameters.

This study aims to identify the most efficient glass type which will improve the office building performance in Addis Ababa. The scope of the study is limited to the fully air-conditioned office performance of buildings in Addis Ababa. The limitation of the study is working on one climate type and taking secondary resources for base case development since Ethiopia does not have a base case model as a benchmark to start the study. However, the methodology can be replicated for all building scales, types, and climate classifications in the country.

2. Methodology

For such types of studies, the first step is to derive a base case. Often the base case is a typical building that can be used to represent many similar typologies. Hence the geometry for this study was taken from the thesis paper, "Evaluation of selected Addis Ababa buildings concerning the green building features" (Haileleul, 2015).

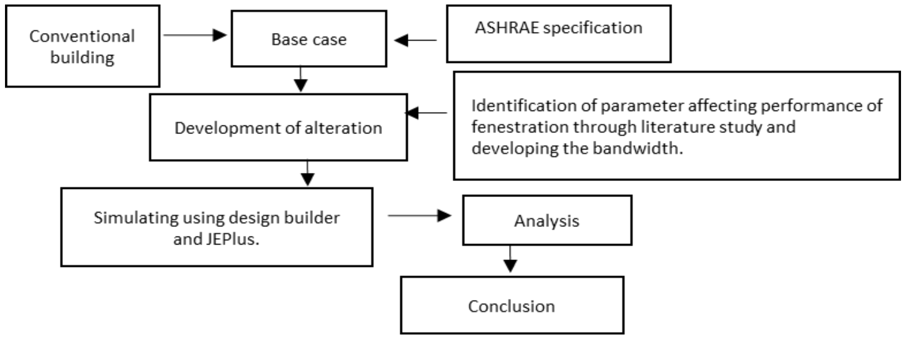


Figure 41: Methodology diagram

The base case HVAC system, Activity, lighting, and occupation schedule were taken as per ASHRAE 90.1 office standards(*ASHRAE, 2007*). The building envelope details, such as the U-Value of the wall, roof, and floor, were taken as per ASHRAE 90.1 (Ashrae and Iesna Addenda, 2009) guidelines for a warm marine climate zone. The climate zone classification was identified from Addis Ababa weather data.

In this study, as Figure 1 presents, computerized simulation was used to evaluate the heating, cooling, and lighting energy consumption. The annual energy consumption was calculated using JEPlus and the Design-Builder interface on a hypothetical sample model with varying parameters. A rectangular base case was modeled in the Design-Builder to represent office buildings in a humid subtropic climate zone (Addis Ababa) to investigate the effect of glass type on the office building's energy performance.

Design-Builder software (version 6.1.0.001) which uses energy plus as its background simulation engine, was used to create the models for testing and analysis. The model was created according to the software's instructions, first by defining the location and then specifying the activity and construction section (*Design Builder Software Ltd - Home*, no date). This step helps to create different models following the various parameters.

As part of the modeling, Addis Ababa weather data was taken as a reference to evaluate the energy load. JEPlus software was used to do parallel simulations for many cases in one set. This software helps study complex parametric analysis in a simple method to collect the result easily (*jEPlus - Parametrics for E+ and TRNSYS download | SourceForge.net*, no date)

Office buildings in Addis Ababa have extensive glazing and window sizes. This study uses different ranges of U-value, SHGC, and VT glass types to measure the performance and recommend best practices. Four glass types were included in the study to represent the High and low values of U-Val, SHGC, and VT (Table 1). These four glass types are bandwidth: different opening distribution, WWR, and orientation for a comprehensive study.

Table 22: Physical properties of glass

Glass type	U-Val	SHGC	VT	Frame type
Sgl Clr 3mm	6.121	0.810	0.881	Aluminum
Sgl Ref -A-H Clr 6mm	5.360	0.277	0.201	Aluminum
Dbl Loe(e2=1) Clr 6mm/12mm Air	1.772	0.563	0.745	Aluminum

Dbl Ref-A-H 6mm/13mm Air	2.449	0.216	0.181	Aluminum

SHGC- Solar heat gain coefficient; VT- Visual transmittance

As per Figure 2, the building orientation varied between 0 and 90 degrees, and five window-to-wall ratios, starting from 10% WWR with a 20% interval, were incorporated. All window opening distributions were included as parameters in the pairing: one side opening, two side opening, and three side opening.

3. Base case

3.1. Base case model

The base case is a G+5 office building with a typical floor plan. The floor area is 1092 m2 with core and office perimeter zones, and the floor plan was modified to make it simple for simulation (Figure 3). The construction template, Activity, light, and HVAC template were adopted as per ASHRAE 90.1 (ASHRAE, 2007), as shown in Table 2, for the climate type of Addis Ababa city. Fenestration was varied as per Figure 2; 600 alterations were developed.

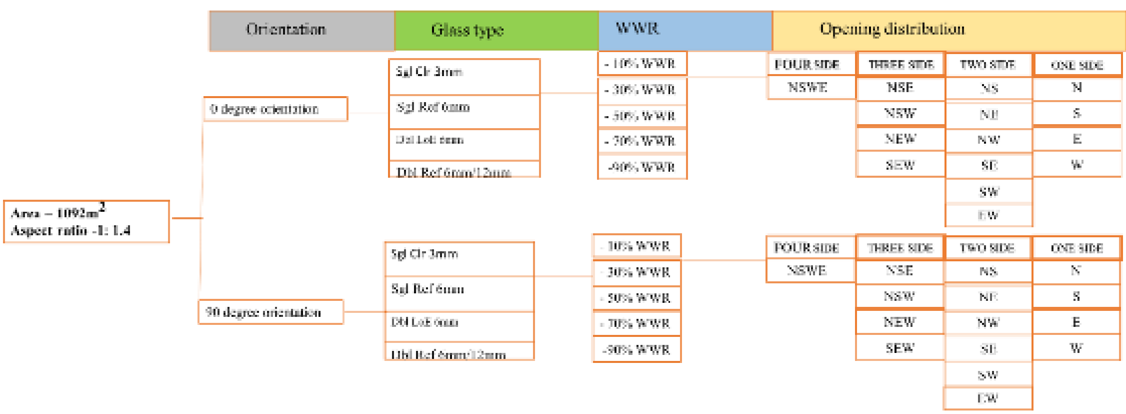
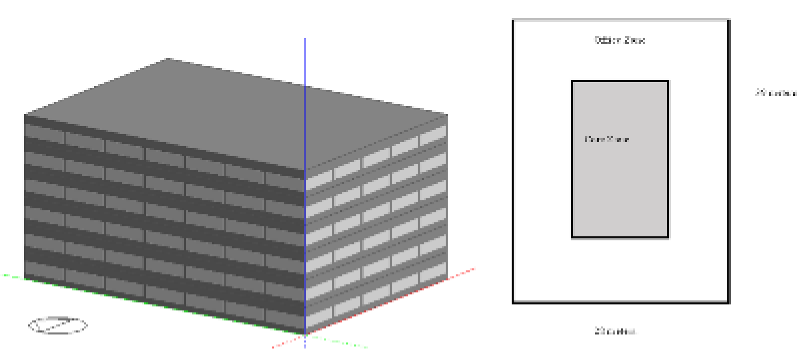


Figure 42: Combinations of selected parameters



Core zone	38%
Office zone	62%

Figure 43: Base case model indicating the geometry (left) and typical floor plan displaying perimeter and core zone (right)

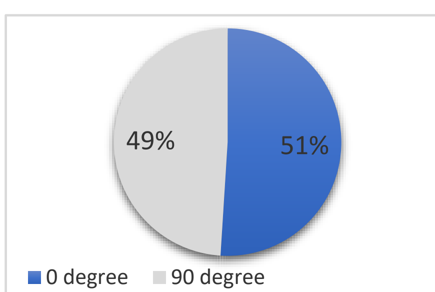
Table 23: Adopted operational conditions and construction specification

Adopted operational conditions		**Construction specification**	
Weather file	ETH_Addis.Ababa-Bole.634500_SWERA	Type	The construction specific as per ASHRAE 90.1 (Ashrae and Iesna Addenda, 2009)
The occupancy profile was inputted from ASHRAE 90.1 office occupancy (ASHRAE, 2007)		Wall- Mass	U- value (w/m2-k)- 0.477
		Roof – Mass	U- value (w/m2-k)- 0.27
The density of the occupancy	18.58 m2/person	floor- Mass	U- value (w/m2-k)- 0.29
		HVAC system	
Metabolic, Clothing, Comfort radiant, Temperature weightage is as per ASHRAE 90.1 office occupancy (ASHRAE, 2007)		HVAC System	Air-cooled VRF system, COP- 2.5 for heating, 3 for cooling, No economizer.
Occupation Schedule	Monday to friday from 8:00 - 18:00 (Jan-Dec)	Mechanical ventilation schedule	7:00-18:00 from Monday to friday
		The Heating Set Point Temperature	20^0c with 13^0c set back as per ASHRAE 90.1 (ASHRAE, 2007)
Luminaire Type	surface mount fluorescent		
light power density	10.5 W/m2.	The Cooling Set Point Temperature	26^0c with 32^0c setback for work hours as per ASHRAE 90.1 (ASHRAE, 2007)
Daylight zone	Office zone and core zone		
Target illuminance level for office as per ASHRAE 90.1 (ASHRAE, 2007)	300 lux for office zone 100 lux for core zone	Lighting schedule - It is ON From 8:00-18:00, from Monday to Friday, but when the required amount of daylight is obtained, the lighting control will TURN IT OFF.	

4. Result and discussion

Data analysis was carried out at three different levels. 1. Merit-based analysis to understand the overall best and worst cases. 2. Regression analysis for evaluating the significance of the property of glass in total energy consumption. 3. Comprehensive study on the glass type and energy consumption was held.

Figure 4 shows that the total energy is not impacted by the building orientation since the building length and width make no difference in the 100 best cases (low energy consumption). As a result, 0-degree



orientation was used to test the glass's performance, and orientation was removed as a parameter from further analysis.

Figure 44:Orientation distribution from 100 best cases

4.1. Merit-based analysis

For Merit-based analysis, the total energy result was collected and arranged in ascending order to select the 100 best and 100 worst cases based on energy consumption. The best cases had the lowest total energy consumption, while the worst cases had the highest total energy consumption.

4.1.1 Hundred Best cases, hundred worst cases

According to Figure 5, out of 100 best cases, Dbl Loe(e2=1) was counted 46 times, followed by Sgl Clr glass 35 times which implies that Dbl Loe(e2=1) is the most energy-efficient glass type compared to the other glass types. Sgl Ref-A-H and Dbl Ref-A-H glass types have a lower count in best cases and high occurrence in worst cases (Figure 6), depicting the poor performance of the glasses type and the cause of high annual energy consumption.

The below best and worst cases indicate the best performance of WWR in different glass types. The best cases reveal that 50% and 70% WWR are performing better in Dbl Loe(e2=1) glass, while 30% is performing better in Sgl Clr glass (Figure 5). For Sgl Ref-A-H and Dbl Ref-A-H glass types to perform better, the WWR must be high, indicating the need for a high VT value for a low window-to-wall (Figure 6). The overall chart implicates that Dbl Loe(e2=1) and Sgl Clr glass types are more energy-efficient than Sgl Ref-A-H and Dbl Ref-A-H.

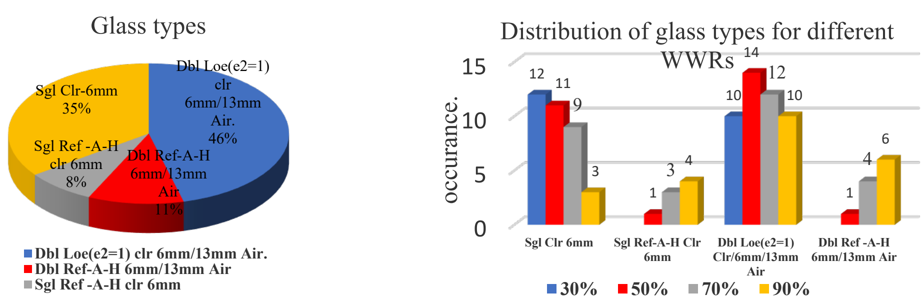


Figure 45: Best-cases glass type distributions (left) and distribution of glass types for different WWRs (right)

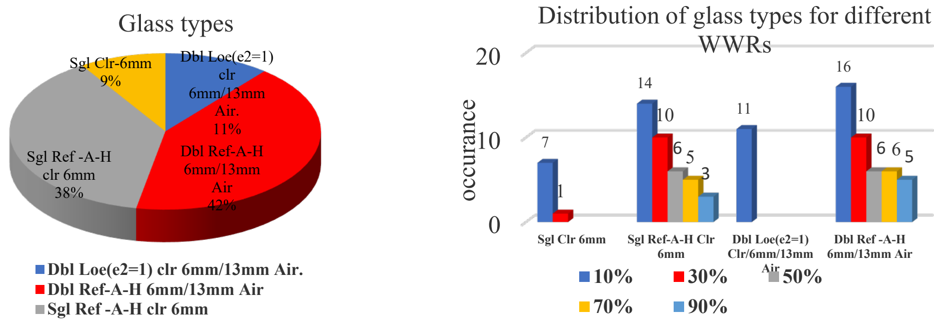


Figure 46: Worst cases glass type distributions (left) and distribution of glass types for different WWRs (right)

4.2. Regression Analysis

The regression analysis determines the strength of a relationship between independent and dependent variables. In this study, the dependent variable is the total energy consumption, whereas the independent variable is the glass's U-Val, SHGC, VT, and window-to-wall ratio. In a regression analysis, P-value determines the significance of the independent variables on the dependent value.

Table 1, Regression analysis displays WWR, VT, SHGC, and U-Val's P-values. WWR has the lowest P-value in the table, indicating that the parameter is highly significant in total energy consumption. However, since this research intends to identify energy-efficient glass types, VT, SHGC, and U-Val values are the focal points.

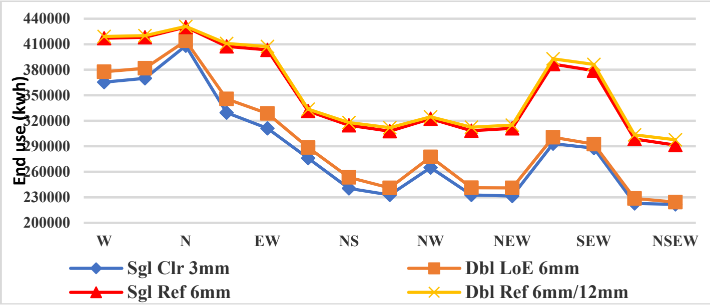
Table 24: Regression analysis

Opening distribution.	**Regression P-value**			
	WWR	VT	SHGC	U-Val
One side opening	4.7E-33	0.02	0.2	0.3
Two sides opening	2.0E-21	0.1	0.3	0.4
Three sides opening	1.6E-07	0.8	0.9	0.8
Four sides opening	0.03	0.6	0.6	0.8

VT is the most significant variable from glass properties, followed by SHGC to influence total energy, particularly in one side opening. The influences of opening distribution on individual P-values are visible in Table 3. As the opening side increases, all three variables become insignificant, as their P-values exceed 0.05. Once the required daylight is obtained, the lighting load becomes stable, and the impact of VT becomes insignificant.

4.3. Performance summary of glass type

This section examines glass performance for each WWR and opening distribution. The simulation result illustrates the energy performance of four glass materials for different WWRs and a list of openings. Each figure represents one window-to-wall ratio.

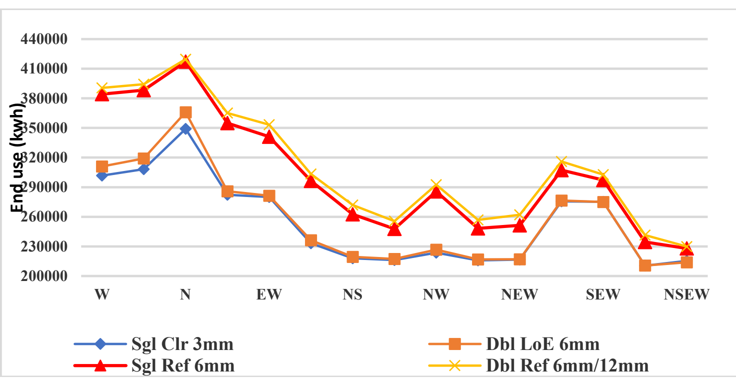


Glass type	The maximum energy consumption value	The minimum energy consumption value
Sgl Clr	408204.27	221688.06
Dbl Loe(e2=1) Clr 6mm/12mm Air	413975.96	224402.75
Dbl Ref-A-H 6mm/13mm Air	430982.91	297656.95
Sgl Ref -A-H Clr 6mm	430199.53	291377.68

Figure 47: Impact of glass type on the total energy – 10% WWR (left) and maximum and minimum energy consumption value - 10% WWR (right)

Figure 7 indicates the effect of altering the glass type in different opening distributions on total end-use. In general, 10% of WWR has the highest total energy consumption of all WWR. Total energy consumption is significantly affected by the change in the glass. The end-use energy consumption is reduced when Sgl Clr glass is used.

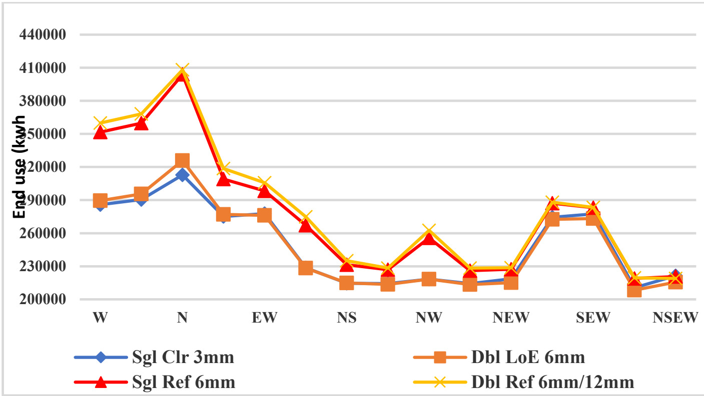
As shown in Figure 7, using Sgl Ref-A-H and Dbl Ref-A-H glass types increases the energy load. The energy consumption in the SW, SE, NEW, NSE, and NSEW opening distribution is low in Dbl Loe(e2=1) and Sgl Clr glass types.



Glass type	The maximum energy consumption value	The minimum energy consumption value
Sgl Clr	349089.5	210443.65
Dbl Loe(e2=1) Clr 6mm/12mm Air	366002.01	210615.55
Dbl Ref-A-H 6mm/13mm Air	419671.74	229837.53
Sgl Ref -A-H Clr 6mm	417175.53	227968.84

Figure 48: Impact of glass type on the total energy – 30% WWR (left) and maximum and minimum energy consumption value - 30% WWR (right)

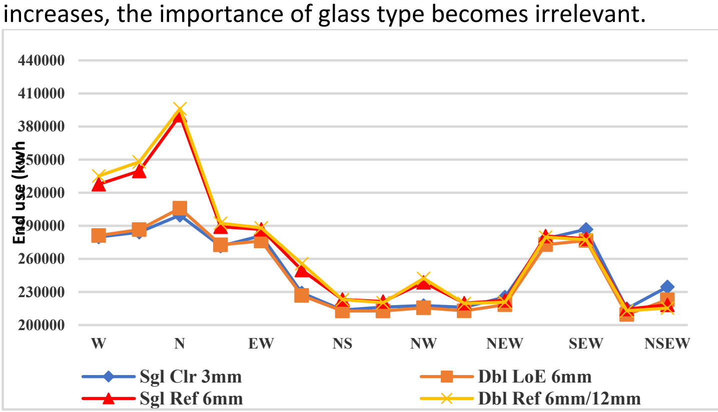
Figure 8 depicts the glass-type effect for a WWR of 30%. According to the figure, using Dbl Loe(e2=1) and Sgl Clr minimizes annual energy consumption, whereas using Sgl Ref-A-H and Dbl Ref-A-H increases energy usage. Opening distribution in NS, SW, NW, SE, NEW, NSE, and NSEW performs efficiently with Dbl Loe(e2=1), Sgl Clr glass type from other openings distribution.



Glass type	The maximum energy consumption value	The minimum energy consumption value
Sgl Clr	312798.05	210554.33
Dbl Loe(e2=1) Clr 6mm/12mm Air	325846.21	208347.92
Dbl Ref-A-H 6mm/13mm Air	408136.41	218978.16
Sgl Ref -A-H Clr 6mm	403899.64	218955.47

Figure 49: Impact of glass type on the total energy – 50% WWR (left) and maximum and minimum energy consumption value - 50% WWR (right)

In Figure 9, the NSE and NSEW opening distributions show that all glass types have similar energy performance, implying that the significance of glass type decreases when the required daylight is obtained in three and four sides openings. Regression analysis also revealed that as the distribution of openings increases, the importance of glass type becomes irrelevant.

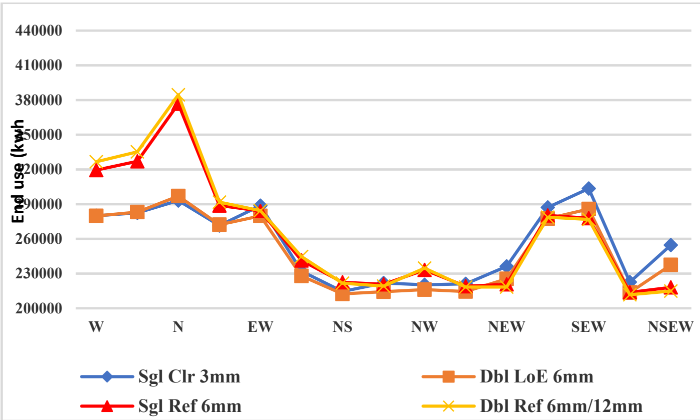


Glass type	The maximum energy consumption value	The minimum energy consumption value
Sgl Clr	299527.6	213575.22
Dbl Loe(e2=1) Clr 6mm/12mm Air	305898.57	209565.13
Dbl Ref-A-H 6mm/13mm Air	396260.95	212944.65
Sgl Ref -A-H Clr 6mm	390210.39	214433.68

Figure 50: Impact of glass type on the total energy – 70% WWR (left) and maximum and minimum energy consumption value - 70% WWR (right)

Figure 10 displays a minor change in energy consumption, and Dbl Loe(e2=1) glass improves annual energy use in some opening distributions.

Figure 11 reveals how all-glass types perform similarly in two-sided openings. Furthermore, for WWRs of 50% and higher, Sgl ref and Dbl ref glass in four-side openings consume less energy; this is because once the required daylight is attained, the glass property significance diminishes, and lighting consumption becomes consistent while the heating and cooling loads cause minor changes.



Glass type	The maximum energy consumption value	The minimum energy consumption value
Sgl Clr	303469.74	214506.3
Dbl Loe(e2=1) Clr 6mm/12mm Air	296958.69	212431.9
Dbl Ref-A-H 6mm/13mm Air	384545.64	211716.71
Sgl Ref -A-H Clr 6mm	376696.38	213728.04

Figure 51: Impact of glass type on the total energy – 90% WWR (left) and maximum and minimum energy consumption value - 10% WWR(right)

In all the given charts, it is clear that The window opening distribution significantly contributes to total energy use. Based on the charts, one side opening, specifically the north side opening, substantially increases total energy consumption due to the high lighting load. Two and three-side openings are the most energy-efficient opening distribution. For 30% and above WWRs, openings in NS, SW, NW, SE, NEW, NSE, and NSEW are energy-efficient opening distributions.

All window-to-wall ratio indicates that Dbl Loe(e2=1) and Sgl Clr provide low annual energy consumption. The physical parameters of Dbl Loe(e2=1) and Sgl Clr glass are as follows: Dbl Loe(e2=1) has a low U-Val with medium SHGC value and a high VT (1.772, 0.563, 0.745), whereas Sgl Clr has a high U-Val with high SHGC and a high VT (6.121, 0.881, 0.810). Despite the different U-Value, both glass types have a high VT and perform better in various WWR and opening distributions. It indicates that the light load has a more noticeable impact on annual energy consumption than the heating and cooling load.

The physical properties of Sgl Ref-A-H (U-Val - 5.36, VT- 0.201, SHGC- 0.277) and Dbl Ref-A-H (U-Val- 2.449, VT-0.181, SHGC- 0.216) show a high annual energy consumption. This glass type has a wide range of U-Values, low VT, and SHGC, contributing to a rise in annual energy consumption. The SHGC value does not impact the total energy consumption significantly. SHGC and VT values are correlated glass properties in which the increase of VT value parallelly affects SHGC value. However, based on earlier studies, it is clear that more than SHGC, VT significantly impacts total energy consumption, especially on insufficient lighting openings.

5. Conclusion

The study concludes that the VT value influences energy consumption more than the SHGC and U-Value. The end-use energy will be high if the glass has a low VT. The plotted result (Figure 7-11) illustrates that Dbl Loe(e2=1) and Sgl Clr glass performed efficiently in all different WWR and opening distributions. However, Sgl Ref-A-H and Dbl Ref-A-H glass types were the cause of high energy consumption due to low VT values. It can be concluded that glass with high VT should be preferred for the Addis Ababa office building. If cost were considered, the Sgl Clr glass type would be the most efficient, but in high WWR (70% and 90%), due to direct solar radiation Dbl Loe(e2=1) is the better choice. Shading is one solution for direct solar radiation, but more research is required to consider the lighting load and shading device types. The following table recommends VT value considering WWR and opening distribution.

Table 25–Recommendation of energy efficient glass type for Addis Ababa office building.

WWR	Preferable opening distribution	Min VT	Max SHGC	Max U-Value (W/m^2. K)
10%	SW, SE, NEW, NSE, NSEW	0.7	0.81	6.1
30% - 50%	NS, SW, NW, SE, NEW, NSE, NSEW	0.7	0.81	6.1
70% - 90%	NS, SW, NW, SE, NEW, NSE, NSEW	0.7	0.81	5.3

Acknowledgments

This research was done for a master's program at the India institute of technology, Department of Architecture and Urban planning, with the sponsorship of the "study in India scholarship" program.

Reference

Alghoul, S.K., Rijabo, H.G. and Mashena, M.E. (2017) 'Energy consumption in buildings: A correlation for the influence of window to wall ratio and window orientation in Tripoli, Libya', *Journal of Building Engineering*, 11, pp. 82–86. doi:10.1016/j.jobe.2017.04.003.

Amaral, A.R. *et al.* (2016) 'A thermal performance parametric study of window type, orientation, size and shadowing effect', *Sustainable Cities and Society*, 26, pp. 456–465. doi:10.1016/j.scs.2016.05.014.

Ashrae, A./ and Iesna Addenda, / (2009) 'ANSI/ASHRAE/IESNA Addenda a, b, c, g, h, i, j, k, l, m, n, p, q, s, t, u, w, y, ad, and aw to ANSI/ASHRAE/IESNA Standard 90.1-2007', 4723.

ASHRAE. (2007) '90.1 User Manual—Energy Standard for Buildings Except Low-rise Residential Buildings. ASHRAE.

Asres, G.A. (2021) 'Renewable Energy Potential, Energy Access, and Climate Change Mitigation in Ethiopia', *Handbook of Climate Change Management*, pp. 2603–2625. doi:10.1007/978-3-030-57281-5_310.

British Fenestration Rating Council (no date) Energy performance, Bfrc.org. Available at: https://www.bfrc.org/energy-performance (Accessed: 22 June 2022).

Carmody, J. and Northernstar, K.H. (2012) *Measure Guideline: Energy-Efficient Window Performance and Selection*. Available at: www.ntis.gov/ordering.htm.

Cuce, E. and Riffat, S.B. (2015) 'A state-of-the-art review on innovative glazing technologies', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 695–714. doi:10.1016/j.rser.2014.08.084.

DesignBuilder Software Ltd - Home (no date). Available at: https://designbuilder.co.uk/ (Accessed: 22 June 2022).

Ethiopia: When to Visit - Journeys by Design (no date). Available at: https://journeysbydesign.com/destinations/ethiopia/when-to-go (Accessed: 25 June 2022).

Gasparella, A. *et al.* (2011) 'Analysis and modelling of window and glazing systems energy performance for a well insulated residential building', *Energy and Buildings*, 43(4), pp. 1030–1037. doi:10.1016/j.enbuild.2010.12.032.

Haileleul, T. (2015) 'Evaluation of Selected Addis Ababa Buildings with respect to the Green Building Features Title of Thesis : Evaluation of Selected Addis Ababa Buildings with respect to the Green Building Features', p. 167.

jEPlus - Parametrics for E+ and TRNSYS download | SourceForge.net (no date). Available at: https://sourceforge.net/projects/jeplus/ (Accessed: 24 June 2022).

Kottek, M. *et al.* (2006) 'World map of the Köppen-Geiger climate classification updated', *Meteorologische Zeitschrift*, 15(3), pp. 259–263. doi:10.1127/0941-2948/2006/0130.

Mondal, M.A.H. *et al.* (2018) 'Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions', *Energy*, 149, pp. 161–172. doi:10.1016/j.energy.2018.02.067.

Paulos, J. and Berardi, U. (2020) 'Optimizing the thermal performance of window frames through aerogel-enhancements', *Applied Energy*, 266. doi:10.1016/j.apenergy.2020.114776.

Yüksek, I. and Karadayi, T.T. (2017) 'Energy-Efficient Building Design in the Context of Building Life Cycle', in *Energy Efficient Buildings*. InTech. doi:10.5772/66670.

Impact of existing building air-conditioning retrofit on cost, COVID-19 transmission and energy

Dominique Hes [1], Jason Monty[2], Grant Skidmore[3] and Liam McGregor[4]

[1] *City of Melbourne, Melbourne, Australia;*
[1]*dominique.hes@melbourne.vic.gov.au, ORCID-0000-0001-6495-9059*[1]
[2, 3, 4] *The University of Melbourne, Melbourne, Australia*

Abstract: The BREATH (Building Retrofit for Efficiency, Air quality, Thermal comfort and Health) project was a research pilot led by the City of Melbourne in partnership with Cbus Property, the University of Melbourne, AG Coombs, SEED engineering, AURECON and Westaflex. It was a rapid retrofit project that tested various air conditioning and ventilation retrofit options with the express purpose of reducing airborne particulates and infection transmission, but also considering the energy and cost consequences. The work was undertaken within an existing building. Open windows, conventional air conditioning, ceiling-mounted HEPA filters, and displacement ventilation were included in this initial pilot. Personal air was also showcased but not integrated into the overall research. Results indicate that some recommendations to reduce transmission may have impacts on power demand. Leaving the windows open on a floor of the 10-story test building led to an estimated 12% increase in air conditioning energy consumption. The best option for reducing transmission risk and improving energy consumption appeared to be a low-level displacement supply air system; provided the workers exercised social distancing and the stratified room temperature profile was maintained. The lower energy consumption of displacement ventilation was estimated to increase the NABERS rating of the building by 0.5 stars. The most cost effective and simplest approach to improvement was in-ceiling fan filtration units, these reduced transmission risk with minor increases in energy consumption if appropriately dimensioned. This paper looks at what these possible interventions mean for office buildings retrofit improvement.

Keywords: Air Quality, HVAC, Energy and cost.

1. Introduction

The primary objective of this pilot study project was to examine, for the first time, the impacts of the energy demand of various building ventilation retrofit options that could be used to reduce the risk of aerosolised viral spread. Particular attention was paid to the potential health implications and energy usage for each option, while considering the level of comfort of the occupants (to the best of our ability without human subjects).

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 339–349.*

This paper details the results from the experiments, summarises the insights gained, and provides recommendations for what this could mean for building retrofit and future research. Before presenting the results and conclusions, the paper outlines the approach, assumptions, and data models that used.

The literature and experience have shown that how a buildings air-conditioning works is a significant contributor to the spread of aerosolised viruses (see review of all paper written since 2007 in Thornton *et al*., 2022; and from a medical perspective Correia e*t al.,* 2020).

A recent paper looking at the impact of the ASHRAE recommendations to minimise COVID-19 transmission looked at the recommendations of increased air rate changes, flushing buildings, no recirculation and HEPA filter machines, showed a potential jump of 30-50% in energy consumption (Aviv *et al*. 2021). For Melbourne for all the metropolitan office buildings this would mean a potential increase of up to 420Gwh of energy and 419,022tonnes CO2e (11% increase) (City of Melbourne, 2020).

For well insulated buildings, it has been established in the literature that for well insulated buildings, ventilation loses are the main cause of energy loss (Stabile *et al.*, 2019). Thus, one would expect for a given building configuration (in terms of insulation), a ventilation retrofit would provide the largest remaining energy savings.

For residential buildings, Kang *et al.* 2022 found that ventilation retrofits can improve indoor air quality by a statistically significant amount, for a relatively minimal upfront cost (maximum of US$4222, with an average total cost of US$2,346). This study was conducted over two years, with one year as a baseline and one year in the retrofit configuration. While the energy analysis from that study is forthcoming, it does highlight that relatively cheap ventilation retrofits can lead to large improvements in indoor air quality.

There are options for healthy retrofits though that can turn this increased impact into a decreased outcome. Using available technology it is possible to rapidly retrofit commercial buildings to use the displacement and radiant thermal comfort options. This could reduce energy consumption but significant amounts, improve comfort, productivity and a sense of safety (Aviv *et al.* 2021). Meanwhile providing jobs for installing the systems and further economic activity around the production of the technology.

In the review of the literature there were no papers of experiments that looked at COVID-19 transmission, clean air provision and energy use for commercial buildings. Given the urgency of this problem, it was a pilot study was proposed examining one floor of a building in Melbourne.

2. Methods

2.1 Experimental Details

The building was 423 Bourke Street, owned by Cbus Property, the project team where given access to the building early in February 2022, a short-term peppercorn lease was agreed on with all the usual tenant requirements. Two floors were used for the study, the tenth floor to test the real-world context of how air moves in a space based on the existing HVAC system. The space has office spaces, meeting rooms, desks, partitions, and all the normal office furniture. The first floor was vacant of furniture and a last 356m^2 space where four conditions could be tested:

- baseline vacant operation (full floor)
- open window operation (full floor)
- in-ceiling HEPA filtered operation (1/2 floor north section)
- column based displacement ventilation operation (1/3 floor south-east section)

2.1.1. Baseline Vacant Operation (full floor)

To start with, the experiment determined the baseline power usage of the vacant space as well as the equivalent-air-change-per-hour (ACHe), value of the space before retrofit modifications were made. The research methods used in this pilot were to collect data on air changes using the aerosol clearance method (*Lee et al.* 2022) and directly measure energy consumption of the chiller with a non-contact ammeter. The aim was to enable a determination of the correlation between chiller power usage and air-conditioning power needs in response to space needs.

The existing HVAC system included a Turbocor TT300W-100-H6 using R22 as coolant for the chiller, air provided through constant delivery, through a standard ceiling duct lay out with supply diffusers in the ceiling and extraction through the ceiling cavity. The weather for the site for Feb-May 2022 was moderate for a South-Eastern Australian summer; with daily high-temperatures for those days experiencing a maximum-high of 38°C, minimum-low of 11°C, average of 22.4°C, and standard deviation of 4.9°C.

The space was vacant, so the energy contribution of people and equipment was created through discrete heat sources. The discrete heat sources were large buckets of water, with commercial aquarium water heaters. The heat load added to the space was a total of 1600Watts evenly distributed throughout the space (on chairs to simulate seated person height). This was determined as a good proxy for the heat emitted by 10 people; each person emitting approximately 80-100 Watts and an additional 60-80 Watts per person for IT equipment.

Specifically, the 1600Watts of heat was generated through two 300Watt and five 200Watt aquarium heaters. These heaters were set to their maximum temperature setting which they were not able to achieve with the volume of water they were submerged in, hence constantly outputting their rated maximum heat.

2.1.2. Open Window Operation (full floor)

The project was specifically interested in the ASHRAE and other recommendations around opening windows, increasing air changes and flushing the building. Given the pilot nature of the research, the fact that building was being demolished within three months of the research starting. Further, that there were still tenants on some floors of the building and there was a limited budget, the research team determined that the recommendation that has the highest correlation between energy and infection transmission risk was opening the windows. Therefore, the component investigated was opening windows and running the HVAC system to meet comfort conditions. The data gathered allowed the impact of opening windows to be examined while leaving the HVAC running in its standard operating mode, in this case 19-21% outdoor air and the remainder recycled indoor air.

The building had a more than typical percentage of wall space of operable windows. As such every-other-window on East-facing wall was opened (resulting in eight 1.0-m by 1.6-m windows being opened) to meet the ~4% floor area window-opening guideline. Windows were opened on only one side of the building prevented crossflow, which is known to markedly increase air exchanges, but is rare in commercial buildings. Further, to the east of the building, there is another building less than 10 meters away sheltering the research building from easterly winds.

Part of the research intent was to be realistic and effective for industry decision making, the research team calculated preliminary high-level costs and pay back calculations based on capital, operational and maintenance expenditure and energy use. Factors not considered were health, absenteeism, productivity, and other associated savings from improved indoor air quality. For the case of opening the windows the assumption was that there were no upfront costs, acknowledging that if a building without operable windows wanted to consider this option there would be significant costs in retrofitting the façade.

2.1.3. In-Ceiling Filtered Operation (1/2 floor)

The research design initially aimed to install five locally made fan-driven HEPA filter units mounted into the ceiling to filter the air. However, because of the realities of running a real-world experiment in a working building it became necessary to run the displacement and the in-ceiling experiment concurrently. This resulted in three units being used. The spaces were divided by floor-to-ceiling construction plastic.

In assessing the existing ducting and HVAC system it was found that there was not an even distribution of air supply. The implications, therefore, for splitting the experiment was that air change rates in each of the sections were different, requiring the researchers to collect data on the air changes for each sub-space. Direct comparison of the three conditions was not possible for this reason, so linear scaling for each condition was employed.

The in-ceiling HEPA units were low power devices (measured at 60-Watts), equivalent to the fan/filter power of a portable HEPA filters but allowing BMS integration, making them a more commercial and generally applicable solution to the problem of increasing the ACHe. The filters in the in-ceiling HEPA units need ongoing replacement to ensure their effectiveness and this was taken into account in the calculations of the cost of this option.

2.1.4. Displacement Ventilation Operation (1/3 floor)

The air-conditioning partner for the research was A.G. Coombs. They conducted HVAC system measurements and designed and installed the displacement units. Displacement systems do not require air to be supplied at the same temperature as mixed ventilation systems. For this reason the air was introduced at 20◦C at floor level. The air coming from the mixed system at the ceiling level was measured at 18◦C, this is higher than usual mixed ventilation supply air which is usually 14-16◦C depending on system design, ceiling height, etc.

2.2. Experimental Approach

The baseline air changes per hour measurements were carried out over four days taking three measurements a day. The intention was to take these readings consistently in the morning, mid-day, and close-of-business. During these readings the research team recorded effective-air-changes-per hour reading as well as temperature readings of the space. The purpose of these three readings were to capture any changes in the space as the outside temperature changes. Due to the short duration of the experimental campaign, the intention of this period was to capture different weather conditions over the four days. For outdoor ambient air temperature the research team used meteorological data, external conditions were reported in the building management system, but the data was incomplete.

2.3. Limitations of the study

There were many elements of this pilot project which need to be considered in reviewing the results. Below each of the elements is discussed and how the research team worked to still ensure outcomes have validity and reliability. In summary this was a pilot project intended to inform industry, working in a real building, with the limitations of non-laboratory and controllable variables.

One of the main limiting factors was that the building was still occupied on several floors. This meant that altering the air handing and comfort systems of the buildings was limited. For the displacement ventilation component the supply air needed to be increased, but as this would increase the (centrally controlled) supply air for all tenants, measurements could only be taken in the mornings before tenants arrived. The tenants also worked across some of the weekends, eliminating the option of weekend 9am-5pm testing.

The second limiting factor was the research was being conducted during the first months of 2022 where COVID-19 was still having significant disruptive impacts on part of the experiment. This added to the need to be agile in research adaptation to whatever problem arose. The hard deadline of the building being demolished did not change, so any COVID induced delay potentially limited data collection. Key problems were supply shortages of the in-ceiling system which meant that the suppliers and researchers had to create an adapted version that was not able to sit flush with the ceiling as was intended.

The third aspect that is of note is that as the building was being decommissioned, so management response was at times not conducive to timely data collection. Several times fire alarms were triggered shutting down the HVAC systems at critical research times and taking significant time to be reset.

All of these impacted the ability to be consistent in the research design realisation of 4 days of measurements of each condition, three times per day. The research team adapted the research so that the other conditions, Displacement Ventilation and In-Ceiling HEPA data readings were taken as the space was available/possible:

- For the displacement ventilation, as the supply air temperature had to be increased, the measurements were taken early in the morning (between 0700 and 0900) on the mornings of 07Apr22, 08Apr22, and 19Apr22.
- For the in-ceiling HEPA measurements, these were taken when the space was available and free.

The implications were that there was limited impact on the air changeover measurements, but they did have an effect on power use. The strategy applied to correct for this was scaling the results up to have a full floor's worth of in-ceiling HEPA and displacement ventilation units in both costing and power.

2.4. Measuring air change rates

To measure the ACHe the experiments used an ultra-low-volume (ULV) fogger to generate 0.1-10-μm diameter aerosols (with a mean diameter of approximately 5-μm). The testing aerosol fluid for most of these measurements was salt-water. In order to prepare the aerosol, the salt was dissolved into room-temperature water until the water was not able to absorb any further salt. The salt water was then spread throughout the space using a Longray Electric Portable ULV 3600E. For some measurements, the research team employed propylene-glycol based theatrical-fog as the aerosol where the intention was to capture explanatory photos or to demonstrate to the partners. Critically, for these tests the building needed to be isolated, that is the building manager needed to turn off the smoke sensors and the Melbourne Fire Brigade needed to be notified.

To carry out the ACHe measurements, a TSI DustTrak DRX aerosol monitor was used. This measured the mass density of aerosol in the space. This started at zero then the ULV fogger was used to fill the space with saline aerosols as the researchers walked around the test space ensuring uniform seeding density. This led to a large aerosol density reading on the DRX device. The measurements then continued to run until the device read 99% of the peak reading value (or lower). This was then used with the following equation (1):

$$ACHe = -ln\,(0.01)\,/\,Time\ for\ 99\%\ of\ clearance\ (hrs) \qquad (1)$$

For the in-ceiling HEPA and displacement ventilation tests, a second TSI device was added, the DustTrak II aerosol monitor. This device also measured the mass density of aerosol. For these two conditions results were measured for both seated and standing height of a simulated office worker, 1.1-m tall when seated and 1.7-m when standing.

Initially, to look at the thermal profile and stratification of the space, the researchers used a thermal imaging camera to take a vertical temperature profile of a column (for the Baseline and Open-Window tests). It was found that there was no discernible temperature profile and found the thermal imaging camera compared well with the BMS temperatures of the space. This has the benefit that at one of the shutdown periods where there was no BMS data the IR camera was able to provide the needed data.

For the displacement ventilation testing, the researchers constructed a vertical array of Protech QM1601 thermocouples. This was built because the accuracy of the thermal profile was a critical piece of information for the displacement ventilation research.

2.5. Power Usage Assumptions and Measurements

In order for the researchers to estimate power for the space, a series of observations and assumptions were made. First, it was observed that the supply fan was always running (except when the system is in an error-state). Because of this, an assumption was made that there was a constant power draw from the supply fan, enabling it to be left of the calculations as it was constant. Secondly, because the testing occurred during summer and late autumn, heating did not impact energy consumption. From these two observations/simplifications, the power usage for the case study was determined and that this power was driven by the chiller.

As mentioned above the building had a Turbocor TT300W-100-H6 using R22 as coolant for a chiller. This chiller has had its power assessed as part of the "Danfoss Turbocor Compressors Retrofit Performance Data Worksheet 2005-08". The power output values given were: 92.0, 46.9, and 28.8 kW of power input for running at 100, 75, and 50 percent capacity, respectively. This data was used to generate an exponential power curve with the following equation (2):

$$P[kW] = 8.7403 * exp\,(0.0232 * CapacityValue\ [\%]) \qquad (2)$$

The measurements taken by the researchers generally agreed with the curve as they were able to time amperage measurements with the BMS chiller load value. They were able to perform a sanity check on these values using a clip-on amperage meter and assuming a constant 0.7-kV voltage for the device to calculate power experimentally. For a few instances where this was checked, the measured power roughly matched the value from the literature; hence considering the greater accuracy for the literature, the literature values were used. This enabled the researchers to estimate power usage across the experiments.

Firstly, they measured the first floor while the system operated normally without intervention. For these days they correlated meteorological conditions with chiller usage and found the best correlation was with the three-day running high temperature (Figure 1). This figure also shows a plotted line of best fit for power usage for days the Open-Window configuration. Using external conditions to estimate chiller usage enabled the research to extrapolate for the days where building data was missing.

Building on Figure 1a for energy use the researchers added the energy implications of the In-Ceiling HEPA units at 60 Watts each or 300 Watts for the floor adding 7.2-kW-hr a day to the baseline state. For Displacement Ventilation, the BMS set point for air coming from the diffusers was increased from 18◦C to 20◦C that is, running the systems at 2◦C warmer. These curves together are plotted in Figure 1b.

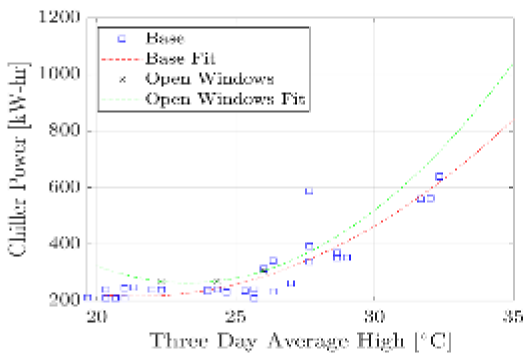


Figure 1a: Correlation between average high temperature and kW-hr used by the chiller

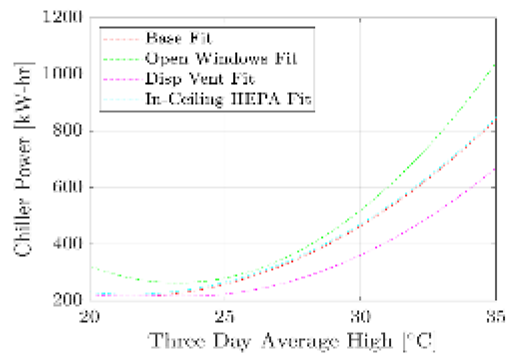


Figure 1b: kW-hr used by the chiller versus average high temperature curves for all cases considered

2.6. Cost Assumptions

To develop the simple cost benefits aspects of the research reporting, the researchers used the Australian Energy Regulator's November 2021 report on energy costs $0.28/kW-hr (AER 2021). Though the AER report speaks to residential prices, in checking with Cbus Property they reported it was at the high end of what they pay, a sensitivity was done to see impact of this on the pay back values.

Costs for the various retrofit options where: for the in-ceiling filtration, $1000 per system (x5) with a $500-$1000 a year maintenance cost to replace the filters ($500 with assumption of in-house installer and $1000 for contracted installer); and the costs for the column-based displacement retrofit was $60,000.

3. Experimental results and discussion

3.1. Equivalent Air Changes per Hour

3.1.1. Base line

The clearance plots for all baseline cases performed had some variation from run to run. Removing the outliers from these runs left the median cases that were similar enough that they could be averaged to get a sense of what a typical run looks like. Considering how many runs repeated within this range, this set of runs (and the average of their output) is considered the "true" baseline. That is, the average ACHe of the first floor of the test building is 9.1.

However, the variability of these runs does highlight an important point, despite the nearly identical conditions in the space, there was quite a bit of scatter for each run. In order to avoid biased results, the researchers excluded both the fastest and slowest runs and focus on the median tests for a given condition.

3.1.2. Open Window

For the open windows measurements there was more deviation in these runs than the baseline. The reason for this was the differing outdoor conditions (wind direction, wind speed, pressure, etc.) from run to run. The ACHe ranged from 12.8 to 77.5. Using the same approach as above the average ACHe was determined to be 20.4.

That is opening windows is an effective way of increasing the air changes (ACHe) in a space, impacting infection transmission by reducing aerosols as they are removed from the space. This is why organisations such as ASHRAE recommend opening windows. Yet as an option, this has implications on energy consumption, thermal comfort and may not be practical.

3.1.3. In-ceiling HEPA

For the In-Ceiling HEPA experiment, where the space was subdivided the first task was to measure a new baseline ACH of the space. Note that for the In-ceiling HEPA and Displacement Ventilation systems, volumetric flow rates were used rather than directly measuring the clearance time. This was because for the Displacement Ventilation option it was not possible to measure the base airflow rate of the subspace until after the retrofit had occurred. For the In-Ceiling HEPA half of the room, ACH value was 5.0 and with the in-ceiling HEPA filtration increased the average ACHe to 10.9.

3.1.4. Displacement ventilation

As mentioned, these tests required changing set points which would have impacted existing tenants in discussion with all involved it was decided to run the Displacement Ventilation tests between 0700 - 0900 on 07Apr22, 08Apr22, and 19Apr22. Enabling six full tests to be carried out.

The results showed that importance of having the right temperature profile. When this was not present the air clearance was severely impacted. Of the experiments, two did not have the correct temperature profile (top lines) because the HVAC had switched to standard operation earlier than anticipated. When this occurred, the air was cooled to a point where the installed heat load was not able to generate the requisite thermal gradient for Displacement Ventilation to operate as designed for this retrofit. These were not included in the generalised results.

The second was the impact of seated versus standing height. Based on the rate of airflow into this part of the space, we calculated an ACH of 7.4 for this portion of the room, average ACHe for seated height is 11.8 minutes and for standing 9.2. The reason for this difference is that the air is entering the space from the floor level of the room and moving up, losing momentum as it spreads and exits the room.

3.2. Quantifying Infection Risk

Infection risk is impacted by many factors, beyond what can be captured by an equation, for example, where one sits in an office, how often one walks around, how many people are in a space, and many factors that cannot be accounted for in an experiment as outlined in this paper. The calculator used came from the work of Jimenez and Peng (2022) based on the transmission of COVID19-Omicron B1.

In addition to the above limitations, the most pertinent limitation of this calculator is that it was designed for standard mixed ventilation; therefore, assumptions were needed to ensure it aligned with this real world application. For clarity and reliability, assumptions were discussed in the full report of the research (Skidmore et al. 2022), and were sense tested with the industry reference group involved in the project. Further, this was peer reviewed by AURECON. Table 1 summarises the ACHe improvements, Table 2 the transmission reduction results.

Table 26: ACHe improvements for each control. Baseline is the measured clearance rate in the space before the intervention (control). ACHe different for each, as space were different sizes

Control Name	Baseline *ACHe*	Control *ACHe*
Open-Window	9.1	20.4
Disp Vent (seated)	7.4	11.8
Disp Vent (standing)	7.4	9.1
In-ceiling HEPA	5.0	10.9
In-ceiling HEPA (no HVAC)	N/A	6.6

Table 2: Number of secondary infections based on COVID estimator tables

Control Name	Baseline	Control	Change	Reduction %
Open-Window	0.49	0.25	0.26	53
In-ceiling HEPA	0.8	0.41	0.39	49
Displacement Vent	0.58	0.1	0.48	83

3.3. Summary of all the results

Bringing all the results together (table 3), each option reduces transmission risk. If an organisation is aiming to reduce energy, improve occupant wellbeing and reduce transmission then the displacement ventilation retrofit presents the best options. There are significant benefits and limitations to this option though which is beyond the scope of this paper to discuss. The in-ceiling filtration gives a good balance between providing reduced transmission and practicality, with its integration in to the BMS offering the ability to manage it centrally, increase and decrease as needed and cost. It’s only downside being an ongoing maintenance cost.

Table 3: Summary of the results for the three tested options.

System	Impact on transmission	Cost be m2 (AUD)	Energy use – $/m2/yr	Energy
Open windows with standard HVAC operations	~53% less infections	Nil (however few office spaces have openable windows)	Costs $6/m2 per year	10-20% increase
In-ceiling air cleaner HEPA Filtration units	~49% less infections	$28m2 + $1.5-3/m2/yr maintenance costs	Saves $4.21/m2 per year	2% increase
Displacement Ventilation air conditioning	~83% less infections	$170m2 – no additional ongoing maintenance costs	Saves $10.67/m2 per year	10-20% decrease

4. Conclusion

This was a rapid research project that was enabled by the critical need for information to support building owner decision-making around building retrofit, transmission of COVID-19 and energy costs. With the limitations of the time, funding, the use of a real-world context, COVID-19 interruptions and so forth, this research aimed to give a sense of existing building options in regard to air provision in terms of COVID-19 transmission, energy use and cost of implementation. Providing safe places for people to live and work is critical, and this does not necessarily have to come at the cost of energy consumption and associated carbon legacy - this is missing from the current literature.

This paper shows that all options examined will improve worker safety from aerosolised viruses. In terms of increasing the effective air-changes-per-hour (as a surrogate for safety), the control order from best to least effective was open-window, in-ceiling HEPA, and displacement ventilation. Though air changes is a good surrogate, in the case of displacement ventilation that provides a different type of ventilation, the benefits are not directly attributed to air changes, but as related to the physics of warm air rising reducing the distance aerosolised viruses travel. Thus, in terms of the decreased risk of modelled infection, displacement ventilation was most effective with open-window and in-ceiling HEPA options approximately equally effective at reducing modelled infection risk.

For architects the current market is shifting from new buildings to reusing existing buildings, there are a great deal of design challenges associated with this, and providing an effective design that works with the options provided in this paper is a critical part of the tool kit.

Acknowledgements

The research was carried out on the lands of the Wurundjeri Woi Wurrung and Bunurong Boon Wurrung peoples of the Eastern Kulin Nation. This project was funded by the City of Melbourne, the building was provided by Cbus Property and research supported by the installation partners AG Coombs, Westaflex and Seed Engineering. With thanks to the industry reference group that included Integral Group, Cundall, AirMaster, Northrop and peer review by AURECON.

References

Aviv, D., Chen, K.W., Teitelbaum, E., Sheppard, D., Pantelic, J., Rysanek, A. and Meggers, F., 2021. A fresh (air) look at ventilation for COVID-19: Estimating the global energy savings potential of coupling natural ventilation with novel radiant cooling strategies*. Applied Energy*, 292, p.116848.

City of Melbourne (2020) CLUE database. Available from: Open Source Repository < https://www.melbourne.vic.gov.au/about-melbourne/research-and-statistics/city-economy/census-land-use-employment/Pages/clue-data-reports.aspx> (accessed 13 July 2022).

Correia, G., Rodrigues, L., Da Silva, M. G., & Gonçalves, T. (2020). Airborne route and bad use of ventilation systems as non-negligible factors in SARS-CoV-2 transmission. Medical hypotheses, 141, 109781.

Jimenez, J. L. and Peng, Z. (2022) COVID-19 Aerosol Transmission Estimator. Available from: Open Source Repository < https://tinyurl.com/covid-estimator> (accessed 13 July 2022).

Kang, I., McCreery, A., Azimi, P., Gramigna, A., Baca, G., Abromitis, K., ... & Stephens, B. (2022). Indoor air quality impacts of residential mechanical ventilation system retrofits in existing homes in Chicago, IL. *Science of The Total Environment*, *804*, 150129.

Lee, J.H.; Rounds, M.; McGain, F.; Schofield, R.; Skidmore, G.; Wadlow, I.; Kevin, K.; Stevens, A.; Marshall, C.; Irving, L.; Kainer, M.; Buising, K.; and Monty, J. 2022, Effectiveness of portable air filtration on reducing indoor aerosol transmission: preclinical observational trials. *Journal of Hospital Infection*, 119, p. 163-169.

Skidmore, G.; McGregor, L.; Rounds, M.; Kevin; and Monty, J. (2022) BREATH (Building Retrofit for Efficiency, Air Quality, Thermal Comfort and Health) Research Project: Deliverable # 2 (2022) Unpublished report. Available from: Open-Source Repository <https://www.melbourne.vic.gov.au/building-and-development/sustainable-building/pages/healthy-energy-efficient-buildings.aspx> (accessed 13 July 2022).

Stabile, L., Buonanno, G., Frattolillo, A., & Dell'Isola, M. (2019). The effect of the ventilation retrofit in a school on CO2, airborne particles, and energy consumptions. *Building and Environment*, *156*, 1-11.

Thornton, G. M., Kroeker, E., Fleck, B. A., Zhong, L., & Hartling, L. (2022). The impact of heating, ventilation and air conditioning (HVAC) design features on the transmission of viruses, including SARS-CoV-2: an overview of reviews. medRxiv, 2021-09.

Impact of the courtyard on the energy performance of conditioned office buildings in Dhaka, Bangladesh

Urmi Sarkar[1] and Avlokita Agrawal[2]

[1, 2] Indian Institute of Technology Roorkee, Uttarakhand, India
{u_sarkar[1], avlokita[2] }@ar.iitr.ac.in

Abstract: The challenge for building design is to maintain comfort inside while the weather outside changes unexpectedly. Therefore, air conditioning (AC) has become an essential component in office buildings as it provides a comfortable indoor environment while also being the primary source of energy consumption growth. Recent studies have emphasized the application of courtyard as a passive design strategy to reduce building energy use in tropical climates, particularly for cooling demand. Unconditioned buildings usually have a positive impact on courtyard design. This study investigates the effectiveness of courtyard design for a fully air-conditioned and mixed-mode naturally ventilated office building in the tropical context of Dhaka, Bangladesh. A typical office building model was developed using Design Builder software, according to the ASHRAE 90.1 standard. Both scenarios fully air-conditioned building and change over mixed-mode control ventilation (same space in different times) were compared in terms of total end-use to observe how the courtyard affected total energy performance. The courtyard was combined with several passive envelope design strategies, including insulation in the wall and roof, shading on the roof, self-shading over the wall, cavity wall, jaali (lattice) walls, and low-E glass. According to the simulation results, a single courtyard design might not be efficient, but a courtyard that integrates different passive design strategies will be efficient in fully air-conditioned and mixed-mode control buildings in Bangladesh's tropical environment.

Keywords: Humid-tropical climate; courtyard; air conditioned-mixed mode control; energy-efficient building.

1. Introduction

The world of sustainable development is facing an increasing number of obstacles, notably in the sector of building energy efficiency, as environmental and energy constraints become more prevalent(He et al., 2022). Globalization, changing living standards and lifestyles, and growing urbanization substantially increase energy demand (Rahman, 2018). Concern for sustainability has always stemmed from the energy challenges and greenhouse gas emissions caused by the use of active ventilation methods(G C Alozie, 2020). The rise in global temperature has increased the use of air conditioners in workplaces to promote comfort and productivity. Air conditioners consume more energy and have a detrimental environmental impact (Aldawoud, 2008).

The preceding issue sparked a desire for passive energy methods for altering the indoor environment. Besides, in the quest for building sustainability and reduced building energy consumption, conditioned buildings have called for alternative means for cooling buildings. However, due to diverse reasons, constructions are now moving toward mixed-mode buildings, using a hybrid method of space conditioning that blends operable windows with mechanical cooling (Ibiyeye et al., 2015). Well-designed mixed-mode buildings can be more comfortable and consume less energy by taking advantage of the strengths of both systems.

Moreover, it is fundamental for the construction industry to place a greater emphasis on energy efficiency by integrating passive solutions from traditional architecture while managing indoor thermal comfort (Tabadkani et al., 2022). The courtyard has proven to improve the thermal comfort of both outdoor and indoor spaces by altering the microclimate in naturally ventilated buildings(G C Alozie, 2020). The incorporation of courtyards into buildings can make a significant contribution to the creation of passive buildings with high energy efficiency (George Chinedu Alozie, 2020).

The integrated design of a building combines envelope design techniques to enhance passive cooling for maximum comfort and energy efficiency. Envelope is an integral part of any building because it protects the structure's inhabitants and has a significant impact on controlling the internal climate. The study includes envelope design strategies as a major passive design component along with courtyard. Bangladesh is a tropical region where the building envelope contributes significantly to solar heat absorption(Rana et al., 2020).

In this study, the effectiveness of courtyard design for a completely air-conditioned and mixed-mode building along with combinations of passive envelope design strategies such as insulation in wall and roof, shade on roof, self-shading wall, jaali wall, cavity wall, and the low-E glass window were investigated for an office building in a tropical context of Dhaka, Bangladesh.

2. Methodology

A two-storied office (Sonali Bank) building has been chosen by a survey-based study which is in Dhaka, Bangladesh. The data on energy consumption in numbers of electricity bills and other required information were gathered. Using the 'DesignBuilder' (version 6.1.0.001) interface on a hypothetical example model with different design parameters, the annual energy consumption was determined. The 'DesignBuilder' is one of the most comprehensive user interfaces for EnergyPlus dynamic thermal simulation engine (Aranda et al., 2017)(Arima et al., 2017). Dhaka has tropical savanna climate according to Koppen’s climate classification which lies in climate zone 1A (ASHRAE, 2020) with the distinct features of a hot, wet and humid tropical monsoon climate. The weather data from Dhaka was used in the modeling process to assess the energy load and specify the activities and construction, opening and HVAC sections.

After performing a simulation of As-is case and its validation, Base case according to ASHRAE 90.1 office standards(S I Rae et al.,2016) has been developed and the courtyard was modified in the layout of base case by running simulation for the both air-conditioned and mixed-mode case. The courtyard case was combined with different passive envelop design features by developing twenty-one ECMs (Energy Conservation Modules) and with forty-two annual simulations in ‘Designbuilder’ to see the impact of courtyard on energy performance with or without these design features. An excel file with the results was organized and utilized for analysis thereafter.

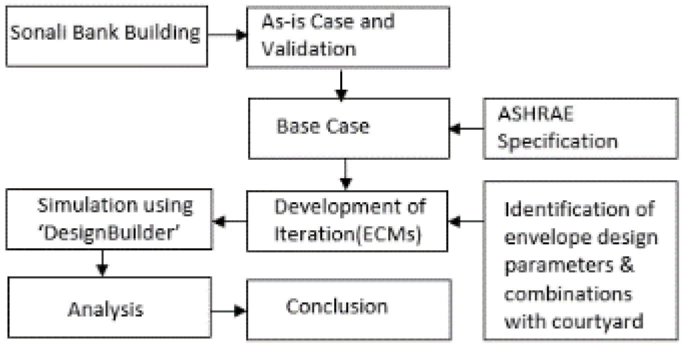


Figure 52: Methodology Diagram

3. As-is case development and validation

The Sonali Bank building is in Kurmitola Cantonment, Dhaka, Bangladesh (23.8103° N, 90.4125° E). It has two floors. The office building model has been established with a total floor area of 1283 m^2. Because the conditioned and unconditioned zones are distinct, the building was divided into major zones and the floor layout for energy simulation. Figure 2 represents different zones of the building.

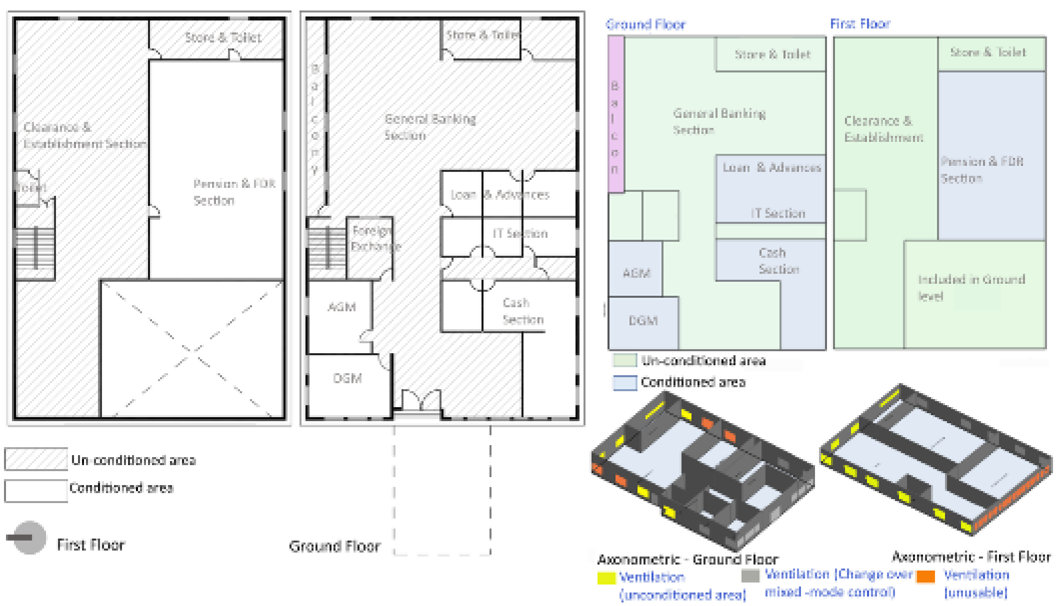


Figure 53: Floor Plans of Sonali Bank Building(left) & layout of plan defined by zone for Design Builder Simulation (right)

'DesignBuilder' configuration template instructs the simulation standard and reference to be straightforward for modelling and altering. Weather data, activity, occupancy, material standards, HVAC and lighting systems were modelled with the building's current state of the situation. According to Dhaka's climate and for work hours as per ASHRAE 90.1 (ASHRAE, 2007) the cooling set back and the heating set back was utilized. Since no natural ventilation was utilized, the conditioned area is assumed to be fully air-conditioned for the purposes of running the As-Is case simulation with a total of 8760 hours.

Table 27: Input for As-is-Case

Features of the Building	Description	Features of the Building	Description
Site:			
Location	Dhaka, Bangladesh	Total building area	1283 m^2
Weather file	BGD_DHAKA_TEJGAON_SWERA	Floor height	5.3 m Ground Floor,3.5 First Floor
Site orientation	90^0		
Activity:			
Occupancy	18.58(sq. m/person)	Computer power density	5 w/m2
Occupancy schedule	9.30 AM-6.0 PM, Sun-Th	Office equipment density	3 w/m2
Construction:			
External wall U-value	1.87 W/m2-k	External floor U-value	0.259 W/m2-k
Roof U-Value	3.954 W/m2-k	Infiltration Flow Rate	0.3 ac/h
Opening:			
U-Value	.778 W/m2-k	Window-wall ratio	30
SHGC	0.8	Shading	0.5m overhang,1st floor
Vt	0.7		
Lighting:			
Lighting power density	7.0 w/m2	Lighting control	No
HVAC:			
System	Split No Fresh Air	Cooling set back temp.	32
Heating set back temp.	13	Cooling system seasonal CoP	3.5
Total energy consumption	120,683 kwh		

As shown in Figure 3, the actual building consumed 80,000 kWh of electricity annually (Source: Principal officer, Sonali Bank). However, the actual building's fully conditioned scenario consumed 120,683 kWh annually.

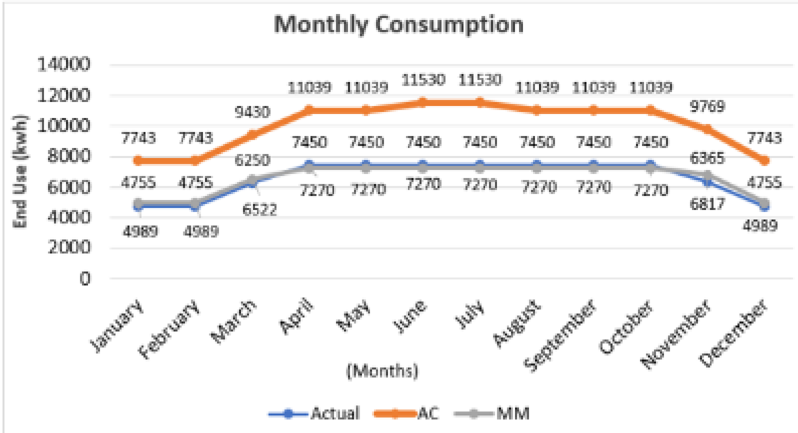


Figure 54: Monthly consumption of actual, AC & MM case

For the validation of As-is case, the model was revised by rearranging the layout into multiple zones to control the HVAC and natural ventilation. All the parameters were kept the same except HVAC. Natural ventilation Mixed-Mode (MM) control was used to see if the results matched the actual consumption to validate the office building model. The yearly consumption of total energy usage of the actual case is 80,000 kwh, which is close to the annual consumption of the As-is case (Mixed-Mode=MM) running control 79,197 kwh. Here the As-is model is validated.

4. Base case development

The As-is case model was modified according to the ASHRAE 90.1(S I Rae et al.,2016) building design energy standard and Dhaka's climate zone 1A categorization to develop the Base Case. By keeping all parameters, same as, As-is case model, only construction, opening and lighting specification were changed for the base case run of the simulation. Two simulations of the ASHRAE base case were performed using the fully conditioned scenario and mixed-mode control. The following Table 2 include the specification between the as-is case and base case models:

Table 28: Specification for ASHRAE As-is Case and Base case

As -is Case		**Base Case**	
Construction:		**Construction:**	
External wall U-value	1.87 W/m2-k	External wall U-value	2.071 W/m2-k
Roof U-Value	3.954 W/m2-k	Roof U-Value	1.540 W/m2-k
External floor U-value	0.259 W/m2-k	External floor U-value	0.259 W/m2-k
Infiltration Flow Rate	0.3 ac/h	Infiltration Flow Rate	0.3 ac/h
Opening:		**Opening:**	
U-Value	5.778 W/m2-k	U-Value	2.70 W/m2-k
SHGC	0.8	SHGC	0.4

As -is Case		Base Case	
Vt	0.7	Vt	0.56
Window-wall ratio	30	Window-wall ratio	40
Shading, Overhang	On 1st floor,0.5m	Shading, Overhang	No
Lighting:		**Lighting:**	
Lighting power density	7.0 w/m2	Lighting power density	10.5 w/m2
Lighting control	No	Lighting control	No
HVAC:		**HVAC:**	
System	Split No Fresh Air	System	Split No Fresh Air
Heating set back temp.	13	Heating set back temp.	13
Cooling set back temp.	32	Cooling set back temp.	32
Cooling system seasonal CoP	3.5	Cooling system seasonal CoP	3.5
Mixed mode:		**Mixed mode:**	
Natural Ventilation	On	Natural Ventilation	On
Control mode schedule control	Mixed-mode temp.	Control mode schedule control	Mixed-mode temp.
Min. outdoor ventilation air schedule	Always 1ac/h	Min. outdoor ventilation air schedule	Always 1ac/h
Airflow control type schedule	Always 0	Airflow control type schedule	Always 0
Total consumption (AC)	120,683 kwh	**Total consumption (AC)**	119883 kwh
Total Consumption (MM)	79,197 kwh	**Total Consumption (MM)**	86,418 kwh

5. Energy conservation module development

The ASHRAE base case has been used to test the impact of the courtyard on the investigated building. A central courtyard as shown in Figure 4 has been modelled with distinct differences in layout, construction, opening, lighting while the activity tab, and HVAC tabs remain the same for each model. Courtyard (C) with one, two, three and four combinations(Table 3) of Insulation in Wall (IW), Insulation in Roof (IR), Shade on Roof (SR), Self-shading of Wall (SSW), Low-E-glass (Low-E-g), Jaali Wall (JW), Cavity Wall (CW) were run with a total forty-two simulations. Following are the twenty-one combinations for the experiment:

Table 29: Energy Conservation Modules (ECMs) courtyard with one, two, three and four combinations:

Strategies/ Courtyard (C)	1.Insulation in wall	2.Insulation in roof	3.Shade on roof	4. Self-Shading of Wall	5.Jaali Wall	6.Low-e-glass	7.Cavity wall	Total
1 Combinations	C+1	C+2	C+3	C+4	C+5	C+6	C+7	7
2 Combinations	C+1+2	C+2+3	C+3+4	C+4+6	C+5+6	C+6+7	C+1+3	7
3 Combinations	C+1+2+6	C+3+4+6	C+3+5+6					3
4 Combinations	C+2+4+6+7	C+1+3+5+6	C+3+5+6+7	C+3+4+5+6				4

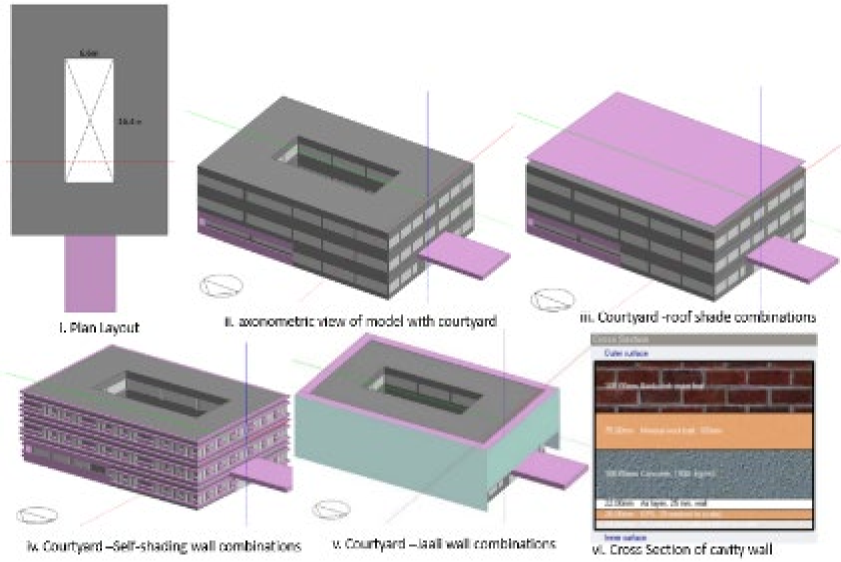


Figure 55:ECMs layout

A central courtyard with (6.6 m×16.4m) was created, as another level was added to equal the total built-up area to compensate for the sacrificed working space by making the courtyard void. As per ASHRAE maximum U-value, wall insulation was used 79.4 mm XPS extruded polystyrene-CO2 blowing, and roof insulation was used 108.60 mm XPS extruded polystyrene-CO2 blowing. The same features were used in ECMs one, two, three, four combination simulation with courtyard.

For all the ECMs combination white coated metal as roof shading material in component block was created as entirely shaded courtyard. Horizontal self-shading walls was created with component block in 'Design-builder'. For making jaali wall, component block has been developed with the maximum transmittance 0.4 for the perforation percentage of existing building's jaali wall. Low-E coated glass (Dbl LoE (e2=.1) Clr 3mm/13mm Air and double-glazed glass are used as window glass type. Cavity has been formed in between the wall according to the cross-section in Figure 4. In all the combinations with courtyard same glass type and cavity wall configuration was used.

6. Result and discussion

The model of courtyard layout with twenty-one combinations has been simulated for both conditioned and mixed-mode controlled buildings with a total forty-two annual simulations. The total energy end-use result was collected and arranged to find out the best case and worst case with the combination of courtyard in different ECM's module. To measure a feature's effectiveness, total annual end-use was counted in the best cases when one, two, three and four envelope design features were combined with courtyard.

Cases	Lighting & Equipment End-use	District Cooling End-use	Total End-use
Base Case (AC)	53,773	66,110	119,883
Base Case (MM)	53,773	32,644	86,418
Courtyard (AC)	35,720	99,749	135,469
Courtyard (MM)	35,547	91,011	126,558

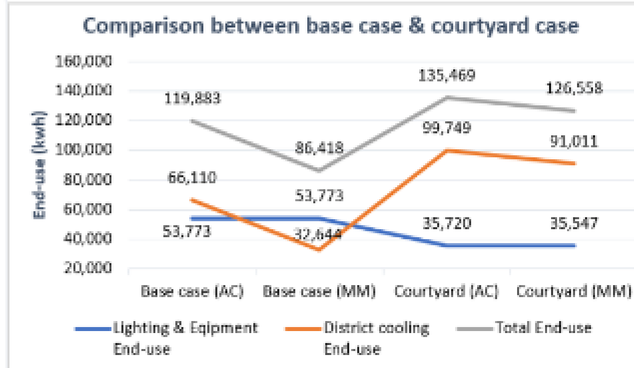


Figure 56 : Base case & Courtyard combinations

The total end-use for the courtyard arrangement were compared to the ASHRAE case AC and mixed mode scenarios. It is evident from Figure 5 that the courtyard is not improving the energy performance of the office building and it has more consumptions than base case because the thermal performance of the building is impacted by solar radiation that is directly received by courtyard surfaces. But the lighting consumption improves with the courtyard.

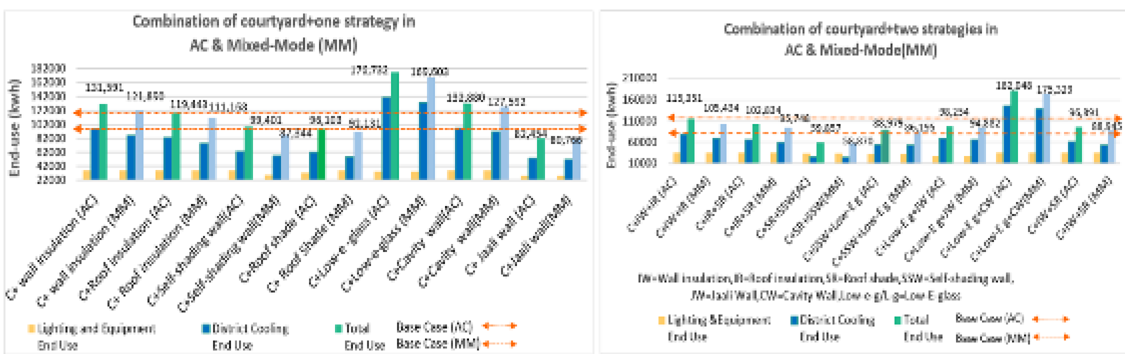


Figure 57:(a) Courtyard +one strategy combination, (b)Courtyard +two strategy combination,

Since the courtyard is not a good alternative for optimizing energy performance in the previously mentioned case, the impact of the passive envelope design with combination of courtyard by developing seven sets ECMs with (courtyard + one passive strategy) has been further evaluated for the both AC and mixed-mode scenarios. The figure 6(a) demonstrates total end-use of the wall's self-shading (99,401 kwh AC;87,344 kwh MM), shade on roof (96,103 AC kwh & 92,131kwh MM) and jaali wall (82,454 kwh AC & 80,766 kwh MM) has the most significant influence when utilizing a courtyard combination. The jaali case's both AC and MM have less energy and lighting end use consumption than base case (119,883 kwh AC and 86,418 MM). Where mixed-mode control scenarios of these cases are more efficient. And energy-efficiency is poor when a courtyard is combined with Low-E glass windows. It has almost reached its maximum end-use in AC 176,732 kwh and in MM 169,603kwh.

While low-e glass double-glazed windows with courtyard combination does not improve annual energy use for this investigation. Another seven sets of ECMs (courtyard + two strategies) were run to test the effectiveness of the Low-e glass windows efficiencies. Figure 6(b) illustrates how a courtyard with a different wall and roof strategy performs better in terms of energy and lighting efficiency. The optimum combination in this case is C+SSW+SR; C+SSW+Low-e-glass and C+JW+Low-e-glass. Mixed mode always performs better than AC scenarios. Here, the worst combination is C+Low-e window -cavity wall. As it has more energy consumption than base case scenarios (Ac & MM). Overall, in this example of Dhaka, shading method is preferable to insulating strategy with the combination of low-e-glass window.

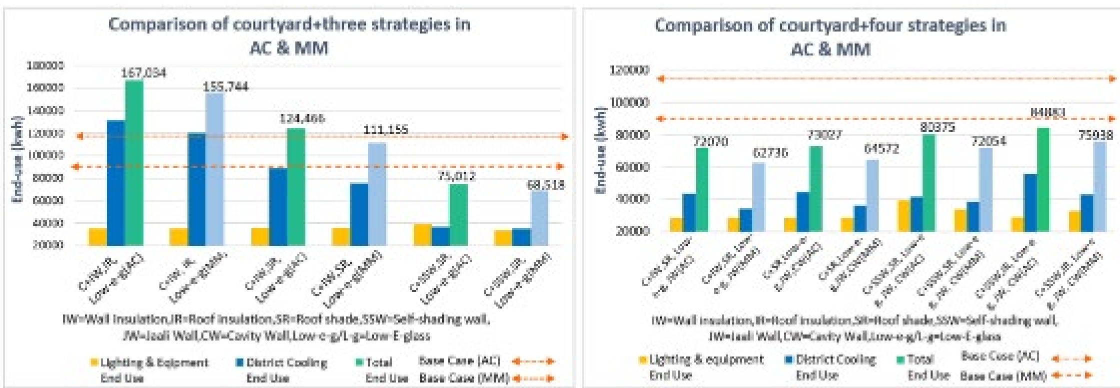


Figure 58: (a) Courtyard +three strategy combination (b) Courtyard +four strategy combination

Figure 7(a) indicates that courtyard with self-shading wall, roof shade and low-e glass performs better for the both AC (Total end-use=75,012 kwh) and mixed-mode (Total end-use= 68,518 kwh) scenarios as it has less energy consumption comparison to base case. Whereas the courtyard, wall insulation, roof insulation, low-e glass has consumed more energy with a total end use of 167,034 kwh (AC) and 155,744 kwh (MM). The results strengthen the findings that shading is the best performing scenario over insulation for the office building.

From previous analysis it was found that mixed-mode scenario of courtyard+ three strategies was working effectively rather than AC. Hence, another eight simulations were run to see if courtyard +four strategies can work better for the both AC and mixed-mode scenarios. Figure 7b) shows the courtyard when implemented in conjunction with four techniques that have the greatest impact on lowering overall end-use consumption for both AC and mixed mode scenario in comparison to both base case scenarios in AC and MM.

Figure 59: All best-worst case together AC &MM

Figure 8 depict both the best-case and worst-case scenarios for a courtyard with air conditioning and mixed mode. The C+1 strategy has consumed more energy than the C+2, C+3, and C+4 strategy combinations. When courtyard with walls or only the roof is combined, it uses a lot of energy. With the combination of the wall, roof, and low-E glass, courtyard is overall efficient. Courtyard with self-shading wall or wall insulation with roof shading is the ideal option for energy optimization. However, the worst alternative in this case is the single or double combination of low-e glass and cavity wall with courtyard. Because it reaches the highest consumption (Figure 8) in compare with the base case. It was determined in the office building of Dhaka that mixed-mode control using a single roof and wall approach was better than a completely air-conditioned building.

7. Conclusion

Twenty-one energy-conservation modules have been studied in this study, and the effects of courtyard when combined with passive envelope energy-efficient building design strategies have been explored. Because the courtyard plan increases the surface area exposed to direct sunshine, it is not a possible best option for this office building. The courtyard and double-glazed Low-E glass windows also exhibit the poorest performance. On the other hand, to reduce heat gain from the outside, ECM modules were developed with alteration of envelope design layout. While applying the techniques, ECM of courtyard-self shading over wall -roof shading (total end-use =59,856 kwh in AC; 58,870 kwh MM) and courtyard-jaali wall-roof shading-low-E glass (total end-use =72,070 kwh in AC; 62,736 kwh MM) combinations produced the most improved outcomes from individual simulations than the base case (119,883 kwh AC and 86,418 MM). In addition, it was found that in Dhaka the mixed-mode management using a combination of courtyard with a wall and roof system is the best choice as opposed to an air-conditioned building. This study lays the framework for identifying the need for mixed-mode control structures that combine passive building design strategies to maximize energy performance.

Acknowledgement

This paper is prepared as part of post graduate program with the sponsorship by Indian Council of Cultural Relations (ICCR), at Department of Architecture and Planning, Indian Institute of Technology, Roorkee.

Reference

Aldawoud, A. (2008). Thermal performance of courtyard buildings. *Energy and Buildings*, *40*(5), 906–910. https://doi.org/10.1016/j.enbuild.2007.07.007

Alozie, G C. (2020). *Environmental Architecture : Courtyard as Element of Sustainable Energy Efficient Building Development*. *20*(1), 56–61. https://doi.org/10.5829/idosi.aejaes.2020.56.61

Alozie, George Chinedu. (2020). *Sustainable Environment: an examination of thermal comfort of residential buildings in warm humid climate of Abia State*. *March 2019*.

Aranda, J., Zabalza, I., Conserva, A., & Millán, G. (2017). Analysis of energy efficiency measures and retrofitting solutions for social housing buildings in spain as a way to mitigate energy poverty. In *Sustainability (Switzerland)* (Vol. 9, Issue 10). https://doi.org/10.3390/su9101869

Arima, Y., Ooka, R., & Kikumoto, H. (2017). Proposal of typical and design weather year for building energy simulation. *Energy and Buildings*, *139*, 517–524. https://doi.org/10.1016/j.enbuild.2017.01.056

ASHRAE. (2020). Climatic data for building design standards. *ASHRAE Standard 169*, *8400*, 384.

Edition, S. I., Rae, A. S. H., Erbe, D., Baselici, P., Beilman, S., Boldt, J., Conrad, E., Cottrell, C., Hanson, S., Heinisch, R., Hintz, S., Hogan, J., Humble, J., Rosenstock, S., Ross, B., Salzburg, M., Taber, C., Brundage, D., Dunlap, J., … Houston, M. (n.d.). *Energy Standard for Buildings Except Low-Rise Residential Buildings*. *6*.

He, C., Tian, W., & Shao, Z. (2022). Impacts of Courtyard Envelope Design on Energy Performance in the Hot Summer–Cold Winter Region of China. *Buildings*, *12*(2). https://doi.org/10.3390/buildings12020173

Ibiyeye, A. I., Mohd, F. Z. J., & Zalina, S. (2015). MIXED-MODE VENTILATION IN MALAYSIA ' S SHOPPING MALLS : A TAXONOMY STUDY Department of Architecture Faculty of Design and Architecture , * Corresponding author : zakyjaafar@upm.edu.my. *UNIVERSITI PUTRA MALAYSIA Alam Cipta*, 72–82.

Rahman, M. (2018). Impact of Climatic Zones of Bangladesh on Office Building Energy Performance by Rahman 2018. *Journal of Buildings and Sustainability*, *1*(1), 55–63. http://www.insightcore.com/journal/impact_climatic_zones_bangladesh_office_building_energy_performance_rahman.html

Rana, M. J., & Hasan, M. R. (2020). The effects of thermal insulation on energy consumption in small office buildings in the context of subtropical monsoon climate. *Journal of Construction Engineering, Management & Innovation*, *3*(4), 275–292. https://doi.org/10.31462/jcemi.2020.04275292

Tabadkani, A., Aghasizadeh, S., Banihashemi, S., & Hajirasouli, A. (2022). Courtyard design impact on indoor thermal comfort and utility costs for residential households: Comparative analysis and deep-learning predictive model. *Frontiers of Architectural Research*, *xxxx*. https://doi.org/10.1016/j.foar.2022.02.006

Improving Indoor Air Quality in Aged Care Ventres using a supplementary ventilation system

Priyadarsini Rajagopalan[1], Jin Woo[2] and Mary Myla Andamon[3]

[1, 2, 3]RMIT University, Melbourne, Australia
{priyadarsini.rajagopalan[1], jin.woo[2], mary.andamon[3]}@rmit.edu.au
ORCID-0000-0001-7445-0985[1], ORCID-0000-0002-6151-8220[2], ORCID-0000-0003-2979-277X[3]

Abstract: Several studies demonstrate the importance of indoor air quality on health, well-being and productivity of occupants. However, much of the research on indoor environments focuses on adult workers in offices, students in school settings, and typical residential buildings. A significant proportion of Australia's population consist of old people in aged care homes who are vulnerable to worsening indoor air quality. This study monitored the air quality and ventilation in the common rooms of aged care centres and explored the benefits of adding a fresh filtered air ventilation system in the rooms. The results of the monitoring showed that the addition of fresh filtered air ventilation system reduced the indoor CO2 concentration levels by as much as 1000ppm. This study improved the understanding on how various design and operating conditions affect ventilation rates and air quality in aged care settings.

Keywords: aged care centre; air quality; ventilation; CO_2 concentration.

1. Introduction

Public concern about the adverse effects of poor air quality in aged care homes in Australia has increased in recent years, particularly highlighted since the COVID 19 outbreak. Homes for the elderly, as with much of the country's critical infrastructure and facilities, are vulnerable to poor performance during such events. A United Nation's estimate projects that the number of older persons (above 60 years old) will more than double by the year 2050, rising from 962 million globally in 2017, to 2.1 billion (UN, 2017). In Australia, people aged 65 years and older made up 14% of the population in the year 2012. This population proportion is projected to increase to 22% by 2061 and 25% by 2101. Similarly, the proportion of people aged 85 years and over in 2012 was 2% of the population, this group is also projected to grow rapidly to 5% by 2061 and to 6% by 2101 (Australian Bureau of Statistics, 2013).

Several studies demonstrate the importance of indoor air quality on health, well-being and productivity of occupants and have found that elderly is susceptible to potential indoor pollutants even at low concentrations. A number of studies in other countries have found the elderly susceptible to potential indoor pollutants even at low concentrations (Aguiar et al., 2014; Bentayeb et al. 2015).

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 361–370. © 2022 and published by the Architectural Science Association (ANZAScA).*

However, much of the research on indoor environments focuses on adult workers in offices, students in schools and typical residential buildings, though people aged 65 years and older make up a significant proportion in Australia. Scientific studies on indoor air quality (IAQ) related impacts on the health of aged care home residents in Australia are limited. This study examined the application of fresh filtered air ventilation systems in the common area of aged care homes. The ventilation rates and carbon dioxide concentration levels were monitored before and after the installation of the ventilation system. The monitoring provided a comprehensive understanding of the actual conditions of the selected aged care homes in different settings and an overview of the various physical and operational factors affecting IAQ in these facilities.

2. Literature Review

2.1. IAQ and its impact on the health of elderly

It is well known that indoor air pollution may adversely affect the elderly's health than other age groups', causing various respiratory diseases such as chronic obstructive pulmonary disease (COPD), asthma, pneumonia and tuberculosis. The elderly can be highly affected by indoor air quality as they are likely to stay longer indoors due to mobility decline in old age. They also have a high chance of developing various respiratory diseases. They can be potentially more exposed to indoor air pollutants including PM10, PM2.5, PM0.1 (particulate matter of aero diameter <10, <2.5 and <0.1 μm respectively), ozone (O3), nitrogen dioxide (NO2), carbon monoxide (CO), sulfur dioxide (SO2), volatile organic compounds (VOCs), allergens and microorganisms (Bentayeb et al., 2013; Maio et al., 2015).

A European geriatric study on health effects of air quality in nursing homes (GERIE study) performed on 600 elderly living in 50 nursing homes, measured the air pollution concentration in the common rooms where the participants spent most of their time for recreation, watching TV, meetings or dining. Although the concentrations of indoor air pollutants did not exceed the existing international and national standards, only 19% of the participant nursing homes were well ventilated (Bentayeb, et al. 2013). Furthermore, Maio et al. (2015) analysed recent literature on air quality and its health effect on the elderly in nursing homes and ascertained that elderly residents are at risk of respiratory health impairment at moderate air pollution concentrations, particularly if they are over 80 years old and living in poorly ventilated buildings. A study among elderly aged over 65 in China assessed the associations between indoor ventilation frequency and cognitive function with a national representative large sample and revealed that a higher indoor ventilation frequency by opening windows more than five times per week was significantly associated with lower probability of cognitive impairment (Wang et al. 2022). Previous research has consistently reported links between high levels of $PM_{2.5}$ with human health, particularly lung function and respiratory diseases. Lee et al. (2007) investigated an association between particulate matter and the peak expiratory flow rate (PEFR) among the elderly and found that smaller particles are likely to have a more adverse respiratory health impact on sensitive individuals such as the elderly. A geriatric study on the health effects of air quality in elderly care centres in Portugal (Mendes et al. 2015) found higher levels of $PM_{2.5}$ in all the elderly care centres during summer and winter, and reported that PM concentrations is a critical parameter of IAQ, both for its sensitivity and for its possible influence on human health However, the same study found no association between indoor air chemical and biological contaminants and respiratory symptoms despite the exceeding concentration levels measured.

2.2. Measuring health, comfort and well-being

Apart from the health effects of physical and chemical exposure, there has been research to investigate the relationships between indoor conditions and occupants' health and comfort, which can be considered as 'wellbeing' in the building related disciplines. Wellbeing is a state of the absence from any illness or discomfort; however, it can be beyond the basic level. It includes emotional and psychological factors as the interactions between indoor conditions and building occupants seem to be far more complex. Bluyssen et al. (2011) categorized the current assessment techniques of wellbeing into the following three categories according to their human model: medical examination, questionnaires and observation and monitoring. Medical examination can provide the information on physical and physiological states of the human body, explaining how the human body responds to stress. Questionnaires give the information on the emotional state, other personal factors and subjective information on physical and psychosocial stressors and factors, on past events and exposures and on behaviour and responses over time. Bentayeb et al. (2015) adopted a combination of methods including medical visit and a standardized questionnaire on sociodemographic factors, and health and potential risk factors to evaluate the elderly in seven European countries and assess respiratory effects of IAQ and comfort parameters.

The Portuguese GERIA study examined the association between elderly quality of life (QOL) and the reported respiratory diseases, using a questionnaire, World Health Organization QOL (WHOQOL)-BREF. The WHOQOL-BREF domains include physical health, psychological health, social relationships and environmental health. Chronic bronchitis, frequent cough, current wheezing, asthma and allergic rhinitis were identified as potential risk factors and the presence of respiratory diseases seems to be an important risk factor for a low QOL among elderly nursing home residents (Carreiro-Martins et al., 2016). Wang et al. (2022) used the Mini-Mental State Examination (MMSE) to test cognitive function of elderly in China. Observation and monitoring can collect information on potential stressors and factors caused by both indoor conditions and psychosocial environment, and on subjective behaviour and responses to certain events.

2.3. Criteria for Ventilation

Australian Standards for Ventilation and Air Conditioning (AS 1668.2 2012) specifies a minimum floor area requirement per occupant and recommends minimum outdoor airflow rate for health care facilities including convalescent homes and nursing homes. However, special requirements determine minimum ventilation rates and filter efficiency (e.g., operating theatres and intensive care rooms). For patient rooms which can be referenced for aged care homes, the minimum outdoor air flow rate is 10-12 Ls^{-1} per person with a net floor area of $10m^2$ per person.

ASHRAE Standard 62.1 (2019) does not prescribe ventilation rates specifically for aged care homes but recommend a range of ventilation rates for outpatient healthcare facilities ranging from 2.5 Ls^{-1} for examination and consultation rooms, 5 Ls^{-1} for physical therapy individual rooms and 10 Ls-1 for physical therapy exercise area. However, ASHRAE Standard 170: Ventilation of Health Care Facilities (ASHRAE 2017b) prescribes 2 ACH for resident rooms and 4 ACH for resident gathering/activity/dining spaces with MERV 13 filter efficiency requirement (equivalent to F6-F7 Australian Standard performance rating). EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (DIN, 2007) outlines a Category I recommendation for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick or elderly persons and prescribes the airflow rate of 10 Ls-1 per person or 1.4 Ls^{-1}/m^2 for living room and bedrooms, mainly outdoor air flow and for continuous operation of ventilation during occupied hours (complete mixing) (DIN, 2007, Table B.5, p37).

3. Methodology

Five aged care homes (AC1, AC2, AC3, AC4, AC5) in Victoria, in the temperate Australia were selected for the study. Except for AC5 located in regional Victoria (85 km from Melbourne), all aged care homes were located in Melbourne area at distances of 43, 23, 16 and 12 km from the central business district (Figure 1). All buildings were low-rise and most of the buildings had brick walls as exterior envelope. Interior walls were painted on plaster or gypsum board lining and internal floor finishes were mainly carpet. Most of the common rooms were sufficiently daylit with internal shading such as roll screens and curtains. Windows were mostly single glazed and tinted and the orientation of windows varied. Over half of the rooms had central air conditioning (AC) units installed, two had reverse cycle AC and the other two had cassette units. It is noted that some rooms had additional electric heaters used during winter.

Figure 60 Location of aged care centres

Ten common rooms in the five aged care homes (Rooms A and B from aged care homes AC1-AC5) were monitored. The supplementary ventilation system was installed in one of the rooms for each facility whilst the other room was monitored as a base case for comparison. IAQ parameters were measured for a duration of 14 months from January 2019 to February 2020. The indoor environmental conditions (air temperature, relative humidity, carbon dioxide (CO_2) concentration levels) were continuously monitored with stationary battery-operated datalogger (HOBO MX1102). Particulate matter was also monitored for a week during four seasons using Aerocet handheld particle counter Model 531S. Microbial (bacteria and mould) concentration levels were also measured. The microbial sampling involved the collection of one air sample from each facility using a sampling pump at a flow rate of 28 Lm^{-1} for two minutes to estimate the total count of microbials before and after the installation of the ventilation system in Common Rooms B (intervention rooms). Only temperature, relative humidity and CO_2 concentrations are reported in this paper. Figure 2 shows the typical monitoring instrumentation and sensors set-up in the aged care homes.

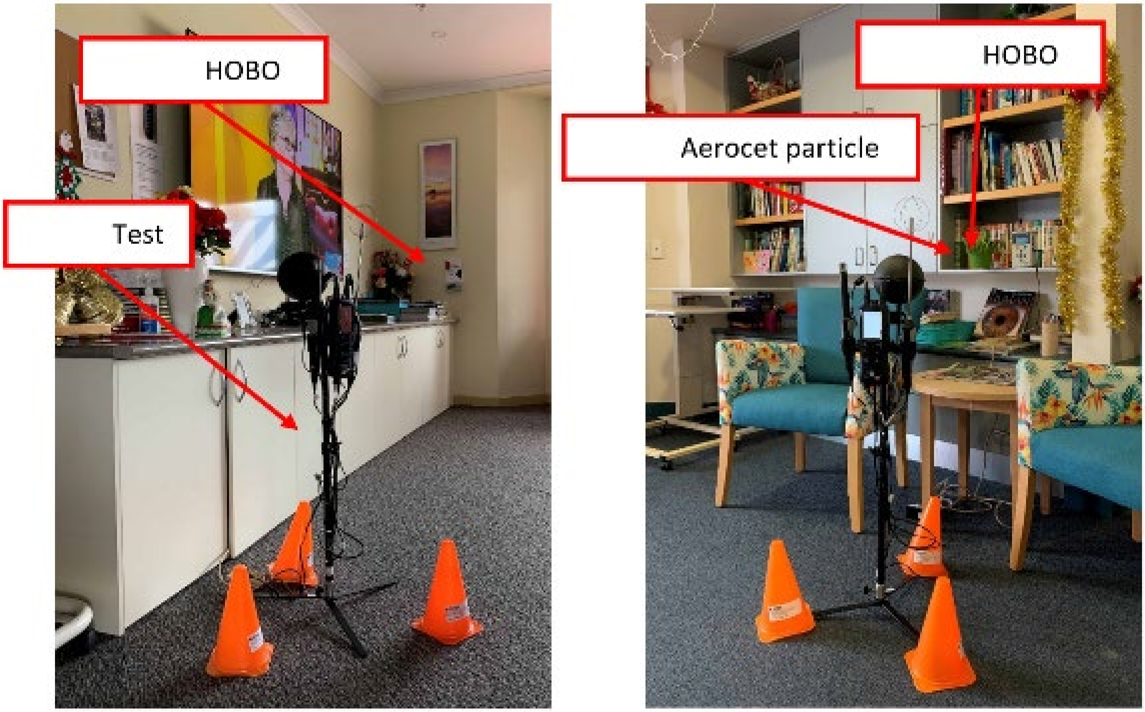


Figure 2 Typical monitoring instrumentation set-up in aged care homes

Common Rooms B (intervention rooms) in aged care homes were fitted with supplementary fresh filtered air ventilation system described above in September-November 2019. The ventilation system supplied supplementary fresh filtered air with G4 filter grade. For aged care homes AC1, AC2 and AC3, the G4 pre-filters were supplemented with F7 filter and added booster fans in January 2020.

3.2. Supplementary ventilation system

The Fresh Filtered Air Heat Recovery Ventilation system (FAHRV) used in this study is shown in Figure 3. The system is made of a metal box fitted with two small DC brushless motors on each side of the heat exchanger which is mounted in the middle of the cabinet (Figure 3a). The motors are controlled by a digital display wall controller (Figure 3b) equipped with CO_2 and $PM_{2.5}$ sensors. The filter box (Figure 3c) is fitted with a standard G4 pre-filter. For further filtration, additional filters such as F7 can be fitted in the same filter box.

Figure 3 (a) Heat recovery ventilation (b) Wall controller (c) Air filter box (Source: Eco Pacific)

After 12 months of monitoring, an additional F7 filter was added in the filter box to supplement the G4 pre-filter. Low noise fans capable to withstand higher pressure drops with the addition of F7 filters was installed to increase airflow rates. Duct connectors were used to fit the boosters in line at the suction of the return air and discharge of the supply air. Upgrades to Rooms AC4B and AC5B were not approved due to the addition of booster fans. The increased airflow rates for the rooms with upgrades system are as shown in Table 1.

Table 30 Air flow rates as measured at supply point

Facility	Original (G4 pre-filter)		Upgrade (plus (F7 filter)	
	Supply air velocity (ms^{-1})	Supply air flow rate (m^3/h)	Supply air velocity (ms^{-1})	Supply air flow rate (m^3/h)
AC1B	1.8	213.84	2.8	332.64
AC2B	1.6	190.08	3.3	392.04
AC3B	2.1	249.48	3.1	368.28
AC4B	1.5	178.20		
AC5B	1.9	225.72		

4. Results

4.1. Indoor temperature and relative humidity

The temperature variations in the ten rooms of the five aged care homes monitored during the four seasons are shown in Figure 4: Season 1 – January to February 2019, Season 2 – March to May 2019, Season 3 – June to August 2019 and Season 4 – September to November 2019. The temperature across the aged care homes did not vary significantly in various seasons. The average temperatures during four seasons ranged between 20.6°C and 23.9°C. Average temperature for Seasons 1 (summer) and 2 (autumn) were around 1°C higher than Seasons 3 (winter) and Season 4 (spring). AC1B had the largest variation of indoor temperature across the four seasons, where minimum was around 18°C and maximum was around 28°C during Season 1. During Season 3, minimum and maximum temperatures were 13°C and 30°C respectively. This room was only occupied couple of hours during the day and heaters and air conditioners were switched off during the unoccupied period.

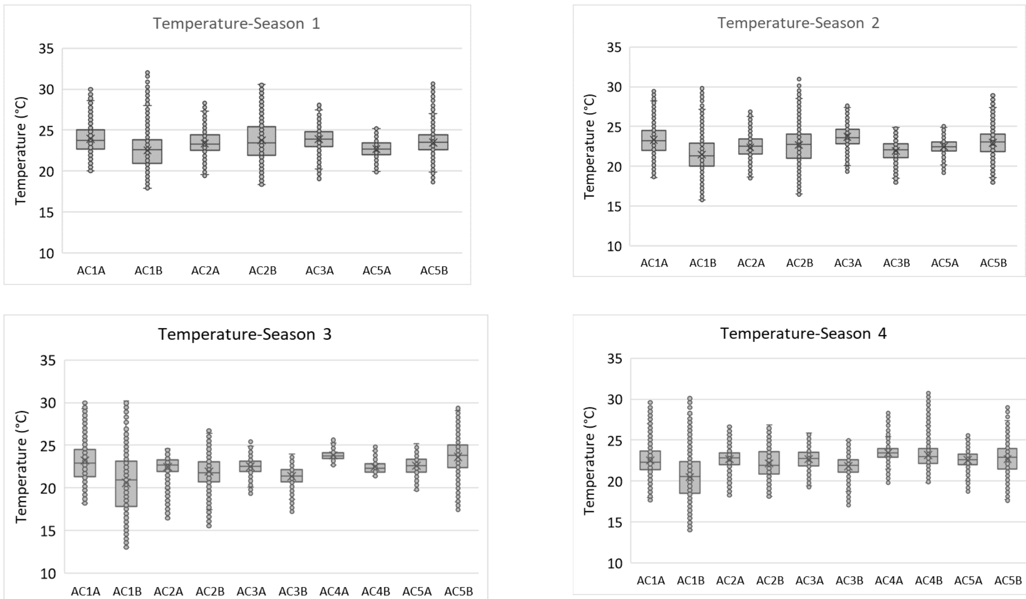


Figure 4 Air temperature (°C) variations across the seasons

The relative humidity variations across the four seasons ranged from 46-62RH% during summer, and 41-54RH% during autumn. The average RH values varied between 35-43RH% during winter and 40-48RH% during spring. The temperature and relative humidity readings demonstrated that indoors conditions are controlled to an accepted level.

4.2. CO_2 concentration levels

The carbon dioxide concentration levels for the ten rooms before installation of the ventilation system are shown in Figure 5. Indoor CO_2 concentrations above ~1000 ppm are generally regarded as indicative of unacceptable ventilation rates (ASTM, 2018). CO_2 levels were significantly high in AC1B where readings above 1000 ppm were noted on many occasions. The highest level was found to be around 2000 ppm. The CO_2 levels normally increase with the number of occupants. During the monitoring period, it was observed that the number of occupants in the room varied from unoccupied to 33 people. On rare occasions such as festive seasons and special events, up to 52 people gathered in one of the rooms.

The ventilation systems in the three facilities (AC1, AC2 and AC3) were upgraded by increasing the airflow rate and by adding an F7 filter with the existing G4 pre-filter. Figure 6 shows the CO_2 concentration levels after the upgrade for a single day. Comparing with Figure 5, the peak CO_2 levels reduced by as much as 1000 ppm in AC1B as a result of increased ventilation.

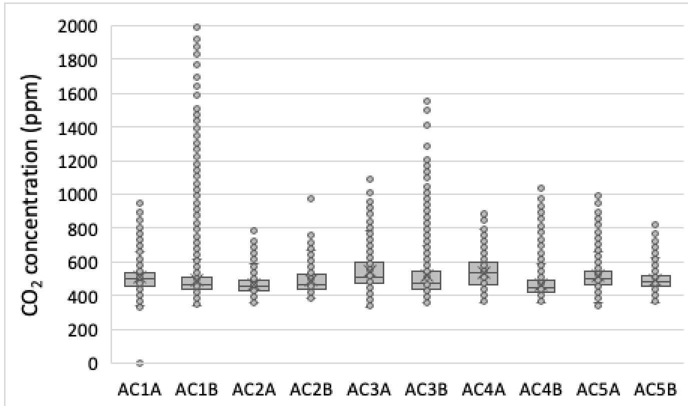


Figure 5 CO_2 concentration levels variations before installation

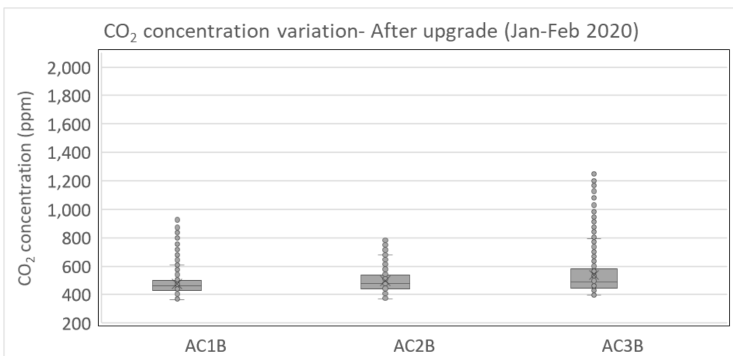


Figure 661 CO_2 concentration levels after ventilation system upgrade

4.3. Ventilation rates

The ten rooms have floor area sizes ranging 48-192 m^2 and volume of 154-616 m^3 (Table 2). The air change rate (ACH) was calculated using the peak-analysis approach. The CO_2 generation rate 0.0052 Ls^{-1} for each resident in the occupied room was used following ASTM D6245 (2018).

The summary of the calculated air change rates (h^{-1}) on the selected days before and after the installation is shown in Table 2. The minimum CO_2 concentration values (C_o) for the ten rooms ranged from 332 ppm-385 ppm. As the number of residents using the space vary considerably every day, CO_2 concentration levels of a single day during maximum occupation was used for ACH calculation. The minimum concentration values were deducted from the maximum CO_2 concentration (C_s). The calculated air change rates ranged from 0.84 ACH to 3.77 ACH (Table 2). ACH levels varied significantly in different seasons. Lowest ACH level of 0.84 was calculated for AC3B. The ventilation rates ranged from 5.52 Ls^{-1} per person to 30.95 Ls^{-1} per person. After the system upgrade in the intervention rooms, the ACH calculated were 2.01, 2.46 and 1.7 for AC1, AC2 and AC3 respectively. The corresponding ventilation rates per person were 9.45 Ls^{-1}, 14.13 Ls^{-1} and 8.36 Ls^{-1} respectively for AC1, AC2 and AC3.

Table 2 Air change rates and ventilation rates

				ACH		Ventilation rates	
Aged care centre	**Room**	***n***	***V* (m³)**	**before**	**After**	**before**	**After**
AC1	AC1A	1-9	154		2.01		9.45
	AC1B	1-22	169	3.62		30.95	
AC2	AC2A	19-21	616		2.46		14.13
	AC2B	6-8	269	1.3		6.92	
AC3	AC3A	14-25	363	0.84	1.7	5.52	8.36
	AC3B	15-25	355				
AC4	AC4A	6-33	543	1.92		5.9	
	AC4B	16-52	576				
AC5	AC5A	6-12	429	3.77		22.71	
	AC5B	5-12	260				

7. Conclusions

This study investigated IAQ in aged care homes using field monitoring that lasted more than a year. In the aged care homes the occupancy rate varied significantly during the day and maximum CO_2 concentration levels reached up to 2000 ppm when the rooms were moderately or fully occupied. The ACH ranged from 0.84 to 3.81 and ventilation rates ranged from 5.52 Ls^{-1} per person to 30.95 Ls^{-1} per person. The results of the monitoring showed that the addition of fresh filtered air ventilation system reduced the indoor CO_2 concentration levels by as much as 1000 ppm. This study provided preliminary information on the actual thermal and air quality performance of aged care homes located in different geographic locations in Victoria; and improved the understanding on how ventilation system design and operating conditions affect ventilation rates and air quality. The findings could be used to inform the operation and maintenance of aged care homes and HVAC systems including fresh air intake, and further guidelines on ventilation standards and cooling policy. It is to be noted that this study was conducted during the pre-COVID period, and it is quite possible that the current fresh air ventilation rates are set much higher.

Even though this study intended to collect the aged care resident’s perception of air quality using a questionnaire, it was noted after the first season of monitoring, that most of the residents were not able to complete the questionnaire accurately. Subsequently, the research team tried to get information about the health data in the form of monthly incident reports such as number of infections and hospital visits during the study period. However, this information was not readily available in most of the aged care homes. Future studies can include collection respiratory health conditions using a standard questionnaire to understand the effect of indoor air quality on health. Further, only common rooms in the aged care homes were monitored in this study while most of the residents spend longer time in their bedrooms. Future studies should be extended to the bedrooms to understand the impact of air quality in bedrooms.

Acknowledgements

This project was funded by the Victorian Department of Environment, Land, Water and Planning. We would like to thank the facility managers and staff at the aged care centres.

References

ABS 2013, 3222.0 - Population Projections in Australia, 2013, Australian Bureau of Statistics (ABS), Canberra.

ASHRAE. (2019a). ANSI/ASHRAE Standard 62.1-2019: Ventilation for Acceptable Indoor Air Quality (pp. 88). Atlanta, GA: American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE).

ASHRAE. (2017b). ANSI/ASHRAE/ASHE Standard 170-2017: Ventilation of Health Care Facilities (pp. 42). Atlanta. GA: American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE).

ASTM. (2018). D6245-18: Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation. West Conshohocken, PA: ASTM International.

AS 1668.2 (2012), The use of ventilation and air conditioning in buildings Mechanical ventilation in buildings, Standards Australia.

Aguiar, L, Mendes, A, Pereira, C, et al. 2014, 'Biological Air Contamination in Elderly Care Centers: Geria Project', *Journal of Toxicology and Environmental Health, Part A*, vol. 77, no. 14-16, pp. 944-58.

Bentayeb, M., et al. (2013). Indoor air pollution and respiratory health in the elderly. J Environ Sci Health A Tox Hazard Subst Environ Eng, 48(14), 1783-1789. doi: 10.1080/10934529.2013.826052.

Bentayeb, M., et al. (2015), Indoor air quality, ventilation and respiratory health in elderly residents living in nursing homes in Europe, European Respiratory Journal, v 45: 1228-1238; DOI: 10.1183/09031936.00082414

Carreiro-Martins, P, Gomes-Belo, J, Papoila, AL, et al. 2016, 'Chronic respiratory diseases and quality of life in elderly nursing home residents', *Chronic Respiratory Disease*, vol. 13, no. 3, pp. 211-9.

DIN. (2007). DIN EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (pp. 54): German Institute for Standardization (DIN).

Lee, J.-T., et al. (2007). The adverse effects of fine particle air pollution on respiratory function in the elderly. Science of The Total Environment, 385(1), 28-36. doi: https://doi.org/10.1016/j.scitotenv.2007.07.005

Maio, S., et al. (2015). Air quality of nursing homes and its effect on the lung health of elderly residents. Expert Review of Respiratory Medicine, 9(6), 671-673. doi: 10.1586/17476348.2015.1105742.

Mendes, A, Papoila, AL, Carreiro-Martins, P, et al. 2016, 'The impact of indoor air quality and contaminants on respiratory health of older people living in long-term care residences in Porto', *Age and Ageing*, vol. 45, no. 1, pp. 136-42.

UN 2017, World Population Ageing 2017-Highlights, Department of Economic and Social Affairs, Population Division, (ST/ESA/SER.A/397),<http://www.un.org/en/development/desa/population/publications/pdf/ageing/WPA2017_Highlights.pdf>

Wang, W., Chen, J., Jin, X. et al. Association between indoor ventilation frequency and cognitive function among community-dwelling older adults in China: results from the Chinese longitudinal healthy longevity survey. BMC Geriatr 22, 106 (2022). https://doi.org/10.1186/s12877-022-02805-1

Integrating energy retrofit to seismic strengthening to safeguard historic unreinforced masonry buildings in Aotearoa New Zealand

Priscila Besen[1] and Paola Boarin[2]

[1] Te Wānanga Aronui O Tāmaki Makau Rau, Auckland University of Technology, Auckland, New Zealand
priscila.besen@aut.ac.nz[1], ORCID-0000-0003-2264-992X[1]
[2] Waipapa Taumata Rau, University of Auckland, Auckland, New Zealand
p.boarin@auckland.ac.nz[2], ORCID-0000-0003-3252-5699[2]

Abstract: Deep energy retrofit of historic buildings can enhance indoor environmental quality, prevent decay and obsolescence, reduce energy use and related greenhouse gas emissions. However, in Aotearoa New Zealand, there are currently no policies to regulate deep energy retrofit in historic buildings and no substantial examples of this practice. On the other hand, there are significant regulations and practical examples of seismic retrofit, especially of unreinforced masonry (URM) buildings. As several seismic upgrade projects are taking place in the country, this study explores the potential of applying energy retrofit concurrently with seismic strengthening. The research investigated three case studies, which are listed heritage URM buildings located in different climates in New Zealand. Their current performance was investigated, and retrofit scenarios were analysed through energy simulation and hygrothermal modelling. Energy models demonstrated a potential reduction of up to 92% in heating demand when comparing the most comprehensive retrofit scenario with the baseline in the coldest climate studied. The potential energy savings from each intervention were then balanced against their heritage impact to assess the most appropriate solutions for each building. The study highlights the benefits of encouraging energy retrofit concurrently with seismic strengthening, so that historic buildings are more resilient not only to seismic threats, but also to a changing climate.

Keywords: Energy Retrofit; Unreinforced Masonry Buildings; Integrated Retrofit; New Zealand Heritage.

1. Introduction

Built heritage plays an important role in making history visible in Aotearoa's cities and in creating vibrant and sustainable urban environments. The reuse, adaptation and retrofit of historic buildings has been gaining increasing attention worldwide as a strategy to reduce both embodied and operational carbon emissions in the built environment. The adaptation of historic buildings to current and future needs is of high importance in New Zealand, as the country has had countless examples of lost heritage [1] due to earthquakes, fire, lack of maintenance and decay related to inadequate indoor environmental conditions.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 371–380.*

In 2017, new regulations came into force for earthquake-prone structures in Aotearoa, which set timeframes for all buildings in the country to achieve minimum structural standards or face demolition [2]. As a result, there are many seismic retrofit projects taking place, especially in historic Unreinforced Masonry (URM) buildings - a type of construction identified as one of the most vulnerable in the country. However, the other future challenges for historic buildings will be to keep good levels of indoor comfort in the climate crisis and to minimise energy consumption [3,4]; these buildings shall be included in adaptation and mitigation programmes. So far, energy considerations have not been extensively included as parameters in retrofit projects in existing national policies or in practice, except for the mandatory upgrade of selected residential rental properties [5]. There is little data on their current energy performance - comprehensive studies have investigated energy use in existing buildings [6], but no in-depth studies focussed specifically on historic built environments. Few research projects have analysed deep energy retrofit of existing building fabric in Aotearoa [7] and there is a lack of information on retrofit options for heritage-listed buildings. Internationally, a few studies have explored the integration between energy and seismic retrofit in built heritage [8–11] and revealed the potential benefits of combining both interventions.

To fill these gaps in knowledge, this research explored the opportunities of integrating energy retrofit and seismic strengthening as a way to safeguard historic URM buildings for future generations. The study analysed the current performance of selected buildings and possible scenarios to integrate seismic and energy upgrades.

2. Methodology

To explore the possibilities of integrating energy retrofit with mandatory seismic upgrades in URM buildings, the research utilised case studies where quantitative and qualitative investigations were conducted. Three case study buildings were selected in different cities, one in each of New Zealand's climate zones (Table 1). All of them are University buildings, are built of URM construction and are listed in the national Heritage NZ Pouhere Taonga list [12]. Buildings A and B had already been seismically strengthened, while building C was in the design process for seismic upgrading. All buildings have single glazing and uninsulated masonry walls, uninsulated floors, and partly insulated roofs.

Table 31: Overview of selected case study buildings

	Case Study A	Case Study B	Case Study C
			
Location and Latitude	Auckland - 37º	Wellington - 41º	Dunedin - 46º
Climate Zone [12]	Zone 1	Zone 2	Zone 3
Heating Degree Hours	20 kKh/a	42 kKh/a	57 kKh/a
Seismic Risk Area [2]	Low Risk	High Risk	Low Risk
Year of Construction	1904	1903-1904	1919-1920

Main architectural styles	Italianate, Arts & Crafts	Gothic Revival, Edwardian	Gothic Revival
Heritage NZ Listing	Category 2	Category 1	Category 1
Seismic resistance capacity (before strengthening)	30% NBS (Earthquake-prone)	Earthquake-prone[2]	10-15% NBS (Earthquake-prone)
Seismic Strengthening Status	Retrofitted in 2014-2016	Retrofitted in 1990-1993	To be retrofitted (currently at design stage)
Main seismic strengthening systems	Plywood diaphragms with tie rods	Sprayed concrete, steel portal frames	Post-tensioning systems
Treated Floor Area	273m^2	5078m^2	1161m^2
Current Use	Offices and meeting rooms	Offices, meeting rooms, lecture theatres	Offices, lecture theatres, laboratories
Window-to-Wall Ratio	18.5%	19.1%	25.1%
Surface Area to Volume Ratio (S/V)	0.81	0.65	0.49

[1] Percentage of New Building Standard not given because ratings were subject to different standards and classifications at the time of strengthening.

Due to the limited knowledge about deep energy retrofit in New Zealand, the case studies were of exploratory and illustrative character. The use of three case studies allowed the exploration of the possibilities in energy retrofit and the evaluation of potential risks and benefits in different climatic contexts in New Zealand to a level of detail that provided reasonable accuracy for the study. The case studies were also of illustrative character, as they demonstrated how energy retrofit projects should be proposed and evaluated for URM buildings, taking into account heritage impact and seismic resilience considerations. The assessment of case study buildings and proposal of energy retrofit scenarios were guided by EN 16883 [14], a well-known European standard which provides guidance on improving the energy performance of historic buildings and is considered as a reference for retrofits around the world. As this standard does not include specific technical parameters and targets for energy retrofit, the study utilised the EnerPHit standard developed by the Passive House Institute [15] as a reference for specific technical requirements and methodologies. EnerPHit was selected because it provides a reliable, performance-based methodology to improve the energy performance and thermal comfort in existing buildings [16–18]. The study was structured into the following five main phases:

(A) Literature review investigating the URM building stock in New Zealand, current challenges and opportunities in integrating energy retrofit to seismic upgrade projects, presented by the authors in past publications [19,20];

(B) Selection and analysis of case study buildings, including an assessment of energy performance, technical, historical and indoor environmental factors, guided by EN 16883 [14];

(C) Hygrothermal simulation of the interventions that presented high interstitial condensation risks to determine suitable materials to be utilised in the proposed energy retrofit. Simulation was developed in WUFI Pro, a software which has been validated by detailed comparison with measurements obtained in laboratory and outdoor testing fields [21].

(D) Development of retrofit scenarios through energy simulation in the Passive House Planning Package (PHPP), assessing the possibility of achieving the EnerPHit standard through the energy demand method [15];

(E) Assessment of impact of retrofit scenarios on heritage conservation, based on EN16883, to understand how interventions would affect the building physically and its heritage significance [14].

This publication focuses on stages B-E. The energy retrofit scenarios proposed for each building (phase D) aimed to investigate the potential savings and benefits from upgrading the building envelope in conjunction with seismic retrofit works. Six progressive retrofit scenarios (Figure 1), ranging from the least invasive works to the most comprehensive upgrades, were identified based on extant literature and best practices [4,22–24].

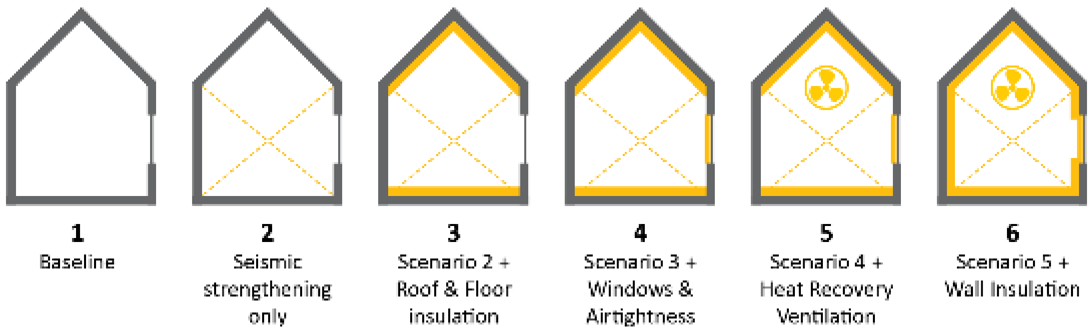


Figure 62: Retrofit scenarios investigated for each case study

Each scenario adds additional components in relation to the previous one. Scenario 1 represents the baseline, consisting of the original building before seismic strengthening or energy retrofit take place. Scenario 2 includes only seismic strengthening works, aiming to analyse how structural elements impact on the building performance, especially trough thermal bridging. Scenario 3 includes roof and floor insulation, which are some of the most common retrofit interventions in New Zealand, and the least invasive in terms of visual impact. Scenario 4 includes upgrades to windows through the addition of secondary glazing, and improvements to airtightness by sealing air leaks in windows and junctions. Scenario 5 introduces heat recovery mechanical ventilation systems to the buildings. Scenario 6 includes the addition of wall insulation to the inside face of walls, while keeping the facades intact. The investigation aimed to test how the selected New Zealand case study buildings could achieve the EnerPHit standard through compliance with the criteria of the energy demand method.

Energy simulation was performed with PHPP version 9.6, developed by the Passive House Institute, which is an integrated tool for stationary energy balance calculations, including all energy flows within the system boundary. The programme is based on European and international standards (including EN ISO 13790). Even though PHPP was originally developed for passive houses, it also provides reliable results for existing and historic buildings - accurate results can be expected for space heating and cooling, primary energy, domestic hot water and electricity demands [4].

Structural elements were considered as fixed factors in the analysis – information on the proposed seismic retrofit systems was collected from structural design drawings for each case study. Cost investigations were outside the scope of the study. Other limitations of the study were the inability to perform blower door tests and in-situ measurements of U-values – these factors were estimated based on the literature review and on the building plans and details.

3. Results and discussion

The energy audit revealed significant issues in energy performance and indoor environmental quality in the selected buildings. The energy consumption in case study C was 40% higher than new buildings with a similar use in the same institution. Thermal imaging revealed gaps in ceiling insulation leading to significant heat losses. An IEQ questionnaire with occupants showed that, in all locations, there was dissatisfaction with indoor temperatures in summer as well as in winter. One occupant in one of the buildings commented that "when the radiators haven't been on, the office is frigid. Mondays can be terrible, as it can take almost all day for the temperature to go up after being off over the weekend." Other comments were that "people bring in bar heaters (from home), both officially and unofficially." Personal heaters and fans were seen in the visual inspections of all buildings, indicating that the building fabric and the mechanical systems were not sufficient to ensure indoor comfort. Single-glazed windows, draughts and lack of insulation were indicated as some of the sources of discomfort for occupants. Even in the cold climate of Dunedin, over half of occupants were dissatisfied with summer indoor conditions.

Considering these issues, retrofit scenarios were proposed and tested based on EN16883 and EnerPHit. Figures 2 and 3 show the results for case studies A and C, which represent the warmest and coldest climates analysed and provide an overview of the overall results. Significant reductions of heating demand were identified through the energy models when comparing the most comprehensive retrofit scenario with the baseline: 92% reduction in Dunedin, 91.6% in Wellington and 89.9% in Auckland. The only retrofit package to achieve the EnerPHit standard in the simulation was scenario 6, the most comprehensive one - it included roof, floor and wall insulation, as well as upgraded windows through secondary glazing, airtightness and heat recovery ventilation. It is also worth mentioning that scenario 5, a relatively less invasive package without wall insulation, also achieved significant savings in heating demand. Frequency of overheating was very low in case study C, under 1%, in all scenarios. In case study A, located in the warmer Auckland climate, frequency of overheating reduced from 9.6% in retrofit scenario 1 to 6.3% in retrofit scenario 6, mainly because of the upgrades to windows.

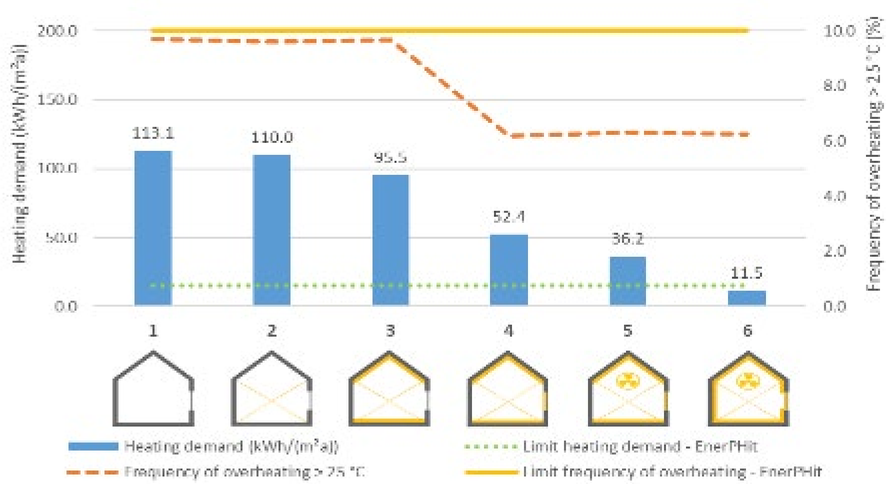


Figure 63: Retrofit scenarios: heating demand and frequency of overheating results for case study A

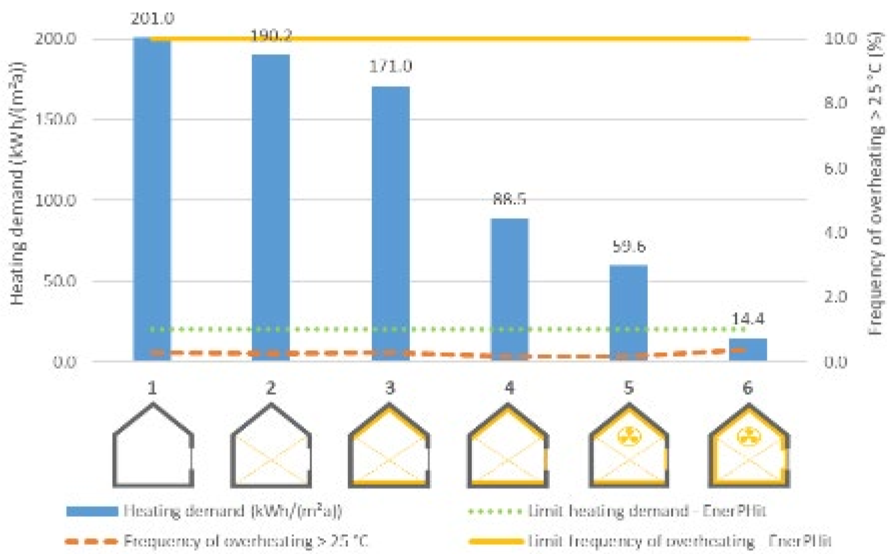


Figure 64: Retrofit scenarios: heating demand and frequency of overheating results for case study C

Seismic strengthening works can impact energy performance positively or negatively, depending on the systems utilised. It was found that, in case study A, the use of plywood diaphragms in the ceiling can be useful to improve airtightness, if appropriately taped in junctions. On the other hand, systems utilising steel beams need to be carefully designed with thermal breaks to minimise thermal bridging. However, in many cases, steel elements were located on the outer layers of the building envelope, not in direct contact with insulation layers, thus the potential thermal bridging was not very significant in these circumstances. External post-tensioning systems, which were considered as an option by the design team for case study C, would be a beneficial technique from a building performance point of view, to avoid the contact between highly conductive materials with internal insulation layers. The use of sprayed concrete in case study B can negatively impact energy retrofitting possibilities: the concrete layer added to walls had already reduced internal spaces and increased the depth of window reveals, hence it would be difficult to install wall insulation to further increase wall thickness.

Considering the risks of introducing internal insulation, a range of different materials were investigated for the study through hygrothermal modelling in WUFI Pro software. Overall, perlite boards and calcium silicate boards achieved the best results in hygrothermal performance, due to their capillary-active properties. In case study C, it was found that mineral wool, wood fibre and cellulose could create significant condensation issues, due to the wall assembly configuration with stone cladding and its reduced drying capacity.

The principle of minimal intervention [25] was applied for building elements with high historic significance. In building B, one room was of particular heritage value: the Council Chambers had historic stained glass windows, highly decorated ceilings and walls. Considering its historic value and the fact that this room is only used for few meetings and events, the study investigated the possibilities of excluding this entire room from energy retrofit interventions. The EnerPHit standard already allows exemptions for U-values of the exterior envelope components to be exceeded if required by heritage authorities [15], however there are no provisions for entire rooms to be excluded from the thermal envelope for certification. Although there could be many challenges in separating the room from the treated building envelope, this was found to be an appropriate solution in this case of high heritage impact. For an appropriate application of the EnerPHit standard in historic buildings, these types of exemptions need to be further explored in order to allow more flexibility for built heritage.

To assess the impact of retrofit scenarios on heritage conservation, the study utilised the tabular risk-benefit scheme by EN16883 to identify the most effective measures and eliminate inappropriate interventions. Two categories from the standard - economic viability and impact on the outdoor environment - were not included in this study as they were outside of its scope. As the focus was on the relationship between energy and seismic upgrades, a new category was proposed: integration of retrofit solutions with seismic strengthening, to assess the applicability of each scenario concurrently with seismic strengthening. Table 2 illustrates the assessment for each retrofit scenario in Case Study C, as an example of how this approach was applied to all case studies.

Table 32: Assessment of impacts based on EN 16883 (2017) - case study C

Assessment categories	**Assessment criteria**	**Retrofit Scenarios**				
		2	**3**	**4**	**5**	**6**
Technical compatibility	Hygrothermal risks					
	Structural risks					
	Corrosion risks					
	Salt reaction risks					
	Biological risks					
	Reversibility					
Heritage significance of the building and its settings	Risk of material impact					
	Risk of visual impact					
	Risk of spatial impact					
Energy	Energy performance and operational energy demand					
Indoor Environmental Quality	Indoor environmental conditions suitable for building fabric preservation					
	Indoor environmental conditions suitable for achieving good occupant comfort levels					
Aspects of use	Influence on the use and the users					
	Ability of building users to manage and operate control systems					
	Compatibility with proposed seismic strengthening systems	2				

Assessment categories	Assessment criteria	Retrofit Scenarios 2	3	4	5	6
Integration of retrofit solutions with seismic strengthening[1]	Access allowed by seismic strengthening (i.e. fabric already affected by interventions)	[2]				

[1]*Proposed new category of assessment, specific to buildings subject to combined energy and seismic retrofit.*
[2]*Not applicable, as retrofit scenario 2 considers seismic strengthening only.*

Legend:

High risk | Low risk | Neutral | Low benefit | High benefit

All retrofit strategies were assessed in terms of their impact on heritage fabric, according to the scale proposed by EN 16883, which includes criteria such as potential reversibility and compatibility. According to this assessment, the intervention with most benefits was the upgrade of windows with secondary glazing, and the intervention with highest risks was wall insulation. Wall insulation was especially problematic in case study B, where seismic retrofit with sprayed concrete had already created a visual impact in internal walls and depth of window reveals, and further increasing wall thickness can be problematic, leading to further reductions in internal space. In all case studies, this assessment showed that, although retrofit scenario 6 had the best results for energy consumption, scenario 5 might be the most desirable from a holistic point of view considering all heritage impacts. This analysis proved to be a useful strategy to ensure an integrated approach in the decision-making process in retrofit projects.

4. Conclusions

URM buildings are valuable pieces of New Zealand's cultural heritage and provide multiple benefits to their surroundings and communities. Their seismic performance issues are well-known in Aotearoa, and this study revealed their energy performance challenges through an energy audit and IEQ assessment of case studies. Although the selected buildings had high energy consumption, their indoor environments were not comfortable: occupants demonstrated significant dissatisfaction with temperatures both in winter and in summer. Without retrofitting these buildings, these issues are likely to be accentuated with more frequent temperature extremes due to climate change.

Overall, the study demonstrated that it is possible to improve the building envelope in URM built heritage and achieve significant energy savings by utilising the EnerPHit standard in a sensible way, if applied in conjunction with heritage-specific retrofit guidelines such as EN16883. The energy models demonstrated a reduction of up to 92% in heating demand when comparing the most comprehensive retrofit scenario (package 6) with the baseline in the coldest climate studied. This retrofit package would achieve the targets for EnerPHit certification; however, the assessment based on EN16883 showed that these upgrades would also lead to significant impacts on heritage fabric, due to the addition of wall insulation internally. Hygrothermal simulation was performed to assess the impact of wall insulation, and it showed that materials such as perlite boards and calcium silicate boards achieved the best results in hygrothermal performance due to their capillary-active properties. However, these interventions are not risk-free and should be taken with caution to avoid condensation issues in the building envelope. Retrofit scenario 5, without wall insulation, provided a good balance between energy performance and heritage impact, but it would not achieve the EnerPHit standard. It is worth mentioning that the frequency of overheating was also significantly reduced in the warmer climate of Auckland in retrofit scenarios 4-6 due to the upgrade of windows with secondary glazing – a valuable improvement for climate change adaptation.

The analysis highlighted that the retrofit of URM buildings should be guided by a holistic approach that encompasses structural, energy efficiency and heritage conservation considerations, among many other disciplines. The study showed that fixed targets might not be appropriate for heritage buildings - the focus should rather be on performance improvement compatible with the safeguarding of heritage values. The balancing act in retrofit decisions can be complex, especially in projects with very limited budgets, therefore, the use of thorough assessment frameworks and energy modelling can be helpful to guide project teams make informed choices for each unique building. There is a need for local guidelines to be further developed to inform adaptation works in heritage buildings in Aotearoa, since there are several limitations with the use of European standard 16883 in this distinct context.

The method presented in this study can serve as a basis for the decision-making process in integrated retrofitting of historic buildings in New Zealand and other countries with similar seismic risks and energy efficiency demands. Overall, the research demonstrated that current seismic upgrade projects can be an opportunity to integrate energy-efficiency improvements to historic URM buildings through sensitive interventions to the heritage fabric. This integrated approach can help improve the resilience of these valuable buildings and ensure they can continue to serve a useful purpose in a post-carbon future.

Acknowledgements

We would like to thank PhD co-supervisor Prof. Errol Haarhoff, external advisor Dr. Kara Rosemeier, the staff at universities who manage the case study buildings, the design teams who shared information about the projects, and all the building occupants who participated in our surveys. The research was supported by a University of Auckland Doctoral Scholarship.

References

R. Wolfe, New Zealand’s Lost Heritage. Auckland, New Zealand: New Holland Publishers, 2013.

Ministry of Business Innovation & Employment. Building (Earthquake-prone Buildings) Amendment Act. Wellington, New Zealand: New Zealand Government, 2016.

S. Roaf, D. Crichton, F. Nicol. Adapting Buildings and Cities for Climate Change: a 21st Century Survival Guide. Oxford, UK: Elsevier Architectural Press, 2009.

A. Troi, Z. Bastian. Energy Efficiency Solutions for Historic Buildings. A Handbook. Basel, Switzerland: Birkhäuser, 2015.

New Zealand Government. Residential Tenancies (Healthy Homes Standards) Regulations 2019. Wellington, New Zealand: New Zealand Government, 2019.

L. Amitrano, N. Isaacs, K. Saville-Smith, M. Donn, M. Camilleri, A. Pollard, M. Babylon, R. Bishop, J. Roberti, L. Burrough, P. Au, L. Bint, J. Jowett, A. Hills, S. Cory. BEES Part 1: Final Report Building Energy End-use Study SR 297/1. Judgeford, New Zealnd: BRANZ, 2014.

P. Leardini, M. Manfredini, M. Callau. “Energy upgrade to Passive House standard for historic public housing in New Zealand”. Energy and Buildings, vol. 95, pp. 211–218, 2015.

G.M. Calvi, L. Sousa, C. Ruggeri. “Energy Efficiency and Seismic Resilience: A Common Approach”. Multi-Hazard Approaches to Civil Infrastructure Engineering, pp. 165–208, 2016.

I. Nardi, T. de Rubeis, M. Taddei, D. Ambrosini, S. Sfarra. “The energy efficiency challenge for a historical building undergone to seismic and energy refurbishment” Energy Procedia, vol. 133, pp. 231–242, 2017.

E. Negro, M. D'Amato, N. Cardinale. "Non-invasive Methods for Energy and Seismic Retrofit in Historical Building in Italy" Frontiers in Built Environment, vol. 5 (125), 2019.

P. la Greca, G. Margani. "Seismic and energy renovation measures for sustainable cities: A critical analysis of the Italian scenario". Sustainability (Switzerland), vol. 10 (254), 2018.

Heritage New Zealand Pouhere Taonga. "The Heritage New Zealand Pouhere Taonga List". Available: https://www.heritage.org.nz/the-list [March 9, 2021].

Standards New Zealand. NZS 4218: 2009 Thermal Insulation – Housing and Small Buildings. Wellington, New Zealand: NZS, 2009.

European Committee for Standardisation. EN 16883:2017 Conservation of cultural heritage — Guidelines for improving the energy performance of historic buildings, 2017.

Passive House Institute. Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard (2016). Available: https://passipedia.org/_media/picopen/9f_160815_phi_building_criteria_en.pdf [April 10, 2021].

C. Jimenez-Bescos, R. Prewett. "Monitoring IAQ and thermal comfort in a conservation area low energy retrofit". Energy Procedia, vol. 147, pp. 195–201, 2018.

F. Moran, T. Blight, S. Natarajan, A. Shea. "The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings". Energy & Buildings, vol. 75 pp. 216–227, 2014.

F. Rodrigues, M. Parada, R. Vicente, R. Oliveira, A. Alves. "High energy efficiency retrofits in Portugal". Energy Procedia, vol. 83 pp. 187–196, 2015.

P. Besen, P. Boarin. "Energy retrofit of historic buildings in Aotearoa New Zealand: current practice, challenges and opportunities". Imaginable Futures: Design Thinking, and the Scientific Method, 54th International Conference of the Architectural Science Association 2020. Auckland, New Zealand: Auckland University of Technology, pp. 471–480, 2020.

P. Besen, P. Boarin, E. Haarhoff. "Energy and Seismic Retrofit of Historic Buildings in New Zealand: Reflections on Current Policies and Practice". Historic Environment: Policy and Practice, vol. 11, pp. 91–117, 2020.

Fraunhofer Institute for Building Physics IBP, What is WUFI®?, WUFI. (2020). Available: https://wufi.de/en/software/what-is-wufi/ [May 20, 2020].

V. Belpoliti, G. Bizzarri, P. Boarin, M. Calzolari, P. Davoli. "A parametric method to assess the energy performance of historical urban settlements. Evaluation of the current energy performance and simulation of retrofit strategies for an Italian case study". Journal of Cultural Heritage, vol. 30, pp. 155–167, 2018.

P. de Berardinis, M. Rotilio, C. Marchionni, A. Friedman. "Improving the energy-efficiency of historic masonry buildings. A case study: A minor centre in the Abruzzo region, Italy". Energy and Buildings, vol. 80, pp. 415–423, 2014.

K. Fabbri, L. Tronchin, V. Tarabusi. "Energy Retrofit and Economic Evaluation Priorities Applied at an Italian Case Study". Energy Procedia, vol. 45, pp. 379–384, 2014.

ICOMOS New Zealand. "ICOMOS New Zealand Charter for the Conservation of Places of Cultural Heritage Value", 2010. Available: https://icomos.org.nz/wp-content/uploads/2020/12/NZ_Charter.pdf [March 9, 2021].

Investigating Urban Post-Industrial Landscapes in India: A Case of Kollam, Kerala

Ar. Sindhuja Sarasram[1], Ar. Hind Haneefa[2], Ar. Janaki S. Nair[3], Ar. Mary Riannan[4], Malavika Suresh[5], Ar. Richa Raje[6] and Dr. Sonal Tiwari[7]

[1,2,3,4,5] Department of Landscape, School of Planning and Architecture, Bhopal, India
{sindhuja.s.sarasram[1], hindhaneefa96[2], janakinair856[3], riannansilvester[4], malavikasuresh26[5]}@gmail.com[1]
[6,7]Department of Landscape, School of Planning and Architecture, Bhopal, India
{richa.raje[6], sonal[7]}@spabhopal.ac.in, ORCID-0000-0003-2929-6100[6], ORCID-0000-0001-8921-6876[7]

Abstract: In India, Industrialization had its beginnings in its colonial history. Several industrial campuses were established in coastal, or riverine belts due to the presence of water as a resource, and for ease of transportation. Such industrial centres as anchor points have witnessed the growth of these urban cores in the decades since, affecting riparian health in proportion to development. The city of Kollam, Kerala is one such example, where a cotton mill established in pre-independent India has been sited neighbouring a sensitive mangrove ecosystem along the Ashtamudi estuary that has been declared a Ramsar wetland. The campus is now non-functional and under neglect since 2008, due to various issues centred around outdated machinery. In this study, effects of industrialization and urbanization in transforming the estuary and mangrove ecosystem of the wetlands were assessed. Data collection was carried out in terms of traverse survey, visual-spatial mapping, quadrat analysis of vegetation. Physiological maps were made to understand natural topography of the area through on-site observations and validated with the help of GIS applications. The results indicated depletion of the mangrove vegetation, consequent decrease in local biodiversity, and disconnect between locals and the water edge. Landscape architects, designers and planners have a role in providing solutions that mitigate urban issues with sensitivity. In Kollam, adaptive re-use of the industrial campus for recreation, symbolizing the dependant livelihood on water and its supporting biodiversity, and promotion of sensitive eco-tourism to re-establishing the connectivity between humans and water were arrived at as primary landscape development strategies.

Keywords: Post-industrial-landscape; urbanization; estuarine-ecosystem; adaptive-reuse.

1. Introduction

1.1. Industrial landscape in India

Industrialization in India began in the 19th century when the Indian sub-continent was a colony (Roy 1999), rich with resources the western world was keen on utilizing. Some of the country's prominent cities and

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 381–393. © 2022 and published by the Architectural Science Association (ANZAScA).*

towns only came into existence during this period- beginning as industrial towns while there were no large settlements prior to that era, due to influential factors such as minerals and other resources on coastal and riverside lands that could be linked through waterways etc. played their parts in the siting of these industries (Bond 1915). Today's well-established railways and roadways networks initially served for transportation of goods and raw materials between resource to industry and industry to port (Albert 1983).

Cotton textile was one of the earliest goods to be mechanized and mass produced, influencing global economy, in the footsteps of the scientific innovations of the industrial revolution. The British established many cotton mills and supporting ports on the western coast of Colonial India (Sahoo n.d.) which have become prominent industrial towns of the post-independent nation. These textile mills were also some of the large-scale industries that had an influence on the landscape by way of pollution, and the people by way of migration and urbanization, (Warshaw 2011) the impacts being social evils, diseases, depletion of existing ecology, etc. resulting in poor quality of life for humans and nature alike.

1.2. Post-industrial scenario

Only over the course of the late 20th century has the world realized the impacts of unchecked industrial development in terms of pollution, untreated waste disposal, etc. (Environmental Impact Assessment for Developing Countries 1987). Nations and international governing bodies have placed regulations and guidelines for the protection of the planet, to reduce negative externalities caused by industries. Also, during these present times, due to the fast-paced development of technology and establishment of global trade, industries and their products need to stay upgraded to stay relevant in today's competitive market. These factors i.e., governing of environmental impact and the nature of the present economy in developing countries such as India result in several industries shutting down or remaining defunct due to lack of funds required to adapt to current demands. In the developing nation, such post-industrial brownfields and derelict pockets are being redefined as urban public spaces (Manufactured Sites-Rethinking the Post-Industrial Landscape 2003).

2. Need for study

In a developing country like India, with many active industrial regions that are expanding and increasingly urbanizing, there are also regions with defunct estates turning into derelict landscapes. Though not active sources of pollution post-abandonment, these brownfields contain untreated effluents from the operational years that continue to remain threats in the soil and ground-water table. Thus, with degradation of natural resources such as water, land, and air, many of these sites are non-conducive to life in any form— flora, fauna, or human (Shahid A. Abbasi 1997).

Industrial cities are younger than the organically developed historical cities, but have grown rapidly and are often the most densely populated regions in nations and there is a highest disparity in the quality of life— they may have both, the largest slums and tallest skyscrapers, in juxtaposition (McKendry 2017).

While Industrialization began simultaneously in the powerful western European countries and their resource-rich colonies, the impacts of pollution and course-correction with respect to the same were devised only in the former. The developing world is still catching up.

Post-industrial sites may be able to offer solutions for the space crunch in the dense urban fabric and serve as breathing spaces (Mclean 2019). The idea of re-thinking for the post-industrial landscape is now being given significance in India, and this study tries to investigate the post-industrial Indian city and its dynamics with brownfields, to address the issues and impacts of the urban post-industrial scenario in India.

3. Challenges

Industrial centres, though are magnets for migration and urbanization, are poorest in terms of quality of life due to pollution, disturbances to existing ecology and biodiversity (Shahid A. Abbasi 1997). Urban grey infrastructure that take over green spaces cause "urban heat islands" (Glossary of Meteorology, Americal Meteorological Society 2020; Mansourmoghaddam 2021) apart from denying other life forms of their habitats, while also causing pollution of various forms resulting in lack of physical and mental wellbeing of residents.

4. Research methodology

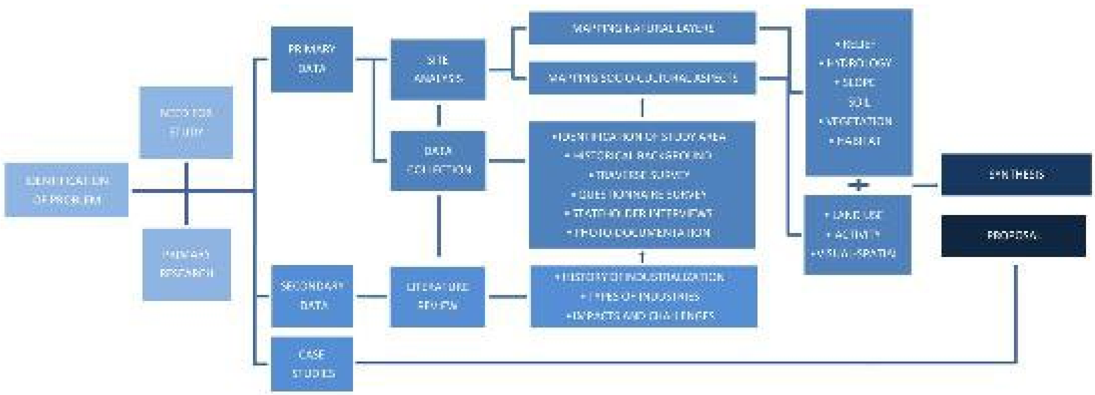


Figure 65: Methodology chart. Source: Authors, 2022

The urban public open spaces in the study area were documented through qualitative methods via interviews of individuals from the local community, visitors, and other stakeholders to understand the natural setting, impacts of human interventions, and the cultural associations the community has had with the landscape.

On-foot traverse survey of study area was conducted, documented through visual data, analyzed and validated with GIS applications. Local community directly involved with the study area were interviewed for collecting oral histories, associations with the cultural and ecological landscape.

Water samples were collected from the site for checking potability and tested. In all, four samples were collected, each from different points along the influence area's watersheds.

4.1. Visual representation of collected data:

With the help of GIS applications, satellite imagery and data collected on site, various maps were prepared including:

A physiographical study including the Landscape character, relief, hydrology, slope, soil, vegetation and habitat mapping of site was documented to understand the influence of the urbanization on the landscape. Anthropogenic activities were also visualized as data on map via land-use, activity mapping and cultural landscape mapping of study area— all layers to be further observed, analyzed and synthesized via the Overlay method (McHarg 1969) to understand the relationships between all the different parametes stated.

The above maps helped us in arriving at listing the issues and potentials in study area.

5. Site context

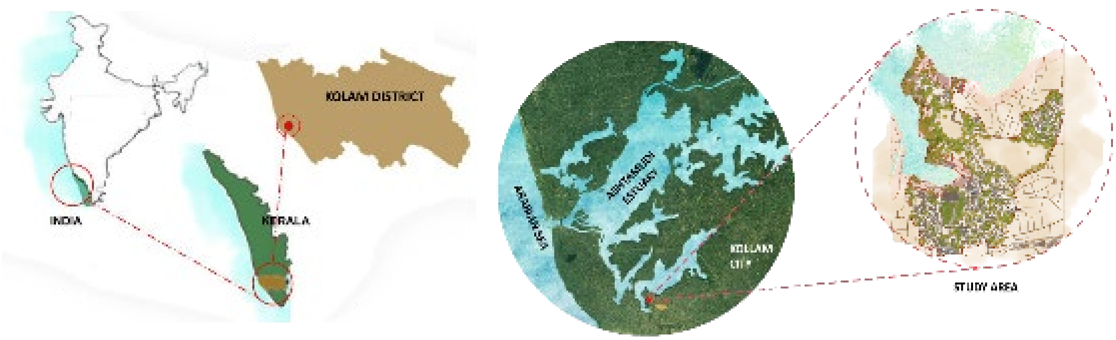


Figure 2: Location of study area by Ashtamudi Estuary. Source: Map generated by authors with GIS application, 2022

The city of Kollam, or Quilon as it was historically known, a port city on the Malabar coast was investigated for this study. Pre-imperialism, the city had trade links with European nations during the age of exploration. This association led to establishment of the early industries here, with the introduction of Cashew to add to the native commercial crops and produce that were exported.

While the coastal belt of Kollam was urbanized early, the 6140ha Ashtamudi estuary with a mangrove ecosystem and a rich bio-diversity was a resource in itself. The estuary has been declared a Ramsar wetland (Ramsar Sites Information Service 2002). In the 19th century, this area with its small-scale trade of coir, fishing and naturalized cashew became a center for new industries such as cotton textile mills, to be operated at larger scales. In 1884, A. D. Cotton mills was established on the estuarine edge. The industry, currently known as Parvathy Mills and under the management of the National Textile Corporation of India, has been defunct since the year 2008 due to pending modernization. This landlocked estate formed the central element of the study area.

5.1. Study area delineation

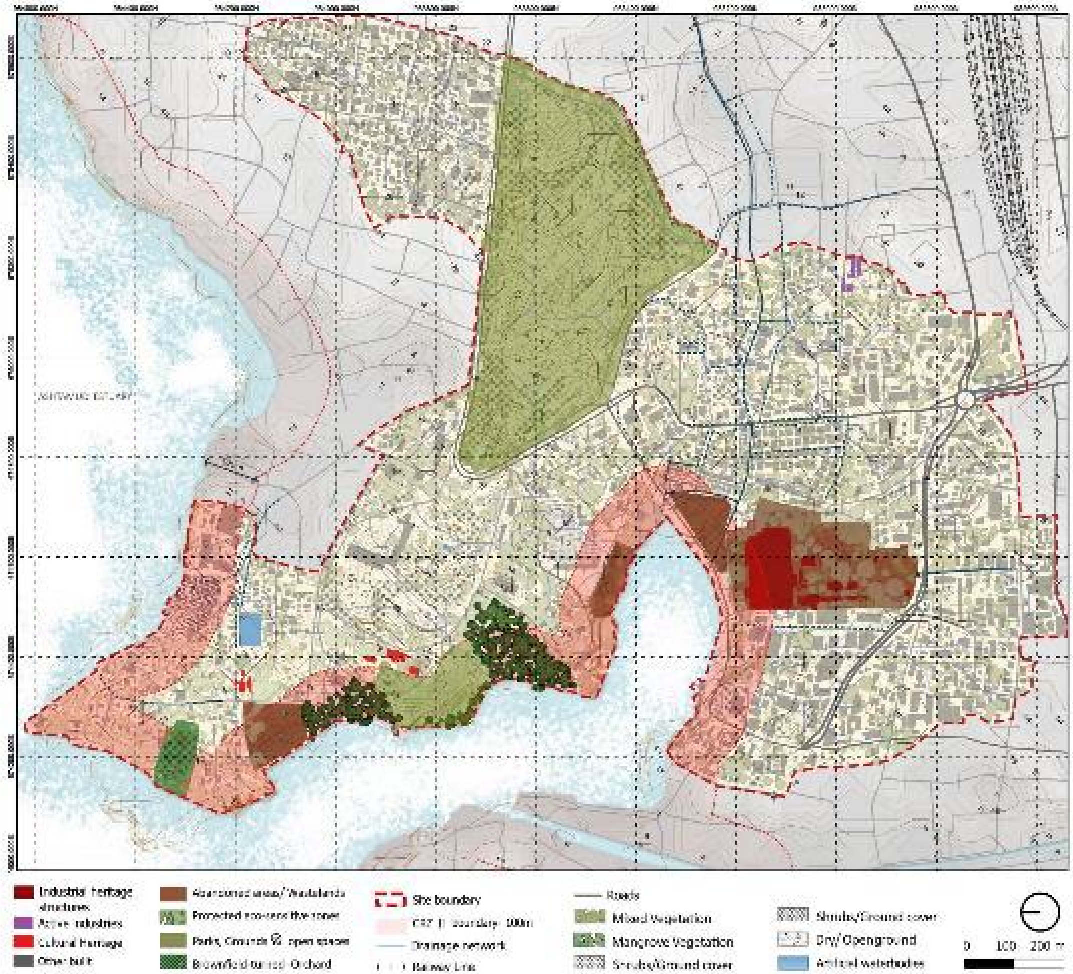


Figure 3: Landscape character map of delineated study area. Source: Map generated by authors with GIS application, 2022

Beginning with the mill and its influence area, the definition of the study region had to be examined from the lenses of ecological and cultural landscapes of the region to not remain limited to the post-industrial heritage, owing to the active urban context that has evolved since the establishment of the textile mill. Hence, the resulted study area was a juxtaposition of siting of the cotton mill, parcels of other smaller post-industrial brownfields and their influence area; the fragmented mangrove corridor; open space pockets of varying proportions; institutions of cultural heritage; and an active municipal waste dump site. It was noted that all the above anthropogenic elements were sited in or near the 100-meter Coastal regulation zone (CRZ- II) along the estuarine edge. The CRZ- II land-use activities come under the purview of the Local Planning Authority and Local Self-government.

The micro-watersheds in the influence area of the above elements were considered for area delineation. Delineated study area is located between 76° 35’ 03.72” E, 8° 54’ 10.60” and 76° 35’ 48.76” E, 8° 54’ 15.12”

5.2. Study area history

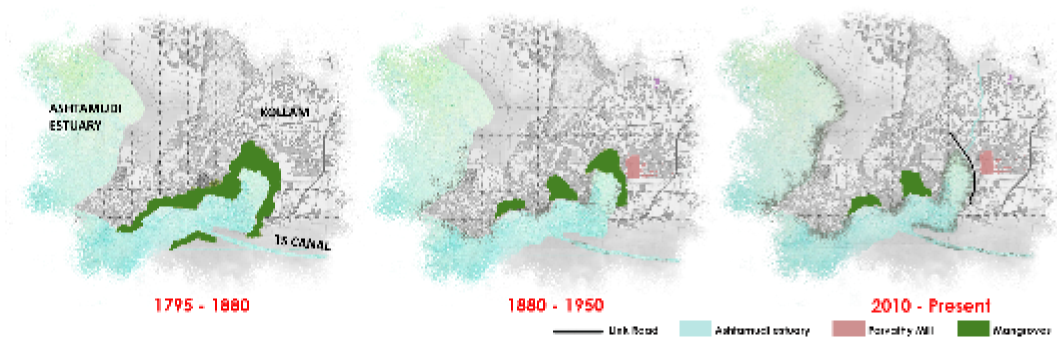


Figure 4: Historical evolution of study area. Source: Map generated by authors with GIS application, 2022

AD 201 - 1795:

Kollam city had been important trading Port since the 3rd century BC when it was part of the *Chera* dynasty. Sited along the Malabar coast, it was considered one among the major trading ports during the 13th century. By the 18th century, it was under the control of European rulers.

1795 - 1880:

The construction of Kollam canal waterway was completed in the 1880s, influencing commerce in the city. Kollam canal became the major travel and trade route. The *Asramam* arm of the *Kureepuzha* creek used to be fed by 6 streams (Kerala State Biodiversity Board n.d.), of which only one— *Manichi thodu* remains in a denaturalized state, while the others have been buried due to encroachment. Due to the development of market areas like *Chinnakada* and active economy, different communities with occupations related to trade migrated near the waterways, leading to the growth of the settlements along this region with the estuary being a resource for domestic purposes such as bathing, drinking, fishing, and commuting etc. and becoming a centre of human activity.

1880 – 1950:

Industrialization expanded during this period, including the cotton mill that was established in 1884. Roadways and railways lines were constructed for transportation of goods and raw materials. This reduced the usage of the canal waterways and the settlement along waterways encroached the buffer zones and consequentially led to sewage disposal and dumping of domestic wastes into the water network.

1950 – Present:

The lake environment had started deteriorating due to the collection of anthropogenic activities- industries, domestic waste etc. that have increased manyfold in the last few decades post-independence with urbanization. The Astamudi estuary was declared a Ramsar wetland in 2002. In 2010, a part of the Ashtamudi riparian edge was reclaimed for construction of Asramam Link Road and the denaturalized edge has impacted the biodiversity.

6. Impacts of textile industry on the landscape

The industrial setup in this case study was a cotton mill, thus the typical processes of the textile industry were studied and checked for the generated toxins and waste that would leave long-lasting impacts.

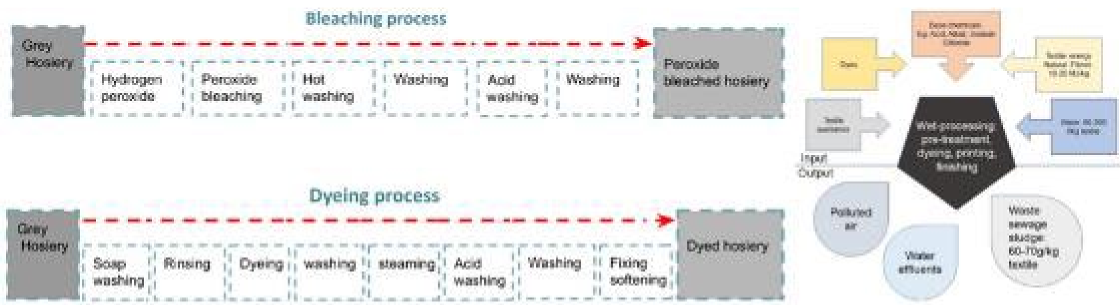


Figure 5: Processes in textile industry and Impacts of textile industry. Source: Flow chart by Authors, 2022, as discussed by Chavan (2001)

7. Study of layers

As stated in the Methodology above, the collected data were analysed with GIS mapping, and corroborated with satellite imagery. Analytical study included the natural layers of Relief, Slope, Soil, Hydrology and, Vegetation. Some of the main finiding are stated below.

7.1. Hydrology:

Figure 4: Natural layers of delineated study area. (Source: Maps generated by authors with GIS application, 2022)

Sl no	Characteristics	Unit	Desirable limit	Permissible limit	A- (Upstream-well)	B- (Midstream-open canal)	C- (Downstream-Discharge point at @ Link road)	D- (Mangrove)
1	Colour	CU	5	25	10	20	30	50
2	Odour				Disagreeable	Disagreeable	Disagreeable	Disagreeable
3	Turbidity	NTU	5	10	2.5	20.6	26.4	53. 1
4	pH at 26°C		6.5 to 8.5		7.11	7.153	7.052	7.376
5	Alkalinity	mg/litre	200	600	181.03	147.35	149.46	421
6	TDS	mg/litre	500	2000	375.2	269.8	294.3	23990
7	Total hardness (as $CaCO_3$)	mg/litre	300	600	226	128	118	6000
8	Ca	mg/litre	75	200	71.38	40.1	37.69	401
9	Mg	mg/litre	30	75	11.66	6.8	5.83	1215
10	Cl	mg/litre	250	1000	68.57	45.06	64.65	15476.1
11	Electrical Conductivity At 25oC	(micro mhos/cm)	Excellent - <250, Good - 250-750, medium - 750-2250, Bad - 2250-4000, Very bad - >4000		659.2	475.4	515.9	41500
13	SO	mg/litre	200	400	22.14	23.81	17.66	304.2
14	F	mg/litre	1	1.5	ND	ND	ND	ND
15	Fe	mg/litre	0.3	1	0.31	1.54	1.45	1.34
16	NO3	mg/litre	45	100	1.51	9.72	8.83	6.54
17	Total Coliforms		Shall not be detected/100 ml		Present	Present	Present	Present
18	E. Coli		Shall not be detected/100 m		Present	Absent	Present	Present

(purple)	**Within the desirable limit**
(light peach)	**Within the permissible limit**
(red)	**Exceeds the limit**

Figure 5: Water test results (Source: Water testing lab, Jalabhavan, Kollam; Central Pollution Control Board 2019).

7.2. Vegetation:

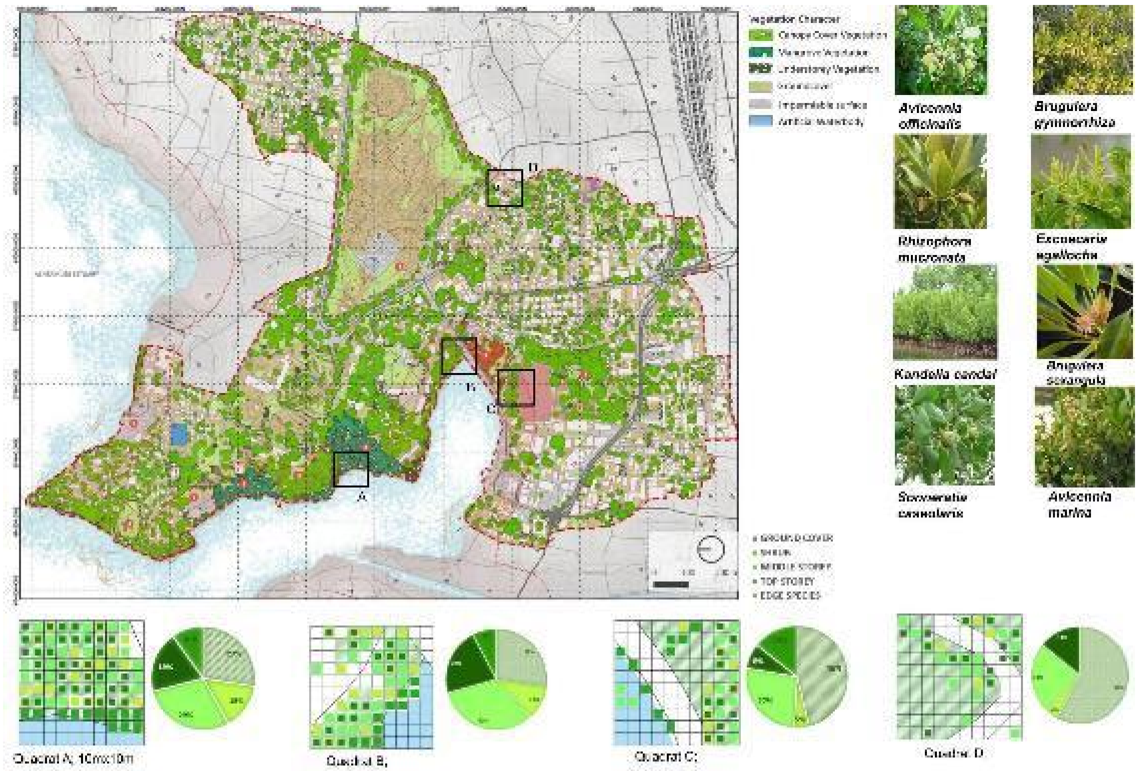


Figure 5: Vegetation study (Source: Maps generated by authors with GIS application, 2022).

Vegetation cover and character in terms of Species and spread were documented on site. Species such as *Bruguiera sexangula, Avicennia officinalis L, Sonneratia caseolaris L.* and other were observed in quadrat A. The observed mangrove plant species have endangered-threatened IUCN Status (N. Ratheesh 2018).

7.3. Socio-cultural layers:

Human activities and landuse patterns were also mapped to understand the influences on the natural landscape, to find the linkages with the issues observed.

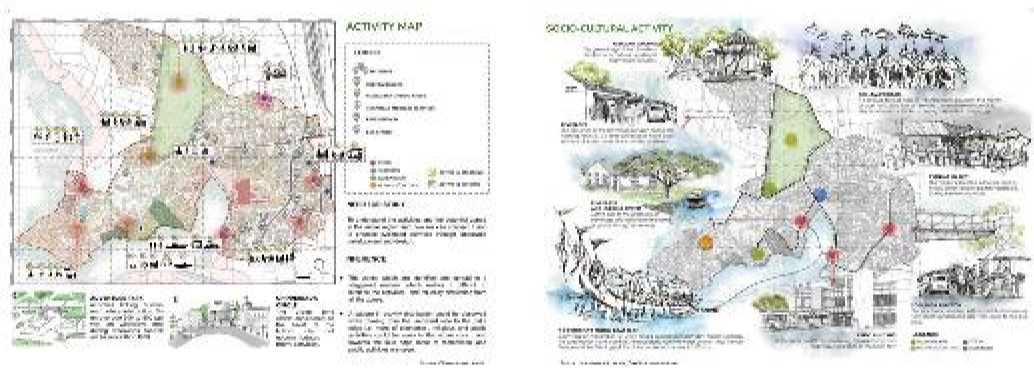


Figure 6: Mapping human activities (Source: Maps generated by authors with GIS application, 2022).

8. Inferences

From the traverse surveys, observations on site and study of natural layers it was synthesized that the local community had lost its cultural connection to the waterbody, with only a superficial dependence on it for local economy-influencing activities in the form of industries, tourism etc. This is reflected from the negligence of the riparian cover and pockets of urban litter lining the water edge.

Thermal discomfort was noted during peak hours in the core urban areas' grey infrastructure with the lack of green cover. Along with a poor walkability between public transport networks, this does not encourage pedestrian-centric movement.

The residential land use has encroached the water edge, depleting the mangrove ecosystem and the bio-diversity dependent on it.

9. Results

In summary, the study area with a rich confluence of natural and cultural heritage elements has great potential to be reclaimed and become a center for eco-cultural tourism.

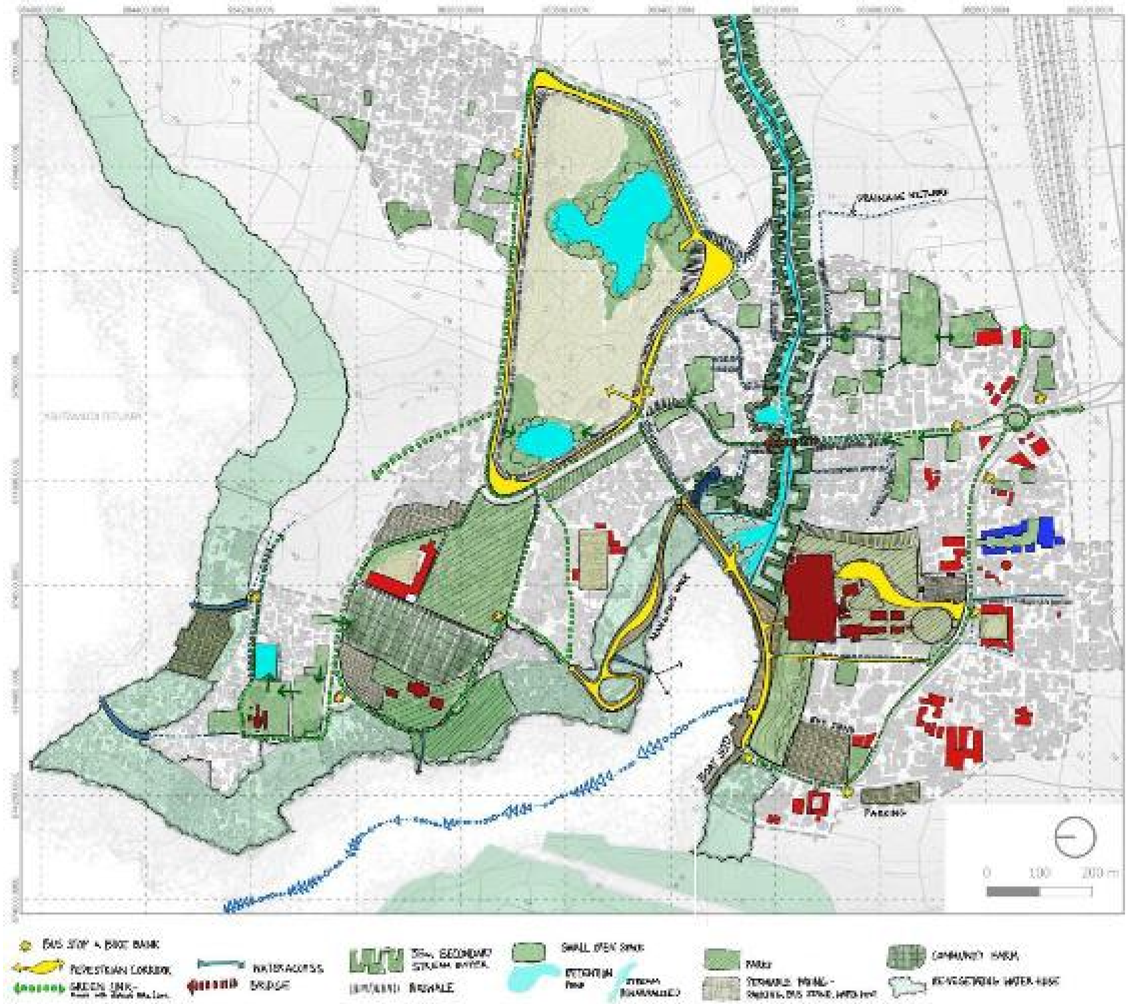


Figure 7: Synthesis and proposed interventions (Source: Maps generated by authors with GIS application, 2022).

A proposal for this urban post-industrial area requires policy guidelines centered around addressing the above issues. The broad categories of interventions can be with respect to:

- Sustainable urban development
- Protection of the surrounding Ashtamudi estuary's ecology
- Tenable eco-cultural tourism
- Improving quality of life

Some of the elaborate strategies that could help improvise the quality of life and reclaim the ecology of the region can be:

Readapting CRZ zone:

- Removal of incompatible land use
- Relinking the connection between the people and the waterbody
- Converting brownfields into Greenfields and creating usable public open space realm that is well connected, by activating the water edge
- Protection of mangrove ecosystem and estuarine ecotone

Developing Blue- Green infrastructure:

- Establishing green infrastructure along corridors and linking open spaces
- Revitalizing the buried streams and renaturalizing them
- Increasing public awareness of the socio-ecological heritage

Combating limitations of Urban core:

- Improving connectivity- pedestrian comfort in the city; sustainable public transport system
- Making space for recreational activities that benefit the local community and city in terms of employment and revenue generation
- Improved waste management system- preparedness and mitigation of pollution and other ill effects of urbanization.

10. Conclusion

Architecture and planning professionals have a responsibility towards finding solutions for mitigating climate change and biodiversity collapse. While post-industrial landscapes and urban nature-based solutions are being implemented across the developed world, in India, it is still a new venture without precedent. Interventions in such affected areas can serve as templates for future projects specific to this climatic context.

Acknowledgements

We'd like to acknowledge our gratitude to the School of Planning and Architecture, Bhopal, and the faculty of Department of Landscape for their support and guidance through this project. We are grateful to the residents of Kollam for their hospitality and co-operation during the site visit to the study area.

References

Albert, Bill. 1983. Transport in the Industrial Revolution. Manchester University Press.

Bond, J. W. 1915. Southern India, Its History, People, Commerce, and Industrial Resources. Foreign and Colonial Compiling and Publishing Company.

2019. Central Pollution Control Board. 11 October. https://cpcb.nic.in/water-quality-criteria/.

Chavan, R. B. 2001. "Indian textile industry - Environmental issues." Indian Journal of Fibre and Textile Research 26(1):11-21.

1987. Environmental Impact Assessment for Developing Countries. Elsevier Science.

2020. Glossary of Meteorology, Americal Meteorological Society. May 29. Accessed 2022. https://glossary.ametsoc.org/wiki/Urban_heat_island.

2022. Guidelines for Drinking Water Quality. Guidelines, Geneva: World Health Organization.

n.d. Kerala State Biodiversity Board. Accessed 2022. https://keralabiodiversity.org/images/bhs/asramam_report.pdf.

Mansourmoghaddam, M., Rousta, I., Zamani, M., Mokhtari, M. H., Karimi Firozjaei, M., & Alavipanah, S. K. 2021. “Study and prediction of land surface temperature changes of Yazd city: assessing the proximity and changes of land cover.” Journal of RS and GIS for Natural Resources 12(4), 1-27.

2003 . Manufactured Sites- Rethinking the Post-Industrial Landscape. Taylor & Francis.

McHarg, ian. 1969. Design with nature. Turtleback.

McKendry, Corina. 2017. Greening Post-Industrial Cities- Growth, Equity, and Environmental Governance. Taylor & Francis.

Mclean, Ross. 2019. Transformative ground- A Field Guide to the Post-industrial Landscape. Routlege.

N. Ratheesh, S. Lekshmi, K. B. Manoj. 2018. “Structural analysis of mangrove vegetation in Asramam, Kollam District, Kerala.” Trends in Biosciences Vol. 11 No.7 pp.1398-1403 ref.17.

2002. Ramsar Sites Information Service. 19 August. Accessed 2022. https://rsis.ramsar.org/ris/1204.

Roy, Tirthankar. 1999. Traditional industry in the economy of colonial India. Cambridge University Press.

Sahoo, Rajib Lochan. n.d. INDIAN COTTON MILLS AND THE BRITISH ECONOMIC POLICY, 1854-1894". Indian History Congress.

Shahid A. Abbasi, S. Vinithan. 1997. Environmental Impact of Industries on Suburban Environments. Discovery Publishing House.

Subramanian, Lakshmi. 2008. Ports, Towns, Cities. Marg Publications.

Warshaw, Leon J. 2011. The Textile Industry: History and Health and Safety. https://www.iloencyclopaedia.org/part-xiv-42166/textile-goods-industry.

Key interactions of safety egress factors in early architecture design in hospitals

Maryse Fahmi[1], Mahesh Babu Purushothaman[2] and Funmilayo Ebun Rotimi[3]

[1,2,3] Auckland University of Technology, Auckland, New Zealand
{maryse.fahmi[1], mahesh.babu[2], funmilayo.ebun.rotimi[3]} @aut.ac.nz, ORCID-0000-0001-5062-272X[2]

Abstract The primary building performance assessing factor for large and complex buildings such as hospitals is the safety of its occupants during emergencies such as fire. Previous research had identified multiple factors in the architectural design of fire emergency evacuations at hospitals. However, globally, fatalities have resulted from fire accidents in hospitals indicating that more factors have complex interactions on the performance and patient safety during fire emergencies. This paper highlights additional factors that influence the architectural design of hospitals to ensure safe egress for occupiers including critical care patients. The research follows a narrative inquiry methodology within the constructivism epistemology and interpretivism framework. The method considers data triangulation consisting of a systematic literature review that explores previously published papers and is substantiated by the limited semi-structured interviews, which provide a realistic understanding of the topic. These interviews are followed by narrative analysis and the results are presented by system dynamics mapping. The research has concluded a total of 9 key factors directly affecting the safety of evacuation in hospitals with the novel factors of patients' mobility rate and evacuation conditions being the most influential factors that need to be considered. The practical implication of this research is that it provides a better understanding of the necessity to include the patients' mobility while designing for safe evacuation in hospitals during fire emergencies.

Keywords Safe egress; evacuation; hospitals; fire.

1. Introduction

A Hospital is defined as a large building where people who are ill or injured are given medical treatment and care (Oxford Dictionary,2022). Fire safety in hospitals is considered a sensitive matter where it is believed that it is the responsibility of society to care for these sick people (Sadeghnia et.al., 2014). The degree of threat associated with the fire can vary from mild to severely dangerous. "Dangerous and violent fires that break out globally claim buildings and sadly lives majorly due to smoke inhalation" (Bush, 2015). Hospitals are no exceptions to fire incidents and spread. Campbell (2017) mentions that the National Fire Protection Association (NFPA) reports an estimated 1140 fire accidents in hospitals or hospices. Also, according to Wapling (2009), The NHS London reports that 16 per cent of all fires in the UK erupt in hospitals and medical centers. In addition, the UK had 5 major hospital fires that required the

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 394–404.*

complete evacuation of about 40,000 patients excluding staff and visitors, one of them was the Royal Marsden Hospital fire, Wednesday 2nd January 2008 (Wapling, 2009). Between 1 July 2006 to 30 June 2016, there was an approximation of 31,000 serious fires in New Zealand including those in hospitals (FENZ Incident Statistics for New Zealand, 2018). New Zealand Waitemata District health (2002) board reported a fire in the operating theatre of Waitakere Hospital. The financial implication of fire failure in buildings is significant, at times it can be 250 million NZD to restore part of the building (Gibson, 2019). According to Home Advisor (2020), the average cost for restoring fire damages on buildings could reach up to 60% of its construction budget.

New Zealand Building Act 2004 specifies that buildings, including hospitals, are to be constructed such that occupants escape from the building if a fire incident occurs (Safety First, 2019). The sensitivity in fire safety design in hospitals is due to the complexity of the environment of these buildings whether in terms of interior design and/or the occupants who are struggling with mobility which complicates the typical evacuation procedures. Passive fire protection companies in the UK describe fire threats to the safety of patients and staff alike as “can bring a hospital to a standstill” (CLM, 2020). It is vital to acknowledge the importance of accessing and adopting measures of safety to limit the effects of fire spread in hospitals. This research paper aims to establish the key points of safe egress in major hospitals by which all types of patients (considering the mobility issues) are guaranteed safety in fire emergency scenarios. This study aims to assess the fire egress process in hospitals, the factors associated with it, and legislation and develop a model that would be considered a useful input for a realistic simulation of such an event. The study approaches fire egress in hospitals from an architectural and construction perspective, with the following question:

“What are the key factors to be considered in the early architectural design stage that brings safe egress in hospitals in case of fire emergencies?”

2. Literature Review

Designing Building UK (2020) identifies safety in terms of the built environment as the protection from serious harm caused by hazards or other undesirable events. Also, according to Herb Scribner (2018), people spend from 80% to 90% of their time inside a building. Thus, a sufficiently high level of safety performance is expected.

“Designing a building to provide fire safety involves decisions on both the construction materials and layout needed to reduce the risk to an acceptable level. The risk is assessed according to the number and mobility of the occupants (occupant load and risk group of the building); the activities undertaken within the building and the nature of the building materials and contents” (Building performance, 2012).

Researchers previously identified the main factors of safe egress that are to be considered for the building’s layout, occupant capacity, and individual patient room capacity. For example, Roberts (2000), Rahouti (2020) and Mozer (2014) identified the following key factors as emergency exits characteristics (EC), Interior layout (IL), Occupants Flow rate(FR), The Required safe egress time (RSET) / Available Safe egress time (ASET) factor (RA), Fire control elements (FC), Building construction materials (BC), Occupant groups (OG), Software simulation (SS), Fire spread (FS), Elevators/ signs ES, and Human behaviour during fire emergencies (HB). The systematic literature review further revealed the importance of these factors and their connectivity which is discussed in the subsequent sections.

2.1. Hospital Buildings and their Occupancy

Hospital building occupants vary between working staff, patients and visitors (Pistoria et.al, 2020). The occupant group includes vulnerable short-term and long-term patients. Unlike the healthy occupant group, patients usually have mobility issues hindering their movement. The average walking speed of a healthy person aged between 20 to 40 years old is 1.34 m/s, and with age progression only, this speed is reduced by up to 44% for the elderly (Bejek et.al 2005). Patients, however, could range widely in terms of age, added to this is the illness that consequently affects their average walking speed (Purser, 2005). Table 1 shows a breakdown of movement rates for different occupant groups present in hospitals (Fahmi M, 2021).

Table 33: Movement rates for different groups of people

Individual	Healthy/young		Elderly (Independently mobile)	Non-Healthy mobility independent person	Wheelchair User	Assistance dependent mobility patient (eg. pushed on a hospital bed)
	Walking	Running				
Speed Rate	1.4 m/s	2.5-2.8 m/s	0.7 m/s	at ≤0.60 to 0.70 m/s	0.43- 0.48 m/s	Depends on the strength of the pusher (no more than 3 mph

2.2. Hospital Building Layout and exits characteristics

The Building Regulation (2012) states that design for every 50 occupants, 2 corresponding exit routes are required in place, and for every 150 occupants, 3 exit routes are required in the building interior layout. Further, the escape route could service more than one internal door but leads to only 1 external exit. This regulation did not consider a linear relationship. Further, “the total combined width of all available escape routes shall allow 8 mm/person for horizontal travel and 10 mm/person for vertical travel. And the widths of individual escape routes shall be no less than 1200 mm for horizontal travel, and 1500 mm for vertical travel required for the passage of beds” (Building Regulation, 2012). Given that a typical hospital bed ranges between 980mm to 1100mm, this means that the 3 emergency exits specified for the 150 patients can allow only 1 bed with one patient through at a time of evacuation.

Further, according to Schroder et.al, (2017), the expected RSET time should be approximately 3 minutes to exit the dangerous area into a safe one. However, CFA Australia (2020) states the speed of fire doubles at a slight slope of 10 degrees and can reach up to 0.27 meters per second and the rate of smoke spread is 0.61 m/s. The Non-Healthy mobility independent person Wheelchair User and Assistance dependent patient mobility rate is less than that of smoke spread, putting them at risk (Bejek et.al 2005). In the codes and literature, the discussion on safe egress for patients under life support and critical monitoring machines is either not discussed or mentioned seldom and generally grouped as patients. For example, the escape routes discussed in the Building Regulation (2012) do not consider the complexity of patient mobility that may put patients of a certain category at risk.

There exists a gap in the literature and NZ building regulations on safe fire egress in hospitals concerning considering the patient mobility rate and allied critical factors that would help design hospitals for the safe evacuation of patients.

3. Methodology

Crotty (1998) lists four elements as part of the framework for the research process which includes epistemology, theoretical framework, methodology, and methods. The safe egress factors are ideal as they are subjected to variation across time. These factors will rely on the interaction of individuals or external changing factors (such as materials) which alternate their values and thus cannot be realistic. This research will utilize constructivist epistemology where the results are constructed based on data collected (Crotty, 1998)

Based on constructivist epistemology, the framework of this study will be based on the interpretivism framework. The framework will help to include an explicit presentation of various information regarding the research topic (safe egress) to offer a wider platform of the knowledge base. The information collected will be based on narrative inquiry where the semi-structured interview questions are derived from the systematic literature review. The data from semi-structured interviews relevant to New Zealand hospitals were obtained from volunteering experts following general protocols. The experts were professionals working in hospitals as health care or administration staff who would be able to communicate in English. The information acquired from these interviews were decoded using primary codes and themes and will be plotted against a Likert scale to interpret the acquired sets of data that provided an understanding of hospital safe egress. The interview notes and journals were used in decoding the experts' opinions. Results obtained from the interviews conducted were cross referenced with the factors obtained from systematic literature review of previous published research. Each of the factors is then analysed in reference to information obtained from these published papers, the New Zealand building regulations and the semi-structured interviews. The results are collated and presented in form of system dynamic mapping.

The reliability of the research was obtained through data triangulation (multiple sources of data) and methodological triangulation (employing more than one method of data collection: semi-structured interviews and systematic literature reviews). The validity of the research was ensured by adopting the same semi-structured interview protocol for different participants. The data triangulation and methodological triangulation also aided to achieve validity. The external validity was achieved by conducting semi-structured interviews of participants from major hospitals. The credibility was be ensured by collecting data from highly peer-reviewed literature and data from participants of reputable organizations. The research was conducted in a normal work setting with high skilled practitioners from highly reputable organizations that ensured transferability.

4. Results

4.1. Systematic literature review.

Table 2 explains the steps in the systematic literature review, and figure 1 explains the country of the articles.

Table 34: Steps of the systematic review.

Process	Individual step	Analysis resulting	No. of articles
Search process and data collection	Identification of keywords: (Safe egress in hospitals; safe egress in architecture; safe egress factors/ measures in hospitals	Previous research and reviews	
	Development of exclusion and inclusion criteria, methodology	Quality of the article and limitations	10
	Specification of relevant search engines and execution of the search (5 engines: GOOGLE SCHOLAR, A WEB OF SCIENCE, SCIENCE DIRECT, SCOPUS)	Title and abstracts (automated based on keywords)	23,000
	Development of A-, B-, and C-list:		
	C-list	Key words w.r.t construction search	6,339
	B-list	Title and abstracts (manual)	
	A-list	Full text	75
	Narrative inclusions	Full text	44

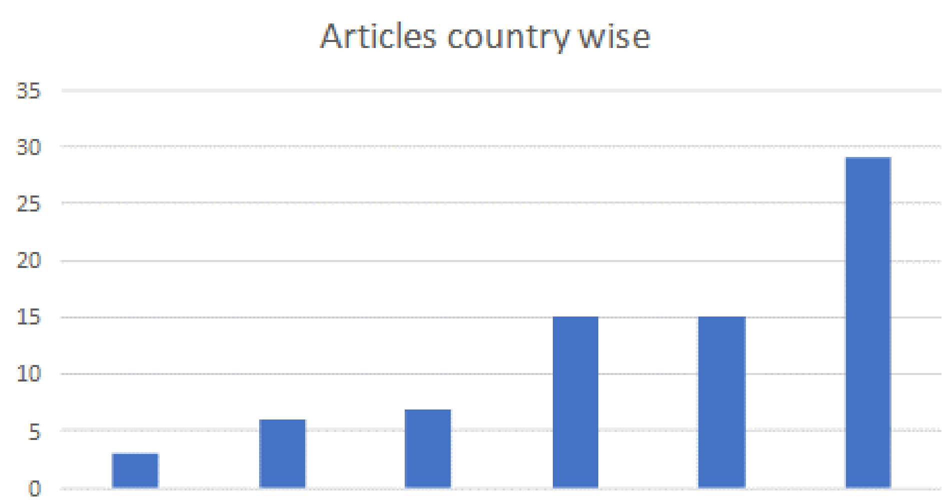


Figure 1: Articles country wise.

Table 3 shows below the summary of each previously published paper reviewed within the research topic. The information provided in the table includes the author's name and year and factors.

Table 35 Factors affecting safe egress

Author/ Article/ Year	EC	IL	FR	RA	FC	BC	OG	SS	FS	HB	ES
Baldwin, Melinek, & Thomas (1971).									✓		
Champneys, et.al (2013).		✓						✓	✓		
Chien & Korikanthimath (2007).			✓					✓			
Chow & Chan (1996).						✓		✓			
Chu et.al (2007)				✓			✓				
Graham & Roberts (2000)	✓	✓		✓							
Hagiwara & Tanaka (1994)	✓	✓	✓								
Harding, Amos & Gwynne (2010).		✓		✓		✓					✓
Horasan (2003)				✓			✓				
Hui (2013).		✓			✓						
Joyce, Lawrence, & Galea (2020)		✓						✓			
Klüpfel& Meyer-König (2005).		✓					✓	✓			
Kobes et.al (2010)		✓							✓	✓	
Lin, et.al (2015).		✓									
Luh et.al(2012)			✓								
Meacham (1999).					✓					✓	
Mózer (2014)		✓		✓		✓					
New Zealand Building code C1-6 AS/3 (2012)		✓					✓				
Notake, Ebihara, & Yashiro (2001).	✓	✓									
O'connor (2016).						✓			✓		
Ozel (2001)			✓	✓							
Purser et.al (2005).							✓				
Rahouti et.al (2020).		✓	✓				✓			✓	
Rahouti, Datoussaïd, & Lovreglio (2016).							✓				
Ronchi, & Nilsson (2013).	✓	✓								✓	✓
Schröder, Arnold, & Seyfried, (2020)				✓							
Tanaka, Hagiwara, & Mimura (1998).	✓										
Tseng et.al (2017)		✓		✓	✓						
Ursetta, et.al (2014).	✓	✓						✓			
Xie, et.al (2016).	✓	✓									
Gerges M., Mayouf (2017)		✓								✓	
Total	6	18	6	4	7	3	7	5	3	4	2

Author/ Article/ Year	EC	IL	FR	RA	FC	BC	OG	SS	FS	HB	ES

Refer to section 2.0 (Literature Review) paragraph 3 for the full names of the acronyms mentioned in the table above (Table 3) and in table below (Table 4).

4.2 Expert opinion

Three field experts were interviewed for this pilot research to discuss and confirm the importance of each of the identified safe egress affecting factors and the results are shown in Table 4.

Table 36: Expert opinion plotted against a Likert Scale

Factors	Expert 1	Expert 2	Expert 3	Average
IL	5	4	5	4.6 (strongly agree)
EC	5	4	5	4.6 (strongly agree)
BC	3	3	4	4.3 (strongly agree)
RA	3	3	4	3.3 (Neutral)
OG	4	4	5	4.3 (strongly agree)
FC	5	5	5	5 (strongly agree)
FS	-	-	-	-
HB	2	-	-	-
FR	5	5	5	5 (strongly agree)
SS	-	-	-	-
ES	2	3	4	3.3 (Neutral)
Occupant mobility rate	5	5	5	5 (strongly agree)

The Factors interlinks derived from the narrative analysis of the field experts and systematic literature review are shown in the figure 2 below

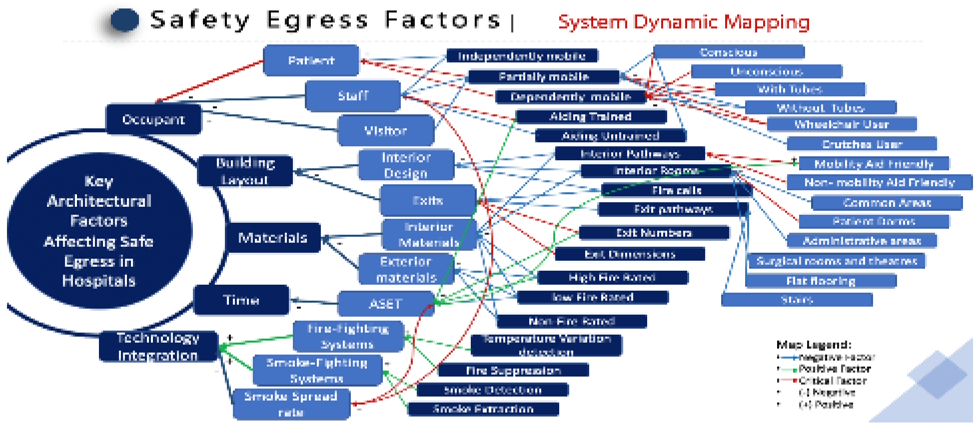


Figure 66: System dynamic mapping

5. Discussion

> "Designing a building to provide fire safety involves decisions on both the construction materials and layout needed to reduce the risk to an acceptable level. The risk is assessed according to: the number and mobility of the occupants (occupant load and risk group of the building); the activities undertaken within the building; and the nature of the building materials and contents"
>
> (Building Regulation, 2012).

Upon the information shared by this statement of the New Zealand Building Regualtion C/AS3 for "Acceptable Solution for Buildings Where Care or Detention Provided (Risk Group SI)", the standard information provided by this new Zealand Code, the data concluded by the systematic literature review conducted for this research and the key points addressed by the interviewed field experts; the concluded key factors affecting safe egress for all types of people present in hospitals in case of fire emergencies are: IL, EC, BC, RA, FC, FR, ES, and OG. The IL factor had been strongly agreed upon by the experts which had 18/30 authors identifying it. The EC factor had been strongly agreed upon by the experts which had 6/30 authors identified it. The BC factor had been strongly agreed upon by the experts which had 3/30 authors identified it. The RA factor had been rated neutral by the experts which had 4/30 authors identifying it. The FC factor had been strongly agreed upon by the experts which had 7/30 authors identified it. The FR factor had been strongly agreed upon by the experts which had 6/30 authors identified it. The ES factor had been rated Neutral by the experts which had 2/30 authors identifying it. The OG factor had been strongly agreed upon by the experts which had 7/30 authors identified it. However, the experts did not comment on FS, HB, and SS despite 3, 4 and 5 authors identifying them respectively. This may be probably because the experts have not experienced these factors in a real-time environment. On the other hand, the experts identified the Occupant mobility rate of patients as a key factor that affects the safe egress in case of fire in hospitals. This could be probably because the experts have had experience in moving the patients around and the difficulty attached to moving the patients with limited ability, on life support, and monitoring systems.

6. Conclusion

The research aimed to provide a better understanding of the necessity to include all factors affecting safe egress in the event of a fire at hospitals through a systematic literature review and semi-structured interviews of experts. The narrative analysis revealed various factors that influence safe egress. There were a total of 7 main factors contributing to the level of safety of egress in the hospital in case of fire emergencies. These factors are as follows: IL, EC, BC, RA, FC, FR, ES, OG and Occupant mobility rate (dependently moveable).

The professional opinions acquired from experts' semi-structured interviews on this topic have identified and confirmed the importance of these 9 factors in dictating safe egress in hospitals. The experts have also confirmed that the mobility rate associated with patients is also to be considered a key factor contributing to the safety level of the egress process. Understanding the different effects of such factors will ensure the constant safety of all patients during a fire emergency especially dependently mobile patients. The study on the influence of the Occupant mobility rate (dependently moveable) concerning the safe egress in case of fire would be beneficial to academics, future researchers, and hospital professionals as well as the occupants, especially patients. The qualitative research had limitations are acknowledged. The systematic literature review and interviews were conducted in English and they may be articles in other languages that could have identified more factors. This limitation is acknowledged. The expert opinion sample size limitation is acknowledged. However the quality control of research methodologies off these effects. The practical implication of this research is that it provides a better understanding of the necessity to include the patients' mobility while designing for safe evacuation in hospitals during fire emergencies. This is a pilot study and researchers are currently undertaking further research into this subject area.

References

Gibson, A. (2019, November 13). SkyCity convention centre fire: Up to $250m to repair. NZ Herald. https://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=12284706

Baldwin, R., Melinek, S. J., & Thomas, P. H. (1971). Fire Spread in Buildings-The Early Stages of Growth. Fire Safety Science, 884, 1-1.

Bejek, Z., Paróczai, R., Illyés, Á., & Kiss, R. M. (2006). The influence of walking speed on gait parameters in healthy people and in patients with osteoarthritis. Knee surgery, sports traumatology, arthroscopy, 14(7), 612-622.

Building Performance (2012, April 10) Acceptable Solutions for Building Where Care or Detention is Provided (Risk Group SI). For New Zealand Building Code Clauses C1-C6 Protection from fire. https://www.building.govt.nz/assets/Uploads/building-code-compliance/c-protection-from-fire/asvm/cas3-protection-from-fire-amendment-3.pdf

Bukowski, R. (2009). Emergency egress from buildings. US Department of Commerce, National Institute of Standards and Technology.

Bush, E. M. (2015, January 28). Smoke inhalation is the most common cause of death in house fires. MSU Extension. https://www.canr.msu.edu/news/smoke_inhalation_is_the_most_common_cause_of_death_in_house_fires

Campbell, R. (2017, October). Fires in health care facilities. NFPA. https://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Fires-in-Health-Care-Facilities

Champneys, A., Fresneda-Portillo, C., Hewitt, I., Liu, X., Hunt, M., Nagapetyan, T., Wood, D. (2013). Estimating the Spread of Fire in Buildings.

Chien, S. I., & Korikanthimath, V. V. (2007). Analysis and modeling of simultaneous and staged emergency evacuations. Journal of Transportation Engineering, 133(3), 190-197.

Chow, W. K., & Chan, Y. Y. (1996). Computer simulation of the thermal fire resistance of building materials and structural elements. Construction and Building materials, 10(2), 131-140.

Chu, G. Q., Chen, T., Sun, Z. H., & Sun, J. H. (2007). Probabilistic risk assessment for evacuees in building fires. Building and Environment, 42(3), 1283-1290.

Crotty, M. (1998). The foundations of social research: Meaning and perspective in the research process. St Leonards, Australia: Allen & Unwin.

Research reports. (2018). Fire and Emergency New Zealand (FENZ). https://www.fireandemergency.nz/research-and-reports/research-reports/

Fahmi M. (2021) Key interactions of safety egress factors in early architecture design in hospitals. Research paper

Fire prevention in hospitals | Potential fire hazards in hospitals. (2021, April 22). CLM. https://clmfireproofing.com/potential-fire-hazards-in-hospitals/

Fire protection compliance — Safety first. (2019, January 18). Safety First. https://www.safetyfirst.co.nz/news/fire-protection-compliance

Graham, T. L., & Roberts, D. J. (2000). Qualitative overview of some important factors affecting the egress of people in hotel fires. International Journal of Hospitality Management, 19(1), 79-87.

Gerges, M., Mayouf, M., Rumley, P., & Moore, D. (2017). Human behaviour under fire situations in high-rise residential building. International Journal of Building Pathology and Adaptation.

Scribner, H. (2019, June 30). 'Indoor generation': Here’s how much time we spend indoors. Deseret News. https://www.deseret.com/2018/5/17/20645140/indoor-generation-here-s-how-much-time-we-spend-indoors

Hagiwara, Ichirou, Tanaka, Takeyoushi (1994). International comparison of fire safety provisions for means of escape. Fire Safety Science, 4, 633-644.

Harding, P. J., Amos, M., & Gwynne, S. (2010). Prediction and mitigation of crush conditions in emergency evacuations. In Pedestrian and Evacuation Dynamics 2008 (pp. 233-246). Springer, Berlin, Heidelberg.

Horasan, M. (2003). Design occupant groups concept applied to fire safety engineering human behaviour studies. Fire Safety Science, 7, 953-962.

Hospital noun - Oxford advanced American dictionary at OxfordLearnersDictionaries.com. (2022). Oxford Learner's Dictionaries | Find definitions, translations, and grammar explanations at Oxford Learner's Dictionaries. https://www.oxfordlearnersdictionaries.com/definition/american_english/hospital

How fire behaves. (2020, August 17). Country Fire Authority. https://www.cfa.vic.gov.au/plan-prepare/how-fire-behaves

Hui, M. C. (2013). An approach to provide cost effective patient fire safety. Asia Pacific Journal of Health Management, 8(1), 39.

Jamali, N., Leung, R. K., & Verderber, S. (2020). A review of computerized hospital layout modelling techniques and their ethical implications. Frontiers of Architectural Research. https://www.sciencedirect.com/science/article/pii/S2095263520300054

Joyce, M. S., Lawrence, P. J., & Galea, E. R. (2020). Hospital evacuation planning tool for assistance devices (HEPTAD). Fire and Materials, (1), 4-9

Klüpfel, H., Schreckenberg, M., & Meyer-König, T. (2005). Models for crowd movement and egress simulation. In Traffic and Granular flow’03 (pp. 357-372). Springer, Berlin, Heidelberg.

Kobes, M., Helsloot, I., De Vries, B., & Post, J. G. (2010). Building safety and human behaviour in fire: A literature review. Fire Safety Journal, 45(1), 1-11.

Learn how much it costs to repair fire & smoke damage. (2020, January). HomeAdvisor - Find Local Home Repair & Improvement Services. https://www.homeadvisor.com/cost/disaster-recovery/repair-fire-and-smoke-damage/

Lin, Q. L., Liu, H. C., Wang, D. J., & Liu, L. (2015). Integrating systematic layout planning with fuzzy constraint theory to design and optimize the facility layout for operating theatre in hospitals. Journal of Intelligent Manufacturing, 26(1), 87-95. https://link.springer.com/content/pdf/10.1007/s10845-013-0764-8.pdf

Luh, P. B., Wilkie, C. T., Chang, S. C., Marsh, K. L., & Olderman, N. (2012). Modeling and optimization of building emergency evacuation considering blocking effects on crowd movement. IEEE Transactions on Automation Science and Engineering, 9(4), 687-700.

Marchant, R. (1999). Some Discussions on Egress Calculations–Time to Move. Int J Eng Performance-based Fire Code, 1(2), 81-95.

Meacham, B. J. (1999). Integrating human behaviour and response issues into fire safety management of facilities. Facilities.

Mózer, V. (2014). An analysis of factors affecting available safe escape time. In Advanced Materials Research (Vol. 1001, pp. 267-271). Trans Tech Publications Ltd.

Notake, H., Ebihara, M., & Yashiro, Y. (2001). Assessment of legibility of egress route in a building from the viewpoint of evacuation behavior. Safety science, 38(2), 127-138.

Ozel, F. (2001). Time pressure and stress as a factor during emergency egress. Safety science, 38(2), 95.

Pistoria, Di Francesco, L., M. J., Auerbach, A. D., Nardino, R. J., & Holmboe, E. S. (2005). Internal medicine training in the inpatient setting: a review of published educational interventions. Journal of general internal medicine, 20(12), 1173-1180.

Purser, J. L., Weinberger, M., Cohen, H. J., Pieper, C. F., Morey, M. C., Li, T., ... & Lapuerta, P. (2005). Walking speed predicts health status and hospital costs for frail elderly male veterans. Journal of rehabilitation research & development, 42(4). https://www.rehab.research.va.gov/jour/05/42/4/pdf/Purser.pdf

Safety in the construction industry. (2020, June 12). Designing Buildings UK. Retrieved September 15, 2020, from https://www.designingbuildings.co.uk/wiki/Safety_in_the_construction_industry

Sarsangi, V., Saberi, H. R., Malakutikhah, M., Sadeghnia, M., Rahimizadeh, A., & Aboee Mehrizi, E. (2014). Analyzing the risk of fire in a hospital complex by “fire risk assessment method for engineering”(FRAME). International Archives of Health Sciences, 1(1), 9-13.

Schröder, B., Arnold, L., & Seyfried, A. (2020). A map representation of the ASET-RSET concept. Fire Safety Journal, 103154.

Tseng, W. W., Shen, T. S., Liao, S. F., & Tseng, C. C. (2017). To Improve the Care Environments by Using Fire Safety Engineering for Existing Small-Scale Hospitals in Taiwan. In Fire Science and Technology 2015 (pp. 373-381). Springer, Singapore.

Ursetta, D., D’Orazio, A., Grossi, L., Carbotti, G., Casentini, S., & Poggi, L. (2014). Egress from a hospital ward: a case study. In Proceedings of Fire and Evacuation Modeling Technical Conference (Vol. 2014).

Verderber, S. (2010). Innovations in hospital architecture. https://doi.org/10.4324/9780203855751

Waitakere Hospital Waitemata District Health Board Final Report (2002, September 29) Report into the Operating Theatre Fire Accident. Medsafe. https://www.medsafe.govt.nz/downloads/alertWaitemata.pdf

Wang, S. H., Wang, W. C., Wang, K. C., & Shih, S. Y. (2015). Applying building information modeling to support fire safety management. Automation in construction, 59, 158-167.

Wapling, A., Heggie, C., Murray, V., Bagaria, J., & Philpott, C. (2009). Review of five London hospital fires and their management: January 2008-February 2009. In Review of five London hospital fires and their management: January 2008-February 2009. National Health Service (NHS London).

Xie, Q., Wang, J., Lu, S., & Hensen, J. L. (2016). An optimization method for the distance between exits of buildings considering uncertainties based on arbitrary polynomial chaos expansion. Reliability Engineering & System Safety, 154, 188-196.

Landscape architects need to address life cycle greenhouse gas emissions in designs – A case study near Sydney, Australia

Sareh Moosavi[1], André Stephan[2] and Martin O'Dea[3]

[1] Belgian Fund for Scientific Research (F.R.S.-FNRS), Brussels, Belgium
[1, 2] Université Catholique de Louvain, Brussels, Belgium
{sareh.moosavi[1], andre.stephan[2]}@uclouvain.be,
ORCID-0000-0002-4819-2772[1], ORCID-0000-0001-9538-3830[2]
[3] CLOUSTON Associates – a division of Beveridge Williams, Australia
mod@clouston.com.au

Abstract: It is often believed that green infrastructure assets are net carbon sinks and this may have contributed to the lack of consideration of embodied greenhouse gas emissions by landscape architects. However, these embodied emissions cannot be ignored. This paper aims to demonstrate the significance of life cycle greenhouse gas emissions in park design and the need for landscape architects to address them. We use a hybrid life cycle inventory approach to quantify the life cycle embodied greenhouse gas emissions of the 26 000 m² Willowdale park, a greenfield development near Sydney, Australia. We take into account operational emissions associated with lighting, operating barbecues and mowing, as well as carbon sequestration in soils and trees. All original quantities are sourced from primary data. Results show that life cycle embodied greenhouse gas emissions are significant, at 1 419 tCO_2e over 50 years (55 $kgCO_2e/m^2$). Initial embodied greenhouse emissions from the day the park opened represent almost 73% of life cycle emissions. It takes 47-48 years for the trees and the soil to sequestrate enough carbon to offset embodied and operational emissions. In other terms, for almost the first five decades, this park remains a net carbon emitter. These results demonstrate the need for landscape architects to understand embodied emissions in construction materials. Equally, they need to plant as many climate-resilient trees that sequestrate enough carbon to offset embodied greenhouse gas emissions in shorter timeframes. Using a detailed and comprehensive life cycle assessment model is critical to achieving climate positive outcomes.

Keywords: Embodied carbon; Carbon Sequestration; Life Cycle Assessment; Landscape Architecture.

1. Introduction

There is an urgent need to reduce global greenhouse gas emissions (GHGE) and to limit global warming to 1.5°C in 2100 to meet the Paris Agreement. The built environment is a major source of GHGE with up to 75% contribution (UN-Habitat, 2011; Anderson *et al.*, 2015). Actions to reduce GHGE has largely focused in the engineering and building sectors (Andrić *et al.*, 2019). However, the way we plan and design

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 405–414.*

our landscapes (i.e. green and blue infrastructures, parks and urban open spaces) has to transform if we want to address global challenges such as climate change. Constructed urban landscapes and green-blue infrastructure are identified as most promising in maximizing opportunities for both climate adaptation and mitigation strategies (Kabisch *et al.*, 2016; Sharifi, 2021). Landscape architects are responsible for designing these spaces, and they need to ensure that their design interventions do not breach the ecological and planetary boundaries. When it comes to designing for climate change, landscape architects' design activities often focus on adaptation through the design of nature-based flood control features (Moosavi *et al.*, 2021), cool green public open spaces (Langenheim *et al.*, 2020), and community-scaled productive landscapes (Bunster-Ossa, 2019). However, adaptation without reducing the sources of GHGE, cannot be sustained. Adaptive efforts would need to constantly meet new benchmarks as the climate continues to change (Grafakos *et al.*, 2018; Hurlimann *et al.*, 2020). To do so, the profession should strive to better understand embodied GHGE, carbon metabolism and operational GHGE from parks and other green infrastructure.

Landscape architects need to be able to understand and account for the net life cycle GHGE associated with design decisions. This includes increasing their knowledge about carbon footprints of materials to avoid using emission intensive materials such as concrete, steel, dimension stone and kiln dried timber, as well as understanding that intensively managed and fertilised lawns can be net emitters, along with the effects of fossil fuel powered maintenance equipment. This needs to be balanced against opportunities to incorporate enough trees that can sequester these initial embodied emissions. It is important to ensure that trees will be large and healthy 50 years into the future. They will need to have sufficient interconnected soil volume, and reliable water from passive irrigation or other sources. With rapidly shifting bioclimatic zones, landscape architects also need to carefully consider species selection that will survive in the projected climatic zone in 2100.

The idea of low carbon landscapes is not new in the discipline of landscape architecture (see Pocock (2007)). However, it has increasingly gained traction in academic literature (Moosavi *et al.*, 2022; Nikologianni *et al.*, 2022). Methodologies for embodied GHGE calculations from a landscape architectural lens are only emerging. Most life cycle assessment tools primarily cater for buildings and hardscape emissions. There are very few tools that can be used to evaluate the emissions draw-down of landscapes. The most common method adapted for green infrastructure and nature-based solutions is carbon footprint analysis, which is an established method for systematically quantifying carbon sinks and sources throughout the lifetime of goods and services (Strohbach *et al.*, 2012a; Romanovska, 2019). There is a need to advance capacity in landscape architecture to consider environmental footprints of design interventions throughout their life cycle, and this calls for tailored methodologies and tools that can be used and adopted by landscape architects. In a recent study, Nikologianni *et al.* (2022) have reviewed and discussed some of the pioneering carbon calculation tools used in landscape architecture, including the most recent Climate Positive Pathfinder Tool developed by landscape architect Pamela Conrad in California. The pathfinder is a design and planning tool that accounts for embodied emissions from construction, carbon sequestration from trees, shrubs and soil, as well as operational emissions. Nikologianni *et al.* (2022) conclude that there is a need for more tools that are better tailored to the needs of landscapes architects, as well as training, guidance and professional development to enable landscape practitioners to use whole-life carbon approaches.

This paper aims to demonstrate the need for landscape architects to engage with life cycle GHGE in their design decisions. Using a single case study approach, this study quantifies the net life cycle GHGE of an urban park in Sydney, Australia. Detailed design documents from the design team in charge of the project were obtained, along with the detailed bill of quantities of all materials used in the park, all land-use changes and all vegetation planted. Using the EPiC database (see Section 2.3), we quantify the life cycle embodied GHGE of all materials. The carbon sequestration in soils, and the proposed trees were estimated based upon their species, over a 50 year time frame.

2. Method

2.1. Overall research approach

Figure 1 depicts the overall research approach adopted in this paper. Firstly, data on the park is collected, including a detailed bill of material quantities, land-use changes, and trees planted. Secondly, the life cycle embodied GHGE associated with materials are calculated. This is followed by the calculation of life cycle operational GHGE, notably lighting. The fourth step involves the quantification of the life cycle carbon sequestration in trees and soils before calculating the net life cycle GHGE of the case study park in the final step. Results are analysed per type of emissions and hot spots are identified.

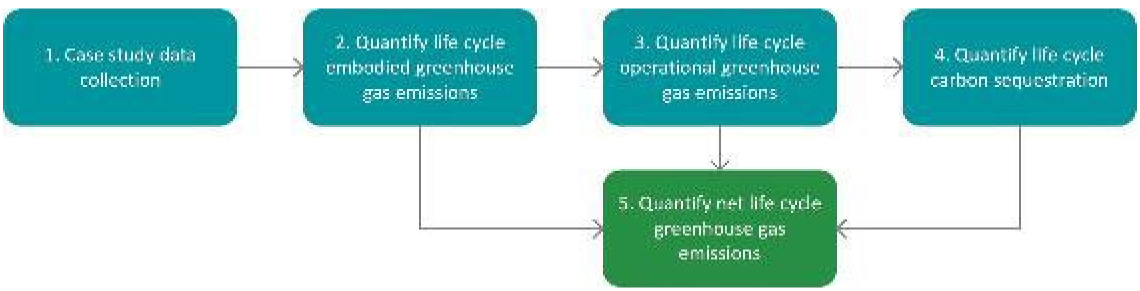


Figure 67: Overall research approach

2.2. Case study description

We use a single case study approach as our main research method (Yin, 2018, p. 49-50). The case study is the Willowdale park built in 2017 and located near Sydney, New South Wales, Australia. Figure 2 depicts the masterplan of the park and Table 1 summarises its main characteristics.

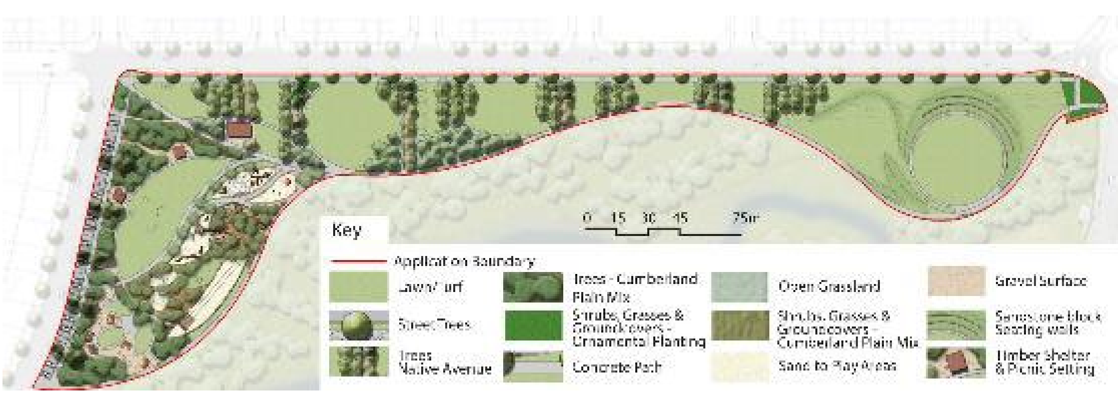


Figure 68: Masterplan of Willowdale Park. Source: CLOUSTON Associates

The park comprises a large playground with sandpits, tensile shade structure, barbecue areas and public toilets. The rest of the park consists of large areas of turf with native trees planted in linear patterns. Sandstone is used extensively in the park design, both in the playground area as well as for the amphitheatre and waterplay area (Figure 3). A total of 405 trees were planted, of which 402 are from six species of the Eucalyptus genus. The Willowdale park was constructed on former farmland in a suburban area.

Figure 69: View from the waterplay area and view hill towards the playground

Table 37: Case study characteristics and quantities of main materials

Characteristic	**Value**
Park name	Willowdale
Location	33.980571 S 150.809571 E, New South Wales, Australia
Year built	2017
Period of analysis	50 years (until 2067)
Total area	~26 000 m²
Lawn area	12 820 m²
Impervious area	8 730 m² (33.5%)
Mass planted area (shrubs, plants, etc.)	4 370 m²
Number of planted trees	405
Mass of concrete (kg)	2 950 524 kg
Mass of sandstone (kg)	581 095 kg
Mass of steel (kg)	74 669 kg
Mass of timber	1 462 kg

2.3. Quantifying life cycle embodied greenhouse gas emissions

Life cycle embodied GHGE associated with all construction materials used in the park are calculated using a hybrid life cycle inventory approach (Crawford *et al.*, 2018) and relying on coefficients from the EPiC database (Crawford *et al.*, 2019b; 2021). This ensures that system boundaries across supply chains are complete. We use a static approach, assuming that embodied GHGE associated with material replacements in the future have the same intensity as today. Only stages A1, A2 and A3 (within the framework of European Standard 15978 (2011)) are taken into account in this study, using a cradle-to-gate system boundary. This means that the transport of materials from factories to the site is not taken into account, nor the construction process itself.

Equation 1 is used for the calculation of life cycle embodied GHGE. In summary, we go through all the construction materials used in the park and multiply them by relevant GHGE coefficients from the EPiC database. The triple sigmas in the equation represent the nested nature across built environment scales, based on the Nested Phoenix model we are using (see Stephan *et al.* (2022)). The replacement of materials over time is also considered based on average service lives. It is important to note that embodied emissions associated with the playground equipment used in the park were not considered in this paper. Furthermore, as the EPiC database does not contain a coefficient for sandstone, a major material in this project (>580 t), we used a process figure from the Athena Database and scaled it up assuming the same truncation error as for dimension stone, a similar product in the EPiC database.

$$LCEGHG_p = \sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M}\left(Q_{m,e,a,p} \times GHGC_m\right) + \sum_{y=CY_p}^{TH}\sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M}\delta_{m,e,a,p,y} \times \left(Q_{m,e,a,p} \times GHGC_m\right)$$

$$\delta_{m,e,a,p,y} = \begin{cases} 1 \Leftrightarrow \frac{(y-CY_p)}{SL_{m,e,a}} \in \mathbb{Z}^+ \\ 0 \Leftrightarrow \frac{(y-CY_p)}{SL_{m,e,a}} \notin \mathbb{Z}^+ \end{cases} \quad \forall\ CY_p < y \leq TH \tag{1}$$

Where: $LCEGHG_p$ is the life cycle embodied GHGE of park p in $kgCO_2e$; A is the total number of assemblies in park p; E is the total number of elements in the assembly a; M is the total number of materials in the element e or the assembly a; $Q_{m,e,a,p}$ is the quantity of material m in the element e in the assembly a in the park p (e.g. m³ of concrete); $GHGC_m$ is the hybrid GHGE coefficient of material m in $kgCO_2e$ per functional unit of material; TH is the time horizon of the analysis, e.g. 2050; CY_p is the construction year of park p, e.g. 2007; $\delta_{m,e,a,p,y}$ is a modified Dirac delta function; $C_{m,e,a,p}$ is the cost of the material m used in element e, in assembly a, in park p, in AUD; and $SL_{m,e,a}$ is the service life of the material m as used in element e and assembly a, in years.

2.4. Quantifying life cycle operational greenhouse gas emissions

Life cycle operational GHGE are obtained by summing the emissions of all end-uses in a given park, e.g. lighting. For each end-use in the park, we multiply the wattage rating of the end-use by the time it is used over one year. We convert that delivered energy to GHGE by multiplying it by a GHGE factor that accounts for Scope 2 and 3 emissions in the electricity generation supply chain (Department of Industry, 2021). We use a static approach and multiply these annual emissions by the period of analysis (time horizon – construction year of the park). This is deemed to have minimal consequences on this study as operational GHGE are very small as compared to embodied emissions. Equation 2 is used to calculated life cycle operational GHGE. Practically, we considered electricity use for lighting, and the electric barbecues on site as well as a diesel mower.

$$LCOPGHG_p = \left(TH - CY_p\right) \times \sum_{e=1}^{E} R_{e,p} \times T_{e,p} \times 3.6 \times 10^{-6} \times EF_e^S \qquad (2)$$

Where: $LCOPGHG_p$ = Life cycle operational GHGE of park *p* in $kgCO_2e$; *TH* and CY_p are defined in Equation 1; E is the total number of operational energy end-uses; $R_{e,p}$ = Wattage rating of end-use *e* present in park p, in W; $T_{e,p}$ = Average annual operating time of end-use *e* in park *p*, in hours; and $EF^S{}_e$ = GHGE factor for the energy source S of the end-use *e* in $kgCO_2e/GJ^{DELIVERED}$.

2.5. Quantifying life cycle carbon sequestration in trees and soils

Carbon sequestration in trees and soils is quantified as per Equation 3, based on (Stephan *et al.*, 2022). The carbon sequestration model for trees is taken from the U.S. Department of Energy (1998). Carbon sequestration in soils is based on an average annual sequestration rate per m² (see Lindén *et al.* (2020) for an example). Carbon sequestrated in trees that die over time is not considered to be remitted as the fate of the tree is unknown decades into the future (it could be harvested and chipped for use as a soft surface in playgrounds). It is important to flag that we modified the survivability factor of trees in this study to better reflect the reality of the context, estimating that 90% of trees planted will survive in 50 years. Should the original factors be kept, only 21.8% of trees survive at that time horizon.

$$LCCS_p = \sum_{t=1}^{T} \sum_{y=PY_{t,p}}^{TH} SF_{t,y,p} \times ACS_{t,y,p} + \sum_{s=1}^{S} \sum_{y=LUCY_{s,p}}^{TH} A_{s,p} \times ACSLUC_{s,p} \times SF_y$$

$$SF_{,y} = \begin{cases} 1 \Leftrightarrow y \leq 2 \\ e^{\frac{-y}{8}} \Leftrightarrow y > 3 \end{cases} \quad \forall\ y \geq 0 \qquad (3)$$

Where: $LCCS_p$ is the life cycle carbon sequestration of park *p* in kgC; *T* is the total number of trees in park *p*; $PY_{t,p}$ is the plantation year of tree *t* in park *p*; $SF_{t,y,p}$ is the survival factor of tree *t* at year *y* in park *p*, which is a function of its species, growth rate and age; $ACS_{t,y,p}$ is the annual carbon sequestration rate of tree *t* for year *y* in park *p*, in kgC/annum; S is total number of soil areas; $LUCY_{s,gi}$ is the year during which the land-use change of soil *s* occurred in park *p;* See Equation 1 for the definition of *TH*; $A_{s,p}$ is the area of soil *s* in park *p*, affected by land-use change, in m²; $ACSLUC_{s,p}$ is the annual carbon sequestration rate for soil *s* in park *p*, in kgC/(m²·a) and SF_y is a saturation function that decreases the annual soil sequestration rate, and is applied from year 3 onwards.

2.6. Quantifying net life cycle greenhouse gas emissions

The net life cycle GHGE of the park are obtained by summing the life cycle embodied and operational GHGE and subtracting the carbon sequestration, converted to emissions by using the ratio of the atomic mass of CO_2 (44) and C (12), as per Equation 4.

$$NLCGHG_p = LCEGHG_p + LCOPGHG_p - LCCS_p \times \frac{44}{12} \qquad (4)$$

3. Results

Figure 4 shows the life cycle GHGE of the park. Overall, embodied GHGE dominated the life cycle GHGE profile representing 1 419 tCO_2e. Carbon sequestration in trees represented 1 950 tCO_2e at 50 years and soils absorbed carbon representing 153 tCO_2e at the same time. Operational emissions represented 27.2% of total emissions over 50 years, but this figure should be much smaller when considering decarbonising electricity grids, and embodied emissions will have a higher contribution. The net life cycle GHGE balance reaches zero after 47 years of the park's lifespan. The leap in embodied GHGE at year 30 in Figure 4 is due to the replacement of certain materials, which is equivalent to the preceding four years of sequestration.

Embodied emissions are driven by sandstone (38.5%), concrete 25 and 32 MPa (35.5%), structural steel (15%), gravel (1.7%), and high-density polyethylene (0.7%). The remaining 8.6% of the life cycle embodied GHGE are spread across 11 other materials, including hardwood and galvanised steel. Operational emissions are driven by lighting (62.7%) and the use of barbecues (35.2%). Mowing represented 2% of the total operational emissions, based on 3 hours of mowing per month.

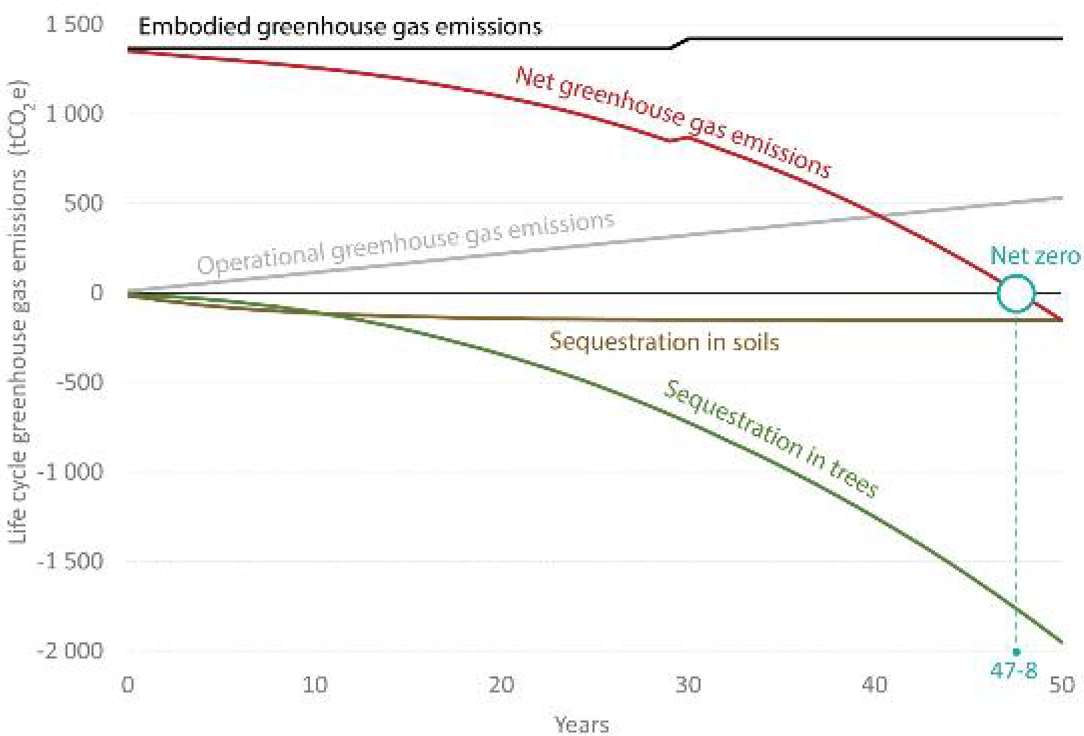


Figure 70: Life cycle greenhouse gas emissions profile of the case study park

4. Discussion and Conclusion

This study has quantified the net life cycle GHGE of a park in Sydney, Australia over 50 years and demonstrated their significance. For the first 40+ years of the life of the park, its net life cycle GHGE balance is largely positive, resulting in the net emission of 52, 46, 33, and 6 kgCO_2e/m^2 of park at years 0, 15, 30 and 45, respectively. It is only after trees grow enough to start sequestrating carbon at a significant rate that they start offsetting the embodied GHGE.

The significant amounts of embodied GHGE associated with a park clearly demonstrate the need for the landscape architecture discipline to consider them. There is currently a lack of consideration of life cycle GHGE in park design, notably embodied GHGE in construction materials. Given that sturdy and hardwearing materials are used in the park design, recurrent embodied GHGE represented 6% of initial embodied emissions, unlike in buildings where they usually represent 30-50% over 50 years, depending on material choices (Stephan and Crawford, 2014; Stephan and Athanassiadis, 2017). As such, landscape architects need to carefully choose their construction materials. The production of key materials such as concrete emit greenhouse gases. Other materials such as steel, aluminium and kiln dried timber, have high emissions due to the current reliance on fossil fuels for their manufacture. These emissions will remain in the atmosphere for decades and the park soil and trees will need decades to sequestrate enough carbon to reach carbon neutrality (around 40 years in the case of this park).

An important contribution of this study is the reliance on a hybrid life cycle inventory approach for the quantification of embodied GHGE. Had process-only data been used instead, the life cycle embodied GHGE would be 958 instead of 1 419 tCO_2e (-32.5%) and the year at which the park would reach 'carbon neutrality' would be moved back by 8 years, to year 40 instead of year 48. This demonstrates the need to use hybrid life cycle inventory data in order to avoid underestimating embodied emissions and overestimating the capacity of the park in acting as a net carbon sink.

In addressing the climate emergency, landscape architects have access to a number of emerging tools to guide design decisions. These include the Climate Positive Pathfinder application and the EPiC database. These tools help empower landscape architects to understand GHGE and make informed decisions on material choices, plant selection and specifications. While generic materials assessments is helpful, there is a need for more data from suppliers and manufacturers to provide consistent, transparent and systemically complete environmental product declarations (EPDs) for specific products. These would provide designers with a more refined choice of materials. However, current EPDs have such variability in their data that they can be unreliable (Resalati *et al.*, 2019). On the sequestration side, much more data and research are required to better understand Australian plants and their long-term performance. In particular, more data is needed on how different trees in urban situations perform under a changing climate. With only 28 years to meet net zero under the Paris agreement, there are research opportunities to evaluate the real sequestration of trees planted 28 years ago in 1994.

As in any scientific inquiry, this study suffers from a number of limitations. Firstly, results are applicable to the case study park only. Design specifications including material compositions, land-use and tree plantations can vary widely between park designs, directly affecting life cycle GHGE. Second, we excluded materials used in the playground equipment (e.g. swings, slides, diggers, etc.). Third, we used a process-based hybrid analysis focusing on a cradle-to-gate approach and did not account for non-material inputs required to build the park. These can represent around 20-40% additional embodied GHGE when it comes to residential buildings (Crawford *et al.*, 2019a) and probably a similar figure when applied to parks. Fourth, minor shrubs and plants were modelled as native grassland, but they may sequestrate more or less carbon depending on the species. Fifth, we used a modified survivability rate in this study but ideally multiple scenarios of trees survivability need to be explored as this significantly impacts the carbon sequestration potential of parks, as also demonstrated by (Strohbach *et al.*, 2012b). Future research will focus on extending the study to other case studies for comparison, including stages A4 and A5 as well as the input-output remainder in embodied GHGE calculations, and further refining the carbon sequestration calculations.

Landscape architects have a unique opportunity to address the climate crisis through good design. While parks can provide cool, green, and shady spaces that people love and enjoy, as well as habitats for other species, landscape architects must be mindful of the projects GHGE. With up to ~75% of greenhouse gases over 50 years having been emitted the day parks are opened, climate mitigation through a reduction in embodied and operational carbon and maximising sequestration is essential to a liveable future. The profession is moving in this direction with the recently published Climate Positive Design Action Plan for Australian landscape Architects, by the Australian Institute of Landscape Architects (O'Dea *et al.*, 2022). The American Society of Landscape Architects (ASLA) is also publishing an action plan in mid-November 2022. There is a growing understanding of the embodied greenhouse gasses in construction and engaging with industry to drive low carbon products. This points to better outcomes for a liveable planet. The data and tools are available. Agency and know-how need to follow.

Acknowledgements

Sareh Moosavi is funded by a Postdoctoral Research Fellowship from the Belgian Fund for Scientific Research (F.R.S.-FNRS) under grant number (FC.43179). The research has also received funding from the Belgian Fund for Scientific Research (F.R.S.-FNRS) *Mandat d'Impulsion Scientifique* grant (F.4547.21). The authors would like to thank Clouston Associates– a division of Beveridge Williams, Australia for providing the primary data for the case study.

References

Anderson, J. E., Wulfhorst, G. and Lang, W. (2015) Energy analysis of the built environment—A review and outlook, *Renewable and Sustainable Energy Reviews*, 44, 149-158.

Andrić, I., Koc, M. and Al-Ghamdi, S. G. (2019) A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries, *Journal of Cleaner Production*, 211, 83-102.

Bunster-Ossa, I. F. (2019) McHarg: The Long View, Shortend, in F. R. Steiner, R. Weller, K. M'closkey and B. Fleming (eds.), *Design with Nature Now*, Lincoln Institute of Land Policy, Philadelphia, 14-17.

Crawford, R. H., Bontinck, P.-A., Stephan, A., Wiedmann, T. and Yu, M. (2018) Hybrid life cycle inventory methods – a review, *Journal of Cleaner Production*, 172, 1273-1288.

Crawford, R. H., Stephan, A. and Prideaux, F. (2019a) A comprehensive database of environmental flow coefficients for construction materials: closing the loop in environmental design, *Revisiting the Role of Architecture for 'Surviving' Development. 53rd International Conference of the Architectural Science Association 2019*, edited by A. Agrawal, Roorkee, India, 28 - 30 November, 353-362.

Crawford, R. H., Stephan, A. and Prideaux, F. (2019b) *Environmental Performance in Construction (EPiC) database*, ed., The University of Melbourne, Melbourne.

Crawford, R. H., Stephan, A. and Prideaux, F. (2021) The EPiC database: Hybrid embodied environmental flow coefficients for construction materials, *Resources, Conservation and Recycling*, 106058.

Department of Industry, S., Energy and Resources, (2021) *National greenhouse accounts factors*, Commonwealth of Australia, Canberra, 87.

European Standard 15978 (2011) *Sustainability of construction works -Assessment of environmental performance of buildings - Calculation method*, European Committee for Standardization (CEN), Brussels, 66.

Grafakos, S., Pacteau, C., Delgado, M., Landauer, M., Lucon, O., Driscoll, P., Wilk, D., Zambrano, C., O'Donoghue, S. and Roberts, D. (2018) Integrating Mitigation and Adaptation, in C. Rosenzweig, P. Romero-Lankao, S. Mehrotra, S. Dhakal, S. Ali Ibrahim and W. D. Solecki (eds.), *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research* Network, Cambridge University Press, Cambridge, 101-138.

Hurlimann, A., Moosavi, S. and Browne, G. R. (2020) Urban planning policy must do more to integrate climate change adaptation and mitigation actions, *Land Use Policy*, 105188.

Kabisch, N., Frantzeskaki, N., Pauleit, S., Naumann, S., Davis, M., Artmann, M., Haase, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K. and Bonn, A. (2016) Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action, *Ecology and society*, 21(2).

Langenheim, N., White, M., Tapper, N., Livesley, S. J. and Ramirez-Lovering, D. (2020) Right tree, right place, right time: A visual-functional design approach to select and place trees for optimal shade benefit to commuting pedestrians, *Sustainable Cities and Society*, 52, 101816.

Lindén, L., Riikonen, A., Setälä, H. and Yli-Pelkonen, V. (2020) Quantifying carbon stocks in urban parks under cold climate conditions, *Urban Forestry & Urban Greening*, 49, 126633.

Moosavi, S., Browne, G. R. and Bush, J. (2021) Perceptions of nature-based solutions for Urban Water challenges: Insights from Australian researchers and practitioners, *Urban Forestry & Urban Greening*, 57, 126937.

Moosavi, S., Hurlimann, A. and Bush, J. (2022) Decarbonizing landscape practice, *Landscape Architecture Australia*, (174), 53-56.

Nikologianni, A., Plowman, T. and Brown, B. (2022) A Review of Embodied Carbon in Landscape Architecture. Practice and Policy, *C*, 8(2), 22.

O'Dea, M., Moggridge, B., Kate, J., Bond, S., Abi, K., McEwen, M., Pfeiffer, A., Hawken, S. and Burke, B. (2022) *Climate positive design action plan for Australian landscape architects*, in A. I. o. L. Architects (ed.).

Pocock, C. (2007) The carbon landscape, *TOPOS*, 61.

Resalati, S., Kendrick, C. C. and Hill, C. (2019) Embodied energy data implications for optimal specification of building envelopes, *Building Research & Information*, 48(4), 429-445.

Romanovska, L. (2019) *Urban green infrastructure: perspectives on life-cycle thinking for holistic assessments*,IOP Conference Series: Earth and Environmental Science, IOP Publishing, 012011.

Sharifi, A. (2021) Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review, *Science of The Total Environment*, 750, 141642.

Stephan, A. and Athanassiadis, A. (2017) Quantifying and mapping embodied environmental requirements of urban building stocks, *Building and Environment*, 114, 187-202.

Stephan, A. and Crawford, R. H. (2014) A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings, *Architectural Science Review*, 57(1), 39-48.

Stephan, A., Crawford, R. H., Bunster, V., Warren-Myers, G. and Moosavi, S. (2022) Towards a multiscale framework for modeling and improving the life cycle environmental performance of built stocks, *Journal of Industrial Ecology*.

Strohbach, M., Arnold, E. and Haase, D. (2012a) The carbon footprint of urban green space—A life cycle approach, *Landscape and Urban Planning*, 104(2), 220-229.

Strohbach, M. W., Arnold, E. and Haase, D. (2012b) The carbon footprint of urban green space—A life cycle approach, *Landscape and Urban Planning*, 104(2), 220-229.

U.S. Department of Energy (1998) *Method for calculating carbon sequestration by trees in urban and suburban settings*, United States Department of Energy, Energy Information Administration, 16.

UN-Habitat (2011) *Cities and climate change: global report on human settlements, 2011*, ed., Routledge.

Yin, R. K. (2018) *Case study research and applications: design and methods*, Sixth ed., SAGE, Los Angeles.

Made to order: incrementally formed cladding systems

Richard Burnham[1]

[1] *University of Tasmania, Hobart, Australia*
Richard.Burnham@utas.edu.au

Abstract: Two 'live' community projects – designed and fabricated in a Masters of Architecture unit – integrate incrementally formed aluminium components into digitally fabricated building systems. Incremental Sheet Forming (ISF) deforms sheet material into three-dimensional forms through pressure imparted by a robot-held tool. Form and patterning are derived from numerically controlled toolpaths. The projects, a cocktail bar and a gateway structure, investigate multiple research and educational objectives. Parameters of the forming process – geometry and patterning, wall angle and thickness, surface preparation and material properties – are assessed through prototyping. The potential for the mass-customisation of unique components with ISF constitutes a significant advantage over alternative metal forming techniques. The projects leveraged two approaches to mass-customisation; one by parametrically adjusting geometrical forms and the other by adopting a 'jigsaw' approach, where each component is a unique part of a larger pattern-making exercise. Forming jigs became an integral part of prototyping, iterated in parallel with the evolution of the component and fixing regime. The ISF formed components contribute to the structural performance of the gateway by bracing the cells of a waffle structure, while providing a structurally independent rainscreen in the cocktail bar. The paper describes previous ISF experiences, learning acquired during prototyping, workflow, and the performance of the assembled components

Keywords: Incremental forming; cladding; education; digital fabrication.

1. Introduction

1.1. Background

The University of Tasmania School of Architecture & Design has had thirty continuous years of experience in student led design-build projects, known as the Learning by Making (LBM) program (Burnham and Wallis, 2012). Over the past decade the program has focused on the design and assembly of digitally fabricated building systems, primarily CNC-milled structures. These structures have interrogated contemporary timber construction, positing that a digitally fabricated system based on sheet materials has significant advantages over stick-based systems (Burnham, 2018). Sheet-based alternatives - using torsion boxes and semi-monocoque arrangements - are potentially more efficient than frame structures in terms of material use, bracing and load transfer. They also have built-in dimensional precision and reliability, making it possible for small to medium structures to be fabricated by a low-skilled workforce. Projects such as the Castle and the Scouthut demonstrated the potential of this system (Burnham, 2018).

While conventional cladding materials (such as corrugated steel sheeting or timber weatherboards) could be applied to the digitally fabricated structures, we felt inclined to experiment with digitally fabricated cladding alternatives. ISF was selected due to its capacity to work with durable, weather resistant sheet materials, as well as the opportunity to leverage parametric characteristics. This was the basic brief given to two successive cohorts of Masters of Architecture students.

1.2. Advanced design research

The Advanced Design Research (ADR) unit provides an opportunity for small groups of Masters of Architecture students to work alongside a lecturer on their personal research interest (Owen and Norrie, 2013). The structure of the unit encourages students to conduct research aligned with one or more of the methodologies defined by Frayling; 'research into design', 'research through design', and 'research for design' (Frayling, 1993). The research activities described here are focused on 'research through design', within which Frayling describes three approaches, all of which are highly relevant to these projects: materials research, development work and action research.

Development work, Frayling suggests, may include customising a piece of technology, "to do something no-one had considered before and communicating the results." Action research, according to Frayling is where a research diary tells in a step-by-step way of a practical experiment in the studios, and the resulting report "aims to contextualise it". Students use Frayling's terminology and definitions as a framework for their research activities. Annotated bibliographies are used to define scope and to establish critical analytic and design parameters, with subsequent assignments based around prototyping, detailed resolution and assembly.

1.3. Incremental sheet forming (ISF)

ISF deforms sheet material into three-dimensional forms through approximately 400Kg of pressure imparted by a robot-held tool. In most instances, the sheet material is stretched as the tool incrementally steps down and steps sideways. Form and patterning are derived from numerically controlled toolpaths, processed from CAD models developed in Rhinoceros and Grasshopper. The primary manufacturing advantage of ISF over other sheet-metal forming processes, such as deep drawing, spinning and stretch forming, is the capacity to manufacture varied objects without having to construct multiple dies (de Souza, 2016). Objects can be 'made-to-order' or mass-customised without significant upfront costs being invested into hardware required for forming. Significant existing research is available on the mechanics and digital parameters of the forming process, including highly detailed analysis of material properties and forming limitations, but there are few realized architectural applications of the technology (Behera, de Sousa and Ingarao, 2017).

1.3. Learning and teaching in the workshop

There is an expectation that students will learn to actively and safely engage with workshop technologies, whether a hammer or sophisticated digital fabrication equipment. Design skills are enhanced through iterative making, by gradually understanding the parameters of a making process or the characteristics of materials and tools. This experiential learning is difficult to achieve in a workshop environment where students are kept at arms-length from tools. There is also a wish to overcome an observed tendency where students see digital fabrication as a one-off process, where precision-cut objects embody the characteristics of 'completion'. Students are encouraged to interrogate the digitally fabricated object by manually adding and subtracting or 'red-penning' it. The LBM program aims to create a workshop environment where students take responsibility for decision-making, learn through communicating with clients, coordinating dimensions, rapid prototyping, managing budgets and their role within a team.

Students develop their understanding of the ISF process through experimentation within the digital and real-world workflows. A Rhinoceros model, referenced to the coordinates of the robot and forming jig, is processed in Autodesk Powermill where parameters are defined: toolpath, stepdown, stepover and feed rate. The surface of the sheet is prepared and clamped. The file is transferred to the robot and run in the relevant safety mode. Simple design challenges, such as making a muffin tray with six different shapes, help to embed the workflow. Critical learning includes development of spatial awareness, aligning digital space with real space, surface preparation, and limitations of wall angle and thickness.

2. Projects

Previous LBM projects provided important foundation learning in ISF cladding. 'Dimples and Pimples' was an aluminium cladding system based on a pattern of circular depressions (Burnham, 2018). When placed against the surface of the structure the equally spaced dimples created a cavity, obviating the need for battening. The intended panel connection, based on a formed groove, failed because the panel edges were significantly deformed during the forming process (Figure 1). A bed of moist sand beneath the sheet provided even resistance across the large sheets, ensuring even depth of forming.

'SoundPod' integrated ISF facial motifs into aluminium wall panels. A student's face was scanned with photogrammetry software. Deformation in the panel edge was avoided by spacing the motifs were sufficiently far enough from the sheet edges and by vacuum pressing the sheets onto plywood. However, this process didn't take advantage of the self-supporting rigidity that forming can provide to the panel.

Figure 1: 'Dimples and Pimples' (Far left and Left). SoundPod panel forming; face Far (Right and Far Right). (Source: Author).

2.1. Junction Arts Festival gateway

The Gateway was located on a gently sloping pathway leading into a park. The brief required it be assembled in less than a day, be demountable and embody characteristics of the echidna. The gateway was formed from three sheet-based systems: a plywood waffle structure, aluminium bracing pyramids, and adjustable steel feet. The 12mm CD plywood waffle structure was derived from a custom Grasshopper script developed by students, taking into consideration relevant loadpaths and non-mechanical jointing systems. The ISF pyramids are formed from 1.6mm 5005 aluminium alloy using a Kuka robot armed with a 22mm diameter dapping punch. The pyramids range from 150-375mm in height, arranged corresponding to the depth of the arch (Figure 2).

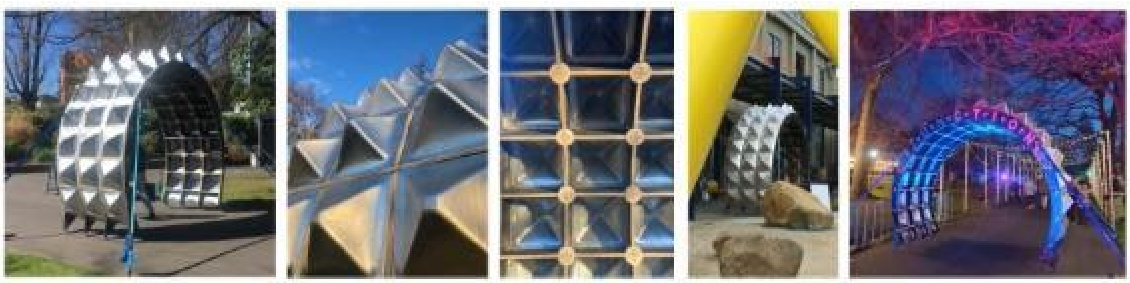


Figure 2: Images of the ISF pyramids installed in Gateway structure. (Source: Author)

The pyramids provide bracing to the waffle structure. The feet are laser cut from 5mm plate and are fittedwith 150mm adjustment, sufficient to take up the slope of the path. The structure is fitted with 4 steel cables-stays to provide additional support.

2.2. DigiShed

The carcass of the DigiShed was conceived as a digitally fabricated alternative to traditional lightweight timber framing AS1684, a response to the inherent characteristics of plywood (Burnham, 2018). Aside from the semi-monococque construction, the other primary consideration was a curved profile to simplify junction detailing and to improve Bushfire Attack Level (BAL) design. Students analysed several cladding options, ultimately selecting a panelised system hung on horizontal aluminium rails fixed to vertical battens (Figure 3). The panels are full length but vary in height with the smallest responding to the curved profile. The patterning across the building is conceived from a single digital image with the maximum depth of the ISF forming across all panels being 40mm, providing consistent structural rigidity.

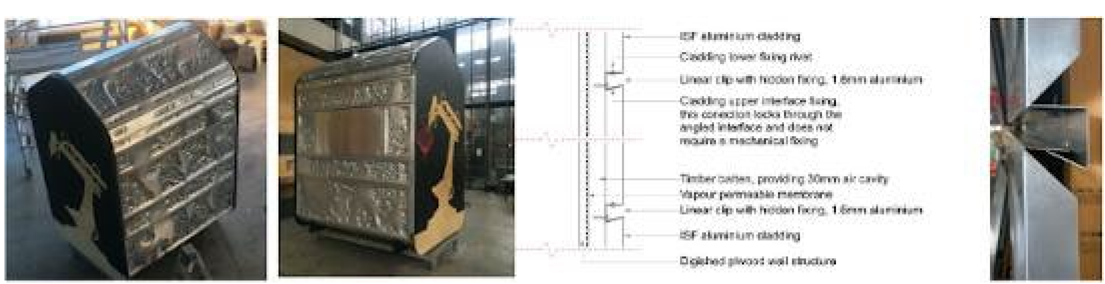


Figure 3: Completed DigiShed and details of panel system. (Source: Author)

3. Mass-customisation

Robotic arms are designed to perform millions of identical tasks. However, there is no advantage in using ISF for mass-production; there are more efficient means of achieving this outcome. The main advantage of ISF over other metal forming techniques is the opportunity to produce multiple unique sheet-metal components, without the cost and time required to make a die for each. ISF is ideally suited to mass-customisation, combining the efficiencies of mass-production with the ability to customize individual components (Piroozfar, P and Pillar, FT, 2013). The case study projects leverage different approaches to mass-customisation, with component variation achieved in form, pattern and texture.

3.1. Form

The cladding components for the Gateway needed to provide bracing to the cells of the waffle structure, as well as providing a striking visual presence from a distance. Simple geometrical forms – cones, domes and pyramids – were tested, both in terms of their visual impact and their forming characteristics. Through experimentation the pyramid was selected because it was found to be capable of deeper forming, most likely because material from the entire square panel is being stretched. Pyramids vary in height - from 150mm to 375mm in increments of 25mm – reflecting the process of gradually extending the depth of forming. The depth limit was caused not by material failure, but by the proximity of the robot's hydraulic hoses to the edge of the jig. A longer tool and deeper jig will test the depth capacity further.

3.2. Patterning

The Digished adopted a 'jigsaw' approach to mass-customisation, where each component is a uniquepart of a larger pattern. The pattern is derived from a single image of spume floating down the Cataract Gorge in Launceston. The image was enlarged and cropped into parts relating to panels. The monochromeimages were converted to 3D using the Rhinoceros 'heightfield' command which extrudes proportionallybased on tone; white is allocated a zero extrusion and black a 40mm extrusion. The result is a physical representation of a tonal landscape. Thirty five tests processed the image at different scales with various combinations of stepovers and stepdowns, in order to achieve optimum clarity. 'Bridges' of white, based on a macro plan of the Tamar River, were added to improve longitudinal rigidity. The pattern works at three scales; at the micro-scale the contour marks made by the tool suggest swirling foam; the mezzo scale forming describes a landscape of ridges, valleys, depressions and mounds; the macro scale describes a strong contrast between the structural 'bridges' and the surrounding mezzo texture (Figure 4).

Figure 4: Left to right: Source image of spume, macro, mezzo and micro patterning (Source: Author)

4. Forming jigs

The sheet material needs to be held firmly to resist the pressure imparted by the robot. Movement of the sheet during forming will result in a loss of accuracy, reduced formed depth or serious safety issues. Generally, the edge of the sheet is clamped onto an adjustable frame bolted to a floor or wall.

4.1. Resistance

Fabricating architectural cladding components introduces specific requirements for the design of a jig. Edge clamping techniques alone may not provide sufficient resistance in larger sheets, with the toolhead tending to deflect the centre of the sheet, rather than forming it. The result, as we initially discovered in 'Dimples and Pimples', is an uneven deformation between depressions near the edge and those closer to the centre. Firmly packed moist sand under the sheet provides even resistance across the sheet. Formed depressions near the centre of the 2400 by 1200mm sheet were 5% shallower than edge depressions with sand, and 30% shallower without sand. A sandbed was found to be unnecessary in small forming sheets and can result in failure of the material if the sand is too firmly packed and has no means of escape.

4.2. Sheet edges

The forming process imparts forces that can result in deformation of the sheet edge after removal from the jig. When conducting tests on forming parameters (wall angle, form, etc.) the condition of the sheet edge is inconsequential. However, in most architectural componentry, edges need to be predictable to comply to a fixing regime, or to connect effectively with the adjoining panel. Post-processing of formed components, for example by folding or crimping, can be extremely difficult due to warped sheet edges or the bulk of the formed object. Folding or other edge treatments should be completed before forming.

4.3. Customised jigs

In both projects the blank aluminium panels were pre-fabricated to precise finished dimensions, with the folded edge details applied in anticipation of the fixing regime to the structure. Generally, the edges involved a single bend, but some required a specific angle and some corners needed to be configured precisely for drainage or for ease of assembly. The blank panels could not be clamped in the same manner as a flat sheet, but instead, required that the jig be specifically configured to accommodate the panel. In other words, the configuration of the jig was in direct response to the design of the panels, which in turn was dependent on the fixing regime of panels onto the structure (Figure 5).

Figure 5: Left to Right: Pyramid jig; test cell; Gateway detail; and Digished panel jig (Source: Author)

4.4. Clamping

Holes drilled in panel edges for screw clamping during the forming process were carefully considered so that they could be re-used in the panel. Thinking through the implications of hole placement was important, ensuring that screws from neighbouring components wouldn’t collide during assembly. For the Digished panels holes in the panel edges were not desirable so an alternative clamping method was developed using timber wedges screwed into the edge of the sand-bed, providing sufficient downward clamping force on the panel edge (see Figure 5).

4.5. Linked thinking

The design of a forming jig was not a single operation. Jigs were fabricated, and then refabricated in parallel with the development of the component and the manner of fixing into the overall structure. For the Gateway the orientation of components in the jig were reversed or mirrored from their relationship when inserted into the structure. For the Digished, there were several different sizes of panels, so the jig was designed to accommodate panel edges in multiple positions.

This ‘linked thinking’, following through the implications of design decisions - from fixing regime, through panel design and back to jig design - was a particularly instructive phase of the learning for students. This type of thinking rarely happens in hypothetical design studios because the myriad of implications of design decisions are rarely require such rigorous testing.

5. Workflow and assembly

5.1. Student safety

To maintain students' active use of the workshop equipment a rigorous safety regime is maintained. The lecturer completes a risk assessment for the unit, identifying the equipment to be used. Students complete an induction for all hand operated equipment (sheet metal guillotine and brake, battery driver, etc.) and digital fabrication tools. Students collectively compose a daily Job Safety Analysis, highlighting specific risks and mitigation strategies. The robotic arm incorporates a variety of safety measures. 'Teach' mode allows the enclosure to be open but requires constant pressure on the controller. 'Expert' mode allows a file to run without pressure on the controller but requires the enclosure is closed. Students undertake a series of slow-motion exercises to become acquainted with robot axes and controller.

5.2. Forming parameters and workflow

The projects include established practices that must be followed for a successful result, as well as parameters that can be adjusted for different results.

5.2.1. Blank panel fabrication

A template was used to scribe cut and fold locations, ensuring dimensional consistency and a friction fit on the forming jigs. Accuracy was critical to the fixing regime of both projects.

5.2.2. Material

Aluminium alloy 5005 was selected having a relatively high modulus of elasticity at 68PSa and is readily available. The Digished used 1.2mm sheets while the Gateway used 1.6mm sheets for added forming depth, wall thickness and bracing capacity.

5.2.3. Toolhead

The toolhead was a hardened 22mm diameter dapping punch welded onto a solid steel rod to facilitate deeper forming. The tool became dramatically misshapen after completing the Digished panels.

5.2.3. Toolpath

Two main toolpath types were tested. 'Optimized constant Z' presses in a constant helical motion which produced a smooth finish but had greater risk of tearing. 'Step Area clearance' presses the whole area down each step, producing a stepped appearance but achieves deeper forming without tearing. Step area clearance was used for both projects with the Axis 6 static to prevent entanglement and collision.

5.2.4. Stepover and stepdown (SO/SD)

After testing multiple combinations the Digished panels were formed with 3mm SO/SD, achieving an optimum balance of detailed forming with speed. A relatively course 5mm SO/SD was used for the pyramids due to the significant increased time investment of a smoother finish (Hamedon, 2016).

Figure 6: Images of stepdown and stepover testing (Source: Author)

5.2.5. Wall thickness and wall angle

These are critical factors, particularly in the Gateway where deep forming and a steep wall angle results in a reduction of wall thickness. The maximum wall angle achieved was 71 degrees, with a reduction of wall thickness from 1.6mm of the raw sheet to 0.35mm of the formed walls. It is interesting to note that while a cone produced a relatively consistent wall thickness, the pyramid produced a noticeable 'drag effect'; after turning a corner the walls became noticeably thinner (Behera AK, 2017).

5.2.6. Surface preparation

Annealing the sheet prior to forming did not result in a noticeable improvement in the forming capacity. The first few step-downs is likely to work-harden the material.

Any metallic swarth left on the sheet, (eg. from drilling through the sheet for clamping) can cause abrasion on the surface if caught by the tool. The surface should be thoroughly cleaned before lubrication.

The sheet material fails quickly without lubrication. A high viscosity SAE30 oil, canola oil and high-quality machine oil were tested with the former producing the smoothest finish (de Souza 2015). The best results were found when the lubricant was evenly spread over the working area, with gravity ensuring that sufficient oil makes it down to the critical working area.

5.3. Panel attachment

Gateway pyramids were screwed directly into the plywood of the waffle structure with 20mm 14g hex-head screws. The Digished panels clipped onto custom C-profile aluminium rails screwed into the plywood structure and fixed with 6g self-tapping stainless-steel screws. The larger panels on the Digished had developed a slight warp after forming but not sufficient to impede attachment. A jig was used to locate the Gateway screw-holes, with slightly different spacing on each side to ensure against screw collisions during assembly.

6. Performance and analysis

6.1. Gateway

The consulting engineer believes the structural capacity of the pyramids exceeds what is required to adequately brace the waffle structure. (However blank panels would also have achieved this.) The pyramids fitted well into the structure, demonstrating the accuracy of the blank panel fabrication and jig. The pyramids are visually engaging but deeper forming (higher pyramids) would have been desirable.

6.2. Digished

The panels are independently rigid in multiple directions. The structure has been placed in an exposed location for several months without leakage or connection failure, demonstrating an effective weather screen There were some small ruptures in the material, most likely due to an abrupt change in the direction of forming. Further work is required to predict and avoid such punctures. They were filled with metallic putty. The patterning is visually effective at all scales.

6.3. Time

The forty-eight Gateway pyramids took between 34 to 82 minutes to form, a total of 2706 minutes. The twenty Digished panels took between 17 to 178 minutes with a total of 1070 minutes, reflecting the relatively shallow depth of forming. The turn-around between panels – unclamping, clamping, surface preparation, safety check and locating of file - took about 10 minutes, with some minor variation depending on the size of the panel.

7. Conclusion

Incremental Sheet Forming has been demonstrated to be an appropriate process to form metal panels, both as an external rainscreen and as an integrated bracing component. The appropriateness of ISF is however reliant on the component sets incorporating either a degree of customization or being produced in relatively small numbers. Compared to off-the-shelf cladding materials, the main drawback to the ISF process is the fabrication time. There is a considerable time penalty applied to achieving a smooth finish with smaller step-downs and stepovers. This has to be balanced against the capacity for creative forming.

The performance of the ISF panels appears to be good. The depth formed by ISF in the Digished is equivalent to traditional sheet-metal systems but has rigidity in more than one direction. Formed depressions can establish separation between structure and cladding and can also provide fixing points. Careful surface preparation, clamping, resistance and jig design are essential to a good outcome.

The project outcomes would not have been achievable without active student engagement with the various technologies. Students in the Masters of Architecture are capable of creatively applying the workflow steps and in safely operating the robot. This has been made possible through carefully choreographed learning activities that gradually ramp up the complexity of the tasks and the responsibility of the students. The intention in the future is to streamline the workflow by moving to KUKA PRC as the processing software, which will enable students to use Grasshopper, not only to design the objects but also to adjust and define toolpaths. There are significant spatial, material and process learnings embedded in many parts of the process: testing basic parameters and simple forming operations, both creative and pragmatic concerns associated with cladding systems, and in making critical connections between various parts of the making process.

Acknowledgements

Our appreciation to the Junction Arts Festival for their support in funding and hosting these projects.

References

Alves de Sousa, R.J. (2016) Incremental Sheet Forming Technologies, Woodhead Publishing, Sawston, Cambridge.

Behera, AK, de Sousa, RA, Ingarao, G et al. (2017) Single point incremental forming: an assessment of the progress and technology trends from 2005 to 2015. Journal of Manufacturing Processes, 27. pp37-62.

Burnham, R, Green, R, Taylor, L, Jones, O, Wilkes, L and Stokes, K, (2018) “The DigiShed: a small structure designed, fabricated and assembled with three emergent digital technologies”, Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association 2018: Proceedings, 28 November - 1 December 2018, RMIT University, pp. 169-176.

Burnham, R, and Wallis, L. (2012) Learning by Making in M. Dodd (ed.) Live Projects: Designing with People, RMIT Press, Melbourne.

Frayling, C. (1993) Research in Art and Design Royal College of Art Research Papers, 1(1).

Hamedon, S. Jaafa, H. and Azhari, A. (2018). Optimization of Surface Roughness and Wall Thickness in Dieless Incremental Forming of Aluminium Sheet using Taguchi, Materials Science & Engineering 319(1): 1-8.

Nicholas, M., Clausen Norgaard, E., Stasiuk, D. and Thomsen, M. (2016). Adaptive Robotic Fabrication for Conditions of Material Inconsistancy – Increasing the Geometric Accuracy of Incremental Sheet Formed Panels. AdvaInformation Technology and Architecture: 114-121.

Owen, Ceridwen and Norrie, Helen (2013), Advanced Design Research: Exploring the Teaching Research Nexus, Designing Education: Proceedings of the 7th International Conference of the Association of Architecture Schools of Australasia, 3-5 October 2013, Melbourne, Australia, pp. 222-237.

Piroozfar, P and Pillar, FT, (eds) (2013) Mass Customisation and Personalisation in Architecture and Construction Routledge, New York.

Modelling optimal residential tree arrangement to curb energy demands under present and future climate conditions

Mina Rouhollahi[1] and John Boland[2]

[1,2] UniSA STEM, University of South Australia, Adelaide, Australia
Mina.rouhollahi@mymail.unisa.edu.au[1], John.Boland@unisa.edu.au[2],
ORCID-0000-0001-5011-7483[1], ORCID-0000-0003-1132-7589[2]

Abstract: Australian Local Government Areas (LGA) failure to compensate their 30% urban tree canopy benchmark depletion: leading to hotter treeless medium density suburbs. This paper presents an Optimal Residential Tree arrangement (ORTa) concept for technical policy guideline updates, as an effective pioneer energy--efficient approach. ORTa is a multi-criteria sustainability framework promoting tree inclusion, deep soil management, soft landscape volume, biodiversity, long-term energy and water conservations and enhanced resident wellbeing. This study has three phases: first phase integrates current urban development and scattered open site assessment; the second phase analyses long term climate-building response, utilising Fourier series solar dependency data, resulting in accurate air and surface temperature predictions. The third phase adds evapotranspiration to AccuRate software, integrating field work data, to calculate crucial tree allocation parameters, validating bi seasonal optimisation criteria. We then evaluate Adelaide and Perth ORTa variations, with a 2050+ climate forecast. Adelaide's longer winters and higher wind velocity affect energy reduction results, with Perth showing double annual conservation. ORTa encourages governments, and accreditation bodies, to value tree microclimate modification strengths and provide stakeholders with education, inspiration and support. CSIRO 2050+ climate projections, strengthen our hypothesis, demonstrating ORTa's 80% climate retention. ORTa policy inclusion will transform research and future tree canopy cover and net-zero strategies.

Keywords: Nature-based solution, Optimal residential tree arrangement, Energy efficiency, Resilient neighbourhood.

1. Introduction

Since Australian climate records began in 1910, the national temperature has altered by an average 1.4 ± 0.24 °C, leading to extreme heat event increases. Continued warmer air temperatures lead to urban heat islands, including extended fire seasons, less serve cold conditions, shorter cold seasons, and decreased cool-season rainfall (CSIRO and Bureau of Meteorology, 2020).

Post 1980 residential polices demanded higher densities and lot subdivision, creating two (or more) smaller lots, eliminating former green space benefits (Duckworth-Smith, 2015; Crommelin *et al.*, 2017), in

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 426–440.*

an attempt to decrease undesirable urban sprawl, due to population growth (Brunner and Cozens, 2013). This grey-cover urban planning set a critical precedent resulting in a dramatic residential tree loss, increasing energy consumption, rising urban heat, and Australian climate degradation (CSIRO and Bureau of Meteorology, 2020). A significant shift towards smaller residential properties has triggered treeless suburban living, overheating, and a demand for long-term energy conservation strategies (Ossola *et al.*, 2020).

Post 2000 metropolitan compact-city strategies focus on public tree planting, including pocket parks and urban forests (Bowler et al., 2010; Zhao et al., 2018), and climate-responsive housing contributions in Urban Heat Island (UHI) mitigation, ignoring residential tree allocations' role in occupant energy intake reduction (Bailey, 2020; Ossola et al., 2020). This study's scope does not examine UHI in an external variable context i. e., roads, sidewalks, or target building reradiation.

Post 2005 industry stakeholders rely on HVAC systems to meet minimum NatHERS standards, in attempt to circumvent residential policy deficiencies, set out in this paper (Department of Industry Science Energy and Resources, 2020). Energy requirement is highly dependent upon environmental condition exposure with low-rated buildings and treeless neighbourhoods tending to be hotter (Australian Building Codes Board, 2016). This paper hypotheses residential tree inclusion would result in lower HVAC dependency and higher energy efficiency.

Current industry trajectory prompts stakeholders depend on engineering solutions i. e., horizontal and vertical shading devices, limiting energy efficiency potential: we hypothesis trees will outperform engineering solutions due to longwave radiation reduction, evapotranspiration generation, air pollution mitigation, efficient heat transfer, long-term expense management and property value growth (Geoghegan, 2002).

Local nature-based solution initiatives, aligned with the latest Intergovernmental Panel on Climate Change Panel (IPCC 2022), are stated as a powerful tool to climate change mitigation, with benefits beyond energy consumption and carbon emission reduction. Labelled as a powerful nature-based solution, residential trees create a healthier, liveable residential community, living in green comfortable environments, promoting generational psychological wellbeing (Bailey, 2020). As Australians enjoy privately utilised space, the major challenge is to overcome planning deficits by implementing optimal residential tree arrangements (ORTa) to successfully redesign current policy trends with private tree canopy enlargement focus.

We hypothesis energy-efficient and green-rich communities are cohorts as trees provide eco-friendly, low-cost, native, organic, and energy-efficient design elements vital to the neighbourhood stormwater management system (Moravej *et al.*, 2022). Due to this cohort relationship hypothesis, we state trees play a vital role in neighbourhood wellbeing including energy efficiency. Residential tree arrangement will curb suburb heat and influence building energy efficiency over and above urban parkland inclusion (Rouhollahi et al., 2022a). we hypothesis an efficient tree-building modification strategy would combine nature-based solutions with existing engineering solutions, to the fullest extent possible.

This study aims to investigate the hypothesis stating ORTa enhancing building energy-efficiency and outperform engineering solutions, as studied in two Australian contexts: Perth (32°S, 116°E) and Adelaide (34.92° S, 138.6° E). The objective is to clarify: 1) tree microclimate benefits for building thermal response, 2) analyse field work data to ensure proper tree study parameters, 3) investigate and compare current engineering solutions to nature-based solutions, 4) present current and future ORTa integrated microclimate benefits.

2. Methodology

To ensure thorough investigation, we analyse the long-term BoM climate benefit upon building thermal response, utilising Fourier series global solar radiation dependency data, resulting in accurate air and surface temperature predictions. In the next phase, we integrate mathematical modelling with field-work data to adjust local weather data, crucial tree allocation parameter prediction is reached. We then conduct 552 simulations, adding evapotranspiration to AccuRate Sustainability, resulting in validated bi-seasonal optimisation criteria. We finally evaluate these ORTa design variations in Adelaide and Perth, with a 2050+ climate forecast (RCP8.5 scenarios published by CSIRO in April 2022).

2.1. Mathematical approaches

Annual and seasonal environmental condition fluctuations inform National Construction Code (NCC) requirements and Building characteristics. We hypothesis applying optimal microclimate conditions to the facades can improve indoor thermal response to decrease heating and cooling demands, as the façade provides a barrier between indoor space and unconditional outdoor space. Although the building envelope design is crucial for attaining a minimum energy-efficiency score, environmental parameter modifications may enhance building thermal response effectiveness.

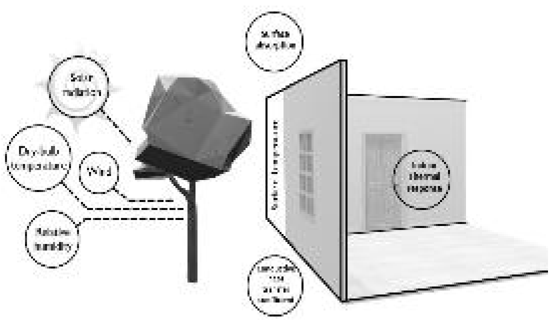


Figure 1: Climate variables' consideration in a building thermal response. (Source: Designed by authors)

As shown in Fig.1, an energy-efficient residential building is acutely responsive to meteorological factors, including temperature, solar radiation, relative humidity, and wind velocity. Fig.1 shows a possible microclimate modification to enhance the building thermal response and facilitate the passive energy possibilities. Our comprehensive study examines 12-year Adelaide climate datasets, including dry-bulb air temperature and global solar radiation. This method breaks down the weather data into deterministic (Fourier series) and stochastic (ARMA + Residuals) components, as adopted in earlier studies (Boland, 1995; Farah *et al.*, 2018), to predict multi-year weather parameter, connecting indoor building environment. This prediction shows weather variable dependency in preparing adjusted simulation weather file.

In addition to outdoor air temperature and solar radiation impacts, building thermal performance is subject to relative humidity and wind. Therefore, we evaluate both convection and radiation heat transfer impact upon building envelopes, approved by a complicated and multifaceted procedure for detailing building surface temperature interactions with microclimate parameters (Ulgen, 2002; Kontoleon and

Eumorfopoulou, 2008). These parameters detail opaque wall exterior surface temperature (T_s) referring to incorporated ambient outdoor temperature (T_o), façade solar radiation (Q_{sol}), surface materials' coating colour, surface absorption, (a_s) and indirectly, wind on leeward or windward facades (defined as conductive heat transfer coefficient (h_o)). A related Study (Rouhollahi *et al.*, 2022b) validates all these mathematical processes, on an actual test-case dwelling energy response. Cross-correlation between outdoor surface temperature and responded indoor temperature shows strong local microclimate-indoor temperature relationship, through a regression model.

2.2. Field work data

Field measurement provides under-canopy air temperature and humidity tailored to local weather data. These case studies are monitored in detail in Mawson Lakes Campus, University of South Australia, Adelaide (Sharifi and Boland, 2018) and Fremantle suburb in Perth (Byrne *et al.*, 2016), as shown in Fig. 2. We set up analogue sensors to record under-tree canopy temperature at 30-minute intervals. Sensors were installed approximately 120 cm above the floor, near tree heartwoods. The simulation calculation uses our adjusted weather data, including annual tree impacts upon air temperature and relative humidity, to formulate dwelling's actual thermal response.

(a) An in-situ measurement station.

Figure 2. Three field sensors (images from Google map and www.joshshouse.com.au)

AccuRate Sustainability V2.3.3.13 SP3 technical process limits tree shade effectiveness as a vertical shading object, excluding evapotranspiration, within 20 m radius within double-storey zones. Due to these limitations, we utilise seasonal hourly field-work data, applying this data as an adjustment to Adelaide and Perth weather data, to show tree shading coverage value and transpiration incorporation. In Excel, mean hourly temperature and humidity differences, in a daily base, are calculated and added to actual dry-bulb temperature and humidity in local weather data. The weather simplification clarifies the evapotranspiration tree impact. 2014 and 2020 local weathers with field measurement data integration develops an adjusted weather data set. The new adjusted weather data is converted to an acceptable AccuRate weather file structure. This process allows authors to calculate tree shade coverage quality and transpiration impacts on dwelling thermal sensibility, inside AccuRate software.

2.3. simulation

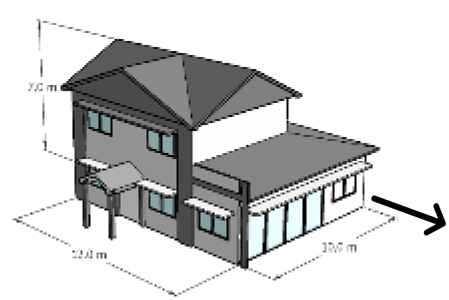
AccuRate Sustainability calculates possible numerical ORTa simulation scenarios, modelling climate impact upon dwelling energy consumption. Australian studies widely utilise AccuRate Sustainability to certify dwelling energy efficiency. The software's Chenath engine estimates the hourly energy consumption, affected by shading objects, excluding evapotranspiration, on each building surface. See (Delsante, 2004) for more details about Chenath engine calculation and validation.

The test-case house is composed of two above-ground levels and a non-conditioned attic. Its dimensions are: 10 m width × 12 m depth and 7 m height (176m2) with a pitched roof (Table 2 shows the geometry model). This test-case house simulates 0.5 m eave shading (roof overhang), horizontal awnings 0.75 m deep and 0.3 m extended projection beyond window width. The case-study representation is aimed at characterising the typical residential neighbourhood geometry and meteorology according to the minimum NatHERS energy-efficiency score as at 2022 (7 stars out of 10). Table 1 shows the fundamental parameter settings for the 7-star base case model.

Simulation design inputs evergreen and deciduous trees as vertical shading objects, each 7 m high, with 6 m evergreen crown diameter and 5 m deciduous crown diameter. Further simplification represents as a geometric tree with two 2-dimensional surfaces formed by a rectangle intersecting at 90°. In calculating seasonal tree change and solar shading ratio, this approach adjusted the following opaque factors: 80% evergreen tree opaque factor, 80% deciduous summer tree opaque factor, 25% deciduous winter tree opaque factor and an average 50% deciduous shoulder season over a monthly time-frame. These opaque factors correspond to moderate tree canopy typology effects during absorbed and transmitted sunlight in summer and winter. Rouhollahi e al. (2022b) validated the original scenario by measured air temperature with and without tree shading in Adelaide.

Table 1. Test-case fundamental parameter settings

Energy service	Typical fit-out requirement
Thermal comfort	7 NatHERS Stars thermal comfort(i.e. Adelaide heating energy consumption requirement of 67 MJ/m2, Adelaide cooling energy of 52; Perth heating of 57 MJ/m2, Perth cooling of 39 MJ/m2 per annum) Ceiling fans in all bedrooms and living spaces. Cooling: Split system reverse cycle Heating: Split reverse cycle air-conditioners
Floor-area (m2)	160
Width (m)	10
Depth (m)	14
Height-excluding attic (m)	7
Windows and Doors	Aluminium windows – Double low-E Glazed: 3 mm Clear/12 mm air gap/3 mm Clear U 3.51. Shading: Fixed shade devices on all North, East, and West glazing (75 cm depth) Entrance door: Timber hardwood



Energy service	Typical fit-out requirement
Thermal mass	External walls: Brick veneer 110 mm with bulk insulation or Lightweight walls of Weathertex® weatherboard or Colorbond® + 40 mm air gap Pitched roof: Colorbond® steel on timber frames with reflective foils. Lower floor: Concrete ground slab Internal walls: Plasterboard 10 mm, Rockwool insulation R2.0
Insulation	Roof (R4 plus foil), ceiling(R2), Walls (R2.5 plus foil). Internal walls (R2)
Heating and Cooling	Living space: Conditioned from 0700-2400. Daytime occupancy. No cooking heat gains. 20 °C heating thermostat setting. Kitchen/Dining: Conditioned from 0700 2400. Daytime occupancy. Cooking heat gains included. 20 °C heating thermostat setting. Lobby: Conditioned from 0700 2400. No occupancy heat gains. 20 °C heating thermostat setting. Bedrooms: Conditioned from 1600 0900. Night-time occupancy. 18 °C heating thermostat setting from 0700 to 0900 and 1600 to 2400, and 15 °C from 2400 to 0700. Cooling thermostat settings in all zones is set to 25 °C for Adelaide and Perth.

ORTa applied to Adelaide, Perth and 2050 forecasting climate scenarios were analysed hourly under 18 different arrangements, 552 simulations. For each tree planting possibility, the main simulation parameters are: 1) tree type; deciduous and evergreen, 2) tree volume; 1 to 3 trees, and 3) Tree-Building distance; 3m and 5m. The adjusted weather data, integrated 2020 local weather data and predicted 2050, RCP 8.5, with tree transpiration impact gathered through field measurement in suburban Fremantle, Perth.

3. Results and discussion

3.1. Microclimate, tree and building envelope

This section focuses on enhancing tree-Building interaction analysis accuracy by utilising weather parameters, delivering reliable thermal energy requirements. The following AR models are used to analyse solar radiation (Equation 1) and ambient temperature (Equation 2).

$$R_{sol} = 1.11\, R_t - 1 + 0.297\, R_t - 2 - 0.027\, R_t - 3 + Z_t \quad \text{Equation 1}$$

$$R_{temp} = 1.04\, R_t - 1 - 0.467\, R_t - 2 + 0.535\, R_t - 3 + Z_t \quad \text{Equation 2}$$

From these equations, standardised residuals are summarised at time t, could depend on R_{t-1} , R_{t-2} in clarified by R_{t-3} , etc., resulting in a dependency upon AR 1-3 combined with residual average. Subsequently, AR (3) model works particularly well during indoor temperature changes. Note, all results shown here are used for a one-step-ahead forecast. In addition, results allow weather prediction, by estimating the correlation between actual values and their effect on indoor temperature.

Further analysis shows residential tree planting modifies under-canopy relative humidity in a statistical sense, while forest and urban parks deliver humidity effect within the buffer zone. Trees moderate temperature due to two distinct processes – evaporation and condensation. Evaporation causes local heat loss diurnally, cooling the air in hot weather. Condensation causes local heat gain, warming nocturnal winter air. Oke et al. (1989) explains 'a well-treed greenspace' provides significant cooling and humidity control in hours immediately after sunset. Wenhui (2020) evaluated an urban park's thermal comfort, having a total area of 6.80 km2 and a greening ratio of 96.5%, by monitoring air temperature and humidity. This study showed a maximum humidity increase by (5±2) % diurnally and (10±5.2) % nocturnally, a small modification surprisingly comparable to residential tree planting.

During high humidity conditions, scattered residential tree humidity uptake is strong, coupled with wind flow around buildings, hence trees' positive effect during extreme weather conditions. Sufficient tree-building distance and faster wind movement remove humidity and trapped warm air near the building's envelopes; altering thermal losses (Hsieh *et al.*, 2016). Wind direction and velocity affect external surface temperature distribution, depending upon façade orientation, hence optimal tree orientation importance. Wind flow around buildings is complex, with limited control over the boundary conditions, hence our comparing between two cities with different wind velocity. Emmel et al. (2007) numerically investigated the wind effect on building thermal response at different velocities in two directions (headwind and crosswind). In a windward façade, a building height less than 10 m, the headwind effect can be ignored. Prakash et al. (2009) showed crosswind affects building envelope when compared to headwind. Moreover, wind impact intensifies, decreasing surface temperature, when parallel to a windward façade. Conversely, by reducing the wind angle, building surface temperature increases. Therefore, air trapping, due to insufficient ventilation and poor tree placement, has a detrimental effect on exterior surface temperature and reduces the building's convective cooling (Hsieh *et al.*, 2016), hence T-B distance importance.

In addition, optimised tree canopy characteristics give maximum thermal benefits as the tree crowns grow large and dense. This beneficial tree shading reduces temperature dependency on solar radiation, resulting in cooler air temperature due to these protective tree mechanisms (Osmond and Sharifi, 2017). Optimal tree allocation increases the urban tree advantages and reduces the short-term tree replacement schedule, demonstrating tree planting cost effectiveness (Clark and Matheny, 1991). A densified residential tree crown functions as a microclimate modifier: absorbing, storing, reradiating longwave radiation, to reduce façade heat absorption, nocturnal cooling and radiative energy loss (Bowler *et al.*, 2010), demonstrating tree crown density importance.

Table 1 compares practical tools for reducing environmental impacts upon dwelling thermal energy saving. The combination of ORTa expands these engineering energy-efficient benefits by dramatically modifying local microclimate, to maintain a comfortable temperature inside home. Trees are the predominant nature-based solution as they directly affect the microclimate and humidity surrounding the building shell, ground level air temperature, improving soil absorption and stormwater runoff.

Table 1: Energy conservation with engineering solutions and nature-based solutions

Ref.	Requirement	References' solution: Engineering solution	Authors' hypothesis: Nature-based solution
(Datta, 2001)	Sun shielding	Shading devices	ORTa
Liu and Harris, 2008, Santamouris *et al.*, 2017)	Cooling/Heating energy saving	Energy-efficient appliances, Shading devices	ORTa / Natural ventilation
(Charron and Athienitis, 2006)	Reducing energy bills	Solar photovoltaic panels/ Windows modification/water-wise irrigation system	ORTa
(Bellia *et al.*, 2014)	window shading	External awnings	ORTa
(Liu and Harris, 2008)	Winter wind protection	Opaque fence panels	ORTa
(Akbari and Matthews, 2012; Woznicki *et al.*, 2018)	Runoff and neighbourhood flooding prevention	Permeable materials	Tree inclusion
(Renouf *et al.*, 2020)	Prevent soil erosion/ Decrease raindrops impact	Geotextile materials/ Crushed rocks	Tree inclusion
(Kong *et al.*, 2019)	Reducing excess humidity and winter mould	Dehumidifier	Shrubs and Tree inclusion
(Doulos *et al.*, 2004)	Cooler summer days	Pool/ Light coloured surface	Tree inclusion
(Mitchell, 2010)	Water efficiency	Water-wise Irrigation system	ORTa
(Kong *et al.*, 2019)	Curb neighbourhood heat	Urban green infrastructure	ORTa

Tree impacts upon building energy consumption are complex (Rouhollahi *et al.*, 2022a) and affect both energy balance and water efficiency, despite tree species. Souch et al. (1993) analysed four tree species' effect, in a control environment, compared to identical tree species in differing environments. Results show microclimate importance, in modifying mid-canopy air temperature and humidity, during tree selection. As landscapers focus on unirrigated sustainable design, or waterwise gardens, ORTa in temperate climate conditions is adaptable to tree species and supports aesthetic traits.

3.2. ORTa variations under two Climate contexts

This study examines climate types, including warm to mild temperate (Australian climate zone 5), experiencing seasonal variation, mild to warm summers and cool to cold winters (Bureau of Meteorology, 2017). Australian zone 5 extends across the southern regions of Western Australia, South Australia, Victoria, and New South Wales. This climate, covering rapidly densifying Australian cities, is critical in developing urban heat mitigation and energy conservation strategies. We selected Adelaide (34.92° S, 138.6° E) and Perth (32°S, 116°E) to represent the majority of Australian metro cities, in which to deploy an energy-saving solution.

We evaluate Adelaide and Perth weather parameters variations, with Adelaide's longer winters and higher winter wind velocity. This climate condition provides a unique opportunity to examine low maintenance nature-based solutions, such as shrubs and trees. These natural heat mitigation strategies extend greenery benefits well beyond their immediate location, exceeding urban heat relief expectations; with minimum maintenance cost in target climate zone (City West Water, 2015).

Adelaide and Perth are 2650 km apart: Adelaide is a South Australian coastal capital with a population of approximately 1.35 million. The mean annual rainfall is 536 mm, with an average 17 rainy days per winter month. Adelaide had 224 clear days over a 30-year data set, with the mean monthly solar exposure of 27.3MJ/m2 in January and 7.6MJ/m2 in June (Bureau of Meteorology, 2017).

Perth, the Western Australian capital, is located on a narrow coastal plain at the end of Australia's southwest border, with a population of approximately 2.21 million. Perth has a reliable average annual rainfall, 737 mm, with 90% falling between April to October. This high volume on the west coast provides high-quality irrigation water for three-quarters of domestic gardens and grasslands (McFarlane, 2016). In addition to urban consolidation policies, managing residential tree allocation will reduce on domestic garden irrigation dependency.

These two temperate case studies provide a reliable climate change template, based on long-term urbanised weather conditions. Bureau of Meteorology (BoM) hourly 1995-2020 historical weather data represents a multi-year average, utilising long-term local weather parameters, comparing weather data from two Adelaide (Kent town and Airport) and three Perth weather stations (Airport, CBD and Swanbourne). The following comparison includes dry-bulb air temperature, global solar irradiance, and wind velocity

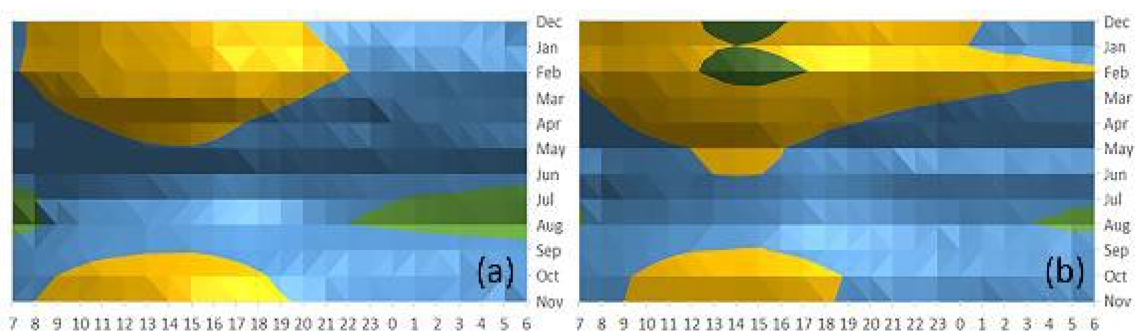


Figure 3: (a) Adelaide's average dry-bulb temperature pattern**;** (b) Perth's average dry-bulb temperature pattern (Source: BoM). Horizontal axis presents 24 hours starting from sunrise. Legend shows four temperature areas (℃).

Figs. 3 (a) and (b) show average monthly air temperature differences in Adelaide and Perth, respectively. These figures adjust the vertical axis from the first month of summer (December) and the horizontal axis from sunrise. The long-term average data indicates a warmer Perth than Adelaide. On average, when Perth is over 30 °C (indicated as a green area), Adelaide is under 30 °C (still in yellow area), a difference of 5.8-8 °C. Both cities have their warmest weather in February and coldest in August, when average low temperature is 9.4°C in Perth and 7.6 °C in Adelaide.

These two graphical representations evidently indicate a broad temperature difference (20-40 °C) in Perth and Adelaide. The Perth yellow indicator details a longer hot season, while Adelaide's expanding blue colour indicates higher heating demands. Thereby, Adelaide winter heating reduction is paramount when compared to summer offset. This diagram shows bi-seasonal approach importance, specifically in Adelaide. In comparison, Perth's residential tree inclusion significantly reduces cooling demands, improving winter efficiency.

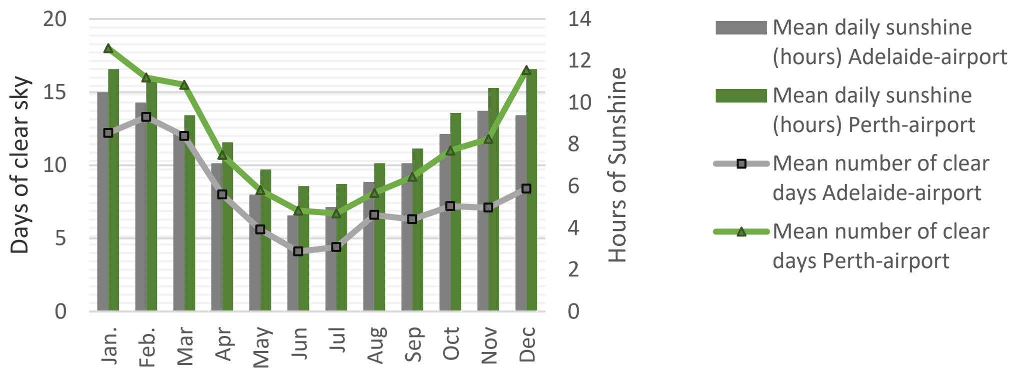


Figure 4: Average daily sunshine and sunny day volume, in Perth and Adelaide. Source: BoM

Solar exposure is an important parameter, varying according to climate and specific building design considerations. The balance between solar access and building façade exposure is essential for measuring façade's surface temperature, therefore, tree allocation is important. Erell (2022) evaluated densified neighbourhood living cost, with different building configurations, to monitor site shading by neighbouring buildings, in Mediterranean climate. Erell's study showed UHI affects these buildings, by diminishing annual energy saving, to approximately 6%. Nikoofard et al, (2011) compared neighbourhood shadowing versus tree shade and to find annual energy saving doubles, in tree scenarios; due long-wave radiation and convection prevention and positive microclimate modification.

Solar access differs significantly depending on latitude and time-frame. Fig. 4 compares sunshine hours of clear days in Adelaide and Perth. Perth has an average 8 sunlit hours per day, year-round, while Adelaide's monthly sunlit hours is less than Perth.

Fig. 4 shows, although February is the warmest month in Perth and Adelaide, January is the sunniest month, 387.5 sunlit hours in Perth, and 326 hours in Adelaide. Likewise, August is the coldest month, and June displays the lowest sunshine amount, 180 hours in Perth and 138 hours in Adelaide. ORTa affects a minimum two summer months and two winter months, due to the correlation between air temperature and solar radiation (refer to the previous section).

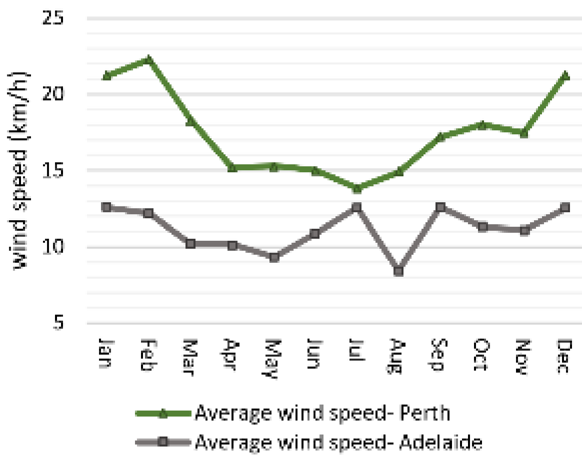


Figure 5: Annual average wind speed (Km/h). Source: BoM

As seen in Fig. 5, although January and February are the hottest months in Perth, the wind velocity level substantially decreases hot temperatures surrounding building's façade. In comparison, wind speed in Adelaide's winter months is influential upon exposed surface heat loss. To determine building thermal response rating, assessors first examine outdoor condition impact, then study building material thermal behaviours. Therefore, ORTa inclusion is implemented to boost building energy conservation without detrimental annual or bi-seasonal thermal response.

3.1 Present and future ORTa energy conservation

In our following result graphs (see Figs. 6-10), cooling and heating energy differences are presented as a thermal energy conservation percentage compared to base-case buildings. Positive values represent an annual or bi-seasonal energy reduction; inversely, negative values indicate increased energy usage. In the graphs, 'Tr' stands for a tree, 'Ever' for evergreen trees and 'Deci' for deciduous trees.

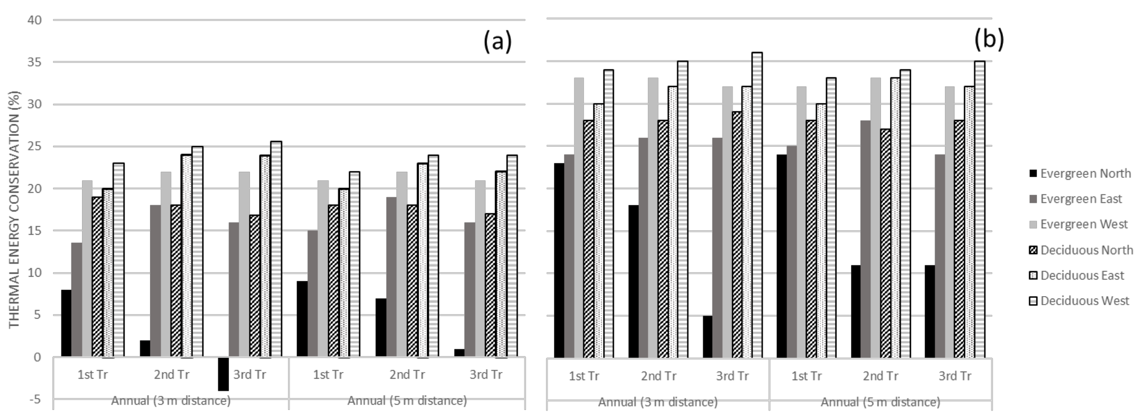


Figure 6. (a) Annual thermal energy conservation in a 3 m and 5 m tree building distance-Adelaide, (b) Annual thermal energy conservation in a 3 m and 5 m tree building distances-Perth

As seen in Fig. 6, planting deciduous trees, in different cardinal aspects, results in higher thermal energy conservation than evergreen trees. Figs. 6a and 6b indicate tree inclusion in Perth's residential suburbs resulting in higher annual thermal energy conservation, compared to Adelaide. In Adelaide, westerly tree planting is optimal; bi-seasonally, easterly and westerly planting provides double the cooling reduction (Fig.7) Perth's shorter cold seasons and lower winter wind results in negligible heating demand increase and ineffectual annual energy saving impact. The following figure focuses on cooling energy conservation. Fig. 7 supports Perth residential tree inclusion importance in any deep soil availability.

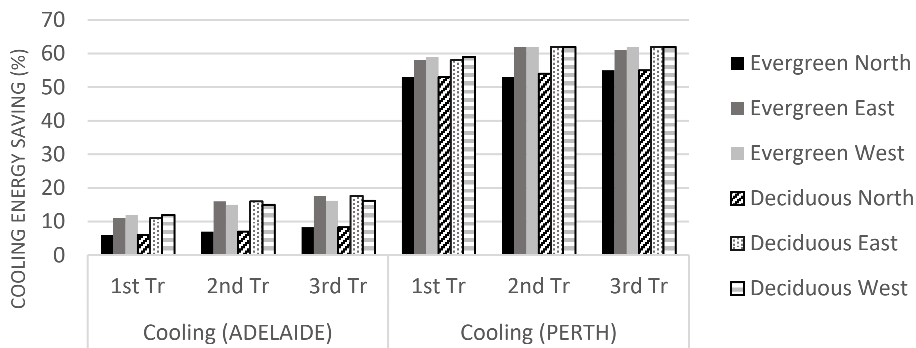


Figure 7. Cooling thermal energy conservation in a 3 m tree building distance-Adelaide and Perth.

Fig. 8 indicates five ORTa possibilities across four data sets including Perth and Adelaide local weather conditions, compared to ORTa future impacts. ORTa recommendations present optimal residential tree distribution, in tree volume order, ranked from 1 to 5, with all configurations based upon minimum tree number and maximum energy efficiency. This figure highlights that a 3 m deciduous Tree-Building distance, causes higher energy conservation overall.

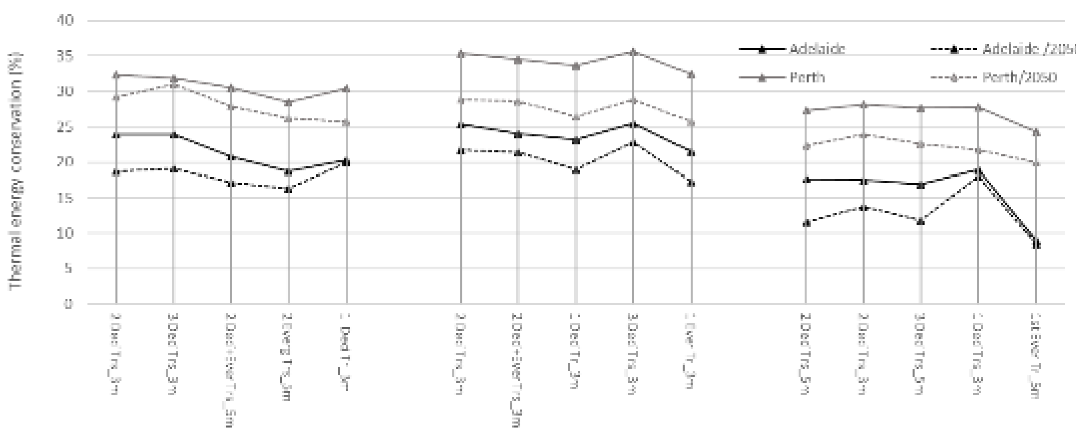


Figure 8. Optimal tree planting scenarios, depending on tree planting possibilities, compared with ORTa future impacts.

Although the annual energy benefit analysis prefers westerly tree planting, current Australian subdivision policies limit tree planting freedom in multiple aspects. This requires bi-seasonal analysis to arrive at a site-appropriate tree arrangement. The black and grey dash-lines show global warming effect as a suburban heat indicator. Although global warming affects ORTa benefits (dash lines), private tree canopy (solid lines) retains approximately 80% energy conservation gains, decreasing the tangible nature of global warming and curbing suburban heat.

4. Conclusion

Ownership, affordable mortgages, living cost and energy bill reduction, influence Australian attitude toward smaller footprint energy-efficient homes. Australian Bureau of Statistics data shows smaller lot size holding largely unchanged building footage demonstrates Australians unwillingness to compromise on bedroom volume, downsizing private open space. However, deep soil absence is not a viable justification for urban tree canopy asset loss. Australians have the power to influence the design process, requesting tree allocation when building or buying their home, in the same way they insist upon a double garage. Focus can shift to boost our natural wellbeing by considering how ORTa can recreate a sustainable future for the next generation.

This study investigated ORTa energy-efficiency enhancement, as demonstrated in two Australian contexts: Perth and Adelaide. Results show energy-efficient and green-rich communities are co-dependent as trees provide eco-friendly, low-cost, native, organic, and energy-efficient design elements vital to the neighbourhood stormwater management system. Due to this dependent relationship, trees play a vital role in neighbourhood wellbeing including energy efficiency. Our study demonstrates trees outperform engineering solutions, in increasing energy efficiency, based on longwave radiation reduction, evapotranspiration generation, air pollution mitigation, efficient heat transfer, long-term expense management and property value growth. Our findings show an efficient tree-building modification strategy combines nature-based solutions with existing engineering solutions, to the fullest extent possible. This study validated tree microclimate benefits for building thermal response, accurate tree study parameters, current nature-based solutions outweighing engineering counterparts and future ORTa integrated microclimate benefit applications. This research encourages tree decision-makers to appreciate private residential green space. ORTa policy inclusion will transform future urban tree canopy cover and net-zero carbon emission strategies.

Acknowledgment

The first author (M.R.) acknowledges the financial support of the RTP scholarship by UniSA (University of South Australia) on behalf of the Australian Commonwealth Department of Education and Training. Raw data (Section 2.2) is based upon fieldwork supported by UniSA RTIS Grants on Cooling Capacity of Urban Green Infrastructures, under grant number 170322. The authors wish to acknowledge Prof. Josh Byrne, who supported and provided raw data for Perth case study.

References

Akbari, H. and Matthews, H. D. (2012) Global cooling updates: Reflective roofs and pavements, *Energy and Buildings*, 55, 2-6.

Australian Building Codes Board (2016) *Natinal Construction code Series*. Available from: <http://www.abcb.gov.au/Resources/NCC> (accessed 20 September 2019).

Bailey, H. (2020) *Costs and benefits of urban tree canopy options for minor infill development in the planning and design code*, in J. Morison (ed.), Attorney-General's Department, Adelaide, Australia, 101.

Bellia, L., Marino, C., Minichiello, F. and Pedace, A. (2014) An overview on solar shading systems for buildings, *Energy Procedia*, 62, 309-317.

Boland, J. (1995) Time-series analysis of climatic variables, *Solar Energy*, 55(5), 377-388.

Bowler, D. E., Buyung-Ali, L., Knight, T. M. and Pullin, A. S. (2010) Urban greening to cool towns and cities: A systematic review of the empirical evidence, *Landscape and Urban Planning*, 97(3), 147-155.

Brunner, J. and Cozens, P. (2013) 'Where have all the trees gone?'Urban consolidation and the demise of urban vegetation: a case study from Western Australia, *Planning Practice and Research*, 28(2), 231-255.

Bureau of Meteorology (2017) *Average annual and monthly maximum, minimum, and mean temperature*. Available from: Commonwealth of Australia <http://www.bom.gov.au/jsp/ncc/climate_averages/temperature/index.jsp?maptype=3&period=an#maps.> (accessed 10 Sep 2017).

Byrne, J., Eon, C. and Newman, P. (2016) *Sustainability tools and frameworks for high performance housing*, Low Carbon Living Ltd, Australia.

Charron, R. and Athienitis, A. (2006) Design and Optimization of Net Zero Energy Solar Homes, *ASHRAE Transactions*, 112(2).

City West Water (2015) *Responding to the urban heat island: optimising the implementation of green infrastructure*. Available from: Victorian Centre for Climate Change Adaptation Research <http://healthyurbanhabitat.com.au/responding-to-the-urban-heat-island-optimising-the-implementation-of-green-infrastructure/> (accessed 7 July).

Clark, J. and Matheny, N. (1991) Management of mature trees.

Crommelin, L., Bunker, R., Troy, L., Randolph, B., Easthope, H. and Pinnegar, S. (2017) As compact city planning rolls on, a look back: Lessons from Sydney and Perth, *Australian Planner*, 54(2), 115-125.

CSIRO and Bureau of Meteorology (2020) *State of the climate 2020*, in C. o. Australia (ed.), Australia,.

Datta, G. (2001) Effect of fixed horizontal louver shading devices on thermal perfomance of building by TRNSYS simulation, *Renewable Energy*, 23(3-4), 497-507.

Delsante, A. (2004) *A Validation of the 'AccuRate' Simulation Engine Using BESTEST*, CSIRO.

Department of Industry Science Energy and Resources (2020) *NatHERS Accredited Software*. Available from: Commonwealth of Australia <https://www.nathers.gov.au/nathers-accredited-software> (accessed 20 Jan 2020).

Doulos, L., Santamouris, M. and Livada, I. (2004) Passive cooling of outdoor urban spaces. The role of materials, *Solar Energy*, 77(2), 231-249.

Duckworth-Smith, A. (2015) Backyard bonanza: improving the quality of 'popular'suburban infill, *Australian Planner*, 52(4), 297-313.

Emmel, M. G., Abadie, M. O. and Mendes, N. (2007) New external convective heat transfer coefficient correlations for isolated low-rise buildings, *Energy and Buildings*, 39(3), 335-342.

Erell, E. and Zhou, B. (2022) The effect of increasing surface cover vegetation on urban microclimate and energy demand for building heating and cooling, *Building and Environment*, 213, 108867.

Farah, S., Saman, W. and Boland, J. (2018) Development of robust meteorological year weather data, *Renewable Energy*, 118, 343-350.

Geoghegan, J. (2002) The value of open spaces in residential land use, *Land use policy*, 19(1), 91-98.

Hsieh, C.-M., Jan, F.-C. and Zhang, L. (2016) A simplified assessment of how tree allocation, wind environment, and shading affect human comfort, *Urban forestry and urban greening*, 18, 126-137.

Kong, D., Liu, H., Wu, Y., Li, B., Wei, S. and Yuan, M. (2019) Effects of indoor humidity on building occupants' thermal comfort and evidence in terms of climate adaptation, *Building and Environment*, 155, 298-307.

Kontoleon, K. and Eumorfopoulou, E. (2008) The influence of wall orientation and exterior surface solar absorptivity on time lag and decrement factor in the Greek region, *Renewable Energy*, 33(7), 1652-1664.

Kuang, W. (2020) Seasonal variation in air temperature and relative humidity on building areas and in green spaces in Beijing, China, *Chinese Geographical Science*, 30(1), 75-88.

Liu, Y. and Harris, D. (2008) Effects of shelterbelt trees on reducing heating-energy consumption of office buildings in Scotland, *Applied Energy*, 85(2-3), 115-127.

McFarlane, D. (2016) *Will Perth have enough water for its diverse needs in a drying climate?*, Planning Boomtown and Beyond, ed., UWA Publishing, Perth.

Mitchell, j. (2010) *The truth about trees*,Permaculture NEWS, Permaculture research institute, Australia.

Moravej, M., Renouf, M. A., Kenway, S. and Urich, C. (2022) What roles do architectural design and on-site water servicing technologies play in the water performance of residential infill?, *Water Research*, 213, 118109.

Nikoofard, S., Ugursal, V. I. and Beausoleil-Morrison, I. (2011) Effect of external shading on household energy requirement for heating and cooling in Canada, *Energy and Buildings*, 43(7), 1627-1635.

Oke, T. R., Crowther, J., McNaughton, K., Monteith, J. and Gardiner, B. (1989) The micrometeorology of the urban forest *Philosophical Transactions of the Royal Society B: Biological Sciences*, 324(1223), 335-349.

Osmond, P. and Sharifi, E. (2017) *Guide to urban cooling strategies*, Infrastructure Sustainability Council of Australia, LOW CARBON LIVING CRC.

Ossola, A., Staas, L. and Leishman, M. (2020) *Urban Trees and People's Yards Mitigate Extreme Heat in Western Adelaide*, Macquarie University, Sydney.

Prakash, M., Kedare, S. B. and Nayak, J. K. (2009) Investigations on heat losses from a solar cavity receiver, *Solar Energy*, 83(2), 157-170.

Renouf, M. A., Kenway, S. J., Bertram, N., London, G., Todorovic, T., Sainsbury, O., Nice, K., Moravej, M. and Sochacka, B. (2020) *Water Sensitive Outcomes for Infill Development: Infill Performance Evaluation Framework*, Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia.

Rouhollahi, M., Whaley, D., Behrend, M., Byrne, J. and Boland, J. (2022a) The role of residential tree arrangement: A scoping review of energy efficiency in temperate to subtropical climate zones, *Renewable and Sustainable Energy Reviews*, 158, 112-155.

Rouhollahi, M., Whaley, D., Byrne, J. and Boland, J. (2022b) Potential residential tree arrangement to optimise dwelling energy efficiency, *Energy and Buildings*, 261.

Sharifi, E. and Boland, J. (2018) Passive activity observation (PAO) method to estimate outdoor thermal adaptation in public space: case studies in Australian cities, *International journal of biometeorology*, 1-12.

Souch, C. and Souch, C. (1993) The effect of trees on summertime below canopy urban climates: a case study Bloomington, Indiana, *Journal of Arboriculture*, 19(5), 303-312.

Ulgen, K. (2002) Experimental and theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor, *Energy and Building*, 34(3), 273-278.

Woznicki, S. A., Hondula, K. L. and Jarnagin, S. T. (2018) Effectiveness of landscape-based green infrastructure for stormwater management in suburban catchments, *Hydrological processes*, 32(15), 2346-2361.

Zhao, Q., Yang, J., Wang, Z.-H. and Wentz, E. (2018) Assessing the cooling benefits of tree shade by an outdoor urban physical scale model at tempe, AZ, *Urban Science*, 2(1), 4.

Net zero cities: Precinct by precinct

Peter Newman[1] and Dominique Hes[2]

[1]Curtin University, Perth, Australia,
p.newman@curtin.edu.au, ORCID-0000-0002-8668-2764[1]
[2] City of Melbourne, Melbourne, Australia;
dominiquehes27@gmail.com

Abstract: A net zero city can be developed precinct by precinct through focussing on precincts around electric mid-tier transit along main road corridors. These are outlined through steps that enable broader design goals to be fulfilled as well as showing how technological innovation fits into precincts.

Keywords: NetZero, precincts, planning, transport.

1. Introduction.

Climate change politics is now requiring all professional practice to build towards net zero outcomes in all that they do (IPCC 2022). This was a requirement of the Paris Agreement but was not really taken up until recently, when the world of finance said they would provide $170 trillion to make net zero happen. Once the business world, including those who build cities, were saying we really need to build net zero now, the big question for government was how do we make net zero cities? What is the planning regulatory framework that is needed as well as the strategic stages that should be taken in their design? This paper will outline how net zero design intention is emerging and the challenges that urban design practitioners face in delivering the global and local outcomes that are increasingly being demanded by communities, politicians and business. Net zero design is now on the desks of practitioners across the world but it is not clearly defined in professional practice. Whatever net zero practice becomes it needs to be integrated into the historic role that cities have always played. It will continue the role of urbanism and urban design to enable the growth of civilized spaces and enhanced human activity through places that encourage interaction, productivity and equity (Hall, 1998; Kostoff, 1991; Glaeser, 2011) as well as net zero outcomes (Seto et al, 2021Newman, 2020). This paper will suggest that the best way to proceed with net zero is one precinct at a time.

2. Why the old urban design needs updating.

Urban design has a long history but the biggest impact on our cities came from the Modernist movement of Le Corbusier from the 1930's that built new cities while emerging from the Great War and the Great

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 441–450.*

Depression (Kostoff, 1991). Modernist design sought to find a way of cleaning up the old city and creating new forms using new materials and infrastructure based around cars and fossil fuels. This has shaped urban development until the sustainability and climate change movement began to question its fundamentals and suggest new approaches particularly ways of overcoming automobile dependence (Jacobs, 1961; Newman *et al*., 2015).

The major problem is that modernist urban design saw the one Manual of design practice for all parts of the city in terms of urban form and transport. In response a theory of urban fabrics suggests that there are three historic periods of urbanism based on the priorities of transport infrastructure (Newman, Kosonen and Kenworthy, 2019) which has created three different cities within each city. There is a very large difference in form, structure and metabolism of each part of the city with the most recent parts (the Automobile City) significantly higher in input resources and output wastes (see table 1). Net zero design needs to respect each fabric and develop them differently with the car dependent suburbs especially important due to their high carbon footprint (Thomson and Newman, 2015).

Table 38: Input Resources and Waste output variations between urban form types. Source: Thomson and Newman, 2015.

INPUT (Per Person Per Year)	**Automobile City**	**Transit City**	**Walking City**
Fuel in Megajoules (MJ)	50000	35000	20000
Power in Megajoules (MJ)	4620	4620	4620
Gas in Megajoules (MJ)	2450	2450	2450
Total Energy in Gigajoules (GJ)	57.07	57.07	57.07
Water in Kilolitres (Kl)	70	70	70
Food in Kilograms (kg)	451	451	451
Land in Metres Squared (m^2)	547	547	547
Urban Footprint in Hectares (ha)	2.22	2.22	2.22
Basic Raw Materials (BRM) for New Building Types Per Person			
BRM 1) Sand in Tonnes (T)	56	22	5.7
BRM 2) Limestone in Tonnes (T)	34	13.2	3.4
BRM 3) Clay in Tonnes (T)	22	8.7	2.3
BRM 4) Rock in Tonnes (T)	33	13	3.3
Total BRM in Tonnes (T)	145	57	15
OUTPUT (Per Person Per Year)	**Automobile City**	**Transit City**	**Walking City**
Greenhouse Gas (Fuel, Power & Gas) in Tonnes (T)	7.13	4.98	2.95
Waste Heat in Gigajoules (GJ)	57.07	39.90	23.65
Sewage (incl. storm water) in Kilolitres (KL)	80	80	80
Construction & Demolition (C&D) Waste in Tonnes (T)	0.29	0.22	0.18
Household Waste in Tonnes (T)	0.63	0.56	0.49

3. Net Zero Design

The Paris Agreement committed all nations to address the climate agenda by achieving net zero greenhouse gas emissions by 2050 in order to keep global warming below 2^0C preferably below 1.5^0C. This was focussed to a more immediate goal of 45% by 2030 in the Glasgow Compact in late 2021. Cities were urged to take up this agenda as they were seen as a major way to help with the transition and indeed

2023 will see a special IPCC Report on Cities and Climate Change. The need to relate to the local aspects of all SDG's and the need for adaptation was also firmly on the agenda from the IPCC 1.5^{0}C report in 2018 through to the Adaptation Report in 2022, always showing the importance of combining adaptation and mitigation.

3.1. Adaptation – using climate-based design to support net zero pathways

Achieving net zero outcomes requires climate resilient urban design that takes into account current and future weather (IPCC, 2022b). It is based on the fact that the world's climate is going to continue to capture more energy through the greenhouse effect. Therefore, we need to design the built environment to be adaptable and to consider the increased chance of floods, fires and extreme heat. This enables the built environment to be more climate resilient as the world continues to heat.

Climate resilient urban design means avoiding development on climate sensitive sites, adaptation of materials and green infrastructure for cooling cities, especially biophilic design, and managing water better. These are necessary first steps in net zero design as many adaptation design tools are also part of the mitigation design tools. These tools need to be applied differently for different parts of cities as explained below on mitigation. Flooding is usually a coastal and river flood-plain issue and forest fires are generally a peri-urban and rural area issue; in many cases this means retreat from such high-risk places and redevelopment with eco-villages using net zero design (Norman, Newman and Steffen, 2020). Manuals for how to do this are increasingly available and training is being conducted as part of professional development as well as academic credentials (ICLEI, 2018).

3.2 Mitigation

The main focus of net zero is on what urban design practitioners can begin to deliver in their projects that are increasingly focussed on mitigation design tools. The dramatic period we are now living in is that cities are able to be reshaped by a highly commercial and attractive new combination of technologies for decarbonising the world: solar, batteries and electric vehicles. These are now more efficient and more able to achieve the multiple goals of net zero along with the broader goals of historic urbanism. We can now build cities better than the previous era based on fossil fuels (Newman, 2020). Hence the new urban economy that is emerging post-COVID is accelerating faster than many could have seen in the past decade, even the IPCC in the 1.5^{0}C report, and it is being driven by cities.

The future is now rapidly emerging around very cheap solar, batteries and electric vehicles of all types including e-micromobility, e-transit and e-cars. At the same time net zero buildings have been developed using new materials, solar design and new appliances such as induction cookers and heat pumps for an all-electric building that is then linked into renewable power, often in net zero precincts where solar can be shared (Newton *et al.,* 2021).

But the key issue for urban design professionals, and indeed urban professionals of all kinds, is that these must be integrated using smart technology systems to provide all the urban and industry systems that are necessary for good urbanism. The key urban design skill for practitioners is the integration of the three core technologies for decarbonization with different parts of the city. One simple example that illustrates this immediately is that EV's in the form of automobiles can still ruin urban centres where place-based walkability is critical; but perhaps net zero corridors through suburbs can be focussed on new technology solar-electric transit and e-microbility with decentralised micro-grids that could help create significant place-based opportunities as well as decarbonising the city.

4. Net Zero in Design Practice

Climate mitigation needs to be focused on how the new technologies of solar, batteries and electric vehicles of all kinds can be integrated with net zero buildings into the form and function of cities using smart city systems. These will need to create decarbonised design in buildings and infrastructure, especially transport. So, the most important net zero design tools are: solar design, electric transit activated corridor design, and local e-mobility and walkability design. Other key net zero practices that are emerging as critical tools in enabling net zero cities are water sensitive urban design, circular economy design, biophilic and permaculture design, and as always integrated design practices. All these design practices need to be applied differently for each kind of urban fabric: central city walking fabric, corridor-based transit urban fabric, outer area car-dependent urban fabric, and to the more rural peri-urban and rural village fabrics such as the Paddock (see Table 2). The Paddock snapshot below shows an example of a project in Victoria, Australia that integrated all of these using regenerative design thinking and the Living Building Challenge as a guiding tool.

Net zero precinct example 1, The Paddock, Castlemaine, Victoria (peri-urban)

On the urban edge of Castlemaine, Australia, 'the Paddock' was designed to be a 27-home development on 1.34ha of degraded land previously cleared for gold mining, then used for sheep farming and chicken sheds before being bought by its current owners. The site was redesigned and regenerated using the Living Building Challenge (LBC) building and community performance standard. LBC is a highly aspirational, voluntary standard that covers a range of performance criteria such as energy, water, place, and includes how development can focus on biodiversity and ecosystem health (Cumming, 2020; Thomson et al, 2022).

The development aims to be energy positive, producing more energy than it needs, but also to have a strong, water, waste, landscape and food production outcomes. It's measures of success are the health of its residents and ecosystem repair with an emphasis on creating the conditions for the return of some iconic biodiversity.

Currently, it is producing more energy than it is consuming across 7 households using 9kwh/day and exporting 14.1 kwh/day (Moyse, 2020); with the other 20 homes not yet lived in for more than 12 months. Furthermore, anecdotally, three of the five species designed for have returned. As part of the development there will be electric vehicle (car and bike) charging, a micro grid (currently no battery), shared washing facilities, orchard, greenhouse, making shed, chickens, bees, etc. and someone that as part of the community has the role to be the handy person and carer for the systems.

Table 2: Summarizing Urban Fabrics and their Net Zero Urban Design Practice Potential.

Net-Zero Urban Spatial Planning Tools	Central City Walking	Inner City Transit	Outer Suburb Automobile	Peri Urban and Rural Bioregional	Remote Settlement
1. Solar design	Strong transport carbon reductions but harder to do solar on buildings. Solar design for energy efficiency essential.	Easier to do solar on buildings and harder on transport carbon reductions. Solar design for efficiency essential.	Easy to do solar on buildings and much harder on transport carbon reductions. Solar design for efficiency essential.	Easier to do solar on buildings and harder on transport carbon reductions. Solar design for efficiency essential.	Easier to do solar on buildings and harder on transport carbon reductions. Solar design for efficiency essential.

2. Electric transit activated corridor design	Electric metro trains buses and Trackless Trams need to service city center with very few electric cars.	Electric metro trains buses and Trackless Trams need to service stations on corridors with some electric cars feeding in.	Electric metro trains buses and Trackless Trams need to service city center with very few electric cars.	Electric buses and Trackless Trams have some potential but mostly electric cars.	Electric cars, trucks and motorbikes only.
3. Local shared E-micro-mobility and walkability design	Last mile support for transit focused on central function of walkability	Essential support for transit stations along with walkability	Necessary to build into any new and old station precincts but must mostly try to reduce impact of electric cars.	Electric bikes can work for local trips but mostly cars need to be accommodated.	Very little role other than in local movement.
4. Water sensitive urban design	Water efficiency easily created in dense buildings but recycling more difficult where space is constrained	Water efficiency easily created in medium density buildings and some recycling where space less constrained	All aspects of water sensitive urban design possible once space is set aside.	Recycling of waste water and stormwater can be fully integrated	Recycling of waste water and stormwater can be fully integrated
5. Circular economy urban design	Low carbon materials for buildings and infrastructure possible; all forms of waste can be recycled once collected			Low carbon materials for buildings and infrastructure possible; not all forms of waste can be recycled unless done locally	
6. Biophilic and Permaculture Design	Biophilic buildings with green walls and roofs and small pocket parks	Emphasis on biophilic buildings, small pocket parks and green corridors	Emphasis on larger landscape-oriented development	Landscapes for carbon offsets, permaculture design the most appropriate for villages	Landscapes for carbon offsets, permaculture design the most appropriate for villages.
7.Integrated design processes	Essential for achieving net-zero				

The urban fabrics in Table 2 are summarized below to show how urban design practice can enable net-zero outcomes.

1. Central city walking cities are less able to install solar PV (with some increasing possibilities of building integrated solar) but are ideal for walkable active transport and e-micromobility (Matan and Newman, 2016), as well as biophilic urbanism in the form of green roofs and green walls (Beatley, 2017; Soderlund, 2019).

2. Transit city corridors are better for solar PV and batteries and are ideal for transit, micro- mobility, and active transport, with some potential circular economy and biophilia with permaculture possibilities (perhaps in community spaces) – see below on Net Zero Corridors.

3. The middle and outer suburbs of the automobile era are very good for solar PV, as demonstrated in Australian cities where most of the poorer outer suburbs installed PV first (Newton and Newman, 2013); they are also good for circular economy processing and permaculture, which need more space, but these areas are likely to require EV cars and buses due to their car dependence along with some new transit activated corridors helping overcome automobile dependence (Newton et al, 2021).

4. Rural villages and peri-urban areas will need to form new localized centers in order to make the most of the benefits of power and transport with integrated solar-PV-batteries-electromobility and with

some agricultural vehicles electrified. Peri-urban areas are likely to be able to have some rail access but are more likely to need EV car-share or cooperative bus services to link them to it and hence to the city. Local transport can use such vehicles and also electric bikes. Peri-urban areas will grow in their usefulness to the rest of the city for the following types of functions (Holmgren, 2018):

- Local food production based on intensive permaculture that has short food miles and local types of food;
- Waste-recycling centers and other new circular economy industries that cannot fit into the more built-up part of the city, for example, the recycling of treated wastewater to recharge groundwater systems;
- Utility-scale solar and windfarms and in future hydrogen-based industry; and
- Carbon sequestration in soils and trees for offsetting the city's excess greenhouse emissions.

Guidelines for how to enable these urban fabrics need to begin with their transport, power, water and waste systems but will all have different economic and social systems that need to be facilitated through community-based participation in the transition to a net zero city. Integrated design processes can proceed when this kind of engagement is enabled as most urban fabrics have their common-sense place-based solutions which are understood by those who live or work in that place (Caldera et al., 2021).

Manuals for net zero design are emerging as the basis of 21st century professional practice in all aspects of urban development and must include urban design as a fundamental factor.

Practice in urban design needs some guidance on how to begin in a city wanting to transition towards net zero and one approach is outlined next.

5. Net Zero Precincts and Corridors

This section sets out a concept for how to begin the net zero transition precinct by precinct. The reality of urban revitalization is that backyard infill is failing and needs to be turned into a precinct-by-precinct process as set out in Greening the Greyfields (Newton et al., 2021). Precinct scale is the best way to utilise the new small scale distributed technologies outlined above. They can be applied differently in each of the different precincts and there are effective examples emerging of how to do this like WGV in in middle suburbs of Fremantle as set out by Byrne and in peri-urban sites like The Paddock.

Net zero precinct example 2, White Gum Valley, Perth WA, Australia (infill urban)

WGV is a multi-typology, medium density residential in-fill development in White Gum Valley. The project was developed using many of the technologies outlined above to demonstrate how it could meet zero-carbon and other United Nations Sustainable Development Goals (SDGs) (Wiktorowicz *et al*., 2018) using One Planet Living accreditation.

The project has 100 units of housing on an old school site and has been redeveloped in close consultation with the local community at medium-density levels of approximately 45 dwellings per hectare. Development of WGV has been facilitated by having only one owner (the land-development agency DevelopmentWA).

WGV features a range of building types, including two-, three-, and four-storey apartment clusters and attached and detached homes. They all rely on leading energy strategies including: Climate-based design, a minimum seven-star energy rating, solar power of 3.5 kW or more, strata-owned solar panels and batteries on apartments using peer-to-peer energy sharing, shared electric vehicle for use by the community, and other features to minimise impact and maximise comfort.

An innovation was to test the viability of solar battery storage on strata buildings, the project demonstrated the potential for a blockchain-based sharing system, and potential for a new 'citizen utility' governance model, gaining attention from around the world (Green & Newman, 2017; Green *et al.*, 2020; Eon *et al*., 2019).

The significance of innovation at WGV is that it demonstrated that a net-zero carbon urban revitalisation project can:

- Be commercially viable
- Contribute to the Paris Agreement target that seeks to achieve deep decarbonisation while also delivering the United Nations SDGs
- Build an integrated development using new green distributed technology and support a first international demonstration of how to share solar energy through blockchain, and
- Ensure community trust and support by meeting other sustainability goals via the One Planet Living international accreditation process.

Precincts could be built along a corridor that is enabled by electric mid-tier transit and thus start the transition beyond a single demonstration site into a cross-city project. This would mean building a series of precincts around stations along main roads where urban regeneration is needed (Newton et al., 2021) and the resulting developments can spread to surrounding suburbs with their shared systems. These net zero Transit Oriented Developments (TOD's) along a main road would require a planning strategy that could be enabled by the provision of a new electric mid-tier transit system (BRT, LRT or Trackless Trams). The result has been called a Transit Activated Corridor (TAC) (Newman *et al*., 2019) and these can spread across a whole city as the integrated net zero systems spread into each form of urban fabric. The result is a multi-nodal city joined together by corridors of electric transport all feeding off the solar systems built into the urban fabric.

The key principle is set out in Figure 1 with a major transport corridor having a mid-tier transit line given priority and at each station a net zero precinct is built with urban regeneration that prioritises feeders and distributors such as e-micro-mobility as well as walking.

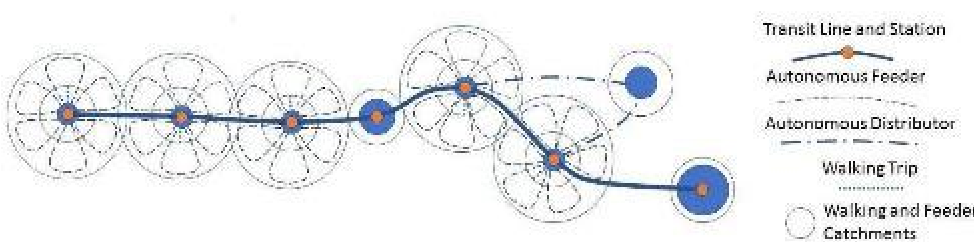


Figure 71: Transit Activated Corridor (Source: Glazebrook and Newman, 2018)

A core part of designing TACs would be a set of detailed design options for how a transit service could travel at speed down a clearway where possible, and then slow down when it enters a station precinct where the design and place focus would be to facilitate walkability and pedestrian activity. This would send the signal that dense urban development would be favoured as it would have a high-quality transit system linking it to the rest of the city and would have a highly attractive urban design quality for enabling people-based activities in and around the stations. This could be called a '70:20 strategy' as the aim would be to bring the road-based transit down the corridor at speed (70 kph max) and then slow down to prioritise walking (20 kph max).

This is a very different approach than on railways and on traditional main roads which mostly separate out urban development from the mobility goals along the different modal routes. Thus, roads chosen for this category would shift their priority for providing mobility services for 'through traffic', to a focus on how they could enable quality transit and urban design along the corridor. This delivers value to both developers and the community requiring mobility along the corridor. It would mean more of a focus on accessibility, sustainability and equity. Compared with car only lanes such routes could carry the equivalent of 6 lanes of traffic easing congestion issues while increasing activity along the corridor through transit and urbanism.

This urban design works in parallel with a global and local initiative called 'Movement and Place' that came out of Transport for London as a way of re-thinking main roads. This has involved the development of various movement and place policies and strategies (see for example: Guidelines for Sustainable Urban Mobility Plans, in Eltis, 2019), which seek to shift the focus to people, accessibility and place over simple mobility based on increasing the speed and capacity of main roads. The need to improve the balance between mobility and place has therefore become the next significant agenda in transport and urban policy especially in net zero corridors as the design tools associated with this approach can enable a transition to net zero cities (Newman et al, 2018).

There are four steps involved:

The first urban design tool is to declare a high-quality transit system down a corridor and zone it in strategic and statutory plans as primarily for transit and dense urbanism. A series of such plans are being developed around the world since Transport for London declared their policy called 'Street Families' (Transport for London, 2021) which sets out the streets that give priority to transit and where density will be given special encouragement. The movement and place framework enables the 'place' prioritisation of streets to create walkable, liveable centres. Such routes could be specified as potential Transit Activated Corridors with associated zoning along the corridor.

A second step in designing a TAC would be to choose the station precincts where an area could become a 21st century net zero development. The precinct area could be 'greenlined' as suggested by Newton et al (2021) so that a process could begin with the owners of buildings in the area. This process should involve full community engagement to enable partnerships to be formed with the residents, businesses, developers as well as design professionals. A design charette can be a major exercise in resolving all the relevant agendas. This can ensure that multiple benefits are found as value increases in the land will be assured and higher quality development can be achieved (Sharma and Newman, 2020).

A third step is an agency or cross-agency group that can provide the integrated design skills to deliver the TAC and its net zero precincts. This would include affordable housing and how new net zero technology can be designed into all the buildings and local transport. Key technologies to be integrated include a microgrid based on roof-top solar that enables both sharing of the net zero power and recharge services for all the electric vehicles, micro mobility, shuttle buses, cars and the mid-tier transit. This integration step will be different for different urban fabrics.

The fourth step in achieving the transition would be to enable the microgrid to spread so that the improved net zero systems can be shared further into surrounding suburbs. This would enable solar and battery storage to be shared as well as electric vehicle recharging services to be shared. The governance of the precinct for such shared services can therefore spread across the city, like tentacles, enabling the net zero transition.

Fundamental design tools developed for TOD's can be used to make station precincts dense and mixed use in order to make them into 'inclusive, safe, resilient and sustainable' places. Such tools include walkable urban design, solar design, water sensitive design, biophilic design, affordable housing design and integrated design as set out in Table 2. This will need statutory requirements to include such best practice outcomes but will need an overlay of net zero technologies and how they can be shared.

6. Conclusions

Net zero design is emerging but still needs demonstration projects in all parts of the city with different solutions for each urban fabric. It should be built precinct by precinct to make the most of the new net zero technologies and local design opportunities. It can start with precincts built along net zero corridors that are enabled by new technology mid-tier transit using traditional approaches to TODs, adding the net zero components into station precincts with smart shared systems that enable new net zero precincts to begin to spread into the whole city.

References

Beatley, T. (2017) Handbook of Biophilic City Planning & Design, Washington, DC: Island Press.

Caldera, S., Desha, C., Reid, S., Newman, P. (2020) Applying a Place Making Sustainable Centres Framework to Transit Activated Corridors in Australian cities, Journal of Sustainable Development of Energy Water and Environment Systems DOI:10.13044/j.sdewes.d8.0360

Cumming, A. (2020) Fair Share. Sanctuary, Winter 2020:51, 28-33. Online: https://static1.squarespace.com/static/587eb908be6594efd8877724/t/5edf153a63b8cc74f6ed4fdd/1591678283315/S51_Fair+share.pdf (accessed 24/07/2022)

Eltis (2019) Guidelines for Sustainable for Urban Mobility Plans, European Commission's Directorate General for Mobility and Transport – edition 2, (accessed 31 July 2022) <https://www.eltis.org/sites/default/files/sump_guidelines_2019_interactive_document_1.pdf >

Eon, C., Breadsell, J., Morrison, G. and Byrne, J. (2019) Shifting home energy consumption through a holistic understanding of the home system of practice. In P. Newton, D. Prasad, A. Sproul, & S. White (Eds.), Decarbonising the built environment: Charting the transition (pp. 431–448). Palgrave Macmillan.

Glaeser, E. (2011) The Triumph of the City, How our Greatest Invention Makes us Richer, Smarter, Greener, Healthier and Happier; Penguin: London, UK.

Glazebrook, G. and Newman, P. (2018) The City of the Future, Urban Planning (ISSN: 2183–7635) Volume 3, Issue 2, Pages 1–20 DOI: 10.17645/up.v3i2.1247

Green, J. and Newman, P. (2017) Citizen utilities: The emerging power paradigm. Energy Policy, 105, 283–293. Doi: 10.17645/up.v3i2.1247 <http://www.sciencedirect.com/science/article/pii/S0301421517300800> (accessed 31 July 2022)

Green, J., Newman, P. and Forse, N. (2020) RENew Nexus: Enabling localised electricity markets through P2P and VPP trading. Power Ledger and Curtin University.

Hall, P. (1998) Cities in Civilization, Pantheon, London.

Holmgren, D. (2018) Retrosuburbia: The Downshifters Guide to a Resilient Future, Permaculture Principles, ABN 12 622 010 084.

ICLEI-Local Governments for Sustainability (2018) Multi level climate action: the path to 1.5 degrees. ICLEI, Bonn, Ger.

IPCC (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, et al (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

IPCC (2022b) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H. Portner et al (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Jacobs, J. (1961) The Death and Life of Great American Cities, Vintage: New York.

Kostof, S. (1991) The City Shaped: Urban Patterns and Meanings Through History. NewYork: Little,Brown and Co.

Matan, A. and Newman, P. (2016) People Cities: The Life and Legacy of Jan Gehl, Washington, DC: Island Press.

Moyse, D. (2020) Return in Light. Renew: 153, 26 Sep 2020. < https://renew.org.au/renew-magazine/efficient-homes/return-in-light/> (accessed 24/07/2022).

Newman, P. and Kenworthy, J.R. (2015) The End of Automobile Dependence: How cities are Moving Beyond Car-Based Planning, Island Press, Washington, DC.

Newman, P., Hargroves, K., Davies-Slate, S., Conley, D., Verschuer, M., Mouritz, M. and Yangka, D. (2019) The Trackless Tram: Is It the Transit and City Shaping Catalyst We Have Been Waiting for? Journal of Transportation Technologies, 9, 31-55. Doi: 10.4236/jtts.2019.91003.

Newman, P., Kosonen, L. and Kenworthy, J. (2016) Theory of urban fabrics: planning the walking, transit and automobile cities for reduced automobile dependence, Town Planning Reviews 87(4):429-458 doi:10.3828/tpr.2016.28

Newman, P., Mouritz, M., Davies-Slate, S., Jones, E., Hargroves, K., Sharma, R. and Adams D. (2018) TRACKLESS TRAMS: Delivering Integrated Transit, Land Development and Finance – a Guide and Manual: with Application to Trackless Trams. Sustainable Built Environment National Research Centre (SBEnrc), Australia.

Newman, P. (2020) COVID, Cities and Climate: Historical Precedents and Potential Transitions for the New Economy, Urban Sci. 4(3), 32; https://doi.org/10.3390/urbansci403

Newton, P. and Newman, P. (2013) The geography of solar photovoltaics (PV) and a new low carbon urban transition theory, Sustainability 5(6):2537–56

Newton, P., Newman, P., Glackin, S, and Thomson, G. (2021) Greening the Greyfields: New Models for Regenerating the Middle Suburbs of Low-Density Cities, Palgrave MacMillan, Melbourne. <https://library.oapen.org/bitstream/handle/20.500.12657/51917/978-981-16-6238-6.pdf?sequence=1> (accessed 24/07/2022).

Norman, B., Newman, P. and Steffen, W. (2021) Apocalypse Now: Australian bushfires and the future of urban settlements. NPJ Urban Sustain. 1:2

Seto, K., Churkina, G., Hsu, A,, Keller, M., Newman, P., Qin, B. and Ramaswami, A. (2021) From Low- to Net-Zero Carbon Cities: The Next Global Agenda. Annual Review of Environment and Resources, 46(1), pp.377-415

Sharma, R. and Newman, P. (2020) Land Value Capture Tools: Integrating Transit and Land Use through Finance to Enable Economic Value Creation, Modern Economy, 11, 938-964. https://doi.org/10.4236/me.2020.114070

Söderlund, J. (2019) The Emergence of Biophilic Design. Cham, Switz.: Springer Int. Publ.

Thomson, G.; Newman, P. (2018) Urban Fabrics and Urban Metabolism: From Sustainable to Regenerative Cities, Resources, Conservation and Recycling, 132: 218-229 http://dx.doi.org/10.1016/j.resconrec.2017.01.010.

Thomson, G., Newman, P., Hes, D., Bennett, J., Taylor, M. and Johnstone, R. (2022) Nature-Positive Design and Development: A Case Study on Regenerating Black Cockatoo Habitat in Urban Developments in Perth, Australia. Urban Sci. 6, 47. https://doi.org/10.3390/ urbansci6030047

Transport for London (2021) London's Street Family: Theory and Case Studies. Available online: <https://tfl.gov.uk/corporate/publications-and-reports/rtf-supporting-documents> (accessed 24/07/2022).

Wiktorowicz, J., Babaeff, T., Breadsell, J., Byrne, J., Eggleston, J., and Newman, P. (2018). WGV: An Australian urban precinct case study to demonstrate the 1.5 °C Agenda including multiple SDGs. Urban Planning, 3(2), 64–81. https://doi.org/10.17645/up.v3i2.1245

Zero Carbon Cities Action Planning Network (2020) Zero carbon cities. <https://urbact.eu/zero-carbon-cities> (accessed 24/07/2022).

Optimizing conditioning systems in the perimeter zones of office buildings

Hung Q. Do[1], Mark B. Luther[2], Jane Matthews[3] and Igor Martek[4]

[1, 2, 3, 4] *School of Architecture and Built Environment, Deakin University, Geelong, Australia*
{qhdo[1], mark.luther[2], jane.matthews[3], igor.martek[4]}@deakin.edu.au ,
ORCID-0000-0002-9677-7636 [2], *ORCID-0000-0003-3367-9278 [3], ORCID-0000-0001-6573-1291[4]*

Abstract: Despite recent advances in thermal comfort research and conditioning technology, providing thermal comfort in office buildings still faces several difficulties resulting in discomfort, reduced occupant efficiency, and increased energy use. This problem is most acute in perimeter zones, which are highly valued, because of the high level of visual comfort, but also are strongly influenced by the external environment. While many envelope solutions have been proposed, little consideration has been given to innovative energy-efficient conditioning systems for perimeter zones. This research seeks to determine the requirements for conditioning systems in perimeter zones.

A pragmatic review of the conditioning characteristics of perimeter zones and their existing conditioning systems in Australian office buildings is discussed. The excessive application of glazing alongside intense and constantly changing solar gains are the main contributing factors to the difficulties in providing thermal comfort in perimeter zones. An evaluation of three commonly used conditioning systems namely, Variable Air Volume (VAV), Under Floor Air Distribution (UFAD), and Chilled Beam (CB), is considered alongside the newly proposed capillary radiant systems. Criteria such as energy consumption, thermal comfort, control–response, and other operational aspects of the four systems, are investigated and evaluated revealing their strengths and limitations. Considering the comparison among various conditioning systems, several parameters are identified, being: 1) capability to achieve comfort, 2) energy efficiency, 3) fast response time, 4) ease of installation and aesthetics, and 5) effective cooling capacity. Empirical testing of the proposed responsive radiant conditioning system is indicated as the next research step, with preliminary testing outcomes also provided.

Keywords: thermal comfort; radiant conditioning system; energy efficiency; perimeter zones.

1. Introduction

In Australia, 39% of the energy used in a typical office building is accounted for by HVAC systems (Residovic 2017). When considering occupant comfort within office buildings, they are often divided into thermal zones by applying various strategies that differentiate interior zones from perimeter zones. The perimeter zones are the areas located near the envelope windows of an office building. The depth of the perimeter zone is 3-5m. Providing comfort for employees within these perimeter zones of office buildings can be particularly problematic.

The use of glazing façades in office buildings is driven by the desire to achieve better visual comfort, by providing natural light and external view. However, this can also create difficulties in maintaining thermal comfort, especially in the perimeter zones. The most significant aspect that contributes to the high level of thermal discomfort in perimeter zones is the heavy solar heat gain (Anderson and Luther 2012). The high level of heat transfer through low R-value windows and air infiltration also leads to poor thermal conditions (Zhang et al. 2020). As a result, while office buildings' occupants prefer perimeter zones for visual comfort, providing thermal comfort for the dynamic conditions of perimeter zones is highly complicated. The common method of perimeter zone conditioning is to intensify the conditioning load to balance the demand. Meanwhile, the systems currently used to tackle this issue face limitations in thermal and energy performance. Hence, an innovative and optimized conditioning system for perimeter zones is in high demand.

We are investigating the potential of such an optimized system and the first step is to analyze what the requirements are. Based on the strength and weaknesses of systems currently used for perimeter zones in office buildings, the specifications for the system are revealed in this paper.

2. Research methodology: literature review

This paper aims to provide a pragmatic review of the current solutions and technologies that can deliver improved thermal and energy performance within perimeter zones. The keywords such as *perimeter zones, near window areas, office buildings, HVAC, conditioning, radiant systems, thermal comfort, and energy efficiency* were used for document searching. Over 300 publications related to the topic of conditioning perimeter zones in modern office buildings were retrieved (using Google scholar and Scopus). Among them, around 50 papers investigate the conditioning solution for perimeter zones and energy efficiency in office buildings, nearly 130 papers and a Ph.D. thesis are about radiant conditioning systems, and 11 standards and guidebooks. While previous studies date back to the 1960s, 25 publications from the last 25 years were selected as this paper focuses on the currently used systems. 13 papers investigate the conditioning systems for perimeter zones and the rest 12 are about radiant conditioning systems. Publications focusing on Australian case studies are prioritized. Analysis of the documented shortcomings of existing solutions can provide valuable insights into the requirements of new potential solutions, and lay the foundation for prototype development and further instrumental experiments.

The conditioning systems used in Australian office buildings can be categorized into two main types, namely convective systems (HVAC) and radiant systems. Existing research has been reviewed to analyze the performance of these conditioning systems, particularly in perimeter zone conditions. The strengths and shortcomings of each system have been analyzed to determine the requirements for a new solution suited to the dynamic perimeter zone conditions. From the literature review, five basic aspects of performance evaluation could be determined:

- Energy performance,
- Thermal performance,
- Control and response time
- Meeting conditioning requirements
- Ease of installation and noise

To understand the reasons behind the strengths and shortcomings of the existing systems, this research also examines their operation principles and mechanisms. The systems are visualized and briefly explained.

3. HVAC systems in Australian office buildings

Heating Ventilation and Air Conditioning (HVAC) systems are the most popular system providing thermal comfort in modern office buildings. Providing fresh air and thermal comfort are the main functions of HVAC systems. There are two main types of HVAC systems namely all-air and water-and-air based on the heat transfer medium (Cho et al. 2018). HVAC systems can also be categorized by their mechanisms such as Constant Air Volume (CAV) or Displacement Ventilation (DV). In Australia, there are three main types of HVAC systems commonly used in office buildings namely: Variable Air Volume (VAV); Under Floor Air Distribution (UFAD); and Chilled Beams (CB). The main advantage of HVAC systems is the fast responding rate (only 10-30 minutes) (Blum 2013).

3.1. Perimeter conditioning with VAV

Most modern office buildings use the Variable Air Volume (VAV) system (Kim et al. 2019). This is an induced convective air conditioning system that replaces the older Constant Air Volume (CAV) system. In a VAV system, conditioned fresh air is supplied from the ceiling (figure 6a). VAV boxes are located at the terminal point of the ducted supply air. The VAV box primarily consists of controlled dampers which regulate the air supply (L/sec), and potentially also a reheat coil, which varies the supply air temperature. The reheating coil addresses the problems of providing fresh air with nearly closed dampers (supply air is too cold) but results in more energy use. The principle is that while the temperature of the supply air is kept constant (13°C), the conditioning load is controlled by varying the volume of supply air. This allows different zones or rooms to be conditioned using a single system.

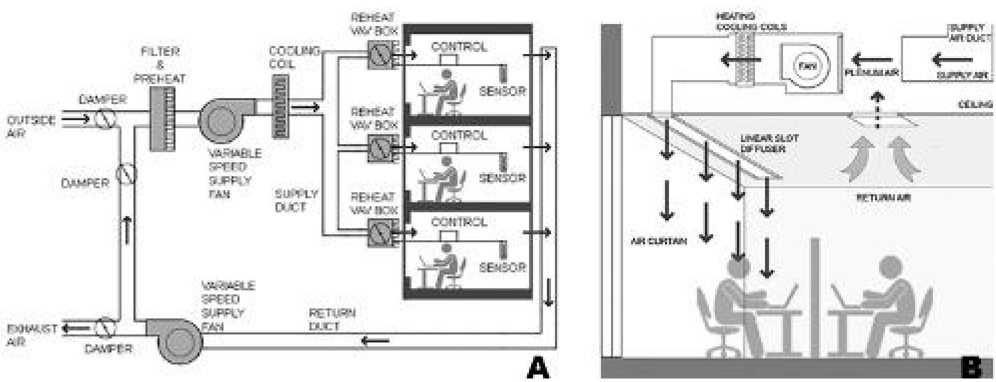


Figure 72: (a) VAV system diagram; (b) Fan Coil Units (FCU)

Conventional air conditioners in perimeter zones need extra conditioning capacity to counter the heavy effect of the external environment. Hence, HVAC systems usually work in combination with perimeter systems such as Fan Coil Units (FCU) (Figure 6B), fan-powered box terminal units (FPTU) (Figure 7), convector radiators (Figure 8), and even packaged air conditioning (PAC)(Cho et al. 2018).

3.1.1. VAV with Fan coil units (FCU)

Fan coil units (FCU) are water-to-air convective systems used to boost conditioning load in specific rooms or areas. FCU blow fresh and conditioned air provided by the central HVAC through hydronic cooling/heating coils, giving the air extra conditioning load (Figure 6B). At perimeter zones, slot line diffusers near the window can be used in combination with FCU (Sheng et al. 2022) (Figure 6B). The long slot line diffusers are used to blow a high volume of conditioned air at the windows to condition them and create an air curtain (Sheng et al. 2022). While the operation cost can be fairly low, the high electricity usage for fans remains a problem for this combination (Cho et al. 2018).

3.1.2. VAV with Fan powered box terminal units (FPTU)

The Fan powered box terminal units (FPTU) are used to efficiently mix the primary air (supply air) from the central HVAC and the recirculation air (plenum air) and control the supply air temperature and volume. There are two types of FPTU namely parallel (Figure 7A) and series (Figure 7B). To supply fresh air, the fan of series FPTU has to be running while this is not the case for parallel FPTU (Edmondson et al. 2011). In both cases, there are coils at the discharge, giving temperature control. A damper allows control of the volume of primary air and is the key feature leading to better energy performance than other combinations (Na, Nam, and Yang 2010). Also, FPTU can be used with a long diffuser to create an air curtain similar to the case of the aforementioned FCU.

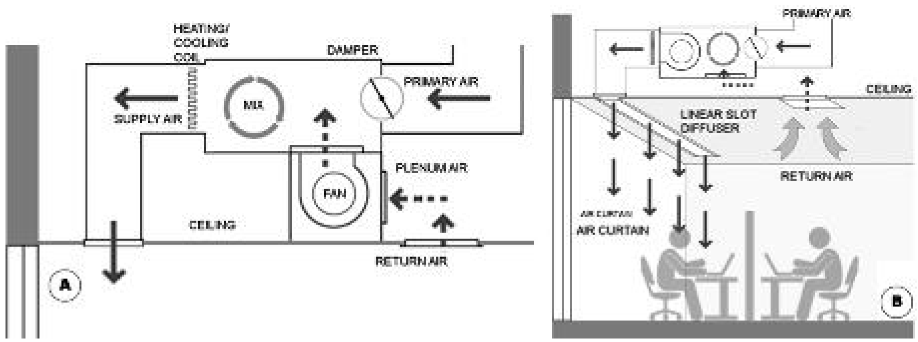


Figure 7: (A) parallel FPTU; (B) Series FPTU

3.1.3. VAV with convective radiator

The convective radiators (heaters) provide additional heating load at perimeter zones(Sheng et al. 2022). Placed right next to the window sill, the radiator will heat the glazing and prevent cold draughts by generating an upward hot air curtain (Sheng et al. 2022) (Figure 8). Overall, this combination uses the same amount of energy as the VAV and FCU combination but may have higher operating costs (Na, Nam, and Yang 2010). This system also has limited radiation effects (Kang and Strand 2010).

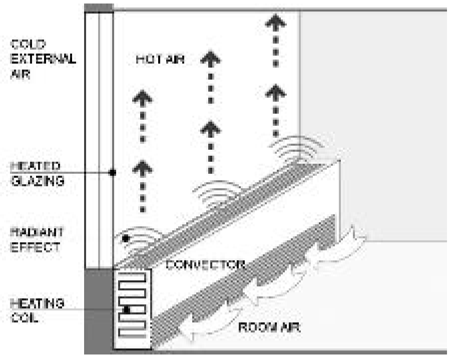


Figure 8: Perimeter convective radiator

3.1.4. VAV with Packaged air conditioning systems (PAC)

Another option is to use packaged air conditioning systems (PAC) with the VAV (Wang et al. 2013). In this system, a "package" is composed of all the main components of an air conditioner. PAC systems' capacity range from 14kw (3 tons) to 53kw (15 tons) and can be chosen to fit the need of specific rooms or areas. However, PAC systems are not energy-efficient due to the heavy fan energy use requiring an advanced control system (Wang et al. 2013). Also, high draught risk is a notable problem of PAC, like other air conditioning systems.

3.2. Under Floor Air Distribution (UFAD)

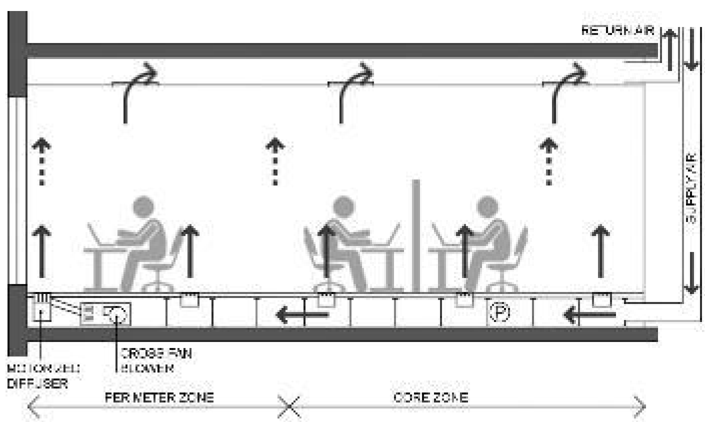


Figure 9: Under Floor Air Distribution

In the Under Floor Air Distribution (UFAD) system (figure 9), conditioned air is introduced to the space from plenums at floor level. At the perimeter zone, floor-mounted blowers blow air vertically along the glazing windows or façade creating a thermal stratification (Lim, Yim, and Kim 2022). In perimeter zones, UFAD is combined with fan-powered terminal units (FPTU) with long slot diffusers at the windows to create an air curtain (Lim, Yim, and Kim 2022).

3.3. Chilled Beam (CB)

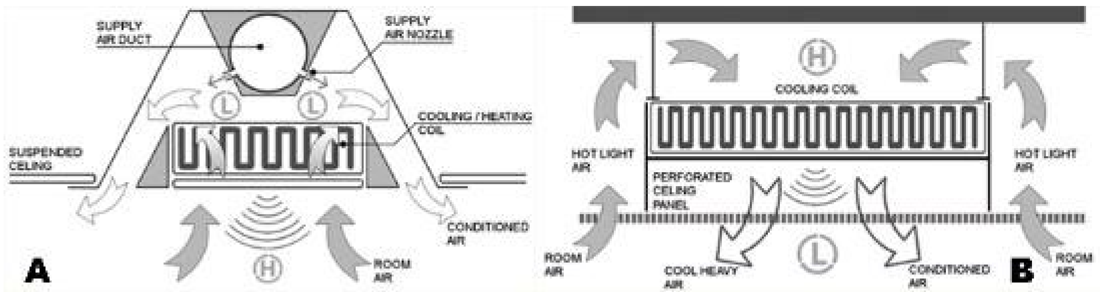


Figure 10: (A) Active chilled beam; (B) Passive chilled beam

A Chilled Beam (CB) system is a water and air conditioning system. A CB system has to work with a separate fresh air supplier. CB systems are mainly convective but may provide additional radiant effects if the cooling/heating coils are not covered. There are two types of CB namely active and passive. In an active CB system (Figure 10A), the main supply air duct actively directs supply air to create a convective vacuum effect leading the room air through the coil. This mechanism allows active CB to have the high conditioning capacity needed for perimeter zones (Kim et al. 2019). In contrast, passive CB systems can be considered cooling convective radiators (Figure 10B). The cooling coils can promote convection and provide a limited radiant effect.

A downside of the chilled beam system is the slow response time (Yang et al. 2019). According to Devlin (2011), chilled beam system response time may be as long as an hour. This makes the chilled beam system unsuitable for the dynamic conditions of perimeter zones (Rhee, Choi, and Tsouvalas 2021) without additional complex control systems to operate them in such conditions (Yang et al. 2019).

4. Radiant systems at perimeter zones

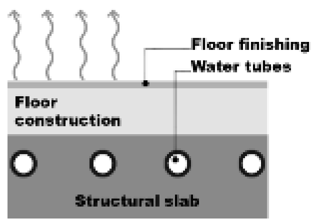
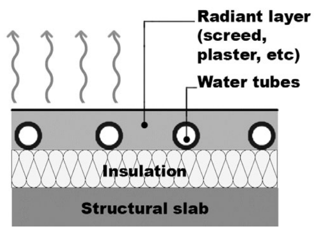
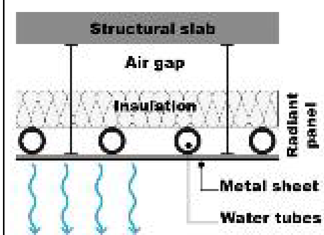
4.1. Radiant system overview

A modern hydronic radiant system is a conditioning system capable of providing thermal comfort similar to the HVAC. However, unlike convective HVAC, a radiant system's primary heat transfer mechanism is radiant (Rhee and Kim 2015). Integrated into interior surfaces such as walls, ceilings, or floors, radiant systems these surfaces into heat sinks or sources. Using the radiant heat transfer mechanism, radiant systems can create a more uniform thermal environment and significantly reduce draught (Rhee and Kim 2015). Radiant systems don't require fans leading to a reduction in energy use and quieter operation (Rhee, Olesen, and Kim 2017). Also, in an office working condition, the human body senses mean radiant temperature (MRT) controlled by radiant systems much more than air temperature (dry bulb temperature) which is controlled by HVAC (Moe 2010). This makes radiant systems more thermally rational than HVAC. New radiant system types with better flexibility that simplifies installation and improved energy performance have been introduced (Ding et al. 2020)

4.2. Types of hydronic radiant systems

Radiant conditioning systems are categorized into three types (Babiak, Olesen, and Petras 2007). Details on the three types of radiant conditioning systems are shown in Table 1.

Table 1: Three different radiant hydronic systems.

System Types	Thermal active building system (TABS)	Embedded surface system (ESS)	Radiant panel (RP)
System Diagram			
Classification	Heavyweight radiant system	Lightweight radiant system	Lightweight radiant system

The first radiant system is the thermal active building system (TABS). In TABS, there is no specific insulation layer, and the hydronic tubing is located deep inside the structural slab. This means the sentinel load is stored and released by the heavy thermal mass of the slab. Hence the thermal mass has significant impacts on the performance of this heavy system such as slow reaction time, potential overheating, and low energy efficiency (Rhee and Kim 2015). The system surface needs about 4 hours to be heated up from 20°C to 29°C (Merabtine et al. 2018). Hence, this heavy system requires an advanced control system involving water flow rate and inlet water temperature (Rhee and Kim 2015).

In contrast, the embedded surface system (ESS) is a lightweight radiant system. In the ESS, the hydronic tubes are isolated from the main structure mass and closer to the room surface. This means the ESS has less thermal mass and lower thermal inertia (Feng 2014). This allows ESS to have better thermal and energy performance with faster reaction time and less energy waste. However, ESS response time is 1-2 hours and the system capacity is limited (Babiak, Olesen, and Petras 2007)

Finally, the radiant panel (RP) is the lightest radiant system. The radiant hydronic tubes are isolated from any considerable thermal mass. This allows the newly developed RP systems to be highly responsive (Miriel, Serres, and Trombe 2002). In our experiments, the RP system can respond to a control command in 5-15 minutes. The RP is commonly used in form of a radiant ceiling and the insulation layer on top can also consider acoustic absorption (Miriel, Serres, and Trombe 2002).

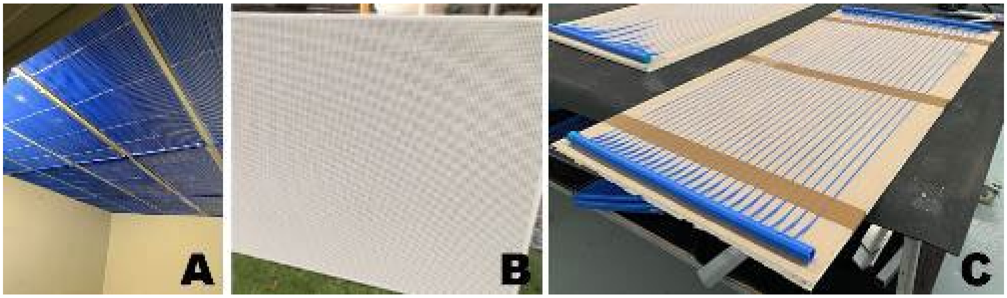


Figure 11: (a) capillary tube mat radiant panel ceiling; (b) perforated metal sheets; (c) capillary tube mat embedded in plasterboard ceiling tiles.

We are integrating lightweight radiant panels into a suspended ceiling system. This idea revolves around turning a suspended ceiling into a thermal active surface. The prototype being built consisted of capillary tube mat radiant panels, rigid foil rigid insulation panels, and plasterboard ceiling tiles or perforated metal sheets (Figure11). Due to low thermal mass, these radiant panels can be highly responsive, and ideal for conditioning dynamic environments such as perimeter zones. The capillary tube mat resembles human blood vanes and can provide improved thermal and energy performance for radiant systems (Zhao et al. 2017).

4.3. Radiant systems at perimeter zones: Heavy vs light.

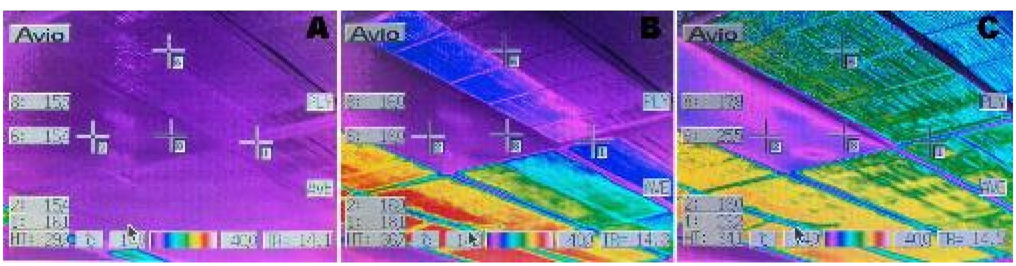


Figure 173: Radiant ceiling respond to command; (a) start; (b) 3 minutes; (c) 5 minutes and after.

The commonly used radiant systems are still heavy and difficult to control TABS systems. As these types of radiant systems are challenging to control and not reactive, control strategy plays a more critical role in ensuring performance (Athienitis 1997). The radiant systems with low thermal mass are more energy-efficient (Babiak, Olesen, and Petras 2007), more responsive, and easier to control; hence do not need a complex control strategy to properly function (Feng 2014). This is a significant advantage of radiant panels over other high thermal mass systems, especially when applied to perimeter zones.

We are developing an instrumental experiment with 11 m² of our newly developed lightweight radiant ceiling (figure 11a). In a demo test run with the pumping speed of 21L per minute and monitored by a thermal camera and thermostat sensors, it only takes 5 minutes for the ceiling surface temperature to reach and be stable at an average of 30°C from the starting point of 15 °C (figure 12).

5. Findings: Pros and cons of existing conditioning solutions

Table 2: Available conditioning systems pros and cons at perimeter zones.

	Thermal performance	Energy performance	Control and response	Meeting load requirement	Other pros and cons
VAV + FCU	• Convection based • Vertical temperature gradients, local discomfort, and high draught risk	• Intensive energy used for fan	• Thermostat control • Fast response in 10-30 minutes	• Can be sized to low, medium, and high capacity	• Can be noisy
VAV + FPTU	• Convection based • Vertical temperature gradients, local discomfort, and high draught risk	• Intensive energy used for fan	• Thermostat control • Fast response in 10-30 minutes	• Can be sized to low, medium, and high capacity	• Can be noisy
VAV + radiat or	• Convection + radiant-based (Heating) • Vertical temperature gradients and local discomfort	• Intensive energy use for radiator	• Thermostat control • Fast response in 10-30 minutes	• Can be sized to low, medium, and high capacity	• Can be noisy
PAC	• Convection based • Vertical temperature gradients and local discomfort	• Intensive energy used	• Thermostat control • Fast response in 10-30 minutes	• Can be sized to low, medium, and high capacity	• Can be noisy
UFAD	• Convection based • Vertical temperature gradients and local discomfort	• Intensive energy used for fan	• Thermostat control • Fast response in 10-30 minutes	• Can be sized to low, medium, and high capacity	• Can be noisy
Active Chilled Beams	• Convection + radiant based • Vertical temperature gradients and local discomfort	• Use less energy	• Thermostat control • Slow response in 1 hour.	• Can be sized to low, medium, and high capacity	• Quieter
Passiv e Chilled Beams	• Convection + radiant-based (Cooling) • Vertical temperature gradients and local discomfort	• Use less energy	• Thermostat control • Slow response in 1 hour.	• Low to medium capacity	• Quieter
TABS	• Radiant + convection based • Low air velocity • Uniform thermal comfort	• Use less energy	• Highly complex control strategy • Respond in 4 hours	• Low to medium capacity	• Quieter • Difficult to install.
ESS	• Radiant + convection based • Low air velocity • Uniform thermal comfort	• Use less energy	• Simple control • Respond in 1 -2 hour	• Low to medium capacity	• Quieter • Difficult to install.
RP	• Radiant + convection based • Low air velocity • Uniform thermal comfort	• Use less energy	• Simple control • Fast response in 5-15 minutes	• Low to medium capacity	• Quieter • Lightweight • Flexible

Based on the above review, commonly used conditioning solutions for perimeter zones can be summarized in Table 2. Overall, radiant systems present several advantages over convective ones:

- Creating uniform thermal environments by reducing temperature gradients and local discomfort.

- Lower air velocity leads to a reduction in the discomfort caused by cold draughts.
- A decrease in the energy load for Fan.
- Incorporating MRT, which the human body senses the most.
- Quieter operation.

However, the heavy radiant system is not responsive and required a complex control strategy. Moreover, heavy radiant systems are difficult to install and maintain. Also, condensation is the main reason for limiting the capability and reducing the application of radiant cooling (Zhang and Niu 2003). This would set the requirements for the proposed conditioning solution for the perimeter zones.

6. Conclusion: optimized conditioning solution in perimeter zones.

Based on the above comparison, an optimized solution should deliver on five performance parameters, as follows:

- The capability of providing an appropriate level of thermal comfort.
- More energy-efficient than typical HVAC systems.
- Fast response time.
- Lightweight, modular, easy to install, and architecturally appealing.
- Increase cooling capacity while remaining condensation-free.

In order to produce a solution delivering the above-mentioned criteria, comprehensive empirical research on prototypes is required. The aforementioned system that we are currently developing shows promise in being able to deliver on these criteria. Currently, instrumental experiments testing the capability of the system are being conducted.

Our system will be monitored with a variety of instruments. The comfort cart will provide data on the air temperature, globe temperature, humidity, and air velocity so that the level of comfort can be calculated. The water flow meter, heat flux sensors, thermostat sensors, and a thermal camera will monitor the system's operation, especially on the energy exchanges and responding time. An energy meter will be used to collect data on the system's energy use. The result will be reported in the upcoming publications.

One important aspect of radiant conditioning is the control mechanism. Currently, conditioning systems are convection based hence it is reasonable for them to be controlled via thermostat sensors. However, this control technic is irrational for radiant systems which utilize MRT and the principle of low air-temperature heating and high air-temperature cooling. Consequently, we have begun to investigate the development of an innovative comfort-based control system and we expect to successfully manufacture such a system. The results of our efforts will be reported in a subsequent publication.

References

Anderson, Timothy, and Mark Luther. 2012. 'Designing for thermal comfort near a glazed exterior wall', *Architectural Science Review*, 55: 186-95.

Athienitis, Andreas K. 1997. 'Investigation of thermal performance of a passive solar building with floor radiant heating', *Solar Energy*, 61: 337-45.

Babiak, Jan, Bjarne W Olesen, and Dusan Petras. 2007. 'Low temperature heating and high temperature cooling: REHVA GUIDEBOOK No 7'.

Blum, David Henry. 2013. 'Analysis and characterization of ancillary service demand response strategies for variable air volume HVAC systems', Massachusetts Institute of Technology.

Cho, Jinkyun, Yundeok Kim, Junemo Koo, and Woopyeng Park. 2018. 'Energy-cost analysis of HVAC system for office buildings: Development of a multiple prediction methodology for HVAC system cost estimation', *Energy and buildings*, 173: 562-76.

Devlin, Nick. 2011. 'Validation of an active chilled beam design for a healthcare facility', *People*, 190: 133.

Ding, Pei, Yanru Li, Enshen Long, Yin Zhang, and Qinjian Liu. 2020. 'Study on heating capacity and heat loss of capillary radiant floor heating systems', *Applied Thermal Engineering*, 165: 114618.

Edmondson, J, Dennis L O'Neal, John A Bryant, and Michael A Davis. 2011. 'Performance of parallel fan-powered terminal units with electronically commutated motors', *ASHRAE Transactions*, 117: 885-93.

Feng, Jingjuan Dove. 2014. 'Design and control of hydronic radiant cooling systems', University of California.

Kang, Daeho, and Richard K Strand. 2010. 'A New Model for Calculating the Convective and Radiant Impact of Radiators and Baseboards in EnergyPlus', *Proceedings of SimBuild*, 4: 185-92.

Kim, Chul-Ho, Seung-Eon Lee, Kwang-Ho Lee, and Kang-Soo Kim. 2019. 'Detailed comparison of the operational characteristics of energy-conserving HVAC systems during the cooling season', *Energies*, 12: 4160.

Lim, Taesub, Woong-Seog Yim, and Daeung-Danny Kim. 2022. 'Analysis of the Thermal and Cooling Energy Performance of the Perimeter Zones in an Office Building', *Buildings*, 12: 141.

Merabtine, Abdelatif, Salim Mokraoui, Abdelhamid Kheiri, Anass Dars, and Abed Al-waheed Hawila. 2018. 'Experimental and multidimensional numerical analysis of the thermal behavior of an anhydrite radiant slab floor heating system: A multi-objective sensitivity study', *Energy and buildings*, 174: 619-34.

Miriel, Jacques, Laurent Serres, and Alain Trombe. 2002. 'Radiant ceiling panel heating–cooling systems: experimental and simulated study of the performances, thermal comfort and energy consumptions', *Applied Thermal Engineering*, 22: 1861-73.

Moe, Kiel. 2010. *Thermally Active Surfaces in Architecture* (Princeton Architectural Press).

Na, Yeon-Jeong, Eun-Ji Nam, and In-Ho Yang. 2010. 'Life Cycle Cost Analysis of Air Conditioning Systems in a Perimeter Zone for a Variable Air Volume System in Office Buildings', *Journal of Asian Architecture and Building Engineering*, 9: 243-50.

Residovic, Caroline. 2017. 'The new NABERS indoor environment tool–the next frontier for Australian buildings', *Procedia Engineering*, 180: 303-10.

Rhee, Kyu-Nam, Sun-Ho Choi, and Agisilaos Tsouvalas. 2021. 'Experimental investigation on the control performance of an active chilled beam system under dynamic cooling loads', *Applied Thermal Engineering*, 194: 117069.

Rhee, Kyu-Nam, and Kwang Woo Kim. 2015. 'A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment', *Building and Environment*, 91: 166-90.

Rhee, Kyu-Nam, Bjarne W Olesen, and Kwang Woo Kim. 2017. 'Ten questions about radiant heating and cooling systems', *Building and Environment*, 112: 367-81.

Sheng, Shaoyu, Toshio Yamanaka, Tomohiro Kobayashi, Jihui Yuan, and Masahiro Katoh. 2022. 'Modeling of supply airflow from slot line diffuser on ceiling for CFD of thermal environment in perimeter zone', *Building and Environment*: 108884.

Wang, Weimin, Srinivas Katipamula, Yunzhi Huang, and Michael R Brambley. 2013. 'Energy savings and economics of advanced control strategies for packaged air conditioners with gas heat', *Energy and buildings*, 65: 497-507.

Yang, Shiyu, Man Pun Wan, Bing Feng Ng, Swapnil Dubey, Gregor P Henze, Suleman Khalid Rai, and Krishnamoorthy Baskaran. 2019. 'Experimental study of a model predictive control system for active chilled beam (ACB) air-conditioning system', *Energy and buildings*, 203: 109451.

Zhang, LZ, and JL Niu. 2003. 'Indoor humidity behaviors associated with decoupled cooling in hot and humid climates', *Building and Environment*, 38: 99-107.

Zhang, Sheng, Yong Cheng, Majeed Olaide Oladokun, Yuxin Wu, and Zhang Lin. 2020. 'Improving predicted mean vote with inversely determined metabolic rate', *Sustainable Cities and Society*, 53: 101870.

Zhao, Min, Weibin Kang, Xilian Luo, Chuck Wah Yu, XZ Meng, and Zhaolin Gu. 2017. 'Performance comparison of capillary mat radiant and floor radiant heating systems assisted by an air source heat pump in a residential building', *Indoor and Built Environment*, 26: 1292-304.

Parametric solar shading for sensitive internal environments: a workflow

Elzine Braasch[1]

[1]*Norman Disney Young, Wellington, New Zealand*
e.braasch@ndy.com

Abstract: Building performance simulation tools provide a unique opportunity to evaluate solar architectural principles during the most influential early stages of the design process. Solar shade devices are typically designed with the intent to reduce solar penetration where possible, improving thermal performance and visual comfort for occupants within the indoor environment. In the case of patient wards, where the presence of direct sunlight is seen to contribute to the recovery of the patient, careful consideration is required to optimise a building's façade such that appropriate natural light is provided but not at the expense of high cooling demand and energy consumption. This study examines the use of parametric modelling as a data-driven design approach to providing façade solutions that balance sunlight entry with optimal thermal and visual comfort for new hospital buildings. A parametric model workflow to design external shades in conjunction with patient ward layouts and overall design methodology is developed. The approach demonstrates the applicability of data-driven design for micro-environments which require specific attention to solar design where conflicting priorities exist.

Keywords: Parametric; Solar; Hospital; workflow.

1. Introduction

The fulfilment of human physiological and psychological needs; being strengthened by the stimulus of change, and weakened by monotony, they are all dependent on the greatest agent of change in our lives – the sun. The study of the sun and its influence has dated back to ancient times, notably to understand its importance within the built environment. New discoveries in the human body have sparked renewed interest in designing for human health and well-being within the built environment and introduced the need for further metrics for design evaluation to include solar admission once again.

Before the reintroduction of solar architecture, past designs had concentrated on means of controlling solar admission rather than developing means for achieving acceptable solar penetration (Ne'eman, et al., 1976). The use of external shading in combination with glazing façade penetrations are designed now to develop creative methods in which the sun can enter a space where needed and mitigated, where it is

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 462–471.*

unwanted. In the cases where an occupant is expected to remain in a space for a long period of time, such as within a patient ward of a hospital, the admission and control of the sun is imperative for the well-being of the individual(s).

1.1. Multi-objective evaluation and current metrics in literature

1.1.1. Daylight Quality

The design of solar shading devices must contend with the requirement for daylight penetration through the façade as they aim to mitigate solar penetration but promote daylight. Studies to date have examined the effects of daylight on patients (Kriszbacher, et al., 2010) and the health benefits (Choi, et al., 2012), and a growing interest is observed in understanding the effects of daylight on the circadian system of those confined to the internal built environment (Acosta, et al., 2017).

The evaluation of daylight quality has defined several metrics related to the measurement of daylight through the building façade. Chief among them is the spatial daylight metric, Spatial Daylight Autonomy (sDA) as a climate-based daylight modelling (CBDM) approach to annual evaluation. SDA is defined by Illuminating Engineering Society (IES, 2012) as a measure of daylight illuminance sufficiency for a given area, reported as a percentage of floor area that exceeds a specified illuminance threshold (e.g. 100-300 lux depending on the functional space) for a specified amount of annual hours (e.g. occupied period). However, the metric is quantitative in nature and does not account for over-exposure to light where discomfort glare could occur.

To account for a range of 'visual comfort', Useful Daylight Illuminance (UDI) provides a better indication of quality, whereby a minimum and maximum threshold of illuminance can be defined. The notion of a 'target illuminance' is argued to be replaced by the determination of the occurrence of a range of illuminance levels that can be said to be 'useful'. The most accepted range of UDI has been derived by Nabil & Mardalievic (2005) where their survey study found a generally accepted threshold of 100 – 2,000 lux, again dependant on the functional space.

1.1.2. Circadian Rhythm

The discovery of a third class of photoreceptors in the human retina which serve to synchronise human circadian rhythms to the 24-hour light/dark cycle, referred to as Intrinsically Photoreceptive Retinal Ganglion Cells (irRGCs), has prompted the study of non-visual effects of light on human health and well-being. There are several parameters known to control the circadian system's response to light that are directly impacted by building design. The development of metrics to enable the evaluation of building design on the circadian system rely mainly on the key considerations of intensity, timing, and duration (Anderson, et al., 2012; Mardaljevic, et al., 2013).

The intensity of light to affect the circadian system is understood 463hroughh the translation of light exposure to biologically meaningful units. The spectral efficiency function of the melanopsin-containing ipRGCs, referred to as the melanopic spectral efficiency function (C-Lambda), can be used to calculate the melanopic illuminance (reported in units of Equivalent Melanopic Lux (EML)) for various light source Spectral Power Distributions (SPD). EML is calculated by multiplying the illuminance (lux) from a given light source with its corresponding Melanopic Ratio, $R_{mel,\ ratio}$. The International WELL Building Institute (IWBI) provides a set of ratios for known light sources' efficacy (IWBI, 2020), with version 1 of WELL Building Standard's Circadian Light Design credit 54 providing assessment criteria for the EML metric for using a quantitative target of 200 EML. This target was originally derived from a past threshold of 250 EML, influenced by a prior study by Amundadottir *et al.* (2016) which found that this EML threshold is shown to predict nearly full saturation (98.5%) in melatonin suppression for a 65-year-old observer, which has since been adapted to better reflect developing research in the field. A new concept, Melanopic Equivalent Daylight (D65) Illuminance (m-EDI), has been recently adopted by the latest version of the WELL Building standard (version 2) (IWBI, 2022) and new thresholds of 150 EML for minimum points and 275 EML for maximum points are provided. The relationship between EML and m-EDI is given by a factor of 0.9058, thereby the prior threshold of 200 EML is equivalent to 181 m-EDI (lux).

An alternative measure of circadian potential from EML is the 'circadian stimulus' (CS) metric first published in 2005 by Rea *et al.* and has been revised over the years to the latest CS_{2018}. Circadian light, CL_A, is established for any SPD to calculate the circadian stimulus. CS is the efficacy of irradiation spectrally weighted to the cornea from the threshold (CS = 0.1) to saturation (CS = 0.7), and provides a minimum threshold of CS = 0.3 necessary for at least an hour in the first part of the day to stimulate the circadian system (Rea & Figueiro, 2018).

EML, m-EDI and CS as metrics are still evolving as research within the field expands with further study. Table 1 provides a summary of the standard recommendations for circadian lighting from the International WELL Building Institute which provide the equivalent EML or CS depending on methodology taken to assess circadian lighting.

Table 39: Standard recommendations for circadian lighting. Source (IWBI, 2022)

Melanopic Daylight Equivalent Illuminance MDEI (lux)	**Equivalent Melanopic Lux (EML)**	**Circadian Stimulus (CS)**
181	200	0.30
136	150	0.25
217	240	0.34
163	180	0.28
109	120	0.21

Andersen *et al.* (2012) in their review of the circadian rhythm clarify the importance of timing in that, "Inadequate or mistimed light exposure can disrupt normal circadian rhythms and have a negative effect on human performance, alertness, health or safety". This is important for the consideration of façade design for differing orientations, where light intensity from the sun, be it direct or through cloud, can impact the amount of light available within the space. Table 2 provides a summary of the four daily time periods proposed to qualitatively categorise time-varied light exposures according to their expected non-visual effect. However, there are no defined thresholds for the different times of the day.

Table 40: Subdivision of the day based on non-visual effect. Source: (Anderson, et al., 2012)

Daily time period	Non-visual effect	Design Translation	Description
0:00 – 6:00	Light exposure delays circadian clock	Avoid sunlight / large amounts of daylight	Circadian system is highly sensitive to light

6:00–10:00	Circadian resetting	Encourage high levels of light – morning sun	Sufficient daylight illuminance can serve to phase advance the clock in the majority of people
10:00–18:00	Light exposure advances circadian clock	Balance eliminating direct sunlight on subjects with high amounts of daylight	High levels of daylight illuminance may lead to increased levels of subjective alertness without exerting substantial phase shifting effects on the clock
18:00–0:00	Altering effects of daylight	Avoid sunlight / large amounts of daylight	Daylight exposure that might trigger the non-visual effect is to be avoided so as not to disrupt the natural wake-sleep cycle

In summarising current literature and procedures outlined, this paper simplifies the inclusion of circadian lighting to the multi-objective analysis suggested by Konis (2016) by evaluating the EML sufficiency at a specific location, using the suggested best-vector approach, reported as a percentage that exceeds a specified illuminance threshold at the vertical plane between the period of 6am – 10am (the resetting period). Given the hospital length of stay, the patient could remain within the ward for any given period of time, from one day to several months, in which case the stimulus frequency proposed by Konis (2016) to consider periods within weeks may not be appropriate. The criteria for 'sufficient' circadian effectiveness autonomy (CEA) are thus estimated by following the same logic from Acosta *et al.* (2017) whereby a minimum of 1 hour in the morning must achieve the circadian target every day.

1.1.3. Thermal comfort

During the early stages of design for a patient ward with a stationary patient, thermal considerations can be simplified to the consideration of direct radiation exposure, assuming the mechanical design will meet the air temperature requirements. Hodder & Parsons (2007) highlight the most sensitive factor to occupant thermal comfort is exposure to solar radiation, whereby solar radiation levels on the body were found to be the main determinant of thermal comfort.

The most applicable metric for direct solar exposure is Annual Sunlight Exposure (ASE) defined by IES (2012) as the percentage of the space that receives more than 1,000 lux for at least 250 occupied hours per year. A space is considered compliant if less than 10% of the assessed area meets the definition described. Further, direct solar exposure on the occupant should be eliminated for afternoon and late evening periods where the solar radiation is at its peak to reduce risk of overheating, which will then significantly increase the need for mechanical cooling, and thus energy consumption.

Solar exposure for sake of health benefits should therefore be limited to one or two hours in the morning, where the additional illuminance can benefit the circadian system, but provide areas within the ward space that experience little to no direct sunlight to give the patient an area to avoid glare. This can be translated to mean that no more than 50% of the targeted location for the patient should receive direct sunlight for too long: a suggested metric of ASE < 50% of the target location area, where ASE is defined by the number of hours a specified point receives direct sunlight for more than 100 hours throughout the year during the morning period of 6am-10am.

1.1.4. Evaluation criteria: A summary

The objectives outlined above are summarised in Table 3 and reflect literature recommendations based on time of day to provide a holistic analysis of all necessary metrics.

Table 41: Evaluation criteria

Daily time period	Circadian Effective Autonomy (e.g. 150-275 EML as 200 EML for a basis)	Spatial Useful Daylight Illuminance (100<x<2,000 lux, 50% UDI)	Spatial Daylight Autonomy (100 lux, 50% DA)	Annual Sunlight Exposure (target) (direct irradiance, 100 hr)	Annual Sunlight Exposure (of room) (direct irradiance, 250hr)
0:00 – 6:00		sUDI % < 0	sDA % < 0	ASE on occupant % = 0	ASE % = 0
6:00–10:00	CEA % > 25 (at least 1 hour of the 4 hours assessed per day)	sUDI > 80% for the assessed period. Balance eliminating direct sunlight on subjects with high amounts of daylight	sDA % > 55	ASE on occupant % < 25-50	ASE % < 10
10:00–18:00			sDA % > 75	ASE % = 0	ASE % < 10
18:00–0:00		sUDI % < 0	sDA % < 0	ASE % = 0	ASE % = 0

2. Methodology

The following sections describe the adoption of previous procedures (Konis, 2016; Mardaljevic, et al., 2014) taken to set up appropriate analysis grids to assess all relative metrics for a single-zoned room to mimic a patient ward (Mardaljevic, et al., 2013) and outlines how previous procedures are expanded to consider the integration of parametrically generated external shading based on the location and potential level of wanted exposure of the patient to direct irradiance from the sun.

2.1. Spatial considerations

The workflow generates the room geometry within the 3-D modelling software Rhinoceros (2022). This software provides the best means to undertake the exercise proposed by this study as it utilises the distributed modelling method to link several building performance simulation (BPS) tools together through the use of middleware (e.g. visual programme language (VPL) provided by the module within Rhinoceros' latest versions, Grasshopper). This enables the designer to consider the impacts of changes from a holistic approach, whereby daylight can be assessed by a reliable ray-tracing program (Radiance) and vice versa for thermal and/or energy (EnergyPlus) using plugins such as the Ladybug Suite.

Table 4 tabulates the constant parameters used within Rhinoceros/Grasshopper and Honeybee/Ladybug to create the analysed space within the generated workflow, along with the element properties such as surface reflectance and glass visible light transmittance that are key to daylight simulation.

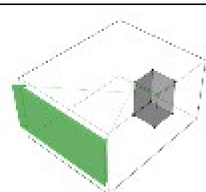
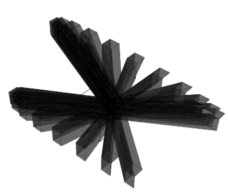
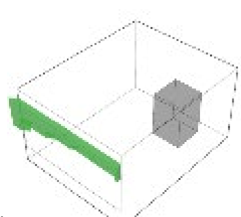
Table 42: Model properties

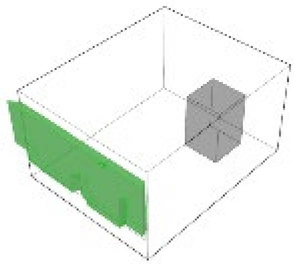
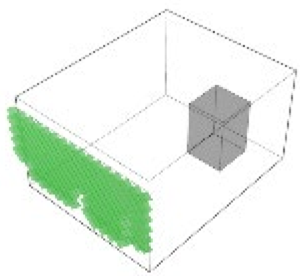
Property	Value
Parametrically generated space	4 x 5 x 2.7m
Test box dimensions	1 x 1 x 1.5 m
Surface reflectance (interior floor)	0.3
Surface reflectance (interior wall)	0.5
Surface reflectance (interior ceiling)	0.8
Glazing visible light transmittance (VLT)	0.6
Climate	Wellington, NZ
Analysis grid	0.25 m spacing ; 0.6 m AFFL
CEA: Number of view vectors per grid point	8

2.2. Parametric shade generation

Given the intent for the test location to be shaded regardless of location or orientation, the external shades are allowed to vary depending on their relation to the faces exposed to the glazing, the location of the sun at every hour of the year, and the size of the exterior window. This shade can be created parametrically, whereby the shape will adapt if any of the aforementioned parameters are altered. The process is outlined below in Table 5.

Table 43: Shade generation process

Step	Rhinoceros Preview	Process description
1		Create an external volume to the external glazing that would entirely block the glazing façade's internal surface based on the furthest vertices of the closest faces of the test box. This methodology would be applicable to any size glazing surface, location, and number.
2		Using the closest faces to the glazing façade internal surface and the solar vectors from a sun path, create extrusions to all solar positions in the sky for the entire year (or analysed period) (illustration showing winter and summer solstices for a north facing façade for a façade in Wellington, New Zealand)
3	 a)	Create a solid external volume by removing the solar extrusions from the external volume in 1 and inverting the volume. This generates a solid block which would block the sun from the test location for the entire year. This shape could be given to the architect at this point to construct custom shades which would serve to block the sun.

Step	Rhinoceros Preview	Process description
3 (cont.)	 b)	Though this process would create a shade volume to fully block the sun, the generated shade becomes problematic when the façade is orientated to be exposed to low-angle sun positions – such as the case within winter (3b). The shade volume must be cut into shaded devices / designs which would serve to cast the shadow illustrated by the shade volume, whilst providing daylight entry to the internal space.
4		The method in which the solar volume is cut will depend on the architectural vision and intent*. For the purposes of this study, the final volume shade has been cut with contours based upon the direction of the sun path at the specified orientations for the equinox and lofted the contours to create individual shade elements. The distance between shades, depth of shades and angle of the shade are then parametrically changed as a demonstration of concept evaluation within this study.

*Architectural design of the external shading will vary per project based upon the design intent of the design team and client aspirations. A shape produced in step 4 could be communicated to the architect as a design input, however attention should be given to how that level of shading to the glazing surface might impact daylight entry to the space. Rules of thumb will not aid the design team in this instance, and instead, the use of parametric tools provided by programs such as Rhinoceros/Grasshopper should be used to understand the trade-offs.

3. Proof of concept: outputs using parametric workflows

The results of a proof-of-concept parametric analysis are provided below. The workflow and proof-of-concept in which the shading is generated is shared as part of this paper (Braasch, 2022).

The conflict for solar exposure exists where the levels of light are encouraged for the beginning of the day and restricted for the afternoon, regardless of orientation. This changes the pattern of solar exposure depending on the orientation, where the sun is allowed entry in the morning period to provide light during the circadian resetting period and restricted for the afternoon-evening period to limit solar gains for energy conservation and thermal comfort purposes. This does not prove a challenge to north-facing facades in the southern hemisphere, but western and eastern facades must contend with the low-angles of the solar positions during winter. Figure 1 to Figure 3 provide an overview of selected design variants of the tested shade generated for the north, east and west to demonstrate as a proof-of-concept how the proposed workflow tackles the challenge for the tested location, and is optimised to achieve CEA > 25% in the morning.

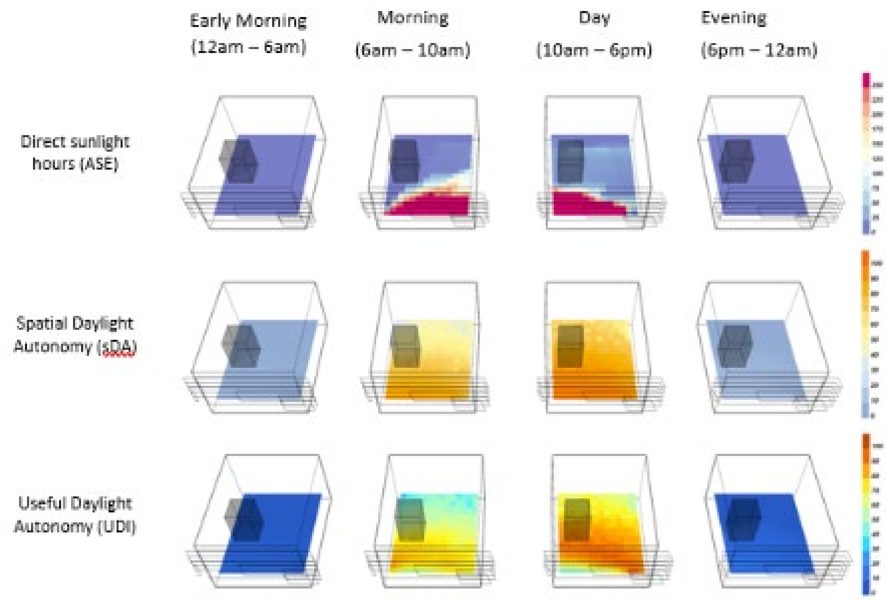


Figure 74: North-facing orientation results across the day with 0.4 m depth, 45 ° tilt and 0.2 m spacing

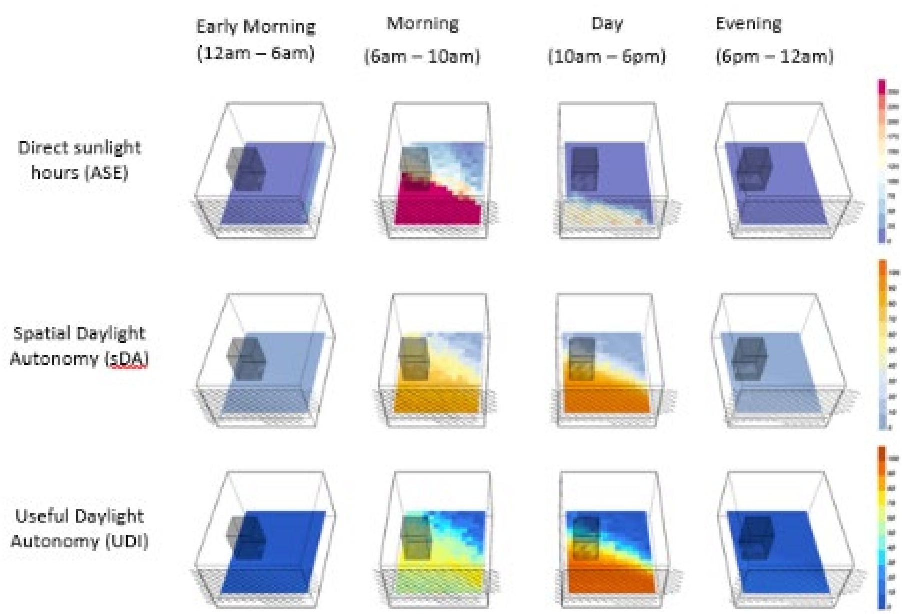


Figure 75: East-facing orientation results across the day with 0.3 m depth, 30 ° tilt and 0.2 m spacing

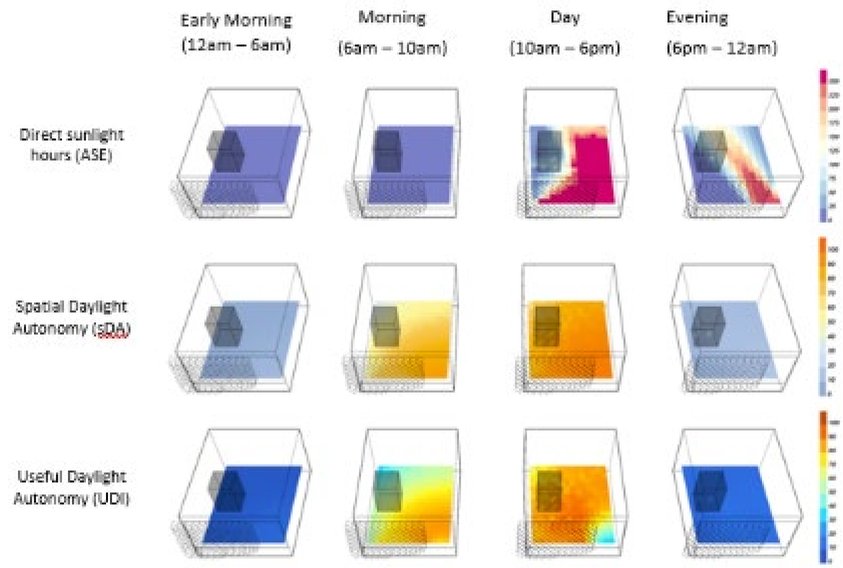


Figure 76: West-facing orientation results across the day with 0.3 m depth, 60 ° tilt and 0.2 m spacing

4. Discussion/Conclusion

The approach to multi-objective analysis suggested by this paper highlights the challenges to the design of external shading devices for specific locations as they are required to consider not only solar mitigation but solar admittance in balance with visual comfort. Very rarely are designs evaluated in terms of time of day for an entire year due to time and effort required and the lack of guidance provided in industry standard frameworks. With the advances made in computer technology of the recent decade, these types of analyses are becoming more prominent and provide an opportunity for architects to better understand the microenvironments which they create. Whilst the intent of providing solar shade to a particular zone within a space can be achieved by reverse engineering a microenvironment to create a bespoke shading device, other considerations to minimising high levels of illuminance and solar gains should also be included to further test the shade and develop the facade design. Further, there is opportunity to incorporate considerably more parameters such as those explored as part of this workflow. The UDI metric in combination with both the sDA metric and CEA overlay, as shown above, illustrates areas closer to the façade provide too much light which could be further addressed with additional shading.

The approach to shade generation presented within this paper provides a steppingstone for discussion with the architectural team during the early stages of design. However, the assessment of multiple objectives is likely to evolve in the future as more research is published in the field. As these types of simulation analyses become more popular during the early stages of design, further investigation is required to determine appropriate solar exposure thresholds for design where body comfort and glare are considered together. The design of solar shades cannot be considered in terms of energy consumption alone, lest we forget the health and well-being of those to whom we design for.

References

Acosta, I., Leslie, R. & Figueiro, M., 2017. Analysis of circadian stimulus allowed by daylighting in hospital rooms. Lighting Research and Technology, Volume 49, pp. 49-61.

Amundadottir, M. L., Lockley, S. W. & Andersen, M., 2016. Unified framework to evaluate non-visual spectral effectiveness of light for human health. Lighting Research and Technology, Issue 0, pp. 1-24.

Anderson, M., Mardaljevic, J. & Lockley, S. W., 2012. A framework for predicting the non-visual effects of daylight - Part I: photobiology-based model. Lighting Research and Technology, Issue 44, pp. 37-53.

Braasch, E., 2022. Workflow shared drive. [Online] Available at: https://drive.google.com/drive/folders/1Rqjqo131OrIOfbng6CG_xgklSHsLx0Si?usp=sharing [Accessed July 2022].

Choi, J. H., Beltran, L. O. & Kim, H. S., 2012. Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility. Building and Environment, Volume 50, pp. 65-75.

de Dear, R. J. & Brager, G. S., 2002. Thermal Comfort in Naturally Ventilated Buildings: Revisions to ASHRAE Standard 55. Energy and Buildings, Volume 34, pp. 549-561.

Deutsches Institut fuer Normung, 2013. DIN SPEC 67600: Biologically Effective Illumination - Design Guidelines. s.l.:DIN.

Hodder, S. G. & Parsons, K., 2007. The effects of solar radiation on thermal comfort. International jounral of biometeorology, Volume 51, pp. 233-250.

Humphreys, M., Nicol, F. & Raja, I. A., 2007. Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach. Advances in Building Energy Research, 1(1), pp. 55-88.

Illuminating Engineering Society of North America, 2012. IES LM-83-12: Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). New York: Illuminating Engineering Society of North America.

IWBI, 2022. Circadian Lighting Design. [Online] Available at: https://v2.wellcertified.com/.

Konis, K., 2016. A novel circadian daylight metric for building design and evaluation. Building and Environment, Issue 113, pp. 22-38.

Kriszbacher, I. et al., 2010. The time of sunrise and the number of hours with daylight may influence the diurnal rhythm of acute heart attack mortality. International Journal of Cardiology, Volume 140, pp. 11-120.

Mardaljevic, J., Andersen, M., Roy, N. & Christoffersen, J., 2013. A framework for predicting the non-visual effects of daylight - Part II: the simulation model. Lighting Research and Technology, Issue 0, pp. 1-19.

Mardaljevic, J., Andersen, M., Roy, N. & Christoffersen, J., 2014. A framework for predicting the non-visual effects of daylight - Part II: The simulation model. Lighting Research and Technology, Volume 46, pp. 388-406.

Nabil, A. & Mardaljevic, J., 2005. Useful daylight illuminance: a new paradigm for assessing daylight in buildings. Lighting Research and Technology, 37(1), pp. 41-59.

Ne'eman, E., Craddock, J. & Hopkinson, R. G., 1976. Sunlight Requirements in Buildings - I. Social Survey. Building and Environment, pp. 217-238.

Negendahl, K., 2015. Building performance simulation in the early design stage: An introduction to integrated dynamic models. Automation in Construction, Volume 54, pp. 39-53.

Rea, M. S. & Figueiro, M. G., 2018. Light as a circadian stimulus for architectural lighting. Lighting Research and Technology, Volume 50, pp. 497-510.

Robert McNeel & Asscoaties, 2022. Rhinoceros 3-D Modelling Program. [Online] Available at: https://www.rhino3d.com/mcneel/contact/ [Accessed 1 July 2022].

Passive prefab: how can existing prefab systems be adapted to meet Passive House requirements?

Hannah Parker[1] and Guy Marriage[2]

[1, 2] Victoria University of Wellington, Wellington, New Zealand
{hannah.parker[1], guy.marriage[2]}@vuw.ac.nz, ORCID- 0000-0002-9794-5451[2]

Abstract: New Zealand housing faces a health and affordability crisis. Our existing housing stock is cold, draughty, and prone to dampness and mould. New houses are being built far below similar climate standards worldwide, and recent New Zealand Building Code Clause H1 amendments do not increase our standards to those comparable climate standards. In addition, current building practices are prone to delays, cost increases, and defects. Given these issues, this paper asks how Passive House standards can be applied to existing prefabrication systems to provide healthy and affordable housing? The research implemented an action research methodology incorporating the adaptation of an existing prefabrication system to Passive House standards. Various existing prefabrication methods were evaluated and the most applicable to the research was selected for further development. The prefabrication system selected was refined through a series of prototypes utilising the plan-design-test-evaluate action research cycle to incorporate lessons from each earlier test. The exploration into increasing an existing prefabrication system to Passive House standard provides a high-performance housing solution utilising current technologies. The panelised system is easily transportable to most sites and is simple to erect, maximising the number of projects which could use it. When constructed, the system meets the rigorous Passive House standards around New Zealand without large-scale changes in the design phase reducing design time and complexity. This research can show that by adapting current successful systems to Passive House standards, the health and affordability of housing can be increased throughout New Zealand.

Keywords: Prefabrication; Passive House; healthy housing; affordable housing.

1. Introduction

Building homes that are not only affordable to construct but affordable to run and prioritise occupants' health is a significant issue within the construction industry. Recent research shows an increased interest in how prefabrication can transform construction by reducing waste, time, and safety issues while improving quality and affordability. With a theoretical framework of high-performance, healthy housing, this paper documents an attempt to combine Passive House performance standards with an existing prefabrication system. A design project undertaken through 2022 has been documented and critiqued to demonstrate a practical application of Passive House standards into an existing prefabrication system.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 472–481.*

This paper documents a Passive House standard prefabrication system and critically reflects on the technical performance, constructability, and application of this system.

2. Background

2.1. Healthy, affordable housing

Two main options are available in the New Zealand (NZ) context of building houses: group home builders and architects/architectural designers. Generally, architects and architectural designers design homes that are more expensive, higher-performing and highly customised. Group home builders like Mike Greer, GJ Gardener, Signature, and Jennian, offer more affordable New Zealand Building Code (NZBC) spec houses of various designs and limited customisation options. Unfortunately, NZBC minimum requirements are not sufficient to create homes that are affordable to run and healthy for inhabitants. NZ homes regularly dropped below World Health Organisation recommended temperatures and were commonly affected by dampness and mould (Stats NZ, 2020). These conditions have been linked with higher winter mortality rates and incidence of cardiovascular and respiratory diseases (Sharpe *et al.*, 2015; Stats NZ, 2021b). As most of us now suffer from some illness and spend up to 90% of our time indoors (Hancock, 2002; Rice, 2019a), creating healthy indoor environments is of utmost importance. The Ministry of Business, Innovation and Employment (MBIE) (2021a) have recently updated the NZBC Clause H1, improving the thermal performance requirements of new buildings to increase their health and affordability. The building industry, content with the status quo, applied much pressure to MBIE around these changes forcing a performance reduction on some of the proposed changes. Although a good start, the new thermal performance requirements do not bring NZ standards up to comparable standards in similar climates worldwide, ensuring another generation of substandard housing is built throughout the country.

The H1 improvements provide increased thermal performance standards to improve the health of houses and the affordability of running these houses but raise another issue: how much will it cost? In a world ravaged by the effects of a global pandemic and fuel shortages, NZ building and housing prices are skyrocketing. Three out of four housing affordability measures are at their worst since records began, and the average cost of a home is now almost ten times the average household wage (CoreLogic, 2022). Those who can save enough to build a new home face another set of challenges. Building costs have increased 34% over the last 12 months, and approximately two-thirds of construction businesses experienced reduced ability to order products and delivery delays (Ministry of Business, Innovation & Employment, 2021b; Duder, 2022). Adding to this is a labour shortage, whereby 90% of firms recruiting had trouble finding local applicants for their roles, and two-thirds received no applications for their opening (Davidson *et al.*, 2021). These factors make building new homes unattainable for most, and there is no sign of improvement. Materials shortages, skyrocketing costs and low minimum standards have created an unsustainable situation of unhealthy, unaffordable homes.

2.2. Healthy, affordable housing, prefabrication, and Passive House

The most common construction practices in NZ of building to the minimum required standard and primarily on-site construction contribute to unhealthy, unaffordable homes. Delays, construction defects, safety issues, and high wastage add costs to a project. Prefabricating elements, walls, and entire buildings off-site can increase quality and safety while reducing labour, delays, waste, and time (Smith and

Timberlake, 2010; Boafo *et al.*, 2016). With timber being the most common construction material in residential projects and one of the best performing products for prefabrication (Wallbaum *et al.*, 2012), there is an opportunity to explore prefabrication of housing to gain the benefits. The New Zealand building compliance system is performance-based, and compliance is established through the deemed-to-comply and alternative solutions route. Although a recent law change has intended to streamline the process, consents for prefabricated elements and buildings are processed by each building consent authority (BCA). Each BCA must ensure that the prefabricated elements meet the required standards (Ministry of Business, Innovation & Employment, 2018). As most prefabrication systems fall under the alternative solutions route and due to a range of factors affecting BCAs, it can be challenging to gain building consent for prefabrication projects (Page and Norman, 2014; Kennerley, 2019; Chen and Samarasinghe, 2020). This, combined with a relatively small appetite for prefabrication within the market, makes implementing it on a project a challenging concept even with the benefits it can provide.

High-performance buildings utilise key design features to minimise energy usage and maximise indoor comfort. Although they come with increased initial costs, this is balanced by reduced lifetime costs and improved physical and mental health of occupants (Smeds and Wall, 2007; Rice, 2019b). Passive House is a set of building performance standards aimed at producing very high-performance, low-energy buildings with good indoor air quality in various climates (Bere, 2013; Johnston and Siddall, 2016; Schnieders et al., 2020). Although there are a large number of different standards internationally (LEED, BREEAMS SKA Rating, Greenstar, Home Quality Mark, Zero Energy Buildings, etc.), Passive House certification relies almost entirely on the building itself, where many others factor in external conditions such as proximity to amenities and landscaping making Passive House the most applicable standard to a system with proposed applications across various climates and situations.

2.3. Research approach

Prefabrication has been widely researched, with many options for different systems proposed. Architectural theses commonly propose new approaches, with very few realised in the real world. X-Frame (Finch, 2017) and Makers of Architecture (Sutherland, 2013) are notable examples of a prefabrication system successfully transitioning from thesis to real-world application. Other academic research focuses on the advantages of prefabrication and the challenges preventing widespread adoption (Tam *et al.*, 2007; Bell and Southcombe, 2012; Burgess *et al.*, 2013; Eglinton, 2013; Page and Norman, 2014; Shahzad *et al.*, 2015; Boafo *et al.*, 2016; Kennerley, 2019; Wasim *et al.*, 2020; Masood *et al.*, 2021). High-performance research is similar in that most academic research focuses on the real-world performance of existing buildings and the health aspects of the created indoor environment (Guerra-Santin *et al.*, 2013; McLeod *et al.*, 2013; Leardini *et al.*, 2015; Foster *et al.*, 2016; Johnston and Siddall, 2016; Forde *et al.*, 2020; Moreno-Rangel *et al.*, 2020; Schnieders *et al.*, 2020). This paper explores the realm between prefabrication and Passive House where little research exists.

A literature review was completed before technical and design experiments. This review identified several factors present in high-performance building design (Lewis *et al.*, 2010; Bere, 2013; Lewis, 2014; Johnston and Siddall, 2016; Schnieders *et al.*, 2020) which could be utilised to increase the performance of existing systems. After assessing these design factors, five common prefabrication methods were tested on a base dwelling to evaluate their existing performance, and from these results, a single system was selected. Through a series of design experiments (physical and digital), the system performance was improved and adapted to meet Passive House requirements. This adapted system will be applied to a site-specific case study to demonstrate the performance and viability of the real-world application.

3. Passive house

The principles and methodology of Passive House design have been implemented successfully across Europe since its inception over 30 years ago (Bere, 2013). They are growing in popularity in NZ, from the first Passive House to Kāinga Ora, now trialling several Passive House social housing projects (Jessop Architects; Kāinga Ora, n.d.a, n.d.b; Toiora High Street Cohousing). To achieve Passive House standards, a range of technical performance criteria are achieved by applying five key design strategies (Hines et al., n.d.):

- Building envelope – super-insulated building envelope with high-performance windows in line with the insulation to keep buildings warm in winter and cool in summer
- Airtightness – an internal airtightness layer, tested during construction, reduces draughts and infiltration, meaning heated or cooled air stays inside where it's needed
- Ventilation – mechanical heat recovery ventilation (MHRV) takes heat from extracted stale air and uses it to warm fresh air reducing the amount of energy required to keep homes warm and keeping internal air fresh even through winter
- Thermal bridge minimisation – reducing areas in the building construction where heat can escape means less energy heating homes in winter and fewer draughts
- Solar gain – managing solar gains to maximise free heat in winter while minimising overheating in summer reduces the energy used to heat the home

The first stage of the research required a good understanding of how the Passive House Planning Package (PHPP) works and the implications of changes to each of these factors. A test dwelling applied the existing and future NZBC standards and NZ architectural standard construction (140mm timber frame with 45mm insulated services cavity) to assess how current practice performs. Various scenarios were put through the PHPP to determine the effects of different design moves, for example, increasing insulation, increasing shading and reducing conditioned volume. The main findings are summarised below:

- Internal blinds or curtains would be sufficient for shading in most locations
- Increasing the treated floor area (TFA) (floor area which is heated or cooled) had a significant positive effect on the performance of the building
- Increasing the amount of insulation in the walls also had a significant positive effect on the performance of the building
- Reducing building volume provided no significant improvement in building performance
- Increasing building volume generated no considerable increase in energy use
- Both old and new NZBC H1 requirements are worse than the architectural standard

The testing focused only on the 47m^2 dwelling, so results will change when applied to a larger home. The site-specific design will be a single dwelling based on the average size of new consented dwellings at approximately 155m^2, including a double garage (Stats NZ, 2021a).

4. Prefabrication systems

In addition to the current practice, four common types of prefabrication were run through the PHPP (Figure 1). Cross-laminated timber (CLT) is a solid timber panel typically with insulation, joinery, and cladding added manually on-site. Structural insulated panels (SIPS) have foam or polystyrene insulation between oriented strand board (OSB) or plywood with or without structural timber splines at panel edges. X-Frame (XF) is a plywood component system currently assembled and insulated on-site with timber structural splines at panel edges when required. Easybuild (EB) is a post and beam structure with prefabricated panels of traditional construction fitted between each post. Roof panels sit on top of the beams. As CLT and XF generally do not feature insulation as standard from the factory, base insulation of 50mm rockwool was applied to the exterior of CLT and 140mm polyester insulation within the XF wall structure and 50mm rockwool on the exterior of the walls.

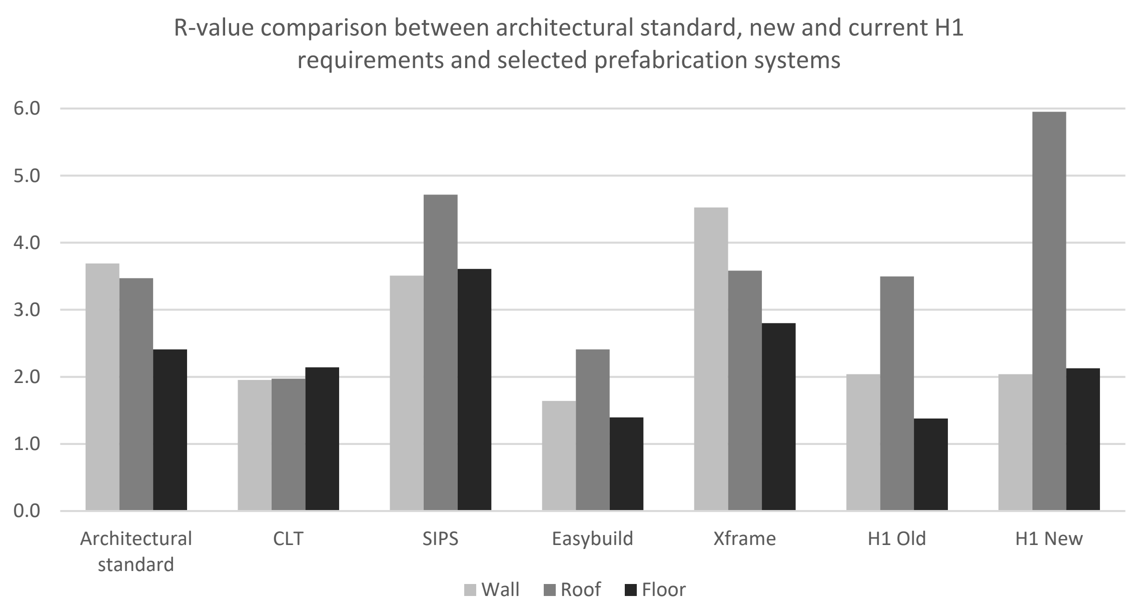


Figure 77: R-value comparison of prefabricated construction systems

EB, compliant with current NZBC H1 requirements, has the lowest performance, with SIPS the highest, aligning with SIPS having the highest insulation values and EB the lowest (Figure 2). CLT performed better than EB despite having similar insulation values, most likely due to a significant reduction in thermal bridging. With the structure in line with the insulation, there are areas of solid timber construction approximately 225mm wide with no insulation every 1200mm in the envelope construction. EB also uses the H1 calculation method to achieve compliance, allowing for insulation values under the prescribed value as long as the building performs as a whole. Although both EB and CLT technically meet NZBC requirements, both have a larger primary energy demand per square metre, with EB being significantly higher.

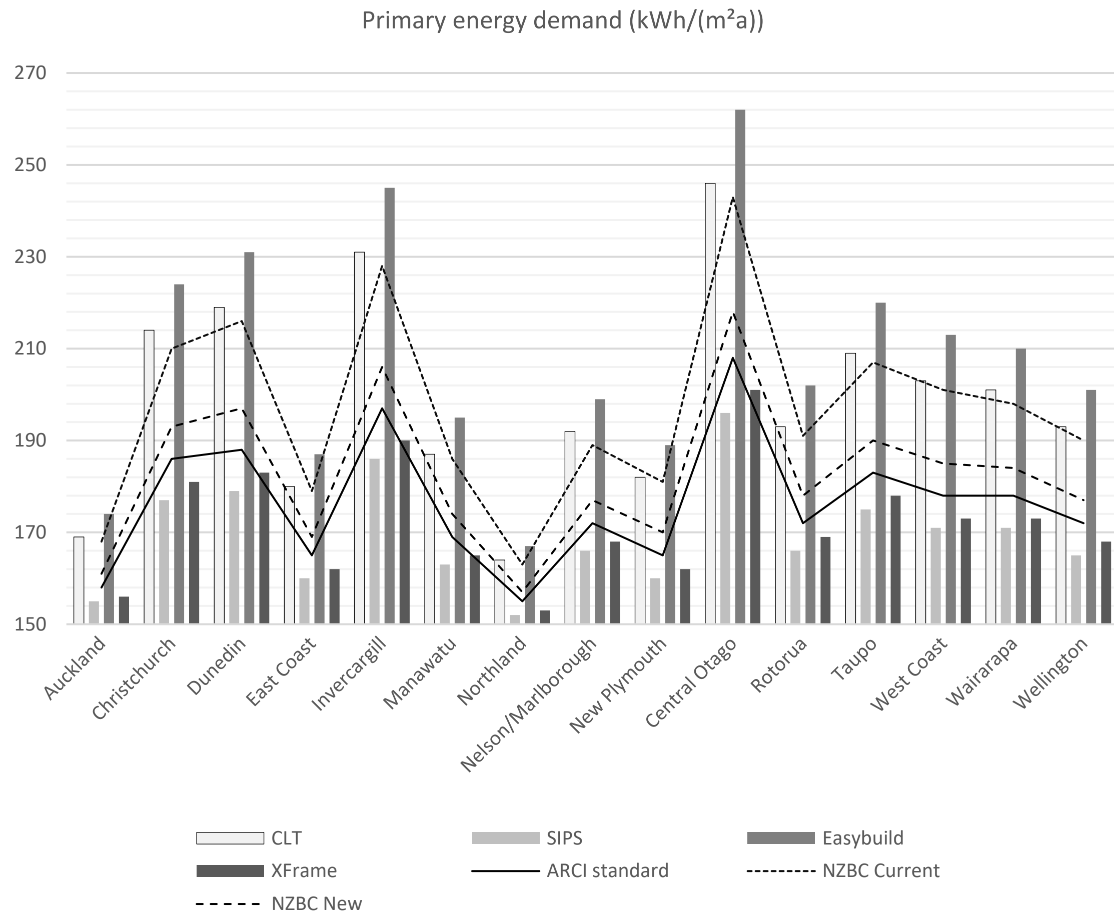


Figure 78: R-values and current performance of prefabricated systems within the PHPP

SIPS have a high base performance and have been used many times in constructing Passive Houses. NZSIP attempted to increase the level of prefabrication by wrapping the panels in the factory. However, this often resulted in damage and failed inspections, so now the wrap is shipped with the panels for on-site installation (Holden, 2018; NZSIP: Structural Insulated Panels, n.d.). There is potential to explore wrapping and installing joinery and cladding in the factories of SIPS as well as CLT. CLT is the largest of the studied prefabrication systems and requires significant machinery for installation, making it unsuitable for challenging sites. XF is constructed of two-dimensional plywood components which can be prefabricated into panels. An opportunity exists to explore the factory assembly of these panels with lining, services, wrapping and cladding.

5. System design and prototyping

The current construction detailing of XF will be assessed in terms of performance, thermal bridging and construction process. The system will be applied to a test dwelling based on the average NZ home of 155m2, including a double garage which will be outside the thermal envelope of the building. This will result in a dwelling of approximately 120m2. This dwelling will be designed using the constraints of the XF system below:

- Plans are designed on a 1200mm module
- Roof pitches are designed with a 14.1°, 26.6°, or 45° slope
- Internal walls will join the external walls at either the centre or edge of the external wall panel
- Window and door joinery will be designed to fit within panels and on a 600mm grid
- Wall heights will be designed at 2400mm, 2700mm, or 3000mm

Using a set of standard appliances, domestic hot water cylinder, MHRV system and heat pump, the XF system will be analysed, and solutions proposed to increase the performance to meet Passive House standards. Each potential solution or alteration to the system will be tested through digital modelling of the geometries to assess constructability, thermal bridge modelling to ensure accurate data from PHPP, and run through PHPP to determine the results of the changes to the system. Changes will also be tested through physical prototypes at full size and scale to demonstrate actual geometry and construction.

6. Results

The outcome is hoped to be a prefabricated panel system utilising XF technology. The system will be prefabricated in the factory and have joinery installed where possible. The outer wrap, battens and external insulation will be installed in the factory, with only cladding installed on-site after taping exterior joins. Internally, a flexible airtightness layer and services cavity battens will be installed to protect the airtightness layer. Joins will be taped on-site before services installation, insulation and internal linings are applied.

Some constraints make the long-term application of the XF Passive system challenging. The first is the reliance of Passive House on the treated floor area of a dwelling. The designed system could theoretically be applied to myriad size dwellings; however additional design time would be required to test and confirm the compliance with Passive House standards. Changing the orientation of the dwelling also affects the solar gains and overheating of the dwelling, which would require additional design time to ensure compliance.

The benefit of XF Passive over other panel systems is the flexibility in the type of insulation used within the panels. Any flexible insulation with the required R-values could be cut to shape and fitted, unlike other systems that require a specific insulating material. There is also potential to use spray insulation if slab insulation is proving challenging.

7. Conclusion

This research has demonstrated that it is possible to prefabricate Passive House compliant dwellings using existing prefabrication systems. Although the study was limited to a single place to limit the scope, it is anticipated that this could be applied to many different dwellings. The XF Passive system demonstrates a viable method for prefabricating Passive Houses although additional design considerations would still be required on every project. Assessment of the climate, orientation, and exact dwelling configuration would be required for each dwelling. Whilst this is likely to be some additional design time during early project stages, this would likely be significantly reduced compared to approaching each Passive House from a zero-starting point. The XF Passive system could also be applied as a solution without Passive House certification, where the performance is taken as it is and is applied to the project in question to achieve far more than the NZBC H1 requirements. As the demand for high-performance, faster, more affordable housing continues to grow, demand for prefabricated solutions with proven viability will continue to grow. XF Passive could fill this demand by utilising an innovative construction technology that reduces the required materials, increasing sustainability.

References

Bell, P. and Southcombe, M. (2012) Kiwi Prefab: Cottage to Cutting Edge. Auckland, New Zealand: Balasoglou Books.

Bere, J. (2013) An introduction to passive house. UK: RIBA Publishing.

Boafo, F.E., Kim, J.-H. and Kim, J.-T. (2016) 'Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways', Sustainability, 8(6), pp. 558–574. Available at: https://doi.org/10.3390/su8060558.

Burgess, J.C., Buckett, N.R. and Page, I.C. (2013) SR279 Prefabrication impacts in the New Zealand construction industry. Available at: https://www.branz.co.nz/pubs/research-reports/sr279/ (Accessed: 20 June 2022).

Chen, H. and Samarasinghe, D.A.S. (2020) 'The Factors Constraining the Adoption of Prefabrication in the New Zealand Residential Construction Sector: Contrators' Perspective', in Transforming New Zealand construction through innovation and performance improvement. New Zealand Built Environment Research, Auckland, New Zealand: Massey University, pp. 172–180. Available at: http://nzbers.massey.ac.nz/index.php/2020-symposium/ (Accessed: 8 March 2022).

CoreLogic (2022) Housing Affordability Report: New Zealand Quarter 4, 2021. Available at: https://www.corelogic.co.nz/reports/housing-affordability-report (Accessed: 29 March 2022).

Davidson, H., Silcock, P., Pennington, T.H. and Kelly, D. (2021) Skills Shortage, Recruitment & Immigration Challenges in the Construction Sector. Available at: https://www.acenz.org.nz/skills_shortage_recruitment_immigration_challenges_in_the_construction_sector (Accessed: 16 May 2022).

Duder, M. (2022) Spare a thought for the builders… Building Material Prices Predicted to Continue Rising, EBOSS. Available at: https://www.eboss.co.nz/detailed/building-industry-insight/building-material-prices-predicted-to-continue-rising-q1-2022 (Accessed: 16 May 2022).

Eglinton, A. (2013) 'Plus side of prefab panels', Build Magazine, 136. Available at: https://www.buildmagazine.org.nz/index.php/articles/show/plus-side-of-prefab-panels (Accessed: 17 March 2022).

Forde, J., Hopfe, C.J., McLeod, R.S. and Evins, R. (2020) 'Temporal optimization for affordable and resilient Passivhaus dwellings in the social housing sector', Applied Energy, 261, p. 114383. Available at: https://doi.org/10.1016/j.apenergy.2019.114383.

Foster, J., Sharpe, T., Poston, A., Morgan, C. and Musau, F. (2016) 'Scottish Passive House: Insights into Environmental Conditions in Monitored Passive Houses', Sustainability, 8(5), p. 412. Available at: https://doi.org/10.3390/su8050412.

Guerra-Santin, O., Tweed, C., Jenkins, H. and Jiang, S. (2013) 'Monitoring the performance of low energy dwellings: Two UK case studies', Energy and Buildings, 64, pp. 32–40. Available at: https://doi.org/10.1016/j.enbuild.2013.04.002.

Hancock, T. (2002) 'Indicators of Environmental Health in the Urban Setting', Canadian Journal of Public Health, 93(1), pp. S45–S51. Available at: https://doi.org/10.1007/BF03405118.

Hines, J., Godber, S., Butcher, B., Siddall, M., Jennings, P., Grant, N., Clarke, A., Mead, K. and Parsons, C. (n.d.) 'How to Build a Passivhaus'. The Passivhaus Trust. Available at: https://passivehouse.nz/resources/resources-downloads/ (Accessed: 22 April 2022).

Holden, M. (2018) Prefabricated Futures: Adaptable and productive construction methods for New Zealand dwellings. Victoria University of Wellington. Available at: https://doi.org/10.26686/wgtn.17072756.v1.

Jessop Architects 'Passive House', Jessop Architects. Available at: https://jessoparchitects.co.nz/passive-house/ (Accessed: 16 March 2022).

Johnston, D. and Siddall, M. (2016) 'The Building Fabric Thermal Performance of Passivhaus Dwellings—Does It Do What It Says on the Tin?', Sustainability, 8(1), p. 97. Available at: https://doi.org/10.3390/su8010097.

Kāinga Ora (n.d.a) Bader Ventura Passive House Pilot, Homes and Communities. Available at: https://kaingaora.govt.nz/developments-and-programmes/our-approach-to-building/bader-ventura-passive-house-pilot/ (Accessed: 16 March 2022).

Kāinga Ora (n.d.b) Kāinga Ora Passive Houses, Kāinga Ora – Homes and Communities. Available at: https://kaingaora.govt.nz/developments-and-programmes/our-approach-to-building/kainga-ora-passive-houses/ (Accessed: 11 April 2022).

Kennerley, T. (2019) Planning barriers for prefabricated housing. ER36. BRANZ.

Leardini, P., Manfredini, M. and Callau, M. (2015) 'Energy upgrade to Passive House standard for historic public housing in New Zealand', Energy and Buildings, 95, pp. 211–218. Available at: https://doi.org/10.1016/j.enbuild.2015.03.031.

Lewis, A., Riley, D. and Elmualim, A. (2010) 'Defining High Performance Buildings for Operations and Maintenance', International Journal of Facility Management, 1(2).

Lewis, S. (2014) PHPP Illustrated: A Designer's Companion to the Passive House Planning Package. RIBA Publishing.

Masood, R., Lim, J.B.P. and González, V.A. (2021) 'Performance of the supply chains for New Zealand prefabricated house-building', Sustainable Cities and Society, 64, p. 102537. Available at: https://doi.org/10.1016/j.scs.2020.102537.

McLeod, R.S., Hopfe, C.J. and Kwan, A. (2013) 'An investigation into future performance and overheating risks in Passivhaus dwellings', Building and Environment, 70, pp. 189–209. Available at: https://doi.org/10.1016/j.buildenv.2013.08.024.

Ministry of Business, Innovation & Employment (2018) Manufactured building solutions, Building Performance. Available at: https://www.building.govt.nz/projects-and-consents/apply-for-building-consent/support-your-consent-application/off-site-construction/ (Accessed: 4 July 2022).

Ministry of Business, Innovation & Employment (2021a) Building Code update 2021, Building Code update 2021. Available at: https://www.mbie.govt.nz/have-your-say/building-code-update-2021/ (Accessed: 18 September 2021).

Ministry of Business, Innovation & Employment (2021b) Construction sector trends monthly media and information overview: November 2021. Available at: https://www.mbie.govt.nz/building-and-energy/building/building-system-insights-programme/sector-trends-reporting/monthly/construction-sector-trends-monthly-media-and-information-overview-november-2021/ (Accessed: 16 May 2022).

Moreno-Rangel, A., Sharpe, T., McGill, G. and Musau, F. (2020) 'Indoor Air Quality in Passivhaus Dwellings: A Literature Review', International Journal of Environmental Research and Public Health, 17(13), p. 4749. Available at: https://doi.org/10.3390/ijerph17134749.

NZSIP: Structural Insulated Panels (n.d.) Smart Panels: 1. Introduction, NZSIP Smart Panels. Available at: https://www.nzsip.co.nz/introduction (Accessed: 22 June 2022).

Page, I. and Norman, D. (2014) SR312 Prefabrication and standardisation potential in buildings. SR312. Available at: https://www.branz.co.nz/pubs/research-reports/sr312/ (Accessed: 20 June 2022).

Rice, L. (2019a) 'A health map for architecture: The determinants of health and wellbeing in buildings', in M. Jones, L. Rice, and F. Meraz (eds) Designing for Health & Wellbeing: Home, City, Society. Vernon Press, pp. 155–185.

Rice, L. (2019b) 'The nature and extent of healthy architecture: the current state of progress', Archnet-IJAR: International Journal of Architectural Research, 13(2), pp. 244–259. Available at: https://doi.org/10.1108/ARCH-11-2018-0005.

Schnieders, J. et al. (2020) 'Design and realisation of the Passive House concept in different climate zones', Energy Efficiency, 13(8), pp. 1561–1604. Available at: https://doi.org/10.1007/s12053-019-09819-6.

Shahzad, W., Mbachu, J. and Domingo, N. (2015) 'Marginal Productivity Gained Through Prefabrication: Case Studies of Building Projects in Auckland', Buildings, 5(1), pp. 196–208. Available at: https://doi.org/10.3390/buildings5010196.

Sharpe, R.A., Thornton, C.R., Nikolaou, V. and Osborne, N.J. (2015) 'Fuel poverty increases risk of mould contamination, regardless of adult risk perception & ventilation in social housing properties', Environment International, 79, pp. 115–129. Available at: https://doi.org/10.1016/j.envint.2015.03.009.

Smeds, J. and Wall, M. (2007) 'Enhanced energy conservation in houses through high performance design', Energy and Buildings, 39(3), pp. 273–278. Available at: https://doi.org/10.1016/j.enbuild.2006.07.003.

Smith, R.E. and Timberlake, J. (2010) Prefab Architecture: A Guide to Modular Design and Construction. Hoboken, UNITED STATES: John Wiley & Sons, Incorporated.

Stats NZ (2020) Around a third of homes too cold in winter and too warm in summer. Available at: https://www.stats.govt.nz/news/around-a-third-of-homes-too-cold-in-winter-and-too-warm-in-summer (Accessed: 16 May 2022).

Stats NZ (2021a) Consents for medium-sized houses increase rapidly in the last decade, Stats NZ Tatauranga Aotearoa. Available at: https://www.stats.govt.nz/news/consents-for-medium-sized-houses-increase-rapidly-in-the-last-decade (Accessed: 22 June 2022).

Stats NZ (2021b) Housing in Aotearoa: 2020. Available at: https://www.stats.govt.nz/reports/housing-in-aotearoa-2020 (Accessed: 30 March 2022).

Tam, V.W.Y., Tam, C.M., Zeng, S.X. and Ng, W.C.Y. (2007) 'Towards adoption of prefabrication in construction', Building and Environment, 42(10), pp. 3642–3654. Available at: https://doi.org/10.1016/j.buildenv.2006.10.003.

Toiora High Street Cohousing 'A Passive House Cohousing Project in Dunedin Central'. Available at: https://highstreetcohousing.nz/ (Accessed: 16 March 2022).

Wallbaum, H., Ostermeyer, Y., Salzer, C. and Zea Escamilla, E. (2012) 'Indicator based sustainability assessment tool for affordable housing construction technologies', Ecological Indicators, 18, pp. 353–364. Available at: https://doi.org/10.1016/j.ecolind.2011.12.005.

Wasim, M., Han, T.M., Huang, H., Madiyev, M. and Ngo, T.D. (2020) 'An approach for sustainable, cost-effective and optimised material design for the prefabricated non-structural components of residential buildings', Journal of Building Engineering, 32, p. 101474. Available at: https://doi.org/10.1016/j.jobe.2020.101474.

Physical environment as a factor in schools' performance and efficiency: A review of previous research

Paulo Vaz-Serra[1], Neeraj Dangol[2], Raghu Dharmapuri Tirumala[3] and Piyush Tiwari[4]

[1, 2, 3, 4] Faculty of Architecture Building and Planning, University of Melbourne, Australia
{p.vazserra [1], neeraj.dangol [2], dtvraghu [3], piyush.tiwari [4]}@unimelb.edu.au
ORCID-0000-0001-5286-0801[1], ORCID-0000-0003-4179-3716[2], ORCID-0000-0002-6614-0167[3], ORCID- 0000-0002-3195-2843[4]

Abstract: The physical environment can considerably influence the efficiency and functionalities of facilities and spaces. Some recent studies examining schools' efficiency consider several factors such as human capital, parents' socioeconomic background, perceptions of teachers and parents towards schools, and financial status. However, very few studies have investigated the influences of schools' physical environment and facilities on their efficiency and students' academic performance. This research aims to review the recent studies on factors influencing schools' efficiency and student academic performance, and the importance accorded to physical environment. The research database, Scopus, is searched using combinations of relevant keywords and various studies that identify the influencing factors. A preliminary analysis of most of these studies indicates that the physical environment's influence on school performance appears peripheral. However, it was identified that physical environment, facilities, and services influence students' academic performance directly and indirectly. One of the limitations highlighted was that many of the studies, which include the physical environment factors in examining schools' efficiency, were based on a single country. The studies were mainly focused on the USA, and only a handful was based on Australia and the rest of the world. This paper identifies the need for more such studies that can contribute to bridging the knowledge on the efficiency drivers of the schools. A better understanding of the drivers for better school performance is needed to lead to an efficient allocation of funding, particularly for public schools in Australia.

Keywords: Efficiency, Literature Review, Performance, Schools, Students.

1. Introduction

The physical environment of the schools is one of the key factors influencing their performance and efficiency (Berman *et al.*, 2018; Uline and Tschannen-Moran, 2008; Schlaffer and Burge, 2020). The performance of schools is considered a combination of educational outcomes, satisfaction outcomes and other general outcomes (Prasetyo and Zuhdi, 2013; Erdogdu and Erdogdu, 2015, Tirumala et al., 2021).

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 482–492.*

The efficiency of schools is measured as a ratio of the outputs to inputs (Raisebeck et al. 2010). To understand the influence of the physical environment and facilities on schools' performance and efficiency, this research explores and reviews the literature on studies looking at various influencing factors. It uses a systematic literature review to identify relevant empirical research with minimum bias. The section on methodology and data elaborates on the process adopted and the search strings used. The subsequent section discusses the findings and results presented in the table of relevant literature and inferences.

2. Methodology and data

This paper uses a systematic literature review to explore recent studies on influencing factors, including physical environment and facilities, on schools' efficiency and performance. A systematic literature review is a research method and process to identify and critically assess relevant previous studies and collect and analyse data from the same (Liberati *et al.*, 2009). This methodology is appropriate for locating empirical research that fits the inclusion criteria specified according to the aim of the study. Bias can be reduced by applying systematic methods. The process adopted in this study was based on Snyder (2019) with six steps: Choosing a database, identification of keywords, setting up inclusion criteria, extracting data, processing data, and conduct content analysis, and identifying and retrieving relevant data. Scopus was selected as an appropriate database because it is "the largest abstract and citation database of peer-reviewed literature: scientific journals, books, and conference proceedings" (https://www.elsevier.com/en-au/solutions/scopus), and it identifies emerging trends and covers a broader breadth of interdisciplinary literature. Moreover, its search tools allow criteria based on subject areas, countries, access, document type, keywords, published years, and other factors to find relevant previous research.

The next step was identifying keywords to search for relevant literature. According to the purpose of this study, the literature related to influencing factors on schools' performance and efficiency was searched, looking at different studies with ways to measure it. Keywords used in these studies were used to search for further studies. Adopting this process iteratively, the following terms were used as keywords to find relevant studies: 'school efficiency', 'school outcomes', 'school facilities', 'infrastructure', 'physical', 'environment', 'resources', and 'measuring efficiency'. To find specific studies on 'Australian' and 'public schools', these two terms were added to two combinations.

Regarding inclusion/exclusion criteria, all types of documents, namely journal articles, book chapters, and conference papers, were included between 1985 and 2021. Non-English literature was excluded from this research. Based on the identified keywords and inclusion criteria, this study collected 513 results and retrieved them to Endnote X9 Library, where duplicates are identified and deleted. Then the remaining data were filtered based on their relevance to the performance of the schools. Filtering was done by reading their titles, abstracts, and keywords. Among retrieved data, 67 were found relevant in varying degrees to the performance and efficiency of different types of schools. Their content was analysed and categorised, and the findings are discussed in the following section.

3. Findings and discussion

The relevant literature content was analysed, and studies were identified and grouped based on factors influencing school performance and efficiency. The main factors are socio-economic conditions (mentioned by 24 studies) and human capital (by 21) in investigating how these factors influence the performance of the schools. Studies related to physical environment, class and school size, and funding and finance are similar in number (between 11 and 12 studies). The relationship between perceptions of teachers, students and parents and schools' outcomes is the least studied (7). Most of the studies (82%) addressed only one of the factors, and some of the studies showed other sub-factors under the physical environment factor. Facilities and services influence schools' performance and students' achievements and indicate these factors are associated. The number of studies addressing these factors is identified and presented in Table 1.

Table 1: Number of studies by factors addressed.

Factors addressed	Number of Studies	Previous studies
Socio-economic conditions	24	Agasisti, 2013; Berman et al., 2018; Blackburn et al., 2014; Braddock and Elite, 2004; Bryant and Norris, 2002; Coleman, 1988; Dancer and Blackburn, 2017; Dfaz and Barrios, 2002; Duran, 2008; Fombuena, 2016; Gillborn, 2003; Gorard and Smith, 2010; Handa et al., 2004; Hoxby, 2001; Jehangir, Glas, and Berg, 2015; Kirjavainen and Loikkanent 1998; Lee et al., 2019; Liouaeddine et al., 2018; Memon et al., 2016; Miningou and Vierstraete, 2013; OECD, 2012; Queiroz et al., 2020; Ward Schofield and Hausmann, 2004; Tajalli and Opheim, 2005
Human capital	21	Alexander et al., 2010; Buddin and Zamarro, 2009; D'Aiglepierre, 2011; Darling-Hammond, Berry, and Thoreson, 2001; Duran, 2008; Fetler, 2001; Goldhaber and Brewer, 1996; Handa et al., 2004; Hanushek and Rivkin, 2006; Hanushek and Woessmann, 2017; Hoernemann, 1998; Javier et al., 2016; Kantabutra, 2005; Kantabutra, 2012; Lee et al., 2019; Melvin and Sharma, 2007; Meunier, 2008; Monk, 1994; Philbin, 1997; Treputtharat and Tayiam, 2014; Wolszczak-Derlacz and Parteka, 2011
School and class size	12	Barrett and Toma, 2013; Conroy and Arguea, 2008; Duran, 2008; Finn and Achilles, 1990; Kantabutra, 2005; Kantabutra, 2012; Lee *et al.*, 2019; McGiverin, Gilman, and Tillitski, 1989; Nyhan and Alkadry, 1999; Okpala *et al.*, 2000; Sanders, Wright, and Horn, 1997; Wößmann and West, 2006
Physical environment	12	Berman *et al.*, 2018; Duran, 2008; Javier *et al.*, 2016; Leung and Fung, 2005; Queiroz *et al.*, 2020; Roberts, 2009; Schlaffer and Burge, 2020; Stafford, 2015; Tanner and Lackney, 2006; Tanner, 2000; Tanner, 2009; Uline and Tschannen-Moran, 2008; Uline *et al.*, 2009
Funding and finance	11	Alexander et al., 2010; Chakraborty and Blackburn, 2013; Dancer and Blackburn, 2017; Dolan and Schmidt, 1987; Erdogdu and Erdogdu, 2015; Lee et al., 2019; Mante and O'Brien, 2002; Prasetyo and Zuhdi, 2013; Pugh et al., 2015; Taylor, 2010; Wolszczak-Derlacz and Parteka, 2011
Perceptions of teachers, students, and parents	7	Alexander *et al.*, 2010; Elliot and Shin, 2002; Kantabutra, 2005; Kantabutra, 2012; Lee *et al.*, 2019; Liouaeddine *et al.*, 2018; Mullick *et al.*, 2013

Figure 1 shows the time distribution of these studies. The number of publications are grouped into different blocks (i) the first block between 1985-1999 and then (ii) five year blocks from 2000 till 2021. The publication trends is similar in all the blocks. While there has been substantial growth in the number of educational institutions, the research outputs on the topic are stagnant, indicating a need for increased research and findings that can provide input to policymakers.

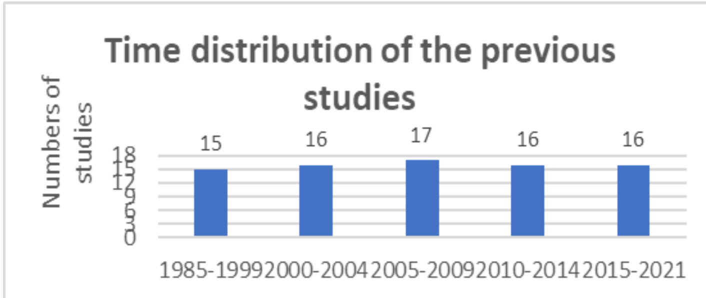


Figure 1: Time distribution of the previous studies

3.1. Physical environment

Only 14% of the studies (12) have discussed about the role of the physical environment in the schools' performance and efficiency. The studies mentioning the physical environment appeared the highest between 2015 and 2021, indicating an increasing interest in construction practices of schools.

School's physical environment and facilities are considered important factors influencing students' performance (Berman *et al.*, 2018; Schlaffer and Burge, 2020; Uline and Tschannen-Moran, 2008). The physical characteristics of a school building and complex are tangible settings where teaching and learning activities occur. How a school building is constructed and maintained affects how its occupants—students and teachers—perceive and utilise the space (Uline and Tschannen-Moran, 2008). Teacher attitudes and behaviours are affected by the quality of the buildings they teach in. Teachers are less likely to be enthusiastic and encourage their students' learning when teaching in low-quality facilities (Uline and Tschannen-Moran, 2008). Students are more likely to participate actively in their own and each other's learning when they feel free to move within and outside their respective classrooms. The distinctive character of several areas within a school may generate a sense of community and a shared commitment to learning objectives.

Adults and students are more prone to violate personal space and agitate one another when physical environments cause them inside a school to move close to one another in crowded areas. However, well-planned passageways make it pleasantly possible for passers-by to move ahead to shared locations. These are the findings of a study by Tanner and Lackney (2006) based on 71 schools in the USA. Numerous design elements and categories have been linked to increased student accomplishment, such as adaptable classroom layouts, well-defined paths, pleasant outdoor areas, large-group meeting spaces, instructional neighbourhoods, and sufficient egress (Tanner and Lackney, 2006). Also, Tanner's (2009) study shows that the school building design, particularly movement and circulation patterns, natural light, and classrooms with views, influence student performance. Movement and circulation patterns include outside walkways, pathways, public areas, and outdoor spaces.

Various aspects of buildings linked to human comfort are found to be associated with student attainment. Such aspects include building age, climate control, indoor air quality, lighting, and acoustic (Uline and Tschannen-Moran, 2008). Stafford's (2015) study, based on schools in Texas, USA, indicates that students' performance on standardised tests improves when the school's indoor air quality is improved. Asthma, respiratory infections, skin rashes, and fever are more serious health impacts that are likely to cause school absences. More minor physical issues, such as itchy eyes and noses, nausea, exhaustion, and dizziness, as well as cognitive issues, like trouble concentrating, memory loss, and delayed mental processing, are less likely to cause students to miss class. Still, they may have a direct impact on how well they learn. A study by Leung and Fung (2005) based in Hong Kong found that most of the changes in facility management components were significantly related to the changes in students' learning behaviours. The study revealed that the environment in newer school buildings significantly improved over that of old school buildings. In the newer schools, each classroom had additional amenities like a bulletin board, library nook, indoor plant, etc., and the chairs were placed in circles. This promotes group focus, communication, and coordination.

According to Duran's (2008) research, pupils who attended schools with poor facilities spent, on average fewer days in class and performed worse on English and math standardised tests. The study is based on 95 elementary schools in New York City. According to the study, the state of academic facilities can influence students' performance on three levels. First, the physical characteristics of a school facility, such as poor temperature control or filthy flooring, urinals, and restrooms, directly interfere with kids' ability to learn there. A second level is a social interaction, including daily interactions between students and teachers, which are affected by the school building conditions. A third level is an environmental level which is created by physical conditions.

Furthermore, the study findings relate the condition of school buildings to social justice because it observes that poor and minority children are more susceptible to attending schools in poor conditions in the USA. Berman *et al.* (2018) also found in their study that school environment conditions are linked to students' academic achievement in the case of public schools in Baltimore, USA. They observed that school building conditions significantly impacted student absenteeism. They discovered 77 per cent of Baltimore's school amenities to be in bad shape, and none of the structures in these schools was deemed acceptable for educational purposes.

Below is a brief discussion on the other parameters that influence the schools' performance and efficiency.

3.2. Human capital

Several studies showed that human capital is important for the performance of schools (Wolszczak-Derlacz and Parteka, 2011; Kantabutra, 2012; Alexander *et al.*, 2010; Hanushek and Rivkin, 2006; Javier *et al.*, 2016). From these studies, it can be inferred that there are three types of school employees: administrators, teachers, and non-teaching staff. Depending on their positions, backgrounds, and experiences, school staff members' human capital may influence students' performance in many ways. Since instructors are directly involved in delivering lessons and interacting with students, their influence on students' performance is thought to be larger than that of administration and non-teaching employees. Numerous studies demonstrate how teachers aid in students' intellectual growth and advise additional research into what makes a successful teacher (Hanushek and Rivkin, 2006). Various findings have been found in several studies that have looked at a teacher's quality in terms of educational achievement, experience, or qualification. For instance, Cho (2009) does not detect the correlation between teacher experience and students' academic achievement that Melvin and Sharma (2007) do.

Studies have used multiple models to examine human capital and student performance (Hoernemann, 1998; Philbin, 1997). The "instructional leadership model" was the first one that academics used to look at the relationships between school administrators and general academic success. The authors explored the relationships between school officials and student performance using a modified model called the "transformational leader behaviours model" (Hoernemann, 1998; Philbin, 1997). Other empirical studies show that the degree of teachers' knowledge about their subject influences the students' output (Buddin and Zamarro 2009; Treputtharat and Tayiam 2014; Ferguson and Brown 2000; Darling-Hammond *et al.*, 2001; Fetler 2001; Monk 1994; Brewer and Goldhaber 1996). Lee *et al.* (2019) found that teachers positively influence students' performance, improving school efficiency. They found a substantial impact on student learning through teachers' ability to explain lessons and tasks. In the same way, if teachers do not participate sufficiently in student learning, it can influence student performance negatively. This finding is based on data from 430 primary schools in Queensland, and the data were analysed using data envelopment analysis. Wolszczak-Derlacz and Parteka (2011) found that having more women in academic positions improves European countries' public higher education institutions. They based their study on a sample of 259 public higher education institutions from seven European countries, where data were collected between 2001 and 2005. According to Hanushek and Woessmann's (2017) study, among other factors that affect school performance, teachers' quality impacts student success in exams. Several contributions agree with the findings regarding the influence of teachers' education and experience on the performance of students and schools.

3.3. Socio-economic conditions

Socio-economic composition is another determinant found to be influential in student performance by several studies (Dancer and Blackburn, 2017; Liouaeddine *et al.*, 2018; Fombuena, 2016; Berman *et al.*, 2018). Research in the USA finds that schools with more white than black students lead to better educational achievement for African American students (Ward Schofield and Hausmann, 2004; Braddock and Elite, 2004). Hoxby (2001) and Ching (2000) support the findings of their studies that students' socioeconomic characteristics substantially affect cognitive and academic capacities, resulting in improved school performance. Social capital is a measure used to assess how interconnected community members are. (Coleman, 1988). The source of social capital is a link between people and social networks, as opposed to the location impact, which is essentially geographic. According to Coleman (1988), social capital is as crucial to one's personal development as human and financial capital. Student educational attainment can be explained in large part by social capital. Communities build social capital by connecting their residents through clubs and social organisations. The networking theory explains how social capital may affect personal growth in various ways (Bryant and Norris, 2002). According to this theory, social capital has three functions: linking, bridging, and bonding. (Bryant and Norris, 2002).

After the well-known Coleman Report (Coleman, 1988), family and environmental factors play a key role in students' success, and failure has been widely accepted. Studies demonstrated that schools are likelier to have lower learning outcomes when more students are from socioeconomically disadvantaged backgrounds (Tajalli and Opheim, 2005; Agasisti, 2013; Jehangir *et al.*, 2015). Students' academic achievement was positively related to parents' education level (Kirjavainen and Loikkanent 1998). Substantially impacted and Vierstraete (2013) did a comparable study in Burkina Faso's schools with a focus on the living conditions of households. Memon *et al.* (2016) discovered that parental education substantially impacted children's success rates in pre-medical entrance exams.

3.4. Perceptions of teachers, students, and parents

According to recent studies, attitudes towards teachers, students, and parents impact how well schools perform (Lee *et al.*, 2019; Kantabutra, 2012; Liouaeddine *et al.*, 2018). This is similar to how customers' and employees' satisfaction is essential in measuring a company's performance.

A teacher's level of job satisfaction is determined by several factors, including pay, benefits, task demands, teacher policies, job profile, leadership, colleagues, interaction, recognition, and career advancement (Slavitt *et al.*, 1986). Other elements influencing student satisfaction include the return on investment, advisor accessibility, a safe campus, clear and appropriate major prerequisites, advisor availability, enough computer labs, unbiased and fair faculty, and information access (Elliot and Shin, 2002). According to Lee *et al.* (2019), students perform better and earn higher grades when they perceive that their school values their input. This implies that teachers should consider and discuss students' opinions in class. This shows that a school is open to student input, which will help students' opinions of teachers and their work.

3.5. Class and school size

Class size, school size, and the teacher-to-student ratio can impact a school's performance (Kantabutra, 2012; Lee *et al.*, 2019; Duran, 2008). When Kirjavainen and Loikkanent (1998) examined variations among Finnish senior secondary schools, they discovered higher learning efficiency levels in institutions with smaller classrooms. Additionally, they observed that schools with more diverse student groups exhibit higher levels of inefficiency. Similarly, studies by Wößmann and West (2006), Barrett and Toma (2013) and Conroy and cost-effectiveness (2008) and found that small class sizes contribute to higher efficiency in academic outcomes. Okpala *et al.* (2000) state that class size measures teachers' ability to interact with students.

The teacher-student ratio can be a proxy for the typical class size. A trade-off between cost-effectiveness and student accomplishment has been discovered in studies on the teacher-student ratio (Wößmann and West, 2006; Barrett and Toma, 2013; Conroy and Arguea, 2008). There has been some discrepancy in previous research on the connection between class size and student achievement. Several researchers say kids learn best in smaller classes (Finn and Achilles, 1990; McGiverin *et al.*, 1989). Other scholars have demonstrated otherwise, indicating that larger class size had better student achievement in several schools, including Sanders *et al.* (1997) and Nyhan and Alkadry (1999). Despite the lack of agreement, research on the connection between class size and student learning performance is ongoing, suggesting that reducing class size is a policy alternative that should be considered (Wößmann and West, 2006; Barrett and Toma, 2013; Conroy and Arguea, 2008).

3.6. Funding and finance

Studies have shown that educational expenditure positively impacts school performance (Prasetyo and Zuhdi, 2013; Erdogdu and Erdogdu, 2015). A positive relationship between financial resources on education and student performance was identified by Dolan and Schmidt (1987) decades ago. These studies explain that higher per-student expenditure and funding give students better access to more qualified teachers who effectively implement pedagogical methods in their classrooms. Consequently, students become capable of achieving higher outcomes.

Dancer and Blackburn (2017) found in the case of Australia how government funding can be influential in improving the efficiency of public schools. They identified that two-thirds of children in Australia go to public schools, and billions of dollars are provided at state and federal levels to operate these schools. They studied the influences of government funding on the efficiency of public schools. Similarly, Chakraborty and Blackburn (2013) examined the cost efficiency of Australian schools based on the operating expenses per student. They used NAPLAN results for Grades 3 and 5 as some of the inputs. They found that using resources has been inefficient in primary schools because students' scores are unsatisfactory. One of its causes is the social disadvantages identified in these schools. Similarly, Pugh *et al.* (2015) estimated the impacts of school expenses on school performance represented by the Australian Tertiary Admission Rank (ATAR) score. Their results indicated that the influence of school expenses on its performance also depends on the school size. Schools with less than 1,500 students can have better positive impacts on higher ATAR scores because of expenditure. In the case of schools with more than 1,500 students, the impacts decrease. The study found that an increase in spending enhances the estimated median ATAR score; however, the impact is negligible.

5. Conclusion

The literature review identified the frequency of studies that identified various factors that influence the schools' performance and efficiency. The number of studies showing the importance of schools' physical environment and facilities is about 14% in 1985-2021. However, it is increasingly being recognized that all the factors substantially influence the schools' performance and efficiency, and, importantly, each other. It has become increasingly important to have well-designed spaces that can provide a conducive ambience, while affording sufficient protection during the natural calamities and health emergencies, as COVID – 19 , yet have the flexibility to offer a wide range of pedagogical approaches. The physical environment, facilities and services are related to other factors influencing students' performance. That way, schools' buildings and the physical environment are designed and constructed can have direct and indirect impacts on students' achievement. For example, the studies discussed above on ways of funding show how funding received by schools affects students' outcomes. However, it would be more beneficial to identify what funding is generally allocated for developing and maintaining schools' buildings and services, which eventually affects teaching and learning. Similarly, school buildings, facilities and physical environment are more likely to influence teachers' perceptions and attitudes towards schools which can affect their teaching. Schools' physical settings can also affect how parents perceive the schools they send their children to. The schools' physical conditions can also affect students' physiological, psychological, and emotional states and attitudes towards school. Studies on how schools' physical environment influences all these factors and, eventually, students' performance and behaviour are rare, particularly in the case of Australia. Most of the research is based in the USA, indicating a necessity of research on relationships between the physical environment of schools and students' performance in other countries, including Australia. Therefore, this review finds a need for such studies that can contribute to bridging the lack of knowledge. This is particularly important for public schools which operate on government funding, including PPP schools, so that the efficiency of the schools can be enhanced by addressing the inadequacy of the physical environment and facilities.

Acknowledgements

The funding support of the Faculty of Architecture, Building and Planning at the University of Melbourne for this research is gratefully acknowledged.

References

Agasisti, T. (2013) The efficiency of Italian secondary schools and the potential role of competition: A data envelopment analysis using OECD-PISA2006 data, Education Economics, 21(5), 520-544.

Alexander, W. R. J., Haug, A. A. and Jaforullah, M. (2010) A two-stage double-bootstrap data envelopment analysis of efficiency differences of New Zealand secondary schools, Journal of Productivity Analysis, 34(2), 99-110.

Barrett, N. and Toma, E. F. (2013) Reward or punishment? Class size and teacher quality, Economics of Education Review, 35, 41-52.

Berman, J. D., McCormack, M. C., Koehler, K. A., Connolly, F., Clemons-Erby, D., Davis, M. F., Gummerson, C., Leaf, P. J., Jones, T. D. and Curriero, F. C. (2018) School environmental conditions and links to academic performance and absenteeism in urban, mid-Atlantic public schools, IJOHEH, 221(5), 800-808.

Blackburn, V., Brennan, S. and Ruggiero, J. (2014) Measuring efficiency in Australian Schools: A preliminary analysis, Socio-Economic Planning Sciences, 48(1), 4-9.

Braddock, J. H. and Eitle, T. M. (2004) The effects of school desegregation, Handbook of research on multicultural education, 2.

Bryant, P. C.-a. and Norris, D. (2002) Measurement of social capital: The Canadian experience.

Buddin, R. and Zamarro, G. (2009) Teacher qualifications and student achievement in urban elementary schools, Journal of Urban Economics, 66(2), 103-115.

Chakraborty, K. and Blackburn, V. C. (2013) Efficiency and Equity in Funding for Government Schools in Australia, Australian Economic Papers, 52(3-4), 127-142.

Coleman, J. S. (1988) Social capital in the creation of human capital, American journal of sociology, 94, S95-S120.

Conroy, S. J. and Arguea, N. M. (2008) An estimation of technical efficiency for Florida public elementary schools, Economics of Education Review, 27(6), 655-663.

d'Aiglepierre, R. (2011) *Économie de l'éducation dans les pays en développement: Cinq essais sur l'aide internationale à l'éducation, la nature publique ou privée de l'enseignement, le choix des parents, l'efficience des collèges et la satisfaction des enseignants*, Université d'Auvergne-Clermont-Ferrand I.

Dancer, D. and Blackburn, V. (2017) *What are the effective public schools? Insights from New South Wales' secondary schools using a Stochastic Frontier Analysis with a panel dataset*, AJOE, 61(2), 141-163.

Darling-Hammond, L., Berry, B. and Thoreson, A. (2001) Does teacher certification matter? Evaluating the evidence, Educational evaluation and policy analysis, 23(1), 57-77.

Dfaz, S. D. and Barrios, G. H. (2002) School efficiency and socioeconomic differences: On the results of assessment exams of the Quality of Education in Chile, Educacao e Pesquisa, 28(2), 25-39.

Dolan, R. C. and Schmidt, R. M. (1987) Assessing the impact of expenditure on achievement: Some methodological and policy considerations, Economics of Education Review, 6(3), 285-299.

Durán-Narucki, V. (2008) School building condition, school attendance, and academic achievement in New York City public schools: A mediation model, Journal of Environmental Psychology, 28(3), 278-286.

Elliott, K. M. and Shin, D. (2002) Student satisfaction: An alternative approach to assessing this important concept, Journal of Higher Education Policy and Management, 24(2), 197-209.

Erdogdu, F. and Erdogdu, E. (2015) The impact of access to ICT, student background and school/home environment on academic success of students in Turkey: An international comparative analysis, C & E, 82, 26-49.

Fetler, M. (2001) Student mathematics achievement test scores, droupout rates, and teacher characteristics, Teacher Education Quarterly, 151-168.

Finn, J. D. and Achilles, C. M. (1990) Answers and questions about class size: A statewide experiment, American Educational Research Journal, 27(3), 557-577.

Fombuena, A. (2016) Emergence of geo-enabled research in social sciences: The case of societal higher education issues, Social Science Information, 55(4), 555-567.

Gillborn, D. (2003) Race, ethnicity and education: Teaching and learning in multi-ethnic schools, ed., Routledge.

Goldhaber, D. D. and Brewer, D. J. (1996) Evaluating the effect of teacher degree level on educational performance.

Gorard, S. and Smith, E. (2010) Equity in Education: an international comparison of pupil perspectives, ed., Springer.

Handa, S., Simler, K. R. and Harrower, S. (2004) Human capital, household welfare, and children's schooling in Mozambique, Research Report of the International Food Policy Research Institute, (134), 1-85.

Hanushek, E. A. and Rivkin, S. G. (2006) Teacher quality, Handbook of the Economics of Education, 2, 1051-1078.

Hanushek, E. A. and Woessmann, L. (2017) School resources and student achievement: A review of cross-country economic research, Cognitive abilities and educational outcomes, 149-171.

Hoernemann, M. E. (1998) Transformational leadership and the elementary school principal, Purdue University.

Hoxby, C. M. (2001) All school finance equalizations are not created equal, The Quarterly Journal of Economics, 116(4), 1189-1231.

Javier, J. R., Coffey, D. M., Schrager, S. M., Palinkas, L. A. and Miranda, J. (2016) Parenting intervention for prevention of behavioral problems in elementary school-age Filipino-American children: a pilot study in churches, Journal of developmental and behavioral pediatrics: JDBP, 37(9), 737.

Jehangir, K., Glas, C. A. and van den Berg, S. (2015) Exploring the relation between socio-economic status and reading achievement in PISA 2009 through an intercepts-and-slopes-as-outcomes paradigm, IJOER, 71, 1-15.

Kantabutra, S. (2005) Improving public school performance through vision-based leadership, Asia Pacific Education Review, 6(2), 124-136.

Kantabutra, S. (2012) Investigating shared vision and size effects on public school performance: A proposed efficiency model, International Journal of Innovation and Learning, 11(3), 217-232.

Kirjavainen, T. and Loikkanent, H. A. (1998) Efficiency differences of Finnish senior secondary schools: an application of DEA and Tobit analysis, Economics of Education Review, 17(4), 377-394.

Lee, B. L., Worthington, A. and Wilson, C. (2019) Learning environment and primary school efficiency: A DEA bootstrap truncated regression analysis, International Journal of Educational Management, 33(4), 678-697.

Leung, M. Y. and Fung, I. (2005) Enhancement of classroom facilities of primary schools and its impact on learning behaviors of students, Facilities, 23(13-14), 585-594.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., Clarke, M., Devereaux, P. J., Kleijnen, J. and Moher, D. (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration, JOCE, 62(10), e1-e34.

Liouaeddine, M., Elatrachi, M. and Karam, E. M. (2018) The analysis of the efficiency of primary schools in Morocco: modelling using TIMSS database (2011), Journal of North African Studies, 23(4), 624-647.

Mante, B. and O'Brien, G. (2002) Efficiency measurement of Australian public sector organizations: The case of state secondary schools in Victoria, Journal of Educational Administration, 40(3), 274-296.

McGiverin, J., Gilman, D. and Tillitski, C. (1989) A meta-analysis of the relation between class size and achievement, The Elementary School Journal, 90(1), 47-56.

Melvin II, P. D. and Sharma, S. C. (2007) Efficiency analysis of K-12 public education in Illinois.

Memon, S., Goswami, P. and Memon, I. (2016) Effects of schooling and parental education on student's achievement in medical entrance test, J Liaquat Uni Med Health Sci, 15(03), 116-120.

Meunier, M. (2008) Are Swiss secondary schools efficient?, in, Governance and performance of education systems, Springer, 187-202.

Miningou, É. W. and Vierstraete, V. (2013) Households' living situation and the efficient provision of primary education in Burkina Faso, Economic modelling, 35, 910-917.

Monk, D. H. (1994) Subject area preparation of secondary mathematics and science teachers and student achievement, Economics of Education Review, 13(2), 125-145.

Mullick, J., Sharma, U. and Deppeler, J. (2013) School teachers' perception about distributed leadership practices for inclusive education in primary schools in Bangladesh, School Leadership and Management, 33(2), 151-168.

Nyhan, R. C. and Alkadry, M. G. (1999) The impact of school resources on student achievement test scores, Journal of Education Finance, 25(2), 211-227.

OECD (2012) Equity and quality in education: Supporting disadvantaged students and schools, Equity and quality in education: Supporting disadvantaged students and schools, ed., OECD.

Okpala, C. O., Smith, F., Jones, E. and Ellis, R. (2000) A Clear Link Between School and Teacher Characteristics, Student Demographics, and Student Achievement, Education, 120(3).

Philbin III, L. P. (1997) Transformational leadership and the secondary school principal, ed., Purdue University.

Prasetyo, A. D. and Zuhdi, U. (2013) The government expenditure efficiency towards the human development, Procedia Economics and Finance, 5, 615-622.

Pugh, G., Mangan, J., Blackburn, V. and Radicic, D. (2015) School expenditure and school performance: evidence from New South Wales schools using a dynamic panel analysis, BERJ, 41(2), 244-264.

Queiroz, M. V. A. B., Sampaio, R. M. B. and Sampaio, L. M. B. (2020) Dynamic efficiency of primary education in Brazil: Socioeconomic and infrastructure influence on school performance, Socio-Economic Planning Sciences.

Raisbeck, P., Duffield, C., and Xu, M., 2010. Comparative performance of PPPs and traditional procurement in Australia. Construction management and economics, 28 (4), 345–359.

Roberts, L. W. (2009) Measuring school facility conditions: An illustration of the importance of purpose, Journal of Educational Administration, 47(3), 368-380.

Sanders, W. L., Wright, S. P. and Horn, S. P. (1997) Teacher and classroom context effects on student achievement: Implications for teacher evaluation, Journal of personnel evaluation in education, 11(1), 57-67.

Schlaffer, J. and Burge, G. (2020) The asymmetric effects of school facilities on academic achievement: Evidence from Texas bond votes, The social science journal, 1-19.

Snyder, H. (2019) Literature review as a research methodology: An overview and guidelines, Journal of business research, 104, 333-339.

Stafford, T. M. (2015) Indoor air quality and academic performance, Journal of Environmental Economics and Management, 70, 34-50.

Tajalli, H. and Opheim, C. (2005) Strategies for Closing the Gap: Predicting Student Performance in Economically Disadvantaged Schools, Educational Research Quarterly, 28(4), 44-54.

Tanner, C. K. (2000) The influence of school architecture on academic achievement, Journal of Educational Administration, 38(4), 309-330.

Tanner, C. K. (2009) Effects of school design on student outcomes, Journal of Educational Administration, 47(3), 381-399.

Taylor, L. L. (2010) Economic approaches to school efficiency, in, International Encyclopedia of Education, Elsevier Ltd, 210-215.

Tirumala R D., Dangol, N.,Tiwari p., and Vaz-Serra P. (2021) Comparative analysis of outcomes under PPP and traditional modes of delivery: a study of schools in Melbourne, Construction Management and Economics, 39:11, 894-911, DOI: 10.1080/01446193.2021.1994147

Treputtharat, S. and Tayiam, S. (2014) School climate affecting job satisfaction of teachers in primary education, Khon Kaen, Thailand, Procedia-Social and Behavioral Sciences, 116, 996-1000.

Uline, C. and Tschannen-Moran, M. (2008) The walls speak: The interplay of quality facilities, school climate, and student achievement, Journal of Educational Administration, 46(1), 55-73.

Uline, C. L., Tschannen-Moran, M. and Wolsey, T. D. (2009) The walls still speak: The stories occupants tell, Journal of Educational Administration, 47(3), 400-426.

Ward Schofield, J. and Hausmann, L. R. (2004) School desegregation and social science research, American Psychologist, 59(6), 538.

Woessmann, L. and West, M. (2006) Class-size effects in school systems around the world: Evidence from between-grade variation in TIMSS, European Economic Review, 50(3), 695-736.

Wolszczak-Derlacz, J. and Parteka, A. (2011) Efficiency of European public higher education institutions: a two-stage multicountry approach, Scientometrics, 89(3), 887-91

Post-Pandemic Study Spaces: Post Occupancy Evaluation of BREEAM Excellence Rated University Building

Ozlem Duran[1] and Jing Zhao[2]

University of Lincoln, Lincoln, U.K
jingzhao@lincoln.ac.uk, 0000-0002-0497-4932

Abstract: This paper presents preliminary findings from a Post Occupancy Evaluation research of a BREEAM excellence-rated university building, to understand the experience of the students using university study spaces under a post-pandemic teaching and learning context. The research uses a combined qualitative and quantitative method and focuses on occupancy patterns, thermal comfort, air quality, noise and lighting level of the study spaces within the building, as well as the students' preferences and experiences of the study spaces. The research collected over 200 questionnaire survey data from students who use the study areas, as well as monitored environmental data and observation data over 5 working days prior to the exam period. The study also compares the field research with the predicted performance simulation model data made before the pandemic, to understand the difference the pandemic has made to the designed usage and environmental comfort of the building. The result suggests that the post-pandemic occupancy level is significantly different from the pre-pandemic design assumptions and environmental control strategies need to be re-evaluated to provide optimum thermal comfort. Furthermore, the result raises questions in relation to overheating predictions in the performance simulation model, suggesting a need to re-evaluate overheating calculation criteria in educational buildings.

Keywords: University buildings, Post-occupancy evaluation, thermal comfort, occupant behaviour.

1. Introduction

The recent pandemic and subsequent lockdown have resulted in an eight-fold increase in the number of people working from home in the UK (Felstead and Reuschke, 2020). This change has also affected higher education in terms of teaching modes, forcing courses to be delivered online, where students took lectures and studied at home for the majority of the time over the past two years. As we move towards a post-pandemic world, many universities nationwide are facing the issue of transitioning from online teaching to face-to-face or hybrid teaching. The university learning spaces are occupied in ways that were never anticipated. Previous research suggested that university campuses have become more focused on social-oriented learning and less on traditional lecture-based learning, as a result of the maturity and

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 493–503.*

accessibility of online teaching (Gui et al., 2021). Such a blended model of teaching and learning would still be relevant in future scenarios. The changing approach to teaching and learning impacts the occupants' behaviour in terms of space use: there may be an increasing need for private/undisturbed spaces for online teaching and learning. On the other hand, it is likely that study spaces may also be used as a group or social space more often than pre-pandemic.

University buildings are occupied predominantly by a group of occupants (students) with a small range of age differences, different daily timetables and study disciplines, the occupancy pattern is very different than in other building typologies and is difficult to predict (Franceschini and Neves, 2022). Therefore, understanding the students' behaviour is significant to overcoming the discrepancies between the predicted and actual environmental comfort and performance (Shi et al., 2019). Previous review articles Franceschini and Neves, 2022; Carlucci et al. (2020) identified a literature gap in the study of occupant behaviour and building performance simulation studies of educational buildings. Out of the 278 identified studies on occupant behaviour and building performance, only 5% were on educational buildings (Carlucci et al., 2020). This is due to the complexity of estimating occupant behaviour in educational buildings. Moreover, Lawrence, R., Keime, C. (2016) highlights the significance of occupancy patterns to a complete understanding of energy efficiency and comfort. Meanwhile, environmental factors, thermal comfort in particular are proven to be impactful on students' intellectual performances (Ricciardi and Buratti, 2018). Thermal discomfort causes distraction and reduction in the students' academic performance and mental tasks (Jowkar et al., 2020; Barbhuiya and Barbhuiya, 2013; Ricciardi and Buratti, 2018). Therefore, measuring the post-pandemic in-use occupant behaviour and understanding students' environmental evaluation of the study spaces, in comparison with predictions made pre-pandemic, are critical in predicting and optimising the environmental comfort and performance of university buildings.

This project has carried out a Post Occupancy Evaluation (POE) on the study spaces of a newly-built university building that has achieved a BREEAM excellence rating (BREEAM, 2022) for its design scheme. The rating was achieved based on a simulation model (produced by an external specialised company) prior to the buildings' completion. However, since the university building was completed in March 2021 during the pandemic, the actual occupancy pattern and environmental control were very different from when it was designed for. As universities slowly returned to face-to-face teaching, the occupancy pattern has again changed dramatically. The preliminary findings from this research show students' preferences for study spaces in a post-pandemic setting in comparison with the building performance simulation assumptions, in terms of environmental factors, as well as their strategies in navigating discomfort.

2. The building

The studied building is located in the East Midlands in the U.K. It is a 5-storey building with a gross internal floor area of approximately 5746m^2. The design of the building adopted a principle to maximise sustainability through informed decisions on site, layout, massing, orientation, building fabric, elevational treatment and Integrated renewable energy systems, as well as biophilic design principles including natural lighting and ventilation, visual links to natural landscape features and natural materials. The thermal parameters of the main building components are listed in Table 1 below:

Table 44: Thermal parameters of the main building components.

Construction Element	U-Values [W /m^2/K]	G-Values	Light Transmittance [LT]
External Walls	0.22		
Floor	0.24		
Roof	0.16		
Windows	1.40	0.45	71%
Doors	2.20		

2.1. Layout and Occupancy

The common study areas are located on the first and second floors of the building and can be accessed directly via the main staircase. For the purpose of this research, we have divided the study spaces into 5 different zones that have distinctive characteristics (Figure 1). Zone 1, 2, and 3 belong to the library (Firstly floor), zone 1 is dedicated to studying using university computers, with some group work areas. Zone 2 is a quiet study area and zone 3 is a silent area. Zone 4 is dedicated to group work (Second floor) comprising eight rooms, among which only two of them have windows. Zone 5 is a tutorial space (Second floor), furnished to allow group seating. It also has direct access to the terrace located on the second floor. The majority of the openable windows face southeast and southwest.

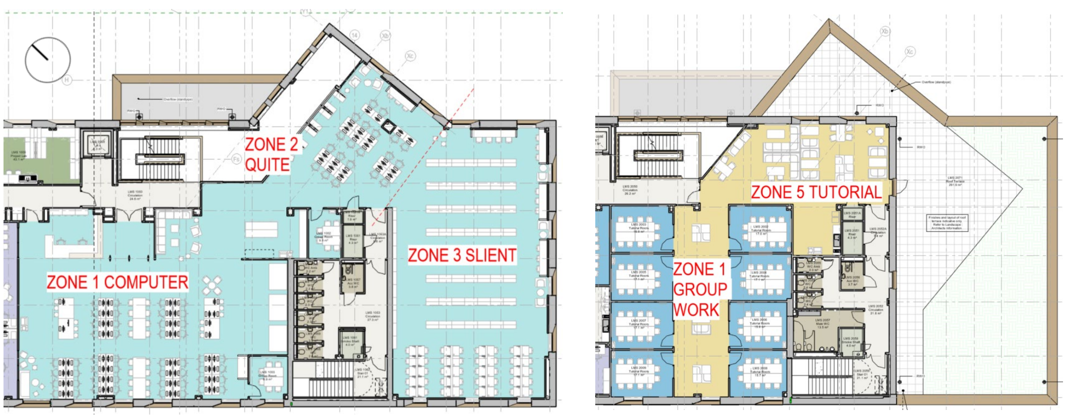


Figure 79: Frist floor (left) and second floor (right) study spaces and surveyed zones

Table 2 shows data used for the simulation model of the study spaces, including the area of each zone, the number of openable windows, predicted peak number of occupants, ventilation rate and lighting setpoint. Zone 1,2,3 were modelled as one zone in the simulation model.

Table 45 Occupational setpoints per zone.

Zone	Area m^2	Estimated peak number of occupants	Ventilation rate l/s/person	Lighting lux	Openable windows
Zone 1, 2, 3	658	256	6.1	500	17
Zone 1	320	150	6.1	500	6
Zone 2	90	50	6.1	500	2
Zone 3	248	56	6.1	500	9
Zone 4	18x8	10x8	10	300	2
Zone 5	161	30	5	500	2+1(door)

2.2. Environmental control strategies

The study spaces adopt a hybrid ventilation system. Due to the acoustic constraints of the local environment and to achieve compliance with Building Bulletin 93 (BB93, 2015), the use of natural ventilation throughout the year is not possible. A hybrid ventilation system is provided to library spaces to provide ventilation of the areas without compromising internal acoustic requirements (55dBA). Learning spaces are heated 24 hours during term times based on a setpoint of 21°C between 7:00-18:00 and 19°C throughout the rest of the day and night. Although the ventilation system has the active cooling capability, when assessed against CIBSE overheating criteria (CIBSE TM52, 2013), considering manually openable windows and the threshold of allowed overheated hours, overheating risk was not detected in the model for the studied areas. Therefore, all the studied zones are equipped with no active cooling.

The hybrid ventilation units are located at a high level within the window module. They are hard connected to intake and exhaust louvres within the window module to provide fan-assisted supply and extract to each space. There is no separate mode for winter or summer ventilation. The units are provided with a wall-mounted controller with integral temperature and CO_2 sensors, accessible by the occupants. The control allows the ventilation system to be boosted temporarily (for an hour) or turned off. The first-floor library has LCD interface screens with remote temperature and CO_2 sensors controlling groups of three hybrid vent units. However, the LCD screens are located behind the library reception and are only allowed to be controlled by library staff. The ventilation system is also automatically controlled and is triggered by the CO_2 levels. If the CO_2 level in the zone exceeds 1000ppm concentration level, the system will increase the flow of external air into the room until the CO_2 level is reduced to under 900ppm. The hybrid ventilation unit has a sound pressure level of 31.9 dBA MAX during daytime hybrid mode (180 l/s).

Lighting strategy follows (CIBSE LG05, 2011)– Lighting for Education. Lighting controls operate based on daylight availability. Lighting controls can automatically detect absence and can be manually turned off or dimmed.

3. Research design

The research design incorporates both quantitative and qualitative data collection. The first part of the data is collected using a questionnaire survey. The questionnaire survey includes two sections: Demographics (age, gender, how much time spent in the study per day and week, students' preferred study area, thermal sensitivity, clothing level and metabolism level prior to entering the study space), as well as environmental comfort (thermal comfort, ventilation, humidity, lighting and acoustics). Each category of the environmental comfort questions adopted a similar structure. It asked the occupants to rate their sensations using a 7-point Likert scale (ANSI/ASHRAE 55, 2010), and their adaptive behaviour, followed by any further comments they wanted to express. Qualitative comments were analysed using a statistical analysis software NVivo (NVivo, 2022).

The survey was conducted by student researchers between 11.05.2022 and 17.05.2022 on 5 weekdays from 9 am to 5 pm. This period was chosen to maximise the respondent rate, as it was just before the exam period. The researchers visited the learning spaces 7 times a day at one-hour intervals. In total, 206 questionnaires were filled in by students who use the study spaces, which gives a confidence level of 95% and a margin of error of 5% (based on the 500 students population using the study spaces). Questionnaires have been collected on-site using paper forms and later transferred to a digital platform for analysis.

The second part of the data collection is the on-site observation made by student researchers. Their observation includes the number of occupants per zone, how many windows were open, as well as temperature and CO_2 values displayed on the screens in each zone at one-hour intervals.

4. Questionnaire survey results

4.1. Demographics and space preference

Demographic questions showed that more females (67%) than males (31%) answered the questionnaire. 49% were aged between 18-20; 41% were 21-25 and 10% were above 25 years old. As shown in Figure 2, more female participants (45%) were sensitive to cold than males (27%). The clothing level for over half of the respondents is moderate, a quarter of the respondents wear heavy clothing. The majority have engaged in a low metabolic rate activity.

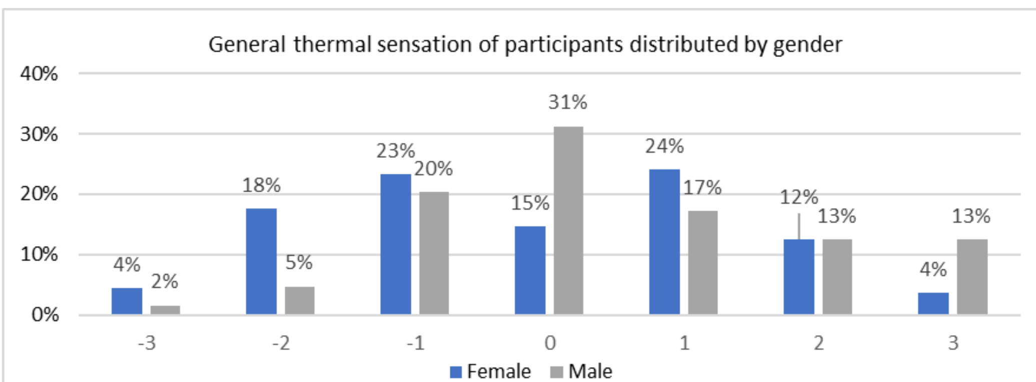


Figure 80 General thermal sensation of participants distributed by gender (-3 very sensitive to cold, 3 very sensitive to heat)

The majority of the students (43%) do mixed group and individual work in the study areas, and 38% of respondents use the study spaces mainly to do individual work (90% of the time). Students' preferences for study space show a bigger demand for focused and private space (31.1%). At the same time, 15% of the answers reveal a need to be able to choose a space where they can socialise with their fellow students. Environmental concerns (lighting, thermal and acoustic) are mentioned in 36.3% of the answers. Spatial quality appeared in 25% of the answers (including the size of the space/work surface, cleanness, window view, comfortable seating, and colour of the wall), in which window view and comfortable seating were the most mentioned qualities. 13.8% of the answers refer to the facilities and connectivity of the study space (such as computers, charging ports, etc).

4.2. Environmental conditions

53% of the respondents found natural light neutral and evenly distributed. Whereas artificial lighting was found to be significantly brighter (Figure 3). Only 29% of the respondents felt that they could adjust the lighting when needed. More than half of the respondents who felt they couldn't adjust the lighting reported that they didn't know where the controls were, and 15% of them didn't know how to use the controls.

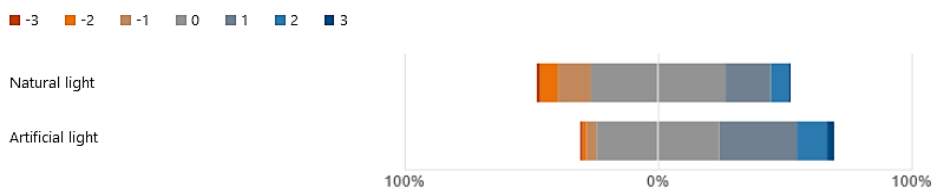


Figure 81 Responses on lighting (-3 too dull, 3 too bright)

Although the majority of the respondents found the temperature was neutral, 23% of the respondents stated it was warm and 10% stated very warm. As shown in Figure 4, Zone 1, 4 and 5 were found to be particularly warmer than other zones in general. Students have reported that it can get too warm and stuffy in smaller rooms (Zone 4). Some students reported that the temperature could get cold during the night and on cold days and stated 'I appreciate windows need to be opened For covid / Fresh air but should be minimised on cold days.

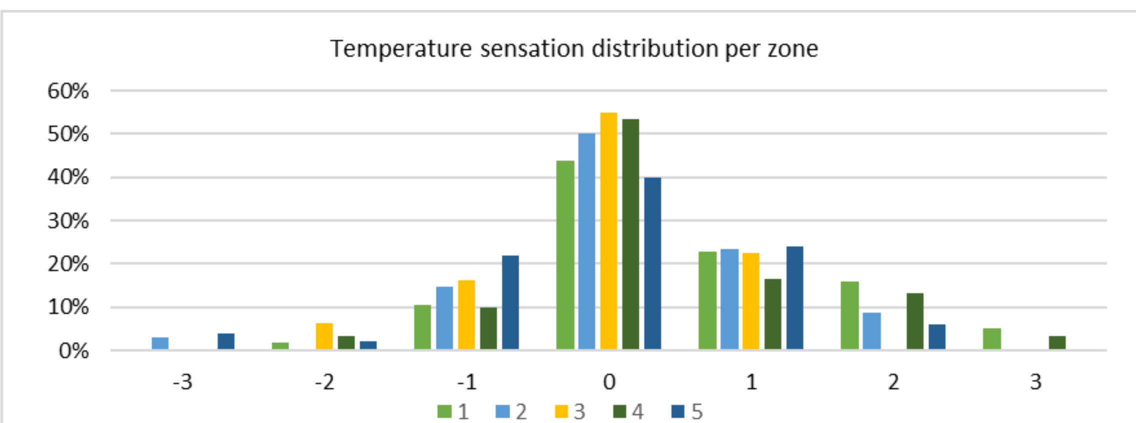


Figure 82 Temperature sensation distribution per zone (-3 too cold, 3 too warm)

To a multiple-choice question on how to mitigate thermal discomfort, the majority of the respondents showed sufficient adaptive behaviours such as changing clothing (58%) and/or opening/closing windows (48%) and having a hot or cold drink (27%). However, 17% of the respondents indicated they were unable to adjust the indoor temperature. They found the control to be 'confusing', and were only able to adjust the fan speed rather than temperature. 81% of the respondents felt neutral about the humidity, and only 15% of respondents considered the indoor environment to be slightly humid.

While over half of the responders found the ventilation neutral. Zone 1 (computer area) was found to be slightly stale in general. 64% of respondents stated that they would open/close the window to adjust the ventilation rate if they felt discomfort. 18% would change their location instead. One respondent located in Zone 4 stated that 'the rooms without windows have poor ventilation, causing headaches'. It is not surprising because, in Zone 4, only two study rooms have external windows. students in those rooms that do not have windows can only use a mechanical system to boost the ventilation for a short period of time. Food odour has been mentioned by many students in the survey where increased ventilation was desired.

Although 58% of the respondents found noise levels neutral, Zone 1 computer area and Zone 5 tutorial area were found to be slightly noisy. The main cause of the noise was believed to be generated indoors by the users of the study areas (62%), and road/traffic noise (25%). Noise generated from mechanical services (including computer noise) was only reported by 8% of the surveyed users. The majority (80%) of the respondents chose the option of 'putting on headphones' in mitigating the unwanted noise whereas a small portion of the users (21%) also indicated the option of changing location.

5. Observation results

Occupancy level per zone and the number of open/closed windows were documented by the researchers. Zone 1 (computer area) is the busiest space throughout the observation period. It is not surprising considering Zone 1 has the largest capacity among all five zones. However, the maximum occupancy level in Zone 1 and 2 (quiet) are both less than 40% of the designed capacity. Zone 3 (silent) has reached a higher 61% of the designed capacity. Zone 4 (group work) has not reached its capacity either, with only 27.5% at the maximum level. Zone 5 (tutorial) has demonstrated a higher usage rate of 57%.

As can be seen from Figure 5, the gradual increase of the external temperature over the monitored 5-day period has been reflected in the internal temperature across all zones. Zone 1 has the highest average and maximum temperature, followed by Zone 5. The highest temperature was recorded to be more than 25 °C on multiple occasions. It is unsurprising given that Zone 1 has the highest occupancy rate, as well as additional internal gains from the computers. This also correlates with the questionnaire survey where Zones 1 and 5 were considered to be warmer than other zones.

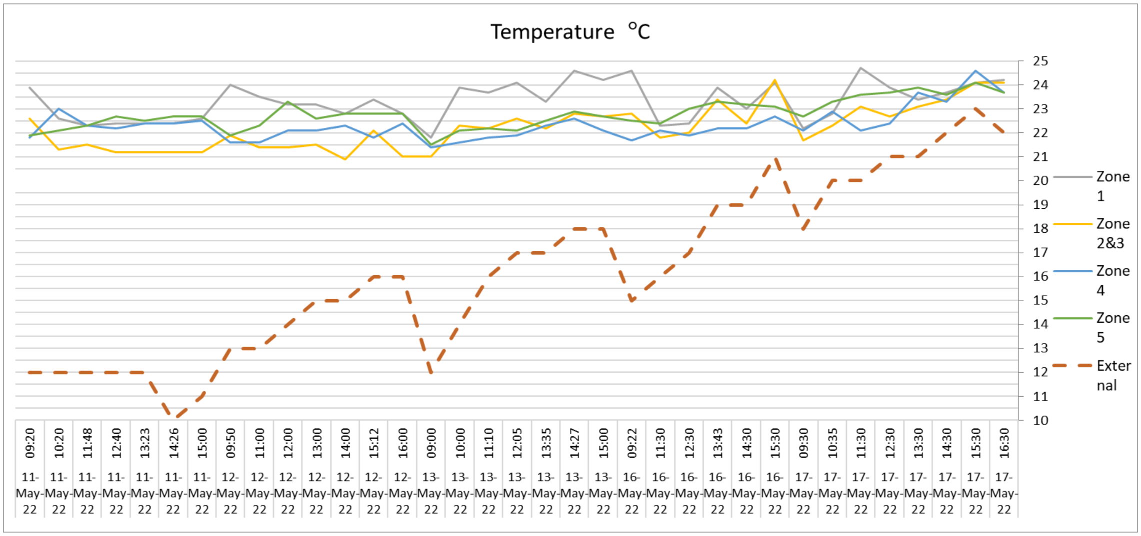


Figure 83 Monitored temperature per zone and exterior temperature throughout 5 days (Zone 2 and Zone 3 were monitored together with one data logger

The monitored CO_2 data (Figure 6) shows a general fluctuation between 400 ppm and 900 ppm, except for Zone 5. The highest CO_2 levels are observed in Zone 4 and 5, in one case reaching 1048ppm, which is over the ventilation trigger set point.

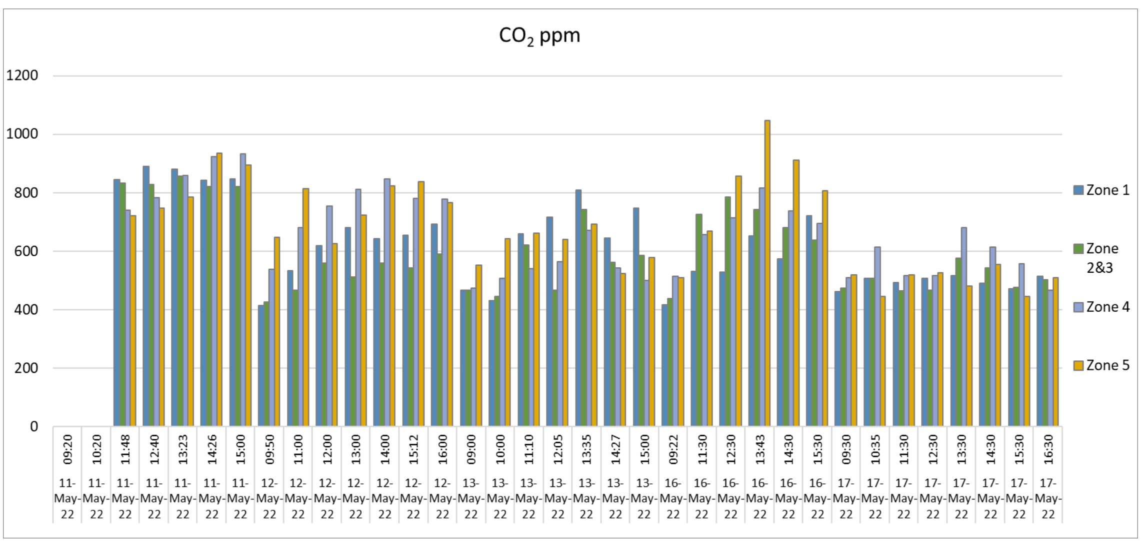


Figure 84 Monitored CO2 meter readings per zone throughout 5 days

Window openings were also recorded during the observation period. The result shows that during the 5 days, occupants started to open windows when the internal temperature reached 21 °C and above. Over 50% of the windows were open on the fifth day when the internal temperature across all zones reached 24°C. However, during the time period when the recorded CO_2 level in any zone reached over 900ppm

(Zone 4 and 5 on day 1 and Zone 5 on day 4), no window was open. In other words, the occupants were more likely to open windows based on thermal comfort rather than air quality.

6. Discussion and Conclusions

The comparison of the simulated model result based on pre-pandemic predictions and the result of the post-pandemic POE research shows a few discrepancies. During the observed period, which was also predicted to have one of the highest volumes of occupancy, the occupancy level on average across all 5 zones remained far below the designed occupancy level. Therefore, the hybrid ventilation system, which was set to be triggered by CO_2 levels, was activated only once throughout the observation period. The simulation model did not predict overheating risk based on CIBSE TM52. Therefore, no cooling was set despite the system having the capability. However, the questionnaire survey revealed that approximately a third of the surveyed occupants found the spaces warm or very warm, despite the majority of the occupants self-identified as sensitive to cold. Most of the occupants preferred opening/closing windows to mitigate thermal discomfort. This behavioural adaptation was observed clearly across all zones, at multiple times throughout the day when internal temperatures were 21 °C-25 °C. Since the designed hybrid ventilation system is triggered only by CO_2 measurement rather than the indoor temperature, the passive cooling strategy became insufficient when the indoor temperature is above comfort level. It relied on behavioural adaptations such as window opening to achieve thermal comfort. As a result, the occupants who preferred quiet or silent study zones reported noise concerns due to the traffic noise being carried through the opened windows from the adjacent busy road. Therefore, despite building simulations failing to detect overheating, the result suggests that the ventilation systems need to be reconfigured to minimise the need for opening windows and could also be activated by temperature instead of solely relying on CO_2 levels.

Adaptive comfort model advocates occupants' behavioural adaptations and personal controls (Baker, 1995). However, providing personal control in open-plan spaces was found to be usually costly and impractical. This leads to temperature and lighting being controlled automatically based on average standards (Myerson et al., 2010). In this research, the respondents repeatedly stated that they do not know how to operate environmental controls. As occupants were only allowed to boost ventilation for a limited time and operate the lighting within a limited range. Behavioural adaptations such as opening/closing windows may be effective for negotiating thermal comfort for those who sit next to the windows. For those who sit in the middle of an open-plan library, however, there are fewer means to adapt.

Furthermore, educational buildings, university buildings, in particular, are occupied at a minimum level, if not completely empty, out of academic term. Unoccupied term falls within the hottest summer period - June, July, and August, when overheating is most likely to occur. Therefore, using CIBSE overheating criteria is unlikely to predict overheating risk. However, study spaces are most likely occupied by students at peak levels during May and early June, when students need maximum concentration and productivity in preparation for their exams. Even though no overheating was predicted in the building performance simulation, high-temperature days still occur during those two months where thermal discomfort would affect students' learning greatly. Adaptive behaviour such as opening windows might not be always suitable due to the outside noise level. This raises the question of whether overheating criteria should be tailored to suit the usage of the building in question and the sensitivity of the occupants' task to thermal discomfort. On the other hand, the window-opening behaviour will become more interesting to examine on colder days and in winter when the legacy of the pandemic could guide such behaviour in a way that bypasses occupants' thermal comfort and ventilation need. More research is needed to explore such occupancy and behaviour patterns and the potential for more energy-efficient practices that are more suitable for a post-pandemic teaching and learning space.

Acknowledgements

This research is made possible by the UROS funding provided by the University of Lincoln, which allowed four student researchers to participate in research design, data collection and analysis. The student researchers are William Pettifer, Alicia Tribe, Gracie Longworth and Kieran Taylor.

References

ANSI/ASHRAE 55, 2010. Environmental Conditions for Human Occupancy, Atlanta, GA, USA: ASHRAE American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

Baker N V, Standeven M A, 1995. A behavioural approach to thermal comfort assessment in naturally ventilated buildings. CIBSE National Conference Proceedings.

BREEAM, 2022. [Online] Available at: https://bregroup.com/products/breeam/how-breeam-works/

Barbhuiya, Saadia, Barbhuiya, Salim, 2013. Thermal comfort and energy consumption in a UK educational building. Build. Environ. 68, 1–11. https://doi.org/10.1016/j.buildenv.2013.06.002

BB93, 2015. Building bulletin 93, Acoustic design of schools: performance standards, Guidance, Department of Education.

Carlucci, S., De Simone, M., Firth, S.K., Kjærgaard, M.B., Markovic, R., Rahaman, M.S., Annaqeeb, M.K., Biandrate, S., Das, A., Dziedzic, J.W., Fajilla, G., Favero, M., Ferrando, M., Hahn, J., Han, M., Peng, Y., Salim, F., Schlüter, A., van Treeck, C., 2020. Modelling occupant behaviour in buildings. Build. Environ. 174, 106768. https://doi.org/10.1016/j.buildenv.2020.106768

CIBSE LG05 . (2011). Lighting for education. London: CIBSE.

CIBSE TM52. (2013). The limits of thermal comfort: avoiding overheating in European buildings. London: CIBSE.

Felstead, A., Reuschke, D., 2020. HOMEWORKING IN THE UK: BEFORE AND DURING THE 2020 LOCKDOWN. https://doi.org/10.13140/RG.2.2.10546.63687

Franceschini, P.B., Neves, L.O., 2022. A critical review on occupant behaviour modelling for building performance simulation of naturally ventilated school buildings and potential changes due to the COVID-19 pandemic. Energy Build. 258, 111831. https://doi.org/10.1016/j.enbuild.2022.111831

Gui, X., Gou, Z., Zhang, F., Yu, R., 2021. The impact of COVID-19 on higher education building energy use and implications for future education building energy studies. Energy Build. 251, 111346. https://doi.org/10.1016/j.enbuild.2021.111346

Jowkar, M., Rijal, H.B., Brusey, J., Montazami, A., Carlucci, S., Lansdown, T.C., 2020. Comfort temperature and preferred adaptive behaviour in various classroom types in the UK higher learning environments. Energy Build. 211, 109814. https://doi.org/10.1016/j.enbuild.2020.109814

Lawrence, R., Keime, C., 2016. Bridging the gap between energy and comfort: Post-occupancy evaluation of two higher-education buildings in Sheffield. Energy Build. 130, 651–666. https://doi.org/10.1016/j.enbuild.2016.09.001

Myerson, J., Bichard, J.-A., Erlich, A., 2010. New Demographics, New Workspace: Office Design for the Changing Workforce. https://doi.org/10.4324/9781315597928

NVivo, 2022. [Online] Available at: Statistical Analysis Software for Mac and Windows | JMP

Ricciardi, P., Buratti, C., 2018. Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions. Build. Environ. 127, 23–36. https://doi.org/10.1016/j.buildenv.2017.10.030

Shi, X., Si, B., Zhao, J., Tian, Z., Wang, C., Jin, X., Zhou, X., 2019. Magnitude, Causes, and Solutions of the Performance Gap of Buildings: A Review. Sustainability 11. https://doi.org/10.3390/su11030937

Regenerative Design Performance assessment: a critical review

Fernando Pavez[1], Duncan Maxwell[2] and Victor Bunster[3]

[1, 2, 3] Building 4.0 CRC, Caulfield East, Victoria, Australia; and
[1, 2, 3] Monash University, Melbourne, Australia. {fernando.pavezsouper [1], duncan.maxwell [2], victor.bunster [3]}@monash.edu
0000-0003-2145-2631[1], 0000-0002-9039-1441 [2], 0000-0002-7665-4567 [3]

Abstract: The global sustainability movement has developed a variety of new design and building methodologies. Regenerative Design (RD) focuses on understanding the dynamic relationship between people, a place and ecosystems. By weaving together the natural and social systems, RD maximises humans' and nature's creativeness and abundance. Projects are not seen as an end product but rather as the beginning of a process that will continue to evolve long after completion. RD approaches to building are receiving increased attention in industry and academia. In this context, developing a clear shared understanding and evaluating the practical implications of this new approach remains an open issue. This critical review attempts to fill this gap by reviewing the concept, its aims, the existence of any performance measurement criteria, design methods and the expected outcomes of the RD approach to design and building. A summary process workflow diagram and an Assessment Methodology (AM) for evaluating RD project progress are proposed. The AM is presented as a series of questions to be answered qualitatively and quantitatively to aid track progress through time. Both diagram and AM may become valuable tools for further discussion about the methodological implications of RD project delivery for the architecture profession and for upgrading architectural education accordingly.

Keywords: Regenerative; circular; design; sustainability.

1. Introduction

The building sector accounts for nearly one-third of the global energy consumption and more than half of global electricity use, and these proportions are expected to grow strongly by mid-century unless strong action is taken (IPCC, 2014). In many countries, it is the biggest driver of resource consumption and waste generation (Pickin et al., 2020; Yu et al., 2022; Zhang et al., 2022). Even in best-case policy scenarios, the energy use in buildings will continue to rise unless effective improvements are implemented in building construction globally (IPCC, 2014). Buildings can also play a critical role in a low-carbon future only if aggressive and sustained action is taken to address “every aspect of the design, construction, and operation of buildings and their equipment around the world” (IPCC, 2014, p.677)—in particular, the linear and fragmented design process.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 504–513.*

Current green building assessment tools contribute to reducing the environmental impacts of the built environment but not to the longer-term regeneration of nature (Cole et al., 2012b). The Regenerative Design (RD) approach promotes a framework for doing so.

According to Wahl (2016), the threat of unstoppable climate change and resource depletion makes humanity aware of its interdependence and acknowledges its dependence on the planet's life support system. Then, the global creative challenge is to evolve buildings and all human activity into a life-sustaining influence on ecosystems globally: to shift from an industrial growth society based on the exploitation of natural resources into a life-sustaining society based on regenerative processes.

This paper briefly presents the current approaches to sustainable design, the main features and process of RD projects, and finally, discusses the characteristics of the regenerative approach to design—focusing on its ethical, process, practical and assessment implications. The final chapter includes the proposal of a new process diagram and an assessment method for the regenerative design and delivery process.

2. Current sustainable design approaches

The terms 'sustainable design', 'sustainable building' and 'green building' are commonly used with no distinctions (Cole et al., 2012b) and are often assessed through rating systems. They usually credit reducing negative impacts such as emissions, resource use, waste, and health and comfort problems (Cole et al., 2012b). These efforts tend to translate into the design as isolated 'box checking' attributes rather than responding to local ecological and social contexts, producing creative synergies, or closing resource loops. Thus, they promote reductionist and fragmented thinking (Reed, 2007).

Green assessment tools are conceived as voluntary mechanisms for objective communication, expecting that eventually, their widespread adoption could transform the market towards better environmental performance. However, they are still far from becoming general to impact the whole building sector (Cole, 2012).

Some of these approaches and methodologies may be considered precedents to RD, such as:

- **Integrative Design Process.** A collaboration work methodology in which architects engage as facilitators with a larger group of stakeholders (Cole et al., 2012b). It requires design teams to collaborate iteratively to optimise project outcomes as a whole instead of its parts (AIA, 2007; Vaidya et al., 2009)—an essential characteristic of RD.
- **The Living Building Challenge (LBC).** A certification programme that pursues more extraordinary biodiversity, soil health, working with local climate, culture and place, and a profound sense of fairness and equity (Hes & du Plessis, 2015, p.170). The RD approach also aims for better health and biodiversity by looking into a local place.
- **Permaculture.** A landscape design process, although not mainly focused on buildings, looks at relationships among communities of organisms to support larger-scale ecosystems to create productive landscapes. This design process starts by observing and building a connection with the site, reading the landscape to understand existing flows and feedback patterns. The design comes by combining system elements so that the exchanges of energy, nutrients and services are optimised to get maximum useful output for input (Hes & du Plessis, p.80). Permaculture's basic design concepts—feedback loops, working with flows and combining system elements—are also extensively applied in RD.

- **Circular Economy.** Circular Economy (CE) understands the regeneration of nature as one of its fundamental principles—besides eliminating waste and pollution and circulating products and materials at their highest value (EMF). It does so by extracting fewer resources, building natural capital in soils and increasing biodiversity through returning biological materials to the earth (EMF, 2022). When applied to the built environment, it has been named ***Circular Construction*** (Almeida et al., 2022).

The regenerative aim of CE, the design processes from permaculture, and the overarching vision of LBC converge on the regeneration of nature for the next step in the built environment evolution.

3. Regenerative design: what is it about?

John T. Lyle introduced the term Regenerative Design (RD). As a response to the current linear throughput models that structure human habitats, which lead to the degeneration of the systems that supply energy, materials and ecosystemic services to cities, he proposed regenerative systems that "provide for continuous replacement, through its own functional processes, of the energy and materials used in its operation" (Lyle, 1994, p.24). Achieving continuous replacement implies shifting design from simple, mechanised technologies to greater complexities rooted in natural processes for energy conversion, water treatment, cycling nutrients and waste assimilation (Hes & du Plessis, 2015, p.85).

In RD, the design team has to ensure the project enhances the health, diversity and resilience of the Social-Ecosystem Systems (SES) by using collaboration and systemic optimisation as the most effective survival strategies found in Nature (Wahl, 2016). The main design patterns proposed by Wahl may be summarised as follows:

- **Symbiosis**. Mutually beneficial and reciprocal relationships.
- **Diversity**. Decentralised and networked distribution of vital systems functions.
- **Redundancy**. A critical risk management strategy: disrupting an essential role in one place does not result in systemic failure.

Lyle (1994) argues that RD aims not just to design a built environment that does not deplete resources or damage natural systems, but through buildings and cities to continue and further develop the ecological functions and the flows of energy and materials of a place, incorporating the complex communities of organisms by joining the web of the ecological community. Hence, RD shapes buildings and urban form to foster community interaction, social cohesion and resilience, developing the systemic ability to respond and adapt to perturbations and fluctuations (Hes & du Plessis, 2015). In response to the "homogenising effects of global culture and the elimination of biodiversity destroying complexity" (Cole, 2012), p.47), RD aims to create the "best vitality that we can create in this place, and in a way that it will continue to inspire and involve" (Hes & du Plessis, 2015, P.135).

3.1. A fundamental paradigm shift

Capra (1997) describes the relationship between humans and the biosphere as dysfunctional—an indication of an anthropocentric worldview that considers humans as "*above or outside of Nature … and ascribes only instrumental or 'use' value to nature"* (p.7). He suggests shifting to an eco-centric view, understanding Nature and humanity as an interconnected and interdependent network of social-ecological systems that co-evolve together.

Since RD works continuously with people and natural processes, it requires many cultural and scientific information for design and management. It suggests a breakdown of hierarchical organisation, broader participation in decisions, and complex, interactive information flow networks instead of hierarchical power transmission structures (Lyle, 1994).

Working on RD projects requires understanding complex adaptive systems. These are characterised by the dynamic interactions between their parts and adjusting to their environment by unpredictably self-organising or changing their composition to fit changing environmental patterns (Hes & du Plessis, 2015). The closest example is a city: removing or changing any of its parts (subsystems) – its transport, energy or water infrastructure networks; all buildings; economy; inhabitants and culture; or its particular environmental endowments – may result in a fundamental and unpredictable change to the entire urban system's behaviour. Therefore, one of the critical skills for a regenerative designer is systems thinking.

3.2. A new design methodology

Most authors posit RD as a process that starts by developing a '*story of place*': a narrative and diagrams to connect people to the project's unique character, essence and potential. This narrative is complemented with a geographic, cultural, economic, climatic and ecological assessment of the site and its dynamic relationships to create a holistic understanding of the site. Cole (2012b) describes 'place' as the inner set into the 'human systems' group, which is nested into the 'ecological systems' group.

Once having a thorough understanding of '*place*' comes the search for a shared vision. This vision represents the full potential of the project and the aims and aspirations of the design team or the stakeholders, usually through facilitated charrettes as '*reflective community dialogue*' (Hes & du Plessis, 2015; Hoxie et al., 2012; Mang & Reed, 2012; Reed, 2007; Wahl, 2016).

The next phase involves developing a concept design, translating the previously defined vision into goals and strategies for a systems design that harmonises the relationships between the built environment and the ecosystems that nurture it. It is developed collectively through charrettes. Some authors mention only the client and design team (Reed, 2007), while others say open community dialogue (Hes & du Plessis, 2015; Wahl, 2016) or both (Hoxie et al., 2012), but all agree on gaining consensus and community ownership to align and verify goals, setting targets, and prioritising strategies.

The planning and roadmap setting are performed iteratively with the community (Hoxie et al., 2012). Then, indicators and metrics are set to monitor progress and receive ongoing feedback (Reed, 2007).

The detailed design documentation and construction are worked through the iteration of ideas in an integrative process for optimising each system in relation to the whole (Reed, 2007). These processes have not received much attention in the RD literature.

After project implementation, a 'co-evolution' process is described as ongoing participative feedback and learning engaging the community in iterative cycles of action and reflection (Reed, 2007). An RD project does not exist in a steady state but as an evolving process of dynamic systems (Mang & Reed, 2012). Some authors even mention growing the stakeholders as regenerative agents by keeping a shared vision and opportunities created by the project (Hes & du Plessis, 2015).

4. Implications of the regenerative approach to design

Although first formulated nearly 30 years ago, RD is still a novel approach to design. It addresses not just the urgent climatic and social crises but proposes a long-term new ethical understanding of the human-natural relationship. The design methodology of RD is not well defined in the literature. Still, there is a broad consensus about features such as open participation, the iterative process, systemic thinking, and visioning for the future mentioned above. However, how and if the performance of an RD project can be assessed remains an unattended issue.

4.1. An emerging design ethic

Ethics' concern is the relationship between the individual and the collective, differentiating social from antisocial conduct as a way of evolving modes of cooperation between interdependent individuals and groups. In RD, this definition gets broader by including the human family and the community of life as a whole. Wahl (2016) argues that a new ethic is needed, one that "*changes the role of Homo sapiens from conqueror of the land community to plain member and citizen of it*" (p.132). He then proposes that the aim of any design effort should be to design for human *and* planetary health.

According to Hes & du Plessis (2015), the point of departure for RD is nature—pointing out that it provides not only the context of RD work but also valuable lessons that designers may observe and learn. These lessons include how it operates for optimum efficiency and no waste using strategies such as excess storage, resource sharing, and ongoing feedback to regulate energy and material flow to avoid over-consumption.

Reed (2007) argues that regeneration is more than making a landscape and local habitat—a place—more productive and healthier but engaging the entirety of what makes it healthy. Furthermore, if holistic thinking goes beyond the immediate concerns of present generations, the aim must be "*to create abundance for future generations*" (Wahl, 2016, p.180). Hence, buildings should not be judged based on how they look but on a deeper questioning of how they were made, out of what materials, by whom and under what work conditions (Wahl, 2016). This consideration has a link to the concern about the origin of materials, as in Circular Construction.

Therefore, the RD approach changes the aim from '*doing less bad*' to creating '*more good*' beyond sustainability but also the ethical and aesthetic judgements. This mind shift change may produce not just how designers think about their work and how to teach it, but even a rethinking of what is sought for and awarded in design competitions.

4.2. Regenerative design process innovation

Reed (2007) characterises RD as a holistic, living systems approach—in contrast to the still fragmented, high-tech-based *sustainable design* approach. It emphasises systems thinking: instead of isolated parts, it understands the context of relationships within the parts and how they influence one another within a whole. Systemic thinking sees the whole as always different from the mere sum of the parts (Capra, 1997).

Moving from *green design* to RD requires some conceptual and practical changes and the tools required. The complex, non-linear interdependencies, in which stakeholders are co-creators of its environment, require a rethinking of the whole design process and the role of designers—requiring them to include many more stakeholders in the decision-making process while moving from being '*experts*' to '*co-learners*' within a community (Du Plessis & Cole, 2011).

Another required mindset shift goes from the current prescriptive and fixed design to build to a reflective, responsive, flexible process that tries to anticipate scenarios because no preconceived formulas exist (Mang & Reed, 2012). This means that usual assumptions need to be challenged, wondering about new possibilities, and breakthrough innovations, by asking questions such as '*why*' and '*what if*' while implementing improvement strategies (Wahl, 2016).

In RD, community dialogue is an iterative process consisting of feedback loops that might refine an idea or even change it entirely because the aims and assumptions may evolve through time (Hoxie et al., 2012). This iterative, participatory, systemic and envisioning design process requires a graphical representation to help future regenerative designers understand it as a whole to apply it more effectively. The permaculture design process is usually presented as a spiral, although it does not give a sequence of design steps. Mang and Reed (2012) propose an artful representation of the RD process in which the design phases move in an ever-upward spiral process in a schematic fashion that does not consider the ongoing feedback loop in the final co-evolution phase.

Figure 1 displays a six-step spiralling RD process that starts from the place and ends in a feedback loop of planning, implementation and reflection. The complete process does not end because the RD process finalises with an ongoing participative feedback mechanism called 'co-evolution' in which the community is expected to develop iterative cycles of planning, action and reflection. In this diagram, the patterns under 'Place' represent the social and ecological interrelated systems present in the site and its context. It includes a short description of the main activities to be performed in each of the six steps.

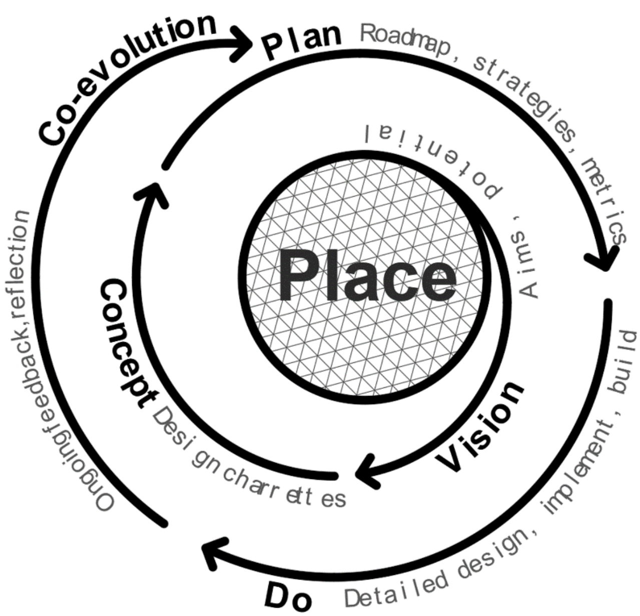


Figure 1. The regenerative design and delivery process.

4.3. Fostering open participation

A transition in organisational structures from rigid vertical hierarchies to more flexible network-like arrangements is underway (Lyle, 1994). In RD, broad participation must expand the information base by including at least interdisciplinary teams. The collaborative co-creation process proposed by Hes & du

Plessis (2015) suggests that there are at least three groups of stakeholders that should be around the table—aside from the design team: the community, the natural systems with which the project will be in a direct relationship, and the people who will be responsible for holding the vision into the future. Under this framework, collaboration is not meant to be about a once-off charette or public workshop but an iterative process of identifying shared values and new relationships and opportunities. It is an ongoing process of co-creation and co-evolution (Hes & du Plessis, 2015) which involves the designers transforming themselves into agents of transformation (Mang, 2016).

Participation does not end when a project is designed or built. The community, officials and implementation partners are expected to relate the project to other local initiatives, support the action plan implementation and help engage stewardship of the plan in the future. Community dialogue provides continuous feedback along the process to check, refine, revise or expand for adapting previous decisions to changing parameters. This dialogue helps empower community members to take ownership of the project goals, action plan execution and ensuring progress (Hoxie et al., 2012). Some regenerative technologies such as water retention, solar heating and cooling, and most means for waste recycling, are necessarily localised, small-scale and inseparable from the local community. Therefore, communities are a vital system within the ecosystem of relationships of a place, as well as strengthening human relationships within them (Lyle, 1994).

By participating in the co-creation and co-evolution of the social-ecological systems where they live, communities may become part of '*autopoiesis*', a process identified as the general pattern of organisation common to all living systems (Capra, 1997). "*In a living system, the product of its operation is its own organisation*" (Maturana, 1980, p.82)—viz. Autopoietic organisations continually make themselves.

According to Hoxie et al. (2012), the design team is responsible for fostering a regenerative mindset in the community meetings. The regenerative mindset requires not just creating an open environment that is open to collaboration but also discovery, support, responsibility, reflection and adaptation. Hence, designers will need to develop new skillsets such as listening, group facilitation and team building, as well as flexibility and adaptability for seeking solutions to priorities that evolve together with knowledge and project definition through time.

In RD, designers assume a facilitator role in the dialogue between all parties involved, including the local ecological systems. However, facilitation is not a skill commonly taught to designers, as it is the antithesis of the current expert-driven design culture in which the consultant knows what is best (Hes & du Plessis, 2015). Positive participation and imaginative visions of the future must be stimulated when discussing locally-based community issues and exploring planning alternatives. However, confrontation, deadlock, and disintegration may happen, avoiding them and guiding the process in positive and creative directions. Instead of dividing those people involved into proponents and opponents, RD must fuel debate among varied options (Lyle, 1994). To develop and maintain healthy, respectful and mutually beneficial relationships requires the ability to listen to community members: listen to what matters to them, their history, their values and dreams (Hes & du Plessis, 2015) and the underlying beliefs that shape the designer's strategies and methods (Mang & Reed, 2012).

4.4. How can RD project performance be assessed?

Most current green building assessment methods are based on sets of indicators of accepted actions and components, which can be translated into quantitative measures such as ratios of energy use or carbon emissions per square metre. However, as RD focuses on the capability of a project for repairing degraded social and natural systems while enabling them to co-evolve positively through time, their success cannot be described or assessed or described so easily.

According to Cole (2012), since the performance of an RD project cannot be known at the design stage, it should provide a measure of the potential invested in developing its ability to support a future co-evolution of human and natural systems. He proposes to apply the usual and well-established building performance metrics such as energy or water consumption in combination with this method.

Wahl argues that under whole systems thinking, there is no use in measuring the efficiency or productivity of a part of a system (e.g. a building) if it produces damage or excessively consumes the natural processes that maintain systemic health. For example, an RD project may consume nature's flows but conserve the stocks while strengthening the local economy, human resources, and civil institutions may increase the social potential (Wahl, 2016).

Because natural systems evolve over long periods, an RD project is a hypothesis that may take decades—or even a century in the case of some forests—to complete and assess. Even the original community members may have moved elsewhere, making it especially difficult to plan, evaluate project success, and ensure ongoing decision-making and feedback. It is unclear who should monitor progress, how it should be funded, and how design decisions can be corrected even after project completion (Tainter, 2012).

The performance measurement of RD projects remains an open question, as there is no available certification scheme or rating system available. Then, how can comparability and improvement be ensured, and most importantly, how can the stakeholders—especially project owners— know if the project achieved specific success criteria? Even though metrics tend to be reductionist and fail to meet overarching ambitions, some metrics need to be used in order to know if a project has been successful or not. However, RD may need different methodologies than the ones used currently in sustainable design. The reviewed literature provides the following essential project features:

a. **Autopoiesis.** Does the project catalyse autopoiesis—the continuing process of community participation in the co-creation and co-evolution of the social-ecological systems where they live, hence continually making themselves?
b. **Co-evolution feedback loop**. Does the project create the conditions for increasing health, resilience and vitality of Social-Ecosystem Systems (increased diversity and resilience, bio-productivity, ecosystem functions, social cohesion, collaboration and well-being) over time?
c. **Symbiosis and diversity**. Does the project enhance the potential and resilience of the Social-Ecosystem Systems and the flows through the site by building symbiotic (mutually beneficial and reciprocal relationships) and diversity at different scales through a decentralised and networked distribution of vital systems functions?
d. **Complex ecosystem flows**. Does the project further develop the ecological functions and the flows of energy and materials of a place, incorporating the complex communities of organisms and the web of the ecological community?
e. **Regenerative technologies**. Are the systems and technologies provided rooted in natural processes and reincorporating essential life-support services of nature such as energy conversion, water treatment, cycling nutrients, and waste assimilation?
f. **Story of place**. Does the project acknowledge and further evolve the specific place's unique character, essence and potential?

g. **Regenerative design process**. Was the process iterative, participative, systemic, and does it provide a vision for the future?
h. **Circular decision making**. Are design decisions made considering a deep questioning of the origin of the materials and their impact on those places, the people who manufacture them, and their work conditions?
i. **Specific project outcomes.** To what extent are the specific project goals achieved so far?

These questions cannot be answered by a number or even by yes or no. Some kind of narrative or diagram is required to explain how each aspect was addressed in a project. However useful, a narrated answer would not help determine the project's success level. This paper proposes a ten-level scale assessment for evaluating progress in the *essential RD project features* listed above. The specific outcomes derived from the project goals can be included under the '*i. specific project outcomes*' question. Thus, the traditional way of measuring green design—e.g. estimated or measured energy consumption, emissions, and waste management—may be part of the assessment if applicable to the specific project. Note that this assessment approach is not meant to be applied once but on an ongoing basis. In this way, project stakeholders can monitor results over time.

5. Conclusion

Regenerative design (RD) represents a new, required progression in the evolution of sustainable design. This does not necessarily mean that the current green building approaches will have to transform into a regenerative approach. The frameworks and assessment methods developed by *sustainable design* will probably still be helpful, even for regenerative projects. Furthermore, meeting international climate change commitments will require enforcing radical energy and resource efficiency for all facilities, not just as a voluntary commitment.

The evolution of sustainable design and the emergence of RD already require designers to become competent in new abilities such as facilitating groups, understanding complex adaptive systems, ecological literacy, and systems thinking. A body of knowledge about methods and tools is needed; however, a deeper understanding of these methodologies will be required to update architectural education.

Some regenerative projects may take many years to deliver results and eventually need iterative, ongoing adjustments, which raises the question of what would be the contractual, economical and practical implications for the involved designers. These considerations may trigger future evolutions in the design-build industry while opening other research pathways for making impactful changes in the planetary trends from the design and building sector.

RD and Circular Economy seek the regeneration of nature as the ultimate aim. This interesting convergence raises avenues for further research in Circular Construction. For example, this link may help progress in the yet unexplored implications of a regenerative approach to procuring materials, supply chain logistics, and construction activities.

There is no guidance in the reviewed literature for assessing whether an RD project is successful or measuring its level of 'regenerativeness'. This paper proposes an assessment methodology for RD projects which may help monitor a project's progress through time. However, the question remains: do we need to compare projects, or should we better focus on the collaboration required to produce meaningful changes to the current planetary trends?

Acknowledgements

This research is supported by Building 4.0 CRC.

References

AIA (2007) *2007: Integrated Project Delivery: A Guide.* The American Institute of Architects.

Almeida, F., Vieira, C. S., Carneiro, J. R. & de Lurdes Lopes, M. (2022) Drawing a Path towards Circular Construction: An Approach to Engage Stakeholders. *Sustainability*, 14(9), 5314.

Capra, F. (1997) *The web of life : a new synthesis of mind and matter*. London: Flamingo.

Cole, R. J. (2012) Transitioning from green to regenerative design. *Building research and information : the international journal of research, development and demonstration*, 40(1), 39-53.

Cole, R. J., Busby, P., Guenther, R., Briney, L., Blaviesciunaite, A. & Alencar, T. (2012b) A regenerative design framework: setting new aspirations and initiating new discussions: Regenerative design and development. *Building research and information : the international journal of research, development and demonstration*, 40(1), 95-111.

Du Plessis, C. & Cole, R. J. (2011) Motivating change: shifting the paradigm. *Building Research & Information*, 39(5), 436-449.

EMF *Circular economy introduction.* Available online: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview (Accessed 20 May 2022).

EMF (2022) *Circular economy introduction*, 2022. Available online: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview (Accessed 20 May 2022).

Hes, D. & du Plessis, C. (2015) *Designing for Hope: Pathways to Regenerative Sustainability*. London: London: Routledge.

Hoxie, C., Berkebile, R. & Anntodd, J. (2012) Stimulating regenerative development through community dialogue: Regenerative design and development. *Building research and information : the international journal of research, development and demonstration*, 40(1), 65-80.

IPCC (2014) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 9: Buildings*.

Lyle, J. T. (1994) *Regenerative design for sustainable development*. New York: John Wiley and Sons.

Mang, P. (2016) Regenerative development and design : a framework for evolving sustainability. Hoboken, New Jersey : Wiley.

Mang, P. & Reed, B. (2012) Designing from place: a regenerative framework and methodology: Regenerative design and development. *Building research and information : the international journal of research, development and demonstration*, 40(1), 23-38.

Maturana, H. R. (1980) *Autopoiesis and cognition : the realization of the living*. Dordrecht, Holland ; Boston: Dordrecht, Holland ; Boston : D. Reidel Pub. Co.

Pickin, J., Wardle, C., O'Farrell, K., Nyunt, P. & Donovan, S. (2020) *National Waste Report 2020. Prepared for the Department of Agriculture, Water and the Environment.* Melbourne, Australia: Dept of Agriculture, W.a.t.E.

Reed, B. (2007) Shifting from 'sustainability' to regeneration. *Building Research & Information*, 35(6), 674-680.

Tainter, J. A. (2012) Regenerative design in science and society. *Building research and information : the international journal of research, development and demonstration*, 40(3), 369-372.

Vaidya, P., Greden, L., Eijadi, D., Mcdougall, T. & Cole, R. (2009) Integrated cost-estimation methodology to support high-performance building design. *Energy Efficiency*, 2(1), 69-85.

Wahl, D. C. (2016) *Designing regenerative cultures.* Axminster, England : Triarchy Press.

Yu, Y., Yazan, D. M., Junjan, V. & Iacob, M. E. (2022) Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies. *Journal of Cleaner Production*, 349.

Zhang, C. B., Hu, M. M., Di Maio, F., Sprecher, B., Yang, X. N. & Tukker, A. (2022) An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. *Science of the Total Environment*, 803.

Retrofit strategies influencing thermal performance in weatherboard-clad dwellings constructed before 2003 in a cool temperate climate

Jack Tan[1], Phillipa Watson[2] and Mark Dewsbury[3]

[1, 2, 3] *University of Tasmania, Launceston, Australia*
jack.tan@utas.edu.au

Abstract: This paper explores simulation-based envelope performance improvements for typical low-quality dwellings in southern Australia. Australia has over 7.6 million detached private dwellings 2005-2006 data reported there were 6.3 million detached dwellings by 2005. Most of these were built prior to the 2003 national energy efficiency regulations. Pre-2003 dwellings are a significant concern as a high proportion of them have poor-quality building envelopes which are likely energy inefficient, costly to heat or cool and unhealthy to live in. Retrofitting them to provide better indoor environments is crucial for long-term sustainability goal. This paper describes a stage of PhD research that is investigating energy, thermal comfort, and health related indoor environmental qualities. Using the energy modelling tool AccuRate, this paper assesses external envelope improvement actions that can improve both energy efficiency and indoor environmental quality. Over 800 simulations were conducted exploring options to achieve a 6 Star NatHERS result. This paper finds that many pre-2003 houses likely have a house energy star rating below 1.5 Stars and that feasible retrofits can improve energy efficiency up to 6 stars. This paper contributes to further understanding envelope retrofit strategies and provides recommendations towards improved energy efficiency outcomes for existing dwellings.

Keywords: Retrofitting existing housing, energy efficiency, thermal comfort, NatHERS.

1. Introduction

Australia currently has over 10.85 million private dwellings, with 70% of these being detached houses (ABS, 2022). Earlier National Housing Survey data indicated that 6.3 million detached houses were built by 2005-06 and that 3-bedroom detached dwellings (53%) formed the largest proportion of all 2005-2006 detached dwellings (ABS, 2008). Much pre-2005 detached housing stock has limited, if any, envelope insulation, as they were designed and constructed prior to the first National Construction Code (NCC) energy efficiency requirements of 2003 (ABCB, 2003). With poor quality construction and related indoor environment challenges, (e.g. thermally uncomfortable rooms; retention of moisture, mould and poor

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 514–525.*

indoor air quality), these existing older dwellings commonly create unhealthy indoor environments for occupants (Baker *et al.*, 2016; Nath *et al.*, 2019). Retrofitting existing housing is therefore needed in Australia to improve indoor environments and for long-term sustainability goals. Improving energy efficiency through retrofits of dwelling fabric is a critical focus as the housing sector consumes approximately 30% of Australia's energy (ABS, 2019) and energy use reductions greatly help: reduce climate impacts (Wang *et al.*, 2011); Additionally, an appropriately conditioned indoor environment can improve occupant health and wellbeing, particularly for children and older people (WHO, 2018), and reduce effects of fuel poverty in households (Howden-Chapman and Chapman, 2012; Howden-Chapman *et al.*, 2012; Xu *et al.*, 2018).

The analysis of over 800 Building Energy Rating (BER) simulations has identified key features of the external envelope that could be prioritized in retrofits to improve heating and cooling based energy efficiency. This short paper focuses on identifying dwelling fabric upgrades (excluding façade wall retrofits) for improving thermal comfort of existing housing in southern Australia, with a specific focus on the simulation results for Devonport. The National Construction Code classes much of Tasmania as Climate Zone 7. Climate Zone 7 is also applicable to areas in Victoria, the Australian Capital Territory and New South Wales. This climate type is selected because of the significant challenge cold and old housing poses to occupant health and fuel poverty (Watson, 2010; Watson and Watson, 2017a).

This paper's focus is on the retrofitted energy performance of typical three -bedroom dwellings with an internal corridor (hallway) and open plan (no hallway) layouts. The AccuRate BER software was used to test simulation based retrofit strategies to ceiling, floor, and windows to improve energy efficiency up to NatHERS 6 Stars. Due to cost and complexity, in this stage of the research, no insulation was added to external walls, as this research shows it is possible to achieve 6-star rating without the more complicated retrofit to external wall systems. The paper first provides some background on retrofitting dwellings in Australia, simulations, and the climate zone choice. It then outlines methods used, including why three-bedroom dwellings are the focus in this paper and how house layouts were chosen. The results of the AccuRate BER simulations are reported with discussion regarding the efficacies and dynamics of the retrofit strategies.

2. Background

Most states in Australia require all new dwellings to meet the NCC energy efficiency requirements to reduce greenhouse gas emissions associated with house energy usage. The NCC provides an Acceptable Construction Deemed to Satisfy (DTS) pathway that includes minimum requirements for the thermal qualities of floors, external walls, roofing, and glazing, or a BER simulation using a NatHERS accredited software. Currently a 6-Star NatHERS rating is required in most states and territories (with 7 Star becoming mandatory in most states/territories in coming years) (Australian Government, 2022). A house rated with a higher star rating tends to need less energy to condition its indoor air to a comfortable temperature. Most of the 6.3 million detached dwellings built in Australia by 2005 (ABS, 2008) are assumed to be significantly under insulated because they were built before NCC's energy efficiency requirements were introduced in 2003. There is strong consensus in Australia (COAG Energy Council, 2018; 2019) that improving existing housing stock is necessary to meet carbon targets by 2025-2050. However, Australia's energy efficiency retrofit efforts are behind compared to international exemplars. While there are energy efficiency requirements for major renovations (defining 'major' varies across jurisdictions but tend to be 50% of floor area), formal guidelines are yet to be implemented nationally. In contrast, Canada and the UK already have some broader form of regulated requirements for retrofitting, (e.g. UK's PAS 2030 & PAS

2035) (Retrofit Academy, 2021; BSI.Knowledge, 2022). Voluntary retrofitting frameworks for existing Australian dwellings, like NatHERS's In-Home package, as well as the Victoria government's National Scorecard, are currently in development and review stages (Sustainability Victoria, 2019; NatHERS, 2022a). These guidelines are expected to be introduced in 2023 to guide assessing energy performance against benchmarks of building envelope design and fixed conditioning and hot water systems.

Focusing simulations on cool-temperate climates provides significant benefits due to these locations with unhealthily low indoor temperatures in winter (Dewsbury, 2011). Improving the energy efficiency of older, internally cold dwellings has also been proven to improve negative health impacts (e.g. respiratory and cardiovascular illness) (Mercer, 2003; Breysse *et al.*, 2011). Occupants, especially those in the more vulnerable and lower income groups, have been found to cope in various ways with old housing, and to not always heat their (thermally poor) homes (Watson, 2010). Rising energy costs also indirectly impacted budgets like food which in turn cause anxiety and depression (Suglia *et al.*, 2011; Pevalin *et al.*, 2017; ABC News, 2022). The living room is often the main space heated in lower income homes but often they were below accepted thermal comfort conditions (Watson and Watson, 2017b). Improving the quality of housing and keeping indoor temperature no lower than WHO's (2007) recommendation of 21°C for living room and 18°C for other rooms (particularly for the very young and very old) often also improves the mental and physical health, sense of security, self-esteem and perception of its occupants, in particular it provides healthy living, including supporting aging in place (Howden-Chapman, 2004; Molinsky *et al.*, 2019). This paper is important to guide Australia policy makers and design professionals by informing and identifying specific retrofit strategies and the broader priorities regarding improving existing dwellings.

The following section describes the methods used to select and represent the external envelope materials, their window floor ratios (WFRs), climate data and buildings airtightness to represent existing dwellings and their retrofit for BER simulations.

3. Method

This paper's BER simulations were completed using the Australian NatHERS accredited AccuRate house energy rating software (version 2.4.3.21 SP1). The retrofit options explored in this paper are thermal insulation improvements of ceiling, floors, and glazing to achieve a 6-Star outcome.

To establish a benchmark for existing housing in Tasmania, more than 800 AccuRate simulations were conducted on uninsulated existing detached one, two, three and four -bedroom dwellings, with an open plan and corridor layout types, ranging in floor areas of 70 m^2 to 160 m^2. Climate data used in the BER simulations were sourced from Australia's Nationwide House Energy Rating Scheme (NatHERS, 2022b), which includes 69 climate zones for Australia. The NatHERS climate files used in this research were climate zone 67 (Devonport), climate zone 23 (Launceston), and climate zone 26 (Hobart). These three climate types represent most of the urban development in Tasmania.

Since the majority of pre 2003 dwellings in Tasmania have timber framed and timber clad external wall systems (CSIRO, 2022b), this material is considered in the simulations. These BER simulations were completed using different permutations of floor and ceiling insulation, window-floor ratios (WFR), airtightness, corridor conditioning, and four cardinal orientations. The three-bedroom house plan was chosen as a pertinent example because it forms the largest proportion of detached dwellings built before 2005 (ABS, 2008). The three-bedroom plans used are shown in Figure 1 and Figure 2. These plans were selected after a survey of approved building plans submitted between 1930 and 1975 to the Devonport local government area. Their uninsulated dwelling NatHERS star ratings are shown in Table 1.

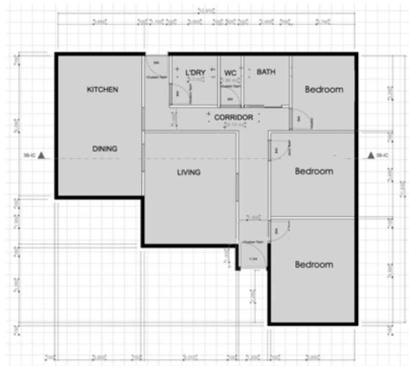


Figure 85. Three-bedroom internal corridor dwelling

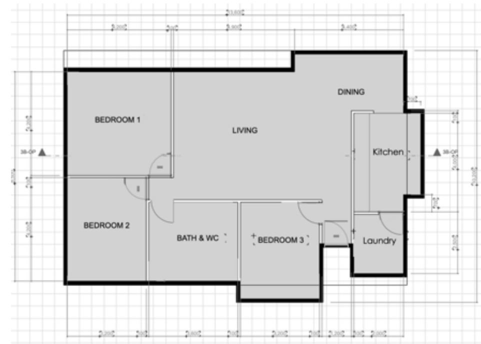


Figure 86. Three-bedroom open plan dwelling

Table 46: NatHERS Star rating result for uninsulated dwellings

Three-bedroom dwelling's internal corridor and layout types	NatHERS Climate Zone		
	67 (Devonport)	23 (Launceston)	26 (Hobart)
With internal corridor/hall (see Figure 1)	1.1 to 1.3 Stars	1.0 to 1.2 Stars	1.1 to 1.3 Stars
Open plan with no internal corridor/hall (see Figure 2)	1.3 to 1.4 Stars	1.2 to 1.3 Stars	1.3 to 1.4 Stars

3.1. Ceiling, floor, & window improvements

Table 2 shows the different floor, ceiling and glazing improvements explored. In each case F0, C0, or W0 refer to the base uninsulated case, whilst F1, F2, C1, C2 and W1 and W2 refer to increased amounts of insulation of floor (F1, F2), ceiling (C1, C2) and glazing (W1, W2) performance. **Error! Reference source not found.** shows the matrix of floor, ceiling, window, and airtightness permutations that were explored.

3.2. Airtightness

Airtightness often has quite significant impacts on building energy performance (AIRAH, 2017). Airtightness of existing Australian dwellings can range considerably from 2 to 38ACH@50; older leaky housings were less airtight at more than 30ACH@50. Nationally, measured airtightness of new dwellings averages 15.5ACH@50 (Biggs, 1988; Ambrose and Syme, 2017). The airtightness benchmark of 10ACH@50 (the default setting of NatHERS software for new dwellings) is used to represent retrofitted building. Lower and higher airtightness levels (above and below 10ACH@50) were also simulated to represent leakier and tighter dwellings.

Table 47. Existing and retrofit material matrix

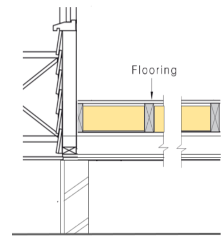
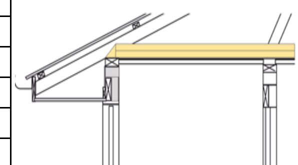
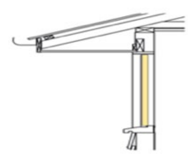
Material code & description		Conductivity (W/m.k)	Thickness (m)	RSI (R) value (m2K/W)	Detail
Floor (F0)	Existing timber floor	0.158	0.019	0.12	
	Glass fibre batts	nil	nil	nil	
	Total	-	0.019	0.12	
Floor (F1)	Existing or new timber floor with insulation	0.158	0.019	0.12	
	R5 Glass fibre batts	0.044	0.264	6.00	
	Total	-	0.283	6.12	
Floor (F2)	Existing or new timber floor with insulation	0.158	0.019	0.12	
	R10 Glass fibre batts	0.044	0.44	10	
	Total	-	0.459	10.12	
Ceiling (C0)	Existing plasterboard ceiling	0.166	0.010	0.06	
	No glass fibre batts	nil	nil	nil	
	Total	-	0.01	0.06	
Ceiling (C1)	New plasterboard	0.166	0.010	0.06	
	R6 glass fibre batts	0.044	0.264	6.00	
	Total	-	0.274	6.06	
Ceiling (C2)	New plasterboard	0.166	0.01	0.06	
	R12 PU rigid foam	0.028	0.336	12.00	
	Total	-	0.346	12.06	
Window W0	Existing 4mm single clear glass, alum. frame	Uninsulated, U=6.7, SHGC = 0.57			
Window W1	New basic double-glazing low-e clear, alum. frame	Thermally broken, air filled high solar gain, U=3.6, SHGC = 0.54			
Window W2	New good double-glazing, low-e clear, alum. frame	Thermally broken, argon filled high solar gain, U=2.9, SHGC = 0.51			

Table 48. Retrofit permutations

Code	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18
F0	■	■	■	■	■						■	■							
F1						■	■	■					■					■	■
F2									■	■				■	■	■	■		
C0	■	■	■										■	■					
C1				■		■	■				■						■	■	■
C2					■			■	■	■		■			■	■			
W0	■										■	■	■	■		■		■	
W1		■		■	■	■													
W2			■				■	■	■	■					■		■		■
ACR@50	10	10	10	10	10	10	10	10	10	5	10	10	10	10	10	10	10	10	5
WFR	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.18	0.31	0.31	0.31	0.31

Australian dwellings' measured airtightness was lower compared to other western developed countries with cold climate. In Sweden houses built in the 1960s have airtightness of 4 to 8 ACH@50, in the UK, dwellings' airtightness is approximately 14ACH@50, in New Zealand it is 11 ACH@50, in the Netherlands it is 12ACH@50 while in Canadian dwellings' airtightness were found to be around 4.4 ACH@50. This is likely due to several of these northern hemisphere countries having a current building regulation that requires the infiltration rate be less than 5ACH@50. It has also been reported that better insulated homes also have better airtightness (Ambrose and Syme, 2015; 2017). The BER simulations were completed on the house plans for 6 different air change rates (ACH@50): 30, 20, 10, 5, 2.5 and 0.6 to understand airtightness impacts on energy consumption. The 30 and 20 ACH@50 were selected to represent 'leaky' older dwellings that have higher air permeability. The 5ACH@50 rate represents airtightness before mechanical ventilation is required, 2.5ACH@50 represents northern European, American, and Canadian standards for new dwellings, 0.6 represents Passivhaus standard. Five (30, 20, 10, 5, and 0.6 ACH@50) airtightness rates were tested against the three cities and four orientations. Wind speeds of the 3 cities from NatHERS climate files were also plotted to understand the wind conditions.

3.3. Impact from selecting daytime conditioning or unconditioned corridors

The air conditioning status of a dwelling's internal corridors can be designed and specified to NatHERS' definitions on daytime conditioned or unconditioned zones (NatHERS, 2019). Both daytime corridor and unconditioned corridor conditioning were tested in the internal corridor dwelling type scenarios.

3.4 Impact of window upgrades

Four variations of Window to floor ratios were explored on the typical 3-bedroom corridor. The review of house plans, as mentioned above, showed WFR's from 0.18 to 0.4. This was also confirmed by more recent data from the CSIRO (CSIRO, 2022a). The four selected permutations were 0.18, 0.26, 0.31 and 0.4. Each of these scenarios was simulated within the three climate zones mentions above.

4. Results and discussion

In this section the outcomes of different retrofit scenarios (S1 to S18) are presented and compared to existing S0 scenario. Annual energy consumption is presented below for each retrofit and these consumption figures are based on NatHERS' AccuRate software's simulated area adjusted heating and cooling energy requirements. Overall, the simulations show that retrofitting critical components of an existing dwelling fabric (without adding any wall insulation) in NCC climate zone 7, for the simulated 3-bedroom house plans, can reduce space conditioning demand by almost 70% and improve thermal performance to 5 stars from a base (uninsulated) dwelling of about 1 star. Detailed results supporting this overall result are presented in sections 4.1 to 4.3 below.

4.1. Insulation upgrades excluding walls

Figure 3 shows the relative improvements in for the simulated cooling and heating energy needs for scenarios S0, and S3 to S9. These all show a reduction of heating and cooling energy greater than 50%. Incremental upgrades of ceiling and floor insulation (strategies S3 to S8), including replacing all existing windows to double glazing without upgrading external walls offers the incremental improvements to around 4.9 Stars if airtightness is at 10ACH@50. When airtightness is tightened further to 5ACH@50 using strategy S9, achieving 5.2 star is possible.

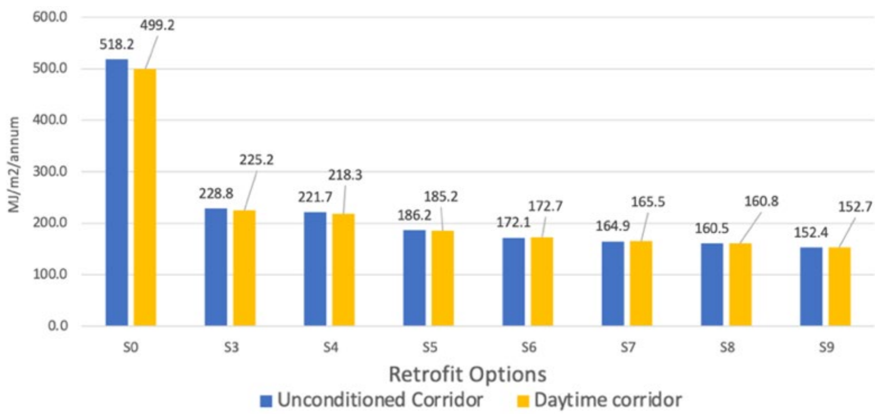


Figure 87. S3 to S9 retrofit energy performance compared to S0 (no retrofit)

Introducing ceiling insulation alone (without other retrofits) improves a 1.2-star uninsulated dwelling to 3.3-star, as shown in the outcomes of S10 and S11 in **Error! Reference source not found.**. S10 retrofit shows an almost 50% improvement (in simulated heating and cooling energy needs) compared to the no insulation scenario (S0). Comparing S6 to S11, ceiling insulation seems to gain the most benefit at around R6 (S6). Doubling the ceiling insulation to R12 (S11) has limited gains. R6 ceiling only retrofit provides 3 to 3.2 star; however, R12 ceiling only retrofit improves it slightly to 3.1 to 3.3 star.

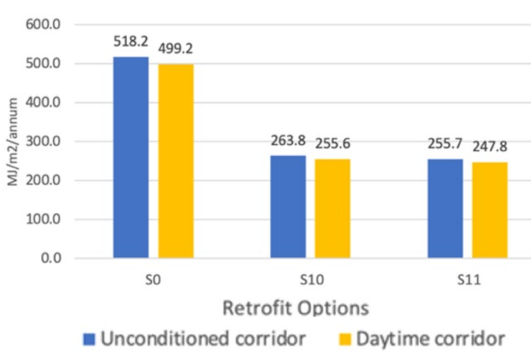


Figure 88. Retrofit improvements S10 & S11 compared to baseline S0 (no retrofit)

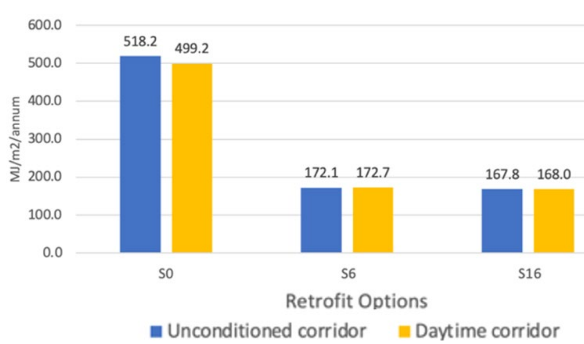


Figure 89. Retrofit improvements S6 & S16 compared to baseline S0 (no retrofit)

Similarly, Figure 5 shows comparative results for floor insulation. S0 has no floor insulation, S6 has R5 subfloor insulation, R6 ceiling insulation and double glazing, whilst S16 has R10 subfloor insulation, R6 ceiling insulation and double glazing. The doubling of subfloor insulation (R5 to R10) provides only a 0.1-star improvement from 4.6 to 4.7 stars.

Figure 6 shows the simulation results when the single glazed windows were replaced with the double-glazing strategies S1 and S2. This action alone improves the uninsulated 1.2-Stars dwelling to 1.6-Stars. Compared to the baseline S0, S1 provides a 7% improvement, whilst S2 provides a 10% improvement in simulated heating and cooling energy use. This strategy is less efficient than retrofitting floor insulation or ceiling insulation as discussed above.

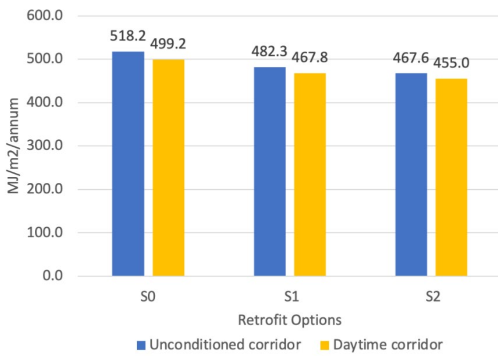


Figure 90. S1 and S2 retrofit energy performance compared to S0 (no retrofit)

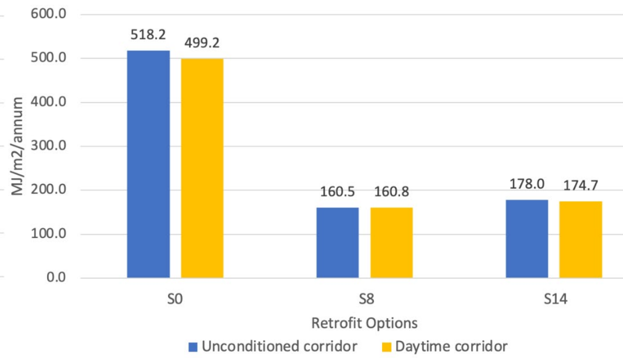


Figure 91. Retrofit S8 and S14 compared to S0 (no retrofit)

Figure 7 shows the impact of glazing area. S0 is uninsulated dwelling with WFR 0.31 before retrofitting. S8 (WFR 0.31) and S14 (smaller WFR 0.18) are retrofits with similar floor (F2) and ceiling insulation (C2) and improved glazing (W2). The star rating of dwelling (S8) with higher WFR 0.31 drops from 4.8- 4.9-stars to 4.3- 4.6-stars when its WFR decreases to 0.18 (S14). The average increase in energy consumption of S14 compared to S8 is around 15.7MJ/m2/annum. The likely reason is that dwellings with lesser window area also led to a lesser solar heat gain through equatorial facing windows, hence more heating is required.

4.2. Daytime conditioned corridor or unconditioned corridor & WFR impacts

Figures 8 and 9 show the differences in simulated heating and cooling energy needs subject to a corridor being conditioned or unconditioned.

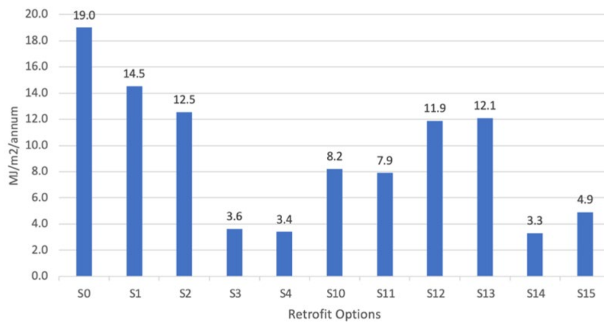


Figure 92. Energy consumption difference between unconditioned corridor & daytime-conditioned corridor dwellings for <4-star retrofits

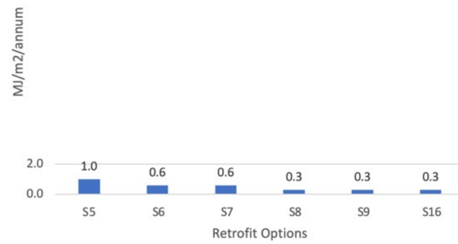


Figure 93. Energy consumption difference between unconditioned corridor & daytime conditioned corridor dwellings for >4-star retrofits

For internal corridor type houses retrofitted to less than 4-star (S0 to S4 and S10 to S13), scenarios where the internal corridor area is daytime conditioned provides slightly higher star rating in most orientations compared to unconditioned corridors. However, even if the Star rating is higher, the daytime corridor conditioning contributes to more overall energy consumption compared to unconditioned corridor settings. If the dwelling is more than 4.2 to 5.2-star, the energy performance is almost similar for daytime conditioned or unconditioned corridor settings, as shown in Figure 8, for scenarios S5 and to S9 & S16. When retrofits S5 to S9 and S16 improve the simulated dwelling to >4 Stars, there is very little difference between unconditioned and day-time conditioned corridor dwelling's total simulated heating and cooling energy consumption (< 1 MJ per metre^2 per annum), compared to retrofits <4-star (S1 to S4 and S10 to S15). The simulations also show that differences in WFR have insignificant or little impact on uninsulated 3-bedroom dwelling types.

4.3. Airtightness impacts

Figure 10 shows the simulated reduction in heating and cooling energy when the uninsulated dwelling is made more airtight. The tightening of an existing 0.9 Star dwelling in Devonport with 30ACH@50 to 10 ACH@50 improves its energy performance by almost 9.5 to 10.2% (to 1.3 Stars). If it is tightened further to 0.6ACH@50 (Passivhaus standard), the increase in performance is 12.9% to 13.7%, (to 1.5 Stars). Airtightness as an energy efficiency strategy is more effective in Devonport compared to Launceston or Hobart. For example, when a leaky building is tightened from 30ACH@50 to 10ACH@50, its energy performance improvement is 10.3% to 10.8% more efficient (depending on orientations) in Devonport, compared to 7.2% to 7.9% in Launceston (least efficient) or 7.7% to 8.1% in Hobart (see Figure 11). The reason for the effectiveness of air tightening in Devonport is likely due to its windier conditions compared to Launceston (which is least windy) and Hobart, see Figure 12.

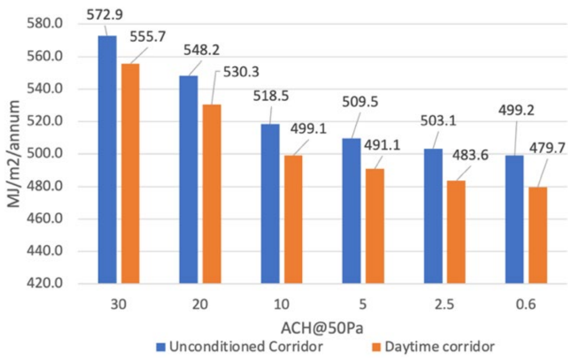


Figure 94. Airtightness in 3-bedroom internal corridor-type dwellings (Devonport)

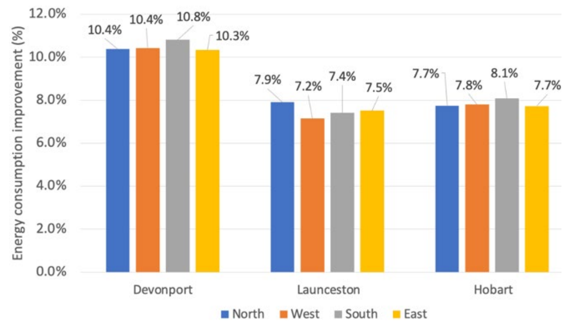


Figure 95. Airtightness efficiency (%) comparison of 30ACH@50 and 10ACH@50 for 3-bedroom internal corridor-type dwellings

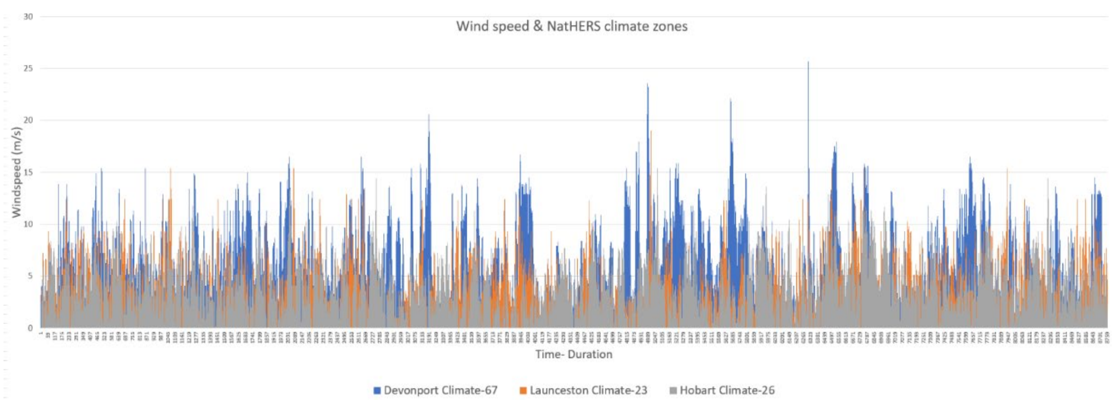


Figure 96. Wind conditions in Devonport, Launceston, and Hobart according to NatHERS climate files

5. Conclusion

Retrofitting dwellings to improve the health of occupants living in colder climate is important and achievable up to below 6 stars without the complications of retrofitting external walls. By improving indoor thermal comfort via the retrofitting (insulation) of ceiling, floors, and windows (thermally insulated windows) *without* adding wall insulation. These retrofits potentially allow existing dwellings to reach NCC energy benchmark of 5.2-star (or up to an additional of 0.3-star if airtightness is improved to 5ACH@50 or lower). Ceiling retrofit (using at least R6 batts) is the most significant retrofit component, contributing to almost 49% of all annual energy reduction. The next significant retrofit is floor (R6 batts) at almost 10% energy reduction contribution, followed by using good double-glazing windows at 9.3% energy performance reduction. Improving airtightness is important for windier cities. More research is needed on the retrofit details impacts for below and above 5 stars to support healthy indoor air quality. This study also shows the validity of using methods to prioritize retrofit strategies in improving energy and thermal comfort performance of existing uninsulated dwellings. It also shows that although conditioning internal corridor dwellings seemed to improve star rating compared to unconditioned corridor counterparts (with retrofits up to less than 4.5 stars), the total annual energy consumption of dwellings with conditioning to their internal corridor is in fact higher than unconditioned corridor type dwellings. The findings have implications for further the research in areas of retrofit design, energy efficiency, building regulations and occupant health impacts.

References

ABC News (2022) *Rising electricity prices, cost-of-living pressures pushing Tasmanians to the limit*.

ABCB (2003) *The building Code of Australia: 1996 Amendment 13*, in A. B. C. Board (ed.).

ABS (2008) *Year Book Australia 2008*.

ABS (2022) *Housing: Census- Information on housing type and housing costs*. Available from: (accessed 21 Oct).

AIRAH (2017) *Air Tightness Metrics to Improve Australian Building Envelope Integrity- Review of Performance Measures*.

Ambrose, M. and Syme, M. (2015) *House Energy Efficiency Inspections Project- Final Report*, CSIRO.

Ambrose, M. and Syme, M. (2017) Air Tightness of New Australian Residential Buildings, *Procedia Engineering*, 180, 33-40.

Australian Government (2022) *Building Ministers' Meeting: Communiqué August 2022*. Available from: (accessed 22 Oct 2022).

Baker, E., Lester, L. H., Bentley, R. and Beer, A. (2016) Poor housing quality: Prevalence and health effects, *Journal of Prevention & Intervention in the Community*, 44(4), 219-232.

Biggs, K. L. (1988) Ventilation Studies of Some Australian Houses, *Australian Refrigeration, Air Conditioning and Heating*.

Breysse, J., Jacobs, D. E., Weber, W., Dixon, S., Kawecki, C., Aceti, S. and Lopez, J. (2011) Health Outcomes and Green Renovation of Affordable Housing, *Public Health Reports*, 126(1_suppl), 64-75.

BSI.Knowledge (2022) *Retrofitting dwellings for improved energy efficiency. Specification and guidance*. Available from: (accessed.

COAG Energy Council (2018) *Report for Achieving Low Energy Homes*.

COAG Energy Council (2019) *Addendum to Trajectory for Low Energy Buildings- Existing Buildings*.

CSIRO (2022a) *Dashboards- Design- Floor and Window Area*. Available from: CSIRO (accessed 22 Jul 2022).

CSIRO (2022b) *Dashboards- Wall Construction- External Wall Type Ranked*. Available from: (accessed Jul 23).

Dewsbury, M. (2011) *The empirical validation of House Energy Rating (HER) software for lightweight housing in cool temperate climates*, PhD, School of Architecture and Design, University of Tasmania.

Howden-Chapman, P. (2004) Housing standards: a glossary of housing and health, *Journal of Epidemiology & Community Health*, 58(3), 162-168.

Howden-Chapman, P. and Chapman, R. (2012) Health co-benefits from housing-related policies, *Current Opinion in Environmental Sustainability*, 4(4), 414-419.

Howden-Chapman, P., Viggers, H., Chapman, R., O'Sullivan, K., Barnard, L. T. and Lloyd, B. (2012) Tackling Cold Housing And Fuel Poverty In New Zealand: A Review Of Policies, Research, And Health Impacts.

Mercer, J. B. (2003) Cold—an underrated risk factor for health, *Environmental Research*, 92(1), 8-13.

Molinsky, J., Herbert, C. and Forsyth, A. (2019) Housing and Planning Supporting Healthy Aging, in, Springer International Publishing, 355-366.

Nath, S., Dewsbury, M. and Douwes, J. (2019) Has a singular focus of building regulations created unhealthy homes?, *Architectural Science Review*.

NatHERS (2019) *Assessor Handbook*, Commonweath of Australia.

NatHERS (2022a) *In Home*. Available from: Commonwealth of Australia (accessed Aug 5).

NatHERS (2022b) *NatHERS Climate Zones and Weather Files*. Available from: (accessed.

Pevalin, D. J., Reeves, A., Baker, E. and Bentley, R. (2017) The impact of persistent poor housing conditions on mental health: A longitudinal population-based study, *Preventive Medicine*, 105.

Retrofit Academy (2021) *Raising the Standards of Retrofit- What is PAS 2035- Is PAS 2035 Mandatory?* Available from: (accessed Sep 8).

Suglia, S. F., Duarte, C. S. and Sandel, M. T. (2011) Housing Quality, Housing Instability, And Maternal Mental Health, *Journal of Urban Health*, 88(6).

Sustainability Victoria (2019) *Comprehensive Energy Efficiency Retrofits to Existing Victorian Houses*,Sustainability Victoria: Melbourne, Australia.

Wang, X., Chen, D. and Ren, Z. (2011) Global warming and its implication to emission reduction strategies for residential buildings, *Building and environment*, 46(4), 871-883.

Watson, P. (2010) *Barriers to renovation for housing sustainability in Tasmania*,School of Geography & Environmental Studies Conference, 2010.

Watson, P. and Watson, S. (2017a) *Warm house, Cold house: a review of measures of thermal comfort used in Get Bill Smart's energy efficiency assessments*, ed., Elsevier BV.

Watson, P. and Watson, S. (2017b) Warm house, Cold house: a review of measures of thermal comfort used in Get Bill Smart's energy efficiency assessments, *Energy Procedia*, 121, 190-197.

WHO (2007) Housing, energy and thermal comfort: a review of 10 countries within the WHO European Region.

WHO (2018) *WHO Housing And Health Guidelines*, 152.

Xu, Z., Crooks, J. L. and Davies, J. M. e. a. (2018) The association between ambient temperature and childhood asthma: a systematic review, *International Journal of Biometeorology*, 62(3).

Smart Cities with no brain: A case for urban design studies utilising open-source platforms

Yang Ye[1]

[1] *School of Architecture, Harbin Institute of Technology, Harbin, China*
[1] *Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, Harbin, China*
yeyang@hit.edu.cn , 0000-0003-2642-0436

Abstract: Urban space quality is the core research target of the Chinese urbanisation project. This is a positional paper, using a brief historical perspective of the progress of Chinese urban design, and a current problematic in Chinese smart-city platforms to foreground future studies in urban quality using open-source platforms and technology. Traditional research and design methods are mostly based on field surveys and analogue design projection. Open-source platforms such as street view images have the characteristics of wide coverage, high accuracy of human-scale street information, and low data collection costs, and can provide some new research ideas for the evaluation of urban space walkability. This paper first reviews the development process of urban quality initiatives in the Chinese, and proposes the prospects for future research.

Keywords: Urban design paradigms; Data based urban design; Smart city platforms.

1.Wang Jiangou's 4 generations of Urban Design paradigms in China

The rapid urbanization of China following the so-called 'opening-up' in 1978 to the present has delivered the greatest *quantity* of urban built infrastructure in human history. However, recent focus of national, regional and local built-development in the 21st century has been on urban *quality* in all of its categories, and this can be traced through the emergence of 'Urban Design' research and practice after 1990 some 20 years after it had emerged in Western settings. The Chinese urban planner Wang Jianguo describes four 'generations' of Urban Design paradigms in China and elsewhere: 1. 'Traditional' (preindustrial) 2. Modernist, 3. Green and 4. Digital. His brief history is significant because in general, post-industrial urban planning, design and development in China has followed European theoretical and practical developments. The Modern, rapid-development period in China saw the most massive rollout of the principles of CIAM, particularly the Charter of Athens, in its single-minded pursuit of the functionalist, 'productive' city. The rebuilding of European cities following the destructions of World War 2 provided the catalyst for smaller scale functionalist projects across Europe. The modernist paradigm was called into question in Europe and America, and later in China for what Wang calls the great 'losses' it delivered,

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 526–536.*

notably environmental impacts, traditional spaces and cultures of interaction. The responses to these impacts delivered the succeeding paradigm of Green Urban Design, in which the 'principle of giving priority to ecology has gradually become a basic consensus in the field' (Wang, 2018). Again, these initiatives and paradigms developed first in the West, from the 1960's and 70's, and were adopted later in China from the 1990's onwards. The primary topics of green urban design, energy and water management, microclimate design and 'greening' strategies were given new impetus with the remarkable developments in information and digital technologies. Revolutionary growth in computing and data technologies precipitated Wang's 4th paradigm, digital urban design, characterized by human / machine interaction, and it is in the geopolitical unfolding of this paradigm that Chinese urban developments have a less linear and more relational interaction with Western Discourse.

2. The 'data' urban design paradigm and its data

In the data paradigm, rapid development of information technology has led to the availability of vast amounts of previously unobtainable data and through bewilderingly multiple channels such as geophysical surveys, social media, mobile phone apps of all descriptions, perception data, and open data from professional institutional platforms, all of which have contributed to the formation of the massive new data environment. The micro-scale data reflecting environmental characteristics and crowd activity behavior is in line with the current urban development direction and has a great impact on current hot topics in urban development (Hao J 2015). Moreover, the multi-dimensional perspective expands the cognition of urban space from the physical environment, spatial activities, and spatial behavior patterns promotes the transformation of human-oriented urban space research from subjective to objective empirical research. Multi-angle analysis and measurement are also the basis for further understanding and deeper research of the city, which reveal the dynamic evolution and structural law behind the urban complex problems through a more real deeper perspective and a broader vision (Yang J 2018). The application of new technology and new data, conducting scientific data screening and analysis, obtaining more detailed and objective analysis results to feedback the design is a feasible direction for further urban spatial quality research.

Urban built environment data is the basis of urban research. The massive data such as open-source platform data, point of interest (POI) data, street view image (SVI) data, open data, urban geographic information system data (GIS), etc., are multi-scale, quantitatively grasp the various physical and spatial environmental characteristics of the city. Unlike traditional data, the open-source map platform, the so-called volunteered geographic information (VGI), such as OSM, covers multiple basic data such as road networks and building outlines, and has the advantages of rich data and open editing (Haklay M 2010, Christian Geiß 2016). POI data reflects format information in various regions of the city and has the advantage of data mining based on spatial location (Hu F 2020, Chen YM 2020, Shi J 2021). Street view image (SVI)has a wide coverage and provides street-level landscape and intuitively reflects the urban façade information, and has the advantage of lower cost than on-site data collection, provide a large sample data source and new research ideas for urban environmental assessment. Street view image is more focused on recording the stereoscopic sectional view of the street level from the perspective of people, which can represent scenes seen or felt from the ground on a fine scale, so it is more suitable to replace on-site observation of urban environmental assessment (Zhang L 2019). Researchers in recent years use machine learning in SVI analysis to objectively measure the micro-elements of the built environment, including, urban visual space indicators (Dai, L 2021), cycling environment (Gullón P 2015), street safety (He L 2017), street disorder (Marco M 2017), street greening (Long Y 2017), etc.

3.Chinese Smart City development as both Top-Down and Bottom-up political economy

There is much evidence characterizing Chinese Smart City development as dependent upon central and local government policy and support. Also, in the wave of smart city construction, various professional institutions and platforms have also begun to share information and data, and actively integrate them into the new common system, relying on the new generation of information technology such as cloud computing and the Internet of Things, combined real-time Perceived information (Fang Y, 2021). GIS platforms established in some regions, and open geographic information public service resources that integrate information from various relevant departments, are often government-supported to ensure that the data content is constantly updated and iterated.

Social media big data includes open platform data such as Twitter, weibo, Flicker, etc. The platform is based on the comments posted by users, whom can also become a content producer, to abundant auxiliary data samples (Yang Y 2021). Subsequently, the real-time information which carries user's emotions and feelings based on open sharing of location, images, and opinions via social media reveal how humans think or act regardless of time or space (Wu Wen 2016). Understanding people's use and experience of urban public space on social media is essential to create a better ground to design and improve the everyday spaces of people (Kim H J 2018). New computer technology has also been applied in researches that could reveal hidden themes in large amounts of data, such as some empirical studies. (Song Y 2020, Wakamiya S 2015, Fang C 2020, Hu Y 2015)

Human activity trajectory data containing valuable information on how urban spaces used are generated by people in their daily lives (Hu S 2021). Generally, this type of trajectory data includes vehicle GPS records, mobile phone data (MPD), location-based service data (LBS), social media data, and mobile app data, covers the interaction between people and the social environment, exploring the relationship between urban functional structure and traffic spatial interaction. Trajectory data can improve efficiency and data collection for planers and the possibility to enhance public participation in local governance (Adlakha D 2017), analyzed the attractiveness of specific environments for activities (Hirsch J A 2014), provides a new perspective to sense people's spatial and temporal preference in urban places (Shen Y 2016, Zhao P 2019).

4.Chinese Platform Urbanism ('City Brains') as Relational Assemblage

The bidirectional characterization of smart-city development is essentially linear and coarse, and does not account for a more complex formation in the political economy of smart cities which mimics the a larger data economy, namely, the economy of platforms, or 'platform capitalism' as described by Political philosopher Nick Srnicek, which investigates the development of digital 'platforms' provided by firms to connect users of data as essential features of the new digital economy. (Srnicek, 2016). Srnicek notes that the business model of these firms is to continually expand, acquire and provide ever more data through the necessity to derive income from as many exchanges as possible between data users. The platform model is increasingly adopted by all enterprises that use data access and traffic to facilitate business and governance ends. Not surprisingly, Smart City enterprises have also demonstrated this tendency. 'Platform Urbanism' or the delivery of smart city data for all aspects of smart city activity has been analysed in specific Chinese case-examples by Federico Caprotti (Caprotti et al, 2022) . The potentials for conflicts between public governance and business imperatives are highlighted by both authors. Regardless of these hazards, Caprotti poses these smart city 'brains' as characteristic of the emerging prevalent model for distributing urban data, including urban design data. Using the Deleuzian concept of 'assemblage', he identifies the potent complexity of these new data/knowledge economies , and the necessity for greater understanding of their relationality and assemblage in order to materialise ('territorialise') effective and trustworthy urban outcomes. Chinese Government action in keeping out many major platforms, such as Google, Facebook and Uber etc, has served to produce a vibrant and expansive Chinese platform industry with such giants as Alibaba, Tencent, Baidu and Huawei, all of whom have massively exported their platforms throughout the world, including, significantly, for the provision of smart-city data and urban governance, through smart-city-specific platforms. The Australian Government has similarly financed the 'Australian Smart Cities Collaboration Platform' through its 'Smart Cities and Suburbs' program. Though the government contribution by the Australian Government is higher than that of any specific Chinese government, the absence of a major industrial investor, such as Alibaba, differentiates this platform from those in China.

5.New Tools and Instruments for multi-dimensional spatial quality detecting and feedbacks

The highly accelerated calculation and the improvement on information processing capabilities caused by the inevitable emergence of various measurement tools and instruments that greatly enriched the types and scope of data, thus the application of new technologies in urban space has greatly changed the limitations of data acquisition in the past urban space environmental assessment and expanded the scope of research methods. New research in brain and cognitive science is changing how we understand and how people perceive and experience the built environment, offering key opportunities for urban planning, urban design, and architecture (Hollander J B). The new technologies represented by machine learning, virtual reality, physiological sensors, eye trackers, etc., provide more detailed spatial representations and more accurate behavior and perception records.

Machine/deep learning is an important topic in artificial intelligence. Deep learning image semantic segmentation can fine-tune street view images to regions and categories which is widely used in street view image analysis. The tools can efficiently identify construction elements such as sky, plants, buildings, and greenery in the human perspective view (Badrinarayanan V 2017). Furthermore, a series of image recognition tools have also been invented and are constantly updated and iterative to recognize the images. These training models recognize the semantic features of the sample model through training on small sample data and are applied in the large-scale automatic measurement of multiple human-scale spatial elements in the built environment. Researchers have applied these machine learning techniques in many ways to recognize the urban spatial quality. (Zhang F 2018, Dubey A 2016, Ki D 2021, Nikhil Naik 2014)

Virtual reality (VR)has been proposed for various purposes such as design studies, presentation, simulation, and communication in the computer-aided architectural design (Fukuda T 2021), VR construct past and future virtual worlds using three-dimensional (3D) computer graphics (CG) objects and can provide interactive movies via real-time rendering processing. Virtual reality technology has also been used in urban design project development, external evaluation, and public participation in assisting decision-making. (Portman M E 2015, Smith J W 2015).

Table 1. New data and application fields in urban spatial quality

	Data	**advantages**	**Application fields in urban spatial quality**	**authors**
Built environment data	VGI data (OSM); POI data;	open-source; High spatio-temporal precision; easy to obtain;	basic data; urban functions organization; street quality assessment; air quality	Christian Geiß Chen YM; Hu F; Shi J;
	SVI data;	easy to obtain; human perspective; large scale; on-site observe; integrate with tech; objective;	urban visual space; walking and cycling environment quality; urban security; neighborhood disorder; street greenery;	Dai L; Gullón P; He L; Marco M; Ying L;
	Open government data;	Large-scale; authority; up-to-date;	smart city; urban mobility;	Yadav P;
Social media data	Locations, photos, opinions and descriptions data from twitter, weibo, ect.	real-time; user-generated content; carry user's emotions or feelings;	monitoring environment quality; urban space experiencing; city crowd mood; extract urban areas of interest;	Wang Z; Kim H J; Song Y; Wakamiya S; Hu Y;
Trajectory data	Tracking data Vehicle GPS; check-in data; MPD, LBS data; smart card data	geo-tagged; overall trip be obtained; passive group data; geo-tagged; no extra equipment; consistency;	physical activity; urban hots pot detection; urban public green space; urban function connectivity; air pollution in urban; urban functions	Hirsch J A Zhao P; Zheng Q; Shen Y; Dias D; Wang Z

Perceptual data	sensor data;	multiple sensory cues; freely move; accurate synchronization;	spatial cognition; built environment perception;	Fukuda T; Portman M E; Smith J W; Hollander J B; KieferP;

Eyeing-tracking allows us to record unconscious eye movement, increase understanding of how people respond to the built environment (Hollander J B 2018), and provide new kinds of data on 'unseen' experiences the determine human behavior. Recent technological developments have led to increasing popularity of eye-tracking methodology for investigating research questions related to spatial cognition, geographic information science, and cartography (Kiefer P 2017). explored the ways that people perceive landscapes, focusing on fixations, saccade amplification, blink rates, gaze paths and built environment (Hollander J B 2018, Lisińska-Kuśnierz M 2020, Simpson J 2019).

Physiological sensors are composed of portable and wearable electrocardiographic sensors (EKG/ECG), brain electrical sensors (EEG), skin electrical sensors, skin temperature sensors (SC, ST), etc., which can record the millisecond response of the human body due to environmental stimuli, measure and record the emotional experience of people in the environment, record some obscure feelings and reflections that are difficult to put into word, and provide a possible new way for objectively monitoring brain function and cognition in the real world (Mavros P 2016). The wearable physiological sensor technology fused with GPS spatial location data can generate a geo-tagged spatial trajectory and provide important support for urban spatial behavior research based on human perspective perception signal data. (Aspinall P 2015, Huang S C L 2019).

Deep learning, virtual reality technology, physiological sensor, Eyeing-tracking, and other technologies have brought new directions for research and the researches of street micro-scale environmental quality measurement by using new technologies has been confirmed by many scholars. Various technologies combined with data make it possible to analyze multi-dimensional measurement result data, enrich the research dimensions in the urban space, offer measurement and evaluation of the urban environment, and assist in the analysis and induction of the correlation effect between the built environment and the perceived behavior.

Table 2 New technology and application fields in urban

types	**advantages**	**Application fields**	**authors**
Deep-learning	large-scale;automatic; refinement; objective;	urban elements identify; urban image recognizing; urban spatial quality; smart city; urban attractiveness	Badrinarayanan V; Dubey A; Ki D; Nikhil Naik; Choiri H
Virtual reality	expending visual sense; stakeholder feedback and participation; immersive;	design; environment planning; participatory design, preference and behavior;	Fukuda T; Portman M E; Loyola M; Smith J W;

Eyeing-tracking	real-time rendering;	street facades quality; spatial cognition; urban spatial visualization; visual engagement in street;	Hollander J B; Kiefer P; Lisińska-Kuśnierz M; Simpson J;
Physio-logical sensor	portable; real-time rendering; intensive;	cognition; urban behavior; physiological effect of urban environment;	Mavros P; Aspinall P; Huang S C L;

6. Proceeding without a city brain: using open-sources

In the context of big data, the construction of smart cities based on data and application is an inevitable trend of urban development, and the measurement and evaluation of urban spatial quality based on the smart city platform is also a necessary basis for urban development. The smart city emphasizes from network to centralization, through the full use of information and communication, better sensing, analysis, and integration of the key information of the city.

Thus, the standards for judging the quality of urban space develops with the needs and development of individual and groups. We propose a prototype that new data and a new tech-driven “five steps” model to quantify the urban spatial quality under the smart city platform.

6.1 Monitor: collecting and updating the data.

It’s necessary to collect the open data, urban sensor equipment data, network platform data, and other scattered information sources in the new data environment at different levels.

6.2 Perceive: data filtering, classifying, and visualizing.

Due to the multi-sourced new data, different technical means are required to automatically process all kinds of data and present them in a more intuitive and vivid form, including analogue representations. And it provides a smart city with basic resources such as storage, computing, and sharing capacity. Based on the analysis of new urban data, people's new behaviors and activities can be analyzed to a more certain extent.

6.3 Judge: establish an evaluation system and quantify the quality.

New technologies and data support the establishment of an evaluation system for evaluating urban quality from multi-dimensions. Based on the evaluation system, the urban quality could be quantified and the spatial quality comprehendingly judge in objective ways. Whether the system can meet the basis of a certain type of city quality and reflect its effectiveness is also an important process to judge.

6.4 React: urban design principles and strategies reacting.

New technologies continuously influence the concept of physical space, people's behaviors and activities have undergone great changes and new demands for urban space have been put forward. Urban spatial design should be considered at all times for networking, becoming a participant in the digital environment, and a component of the smart city network. Sustainability, networking, and flexibility are all urban spatial characteristics to be considered in the near future.

6.5 Design: design and update for the near future.

Enhance urban design and urban spatial quality with a more objective, refined, sustainable, and human-oriented direction.

With or without brain-supported smart city platform, urban space design has significant future implications. How does the space design process respond to the digital wave? What changes will happen to its role in the city? How to implement the design based on the results of objective data analysis in a city, how to renew the existing urban space conditions on the existing basis is the focus of the design process. The circulation process of urban space quality design and update constituted by collection and update of urban spatial data, monitoring, screening, classification and visualization of data, establishment, and judgment of the evaluation system, generation of principles and strategies of space design, generation of principles and strategies of space design, design the urban space reflect the next stage of the design process.

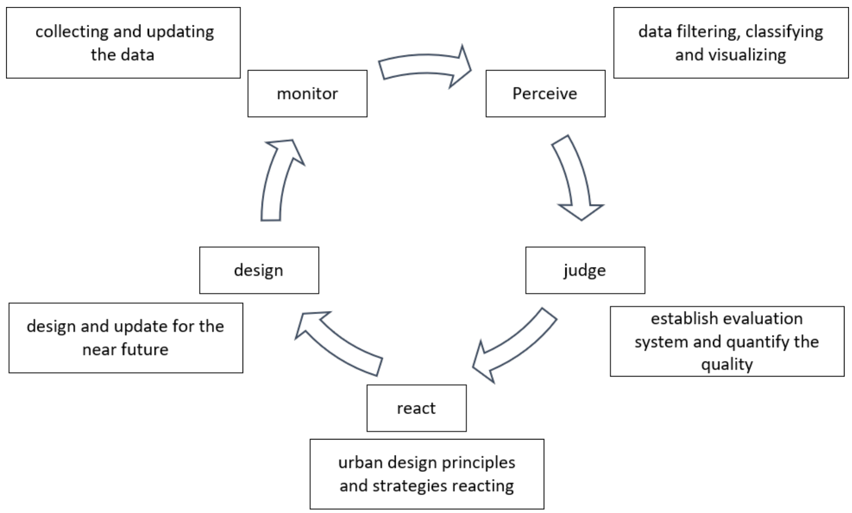


Figure 1: Urban spatial quality development under the smart city platform

7.Conclusion

The smart city platform in China is a work-in-progress, the political economy and governance of which is still emerging. It is clear however, that the participation of major private sector actors in developing the 'City Brain' platforms is currently a highly necessary precipitate for integration, and these are currently limited to specific cities and projects in China. Nevertheless, the imperative for Urban quality improvement remains. While new technologies and new data have given us new in-depth possibilities and new research directions in research methods, and the use of data is closely related to all aspects of social life, the combination of new methods and data in open-source environments, with a variety of modelling techniques, provides a pathway of thinking about scientific issues in urban space, to find more effective urban design methods to adapt to the development trend of smart city initiatives. The focus on smart cities is not limited to new technologies and data itself, but on the impact of new technologies and data on urban design in real, territorialised space. How will our way of designing, managing, and using space change? How to integrate the concept of the network into the design? How to consciously guide the development of spatial planning and design in the right direction and lead the wave of future digital world development? How to use technology and the digital Internet to enhance the value of design? These will be the problems we have to face.

Acknowledgements

This Paper is Sponsored by NSFC Funding No. 52008128. Of the Chinese Government.

Reference List

Adlakha D. (2017) Quantifying the modern city: emerging technologies and big data for active living research . Frontiers in public health, 5: 105.

Badrinarayanan V, Kendall A, Cipolla R. (2017) Segnet: A deep convolutional encoder-decoder architecture for image segmentation . IEEE transactions on pattern analysis and machine intelligence, 39(12): 2481-2495.

Caprotti, F., Liu, D. (2022) Platform urbanism and the Chinese smart city: the co-production and territorialisation of Hangzhou City Brain. GeoJournal 87, 1559–1573.

Chen Y, Chen X, Liu Z, et al. (2020) Understanding the spatial organization of urban functions based on co-location patterns mining: A comparative analysis for 25 Chinese cities . Cities, 97: 102563.

Choiri H.H. (2017) Quantifying and Predicting Urban Attractiveness with Street-View Data and Convolutional Neural Networks; Delft University of Technology: Delft, The Netherlands.

Dai L, Zheng C, Dong Z, et al. (2021) Analyzing the correlation between visual space and residents' psychology in Wuhan, China using street-view images and deep-learning technique . City and Environment Interactions, 11: 100069.

Dias D, Tchepel O. (2014) Modelling of human exposure to air pollution in the urban environment: a GPS-based approach . Environmental Science and Pollution Research, 21(5): 3558-3571.

Dubey, A.; Naik, N.; Parikh, D.; Raskar, R.; Hidalgo, C.A. (2016) Deep learning the city: Quantifying urban perception at a global scale. In Proceedings of the European Conference on Computer Vision, Amsterdam, The Netherlands, 11–14 October; pp. 196–212.

Fang Y, Shan Z, Wang W. (2021) Modeling and Key Technologies of a Data-Driven Smart City System . IEEE Access, 2021, 9: Feng Y, Huang Z, Wang Y L, et al. A SOE-Based Learning Framework Using Multi-Source Big Data for Identifying Urban Functional Zones. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 91244-91258.

Fukuda T, Novak M, Fujii H, et al. (2021) Virtual reality rendering methods for training deep learning, analysing landscapes, and preventing virtual reality sickness. International Journal of Architectural Computing, 19(2): 190-207.

Geiß C, Schauß A, Riedlinger T, et al. (2017) Joint use of remote sensing data and volunteered geographic information for exposure estimation: evidence from Valparaíso, Chile. Natural Hazards, 86(1): 81-105.

Gullón P, Badland H M, Alfayate S, et al. (2015) Assessing walking and cycling environments in the streets of Madrid: comparing on-field and virtual audits. Journal of urban health, 92(5): 923-939.

Haklay M. (2010) How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. Environment and planning B: Planning and design, 37(4): 682-703.

Han Z, Long Y, Wang X, et al. (2020) Urban redevelopment at the block level: Methodology and its application to all Chinese cities. Environment and Planning B: Urban Analytics and City Science, 47(9): 1725-1744.

Hao J, Zhu J, Zhong R. (2015) The rise of big data on urban studies and planning practices in China: Review and open research issues. Journal of Urban Management, 4(2): 92-124.

He L, Páez A, Liu D. (2017) Built environment and violent crime: An environmental audit approach using Google Street View. Computers, Environment and Urban Systems, 66: 83-95.

Hirsch J A, James P, Robinson J R M, et al. (2014) Using MapMyFitness to place physical activity into neighborhood context. Frontiers in public health, 2: 19.

Hollander J B, Purdy A, Wiley A, et al. (2018) Seeing the city: Using eye-tracking technology to explore cognitive responses to the built environment. Journal of Urbanism: International Research on Placemaking and Urban Sustainability.

Hollander J B, Sussman A, Lowitt P, et al. (2021) Eye-tracking emulation software: a promising urban design tool. Architectural Science Review, 1-11.

Hollander J B, Sussman A, (2020) Purdy Levering A, et al. Using eye-tracking to understand human responses to traditional neighborhood designs. Planning Practice & Research, 35(5): 485-509.

Hu F, Liu W, Lu J, et al. (2020) Urban function as a new perspective for adaptive street quality assessment. Sustainability, 12(4): 1296.

Hu S, Gao S, Wu L, et al. (2021) Urban function classification at road segment level using taxi trajectory data: A graph convolutional neural network approach. Computers, Environment and Urban Systems, 87: 101619.

Hu Y, Gao S, Janowicz K, et al. (2015) Extracting and understanding urban areas of interest using geotagged photos. Computers, Environment and Urban Systems, 54: 240-254.

Ki D, Lee S. (2021) Analyzing the effects of Green View Index of neighborhood streets on walking time using Google Street View and deep learning. Landscape and Urban Planning, 205: 103920.

Kiefer P, Giannopoulos I, Raubal M, et al. (2017) Eye tracking for spatial research: Cognition, computation, challenges. Spatial Cognition & Computation, 17(1-2): 1-19.

Kim H J, Chae B K, Park S B. (2018) Exploring public space through social media: an exploratory case study on the High Line New York City . Urban Design International, 23(2): 69-85.

Lisińska-Kuśnierz M, Krupa M. (2020) Suitability of eye tracking in assessing the visual perception of architecture—A case study concerning selected projects located in cologne . Buildings, 10(2): 20.

Long Y, Liu L. (2017) How green are the streets? An analysis for central areas of Chinese cities using Tencent Street View . PloS one, 12(2): e0171110.

Loyola M, Rossi B, Montiel C, et al. (2019) Use of Virtual Reality in Participatory Design.

Marco M, Gracia E, Martín-Fernández M, et al. (2017) Validation of a Google Street View-based neighborhood disorder observational scale . Journal of urban health: bulletin of the New York Academy of Medicine, 94(2): 190.

Mavros P, Austwick M Z, Smith A H. (2016) Geo-EEG: towards the use of EEG in the study of urban behaviour . Applied Spatial Analysis and Policy, 9(2): 191-212.

Naik N, Philipoom J, Raskar R, et al. (2014) Streetscore-predicting the perceived safety of one million streetscapes[C]//Proceedings of the IEEE conference on computer vision and pattern recognition workshops. 779-785.

Portman M E, Natapov A, Fisher-Gewirtzman D. (2015) To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning . Computers, Environment and Urban Systems, 54: 376-384.

Shen Y, Karimi K. (2016) Urban function connectivity: Characterisation of functional urban streets with social media check-in data . Cities, 55: 9-21.

Shen, Z.; Li, M. (2018) Big Data Support of Urban Planning and Management: The Experience in China; Springer: Cham, Switzerland.

Shi J, Gao H, Cheng H, et al. (2021) Study on the exposure risk based on the PM2. 5 pollution characteristics of POIs and their attractiveness to the crowd . Human and Ecological Risk Assessment: An International Journal, 27(4): 980-998.

Simpson J, Thwaites K, Freeth M. (2019) Understanding Visual Engagement with Urban Street Edges along Non-Pedestrianised and Pedestrianised Streets Using Mobile Eye-Tracking . Sustainability, 11(15): 4251.

Smith J W. (2015) Immersive virtual environment technology to supplement environmental perception, preference and behavior research: a review with applications . International journal of environmental research and public health, 12(9): 11486-11505.

Song Y, Fernandez J, Wang T. Understanding perceived site qualities and experiences of urban public spaces: A case study of social media reviews in Bryant park, New York city . Sustainability, 2020, 12(19): 8036.

Srnicek, N. (2016) Platform Capitalism. Cambridge, Polity.

Rzotkiewicz A, Pearson A L, Dougherty B V, et al. (2018) Systematic review of the use of Google Street View in health research: Major themes, strengths, weaknesses and possibilities for future research . Health & place, 52: 240-246.

Wakamiya S, Belouaer L, Brosset D, et al. (2015) Measuring crowd mood in city space through twitter[C]//International Symposium on Web and Wireless Geographical Information Systems. Springer, Cham, 37-49.

Wang Z, Liu H, Zhu Y, et al. (2021) Identifying Urban Functional Areas and Their Dynamic Changes in Beijing: Using Multiyear Transit Smart Card Data . Journal of Urban Planning and Development, 147(2): 04021002.

Wang Z, Ke L, Cui X, et al. Monitoring environmental quality by sniffing social media . Sustainability, 2017, 9(2): 85.

Wen W, Wei W. (2016) Social media as research instrument for urban planning and design, 2016 Eighth International Conference on Measuring Technology and Mechatronics Automation (ICMTMA). IEEE, 614-616.

Yang J, Schultz H, Zheng Y, et al. (2018) Considerations of the Paradigms of Urban Design Teaching Application about Big Data[C]//Proceedings of the International Symposium on Big Data and Artificial Intelligence. 48-52.

Yadav P, Hasan S, Ojo A, et al. (2017) The role of open data in driving sustainable mobility in nine smart cities .

Yang Y, Hsu J H, Löfgren K, et al. Cross-platform comparison of framed topics in Twitter and Weibo: machine learning approaches to social media text mining. Social Network Analysis and Mining, 2021, 11(1): 1-18.

Zhang F, Zhou B, Liu L, et al. (2018) Measuring human perceptions of a large-scale urban region using machine learning . Landscape and Urban Planning, 180: 148-160.

Zhang L, Pei T, Chen Y, et al. (2019) A review of urban environmental assessment based on street view images. J. Geo-Inf. Sci, 21: 46-58.

Zhao P, Liu X, Shen J, et al. (2019) A network distance and graph-partitioning-based clustering method for improving the accuracy of urban hotspot detection. Geocarto International, 34(3): 293-315.

Zheng Q, Zhao X, Jin M. Research on urban public green space planning based on taxi data: A case study on three districts of Shenzhen, China. Sustainability, 11(4): 1132.

Study on the influence of subway entrance space layout on indoor air quality

Wei Wang[1], Lei Zhang[2], Sihan Xia[3] and Mengmeng Da[4]

[1, 2, 4] School of Architecture and Urban Planning, Anhui Jianzhu University, Hefei 230601, Anhui, China; vivi.gan@126.com[1], koalei@126.com[2], 893453817@qq.com[4], 0000-0002-6411-6104[1], 0000-0002-8704-7981[2], 0000-0002-6822-6837[4]

[1] Key Laboratory of Built Environment and Health, Anhui Jianzhu University, Hefei 230601, Anhui, China

[3] School of Architecture, Harbin Institute of Technology, Harbin, China

xsh_25@126.com, 0000-0002-6206-2376[3]

Abstract: With the increasing area covered and the number of people served by subways due to rapid urbanization, air quality in subway stations on the health of passengers and staff has received increasing attention from society and scholars. In previous studies, the removal and control of underground pollutants have mainly focused on the indoor air conditioning and ventilation of metro stations rather than on optimizing architectural design. Therefore, this study focuses on the effect of subway entrance space layout on indoor particulate matter distribution. Our research selected three morphological indicators, namely, entrance direction, roof shape, and entrance height/width ratio, as the influencing factors. Indoor pollution in the form of subway entrances in different places was simulated after actual monitoring and verification. The results show that (1) the particle interception rate of the lateral entrance is twice as high as that of the forwarding entrance; (2) when the entrance height-width ratio is less than 1:1, the larger the entrance width is, the better the overall air quality of the subway station; (3) the abatement effect of roof morphology on the indoor particulate matter is ranked as sloping roof > flat roof > no roof. In general, the spatial morphology design can influence the entry of particulate matter into the metro station and reduce the direct infusion of outdoor pollutants through air convection and return flow.

Keyword: Metro stations; underground pollutants; CFD; spatial form; optimization strategy.

1.Introduction

To alleviate urban traffic congestion and to comply with the growth in demand for green transportation and sustainable development, the frequency of metro use is increasing (Genyin, et al., 2020; Zhao and Shen, 2019). More than 50% of residents in Chinese megacities such as Beijing and Guangzhou prefer to take the subway in their commute, and with the passenger flow rising year by year, the subway has become an essential mode of transportation for people's daily commute (Lu, et al., 2016; Zhou, et al., 2021). As an essential part of urban underground space, subways have relatively closed building forms and are primarily located in busy areas with many pollution sources. Therefore, a large number of pollutants and harmful substances are accumulated inside the subway, including carbon dioxide, total volatile organic compounds (TVOC), formaldehyde, microorganisms, respirable particulate matter (PM_{10}), and fine particulate matter ($PM_{2.5}$).

Studies have demonstrated that the impact of wind environment on PM mass and concentration in subway stations can be modified by regulating indoor airspeed, controlling airflow direction (Martins, et al., 2016), changing train track design (Moreno, et al., 2014), and the presence of PSD (Platform screen doors) (Querol, et al., 2012). Therefore, from the perspective of metro building planning and design, in addition to ensuring its safety, economy, aesthetics, and applicability in the first place, attention should also be paid to the issue of securing its internal ambient air quality.

In order to optimize the air quality inside the subway from the perspective of spatial morphology design this paper classifies the existing subway entrance space morphology in Hefei through research, establishes several CFD calculation models, and on this basis, analyzes the influence of its entrance space layout on the air quality of underground space and proposes an optimal design strategy to reduce particulate pollution in underground space.

2. Classification of subway entrance types

Our research team selected the Hefei metro stations for the whole line research, and ifferent subway entrances are classified by selecting typical measurements and drawing relevant models. This paper uses independent subway entrances as the main object of study for in-depth research on spatial forms.The subway station domain (except the station hall) consists of the external environment and the internal space. This study divides the internal space into three sections. The upper section is above-ground entrance space; the middle section is vertical traffic space; the lower section is connecting space between the subway entrance and the station hall. We analyzed the different parameters of each part of the metro station obtained from the research and selected the commonly used parameters as classification indicators.

Lateral entrance and front entrance are the two main types of openings for metro entrances (Table 1). Lateral entrance openings are commonly used for longer entrance spaces, while narrower entrances often use the front entrance method. The three main forms of entrance canopies are the sloping roof, flat roof and no roof. For example, with a flat roof, the entrance's height is 3.8m, and the entrance width is typically 2.6-8m. The four most common typical entrance aspect ratios of 1:2 (3.8m: 7.6m), 1:1.5 (3.8m: 5.7m), 1:1 (3.8m: 3.8m) and 1:0.7 (3.8m: 2.66m) are selected as typical variables.

Table 1 : Typical classification of upper space

Upper Space	Typical classification of upper space		
Entrance direction			
	Lateral entrance	Front entrance	
Roof form			

	Sloping roof	Flat roof	No roof	
Entrance aspect ratio				
	1 : 2(3.8m : 7.6m)	1 : 1.5(3.8m : 5.7m)	1 : 1(3.8m : 3.8m)	1 : 0.7(3.8m : 2.66m)

3. Methods

3.1. Experimental validation

3.1.1. Sampling location and schedule

Hefei city (30°57′-32°32′N, 116°41′-117°58′E) is a typical city with hot summer and cold winter climate zone, located in the Jianghuai Plain, with a subtropical monsoon climate. The research object is selected from the No.2 subway entrance of University Town North of Hefei Metro line 3 (Figure 1). Hefei metro is set PSD, which makes the indoor air is rarely affected by the piston ventilation and the pollution generated by the friction of train movement. The main source of $PM_{2.5}$ pollution comes from Jade Road, a two-way ten-lane main road. During the monitoring period, the weather in Guangzhou was fine, and it did not rain. The main wind direction was south, the hourly average wind speed was 1.8-3.3m/s, and the subway entrance faced the main wind direction.

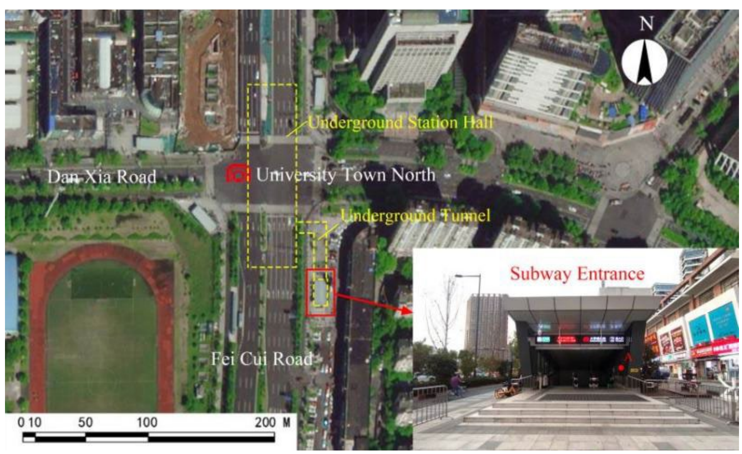


Figure 1: Map showing the sampling subway entrance.

The monitoring was conducted during the peak traffic periods (8:00-9:00 and 19:00-20:00) and the flat traffic periods (11:00-12:00) on August 19-21, 2022. Five sampling points were set up in the subway entrance area (Figure 2a). Point A was located at the subway entrance boundary, point B at the upper end of the escalator, point C at the lower end of the escalator, point D at the corner of the canal, and point E at the boundary between the canal and the station concourse.

3.1.2 Simulation Model and experimental validation

Figure 2 shows the computational domain and grid used for the simulation with 1939690 grids. Based on the measured average data at point A, the intensity release of $PM_{2.5}$ was initially set to 2.0×10^{-7} kg/s. The wind speed was set to 2 m/s, and the rest of the boundary conditions were the same as described in 3.2.3.

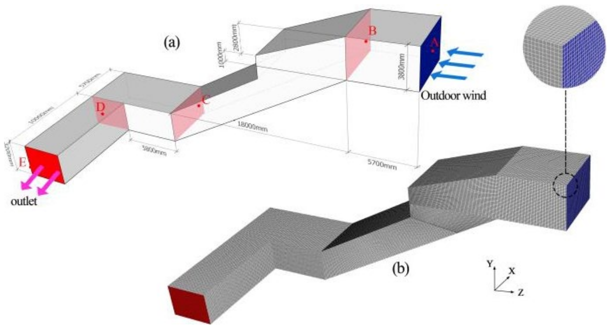


Figure 2: Geometry (a) and mesh (b) of the CFD simulation.

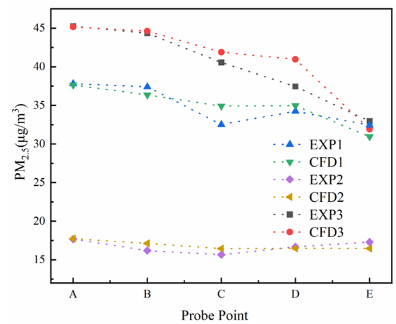


Figure 3: Comparison of numerical simulation and experiment for different time periods.

The comparison between the data obtained from CFD simulations and the monitoring measurements is shown in Figure 3. EXP1, 2 and 3 correspond to the average $PM_{2.5}$ mass concentrations for three different time periods: morning peak, midday and evening peak, respectively. The simulation results are in good agreement with the monitoring data. With the depth of the location, the simulated and monitored $PM_{2.5}$ mass concentrations show a decreasing trend. It is verified that the internal environment of the subway is mainly influenced by the particulate matter caused by road traffic. The minimum error between the simulated results and the monitored data is 0.6% (point B), and the maximum error is 9.4% (point D). Based on the above validation results, the CFD simulation data could be further used to analyze the spatial distribution of PM in the subway entrance area.

3.2. Numerical simulation

3.2.1. CFD set up

In this study, the CFD commercial software ANSYS FlUENT 19.2 is used. The RNG k-ε two-equation turbulence model simulates the airflow field. The Lagrangian particle trajectory tracking model was used to track the dispersion behaviour of the particles, which provides more detailed information on the particle motion than the Eulerian-Eulerian approach (Greenfield and Quarini, 1998). Numerical simulations were carried out using a finite volume solver to check the interception efficiency of the different index entrance spaces for external particulate matter. Following field measurements to obtain parameters for the physical model, 10 simplified CFD calculation models were created. Among them, the flat roof as a typical form has a total of 8 models with different parameters, while the sloping roof and roofless models are its comparison object. As shown in Figure 4, the inlet represents the metro station's front entrance/lateral entrance and has dimensions of 3.8m × xm, with width x being used to control the entrance aspect ratio. The outlet represents tunnel exits with dimensions of 3.2m × 5.7m or 3.2m × x m. A structured mesh grid was used for the entire computational domain.

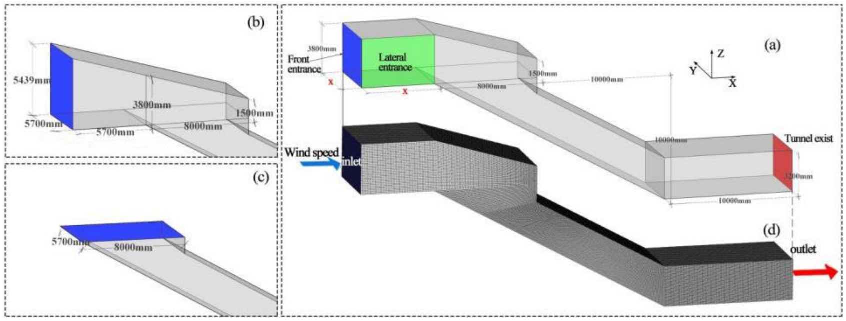


Figure 4: The geometry model and dimensions of flat roof (a), Slopping roof (b) and no roof (c) and the computational mesh grid (d).

The simulations were set up with three different wind speeds (velocities of 1, 2 and 3 m/s), two different opening directions (forward and lateral), three roof forms (flat, slopping and no roof) and four different entrance heights to width ratios (1:0.7, 1:1, 1:1.5 and 1:2). A total of 30 simulations were carried out for different combinations of conditions. The full simulations are presented in Table 2.

Table 2: Simulated cases.

Entrance direction	Roof form	Entrance aspect ratio	Wind speed(m/s)
Front entrance, Lateral entrance	Flat roof, Slopping roof, No roof	1：0.7 (3.8m：2.66m), 1：1 (3.8m：3.8m), 1：1.5 (3.8m：5.7m), 1：2 (3.8m：7.6m)	1, 2, 3
Total number of simulation cases：2×4×3+2×3=30			

3.2.2. Boundary conditions for CFD simulation

Since the air-fluid in the subway is an incompressible fluid, the uncoupled implicit algorithm is used for the set of control equations (Ren, et al., 2019). The properties of the fluid are constant except for the buoyancy term and the density variation, which is linear with temperature. The Boussinesq approximation is adopted for the density of the fluid. The wind enters the subway station perpendicular to the entrance, as shown in Figure 4d.

The convective term discretization of the velocity equation and the k-ε equation in the three coordinate directions is applied in a first-order upwind scheme, and the SIMPLE algorithm does the pressure and velocity coupling. The results are deemed to converge when the residuals reach 10^{-5}. The simulation environment set up different particle diameters of 1 μm, 2.5 μm, and 10 μm were set up in the simulation environment. The particles were placed from the inlet by means of a "surface" with no initial velocity (Aarnio, et al., 2005). Each diameter particle was released with the same intensity of 5-10-6 kg/s .

3.3. Evaluation indexes of subway entrance dust insulation effect

3.3.1.Average particles concentration

Relative to the local concentration analysis, the average indoor concentration at the subway entrance can reasonably reflect the overall particulate matter level in the front section of the subway area. In this study, the average particle concentration $C_{average}$ is used as one of the indicators to represent ventilation efficiency. $C_{average}$ is defined as follows.

$$C_{average} = \frac{\sum C_i V_i}{\sum V_i} \tag{1}$$

Where C_i is the concentration of the ith grid particle in the computational domain, V_i is the volume of the ith cell, and V_i is the total volume of the entire computational domain.

3.3.2.nterception efficiency of particles

The definition of interception efficiency is the ratio between the different number tracks of particles in exit and entrance to the number tracked of particles in the entrance, Sub subway passengers and staff spend more time in the station concourse than the entrances, so this paper focuses more on this index.

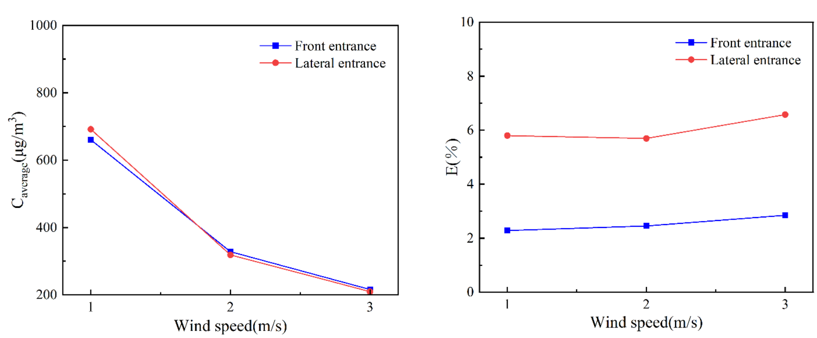
$$E = \frac{N_{in} - N_{out}}{N_{in}} \times 100\% \tag{2}$$

Where N_{in} is the number of particles tracked from the inlet into the interior, and N_{out} is the number of particles tracked from the exterior to the outlet.

4. Results and Discussion

4.1 Effects of entrance direction on distribution and Interception efficiency of particles

Figures 5 show the average concentration and interception efficiency inside the subway opening space for different entrance directions at wind speeds of 1m/s, 2m/s, and 3m/s for an entrance height of 3.8m and width of 5.7m, respectively. There is no significant difference in the concentration of particulate matter in the calculation domain for different opening directions. However, from the viewpoint of interception rate, the interception rate of particles in the lateral entrance is 2-3 times higher than that in the forward entrance. It indicates that the entrance direction can influence the pollutants entering the station hall. The main reason is not that the particles are suspended in the front space of the subway entrance but that they are absorbed by the walls, settled by gravity or escape from the entrance. Meanwhile, when the wind speed increases from 1m/s to 3m/s, the average particle concentration of forwarding and lateral entrances decreases by two-thirds.



(a) (b)

Figure 5: Comparison of the effects of different wind speeds on indoor air quality at the entrance direction of subway stations.

Figure 7 shows that the lateral inlet particles form a backflow on the right side of the inlet, which directly leads to the escape of particles from the right end of the inlet (The definition of the profile is shown in Figure 6). Moreover, the concentration of particulate matter in the centre of the return flow is low, which indicates that the particulate matter settles a lot in the return flow due to the reduced velocity and the influence of gravity. Meanwhile, due to the more pronounced turbulence in the lateral inlet, low concentration areas appear at many edges of the wall, so the lateral inlet has a higher interception rate than the frontal inlet.

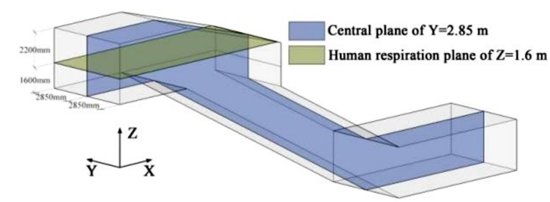


Figure 6: The central plane of Y=2.85 m and human respiration plane of Z=1.6 m distinguished by color.

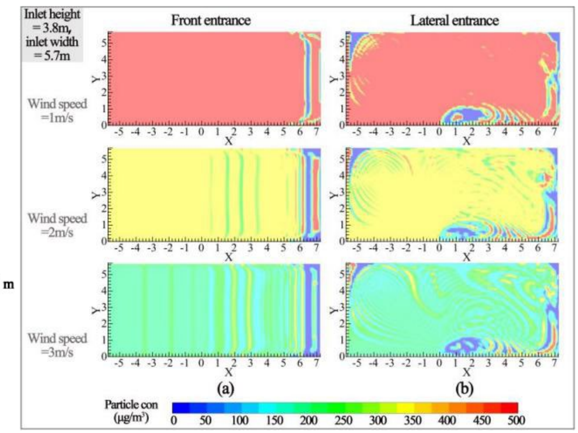


Figure 7: Contours of human respiration X-Z plane (Z = -2.2 m) particles distribution under different inlet directions at the condition of wind inlet height equal to 3.8m, inlet width equal to 5.7m.

4.2 Effects of the entrance aspect ratio of distribution and Interception efficiency of particles

Figure 8 shows the variation of the average particle concentration in the calculation domain for an inlet height of 3.8m and widths of 2.66m, 3.8m, 5.7m, respectively. When the inlet direction is positive, the wind speed is one m/s, and the inlet width increases from 2.66 m to 7.6 m, reducing indoor particulate matter concentration by 64.9%. A significant decrease in the particle concentration at the subway entrance as the inlet width increases. In addition, the entrance direction influences the average particle concentration when the entrance width is narrow. However, the influence gradually disappears with the widening of the entrance.

We extrapolate the particle retention trajectories for a set of simulated cases with a wind speed of 1 m/s, lateral inlets, and inlet widths of 3.8 m and 7.6 m (Figure 9). It can be seen that a large number of particles produce gyration but cannot be discharged from the inlet when the inlet is narrower, resulting in a stagnation zone with a larger volume and higher concentration in Fig. 9a compared to Fig. 9b. Comparing the details of the gyratory zone, we can find that when the inlet width is larger, the particles tend to move downward faster and receive less resistance, a tendency that is closer to the opening form of the positive inlet. Therefore there is no significant difference in the average particle concentration between the forward and lateral inlets when the inlet is wider.

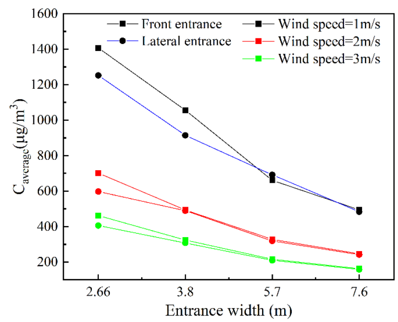


Figure 8: Comparison of the influence of height to width ratio of subway station entrance on indoor air quality under different wind speeds

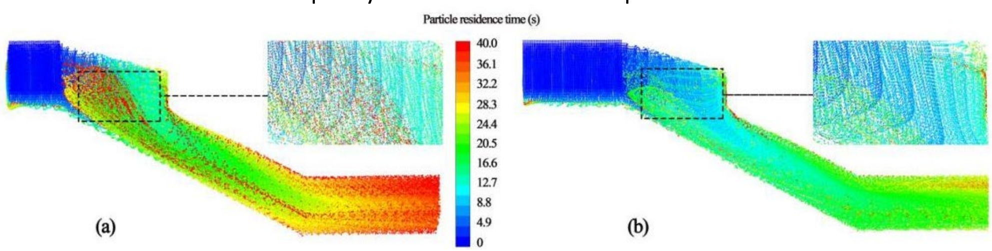


Figure 9: Particle Traces Colored by Particle Residence Time for Different Inlet Widths at Wind Speed of 1m/s and Lateral Inlet. [(a) Inlet width=3.8m; (b) Inlet width=7.6m]

Figure 10 shows the variation of inlet interception rate of particles for inlet height of 3.8 m and widths of 2.66 m, 3.8 m, 5.7 m, and 7.6 m (height to width ratios of 1: 0.7, 1: 1, 1: 1.5, and 1: 2), respectively. The inlet width of 2.66m has the highest interception rate. When the inlet width is 3.8m, the interception rate is the lowest, indicating that the inlet height to width ratio of 1:1 is the least effective in intercepting the particles. Furthermore, when the inlet width increases, the particle interception rate no longer changes significantly.

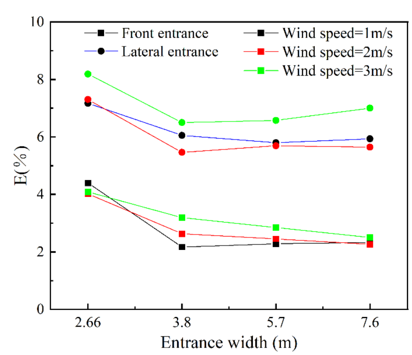


Figure 10: Comparison of the effect of subway station entrance width on the interception efficiency of particulate matter under different wind speeds

4.3. Effects of Roof form on airflow and particle distribution

Three models with positive inlet, inlet width of 5.7m, and flat roof, sloping roof, and no roof were selected for simulation under different wind speeds. Observing Figure 11, it can be found that when the roof is flat (Figure 11a), the overall particle concentration in the entrance space is the highest, and the concentration distribution is relatively uniform. Compared with the flat roof, the sloping roof entrance shows two fluctuating areas of concentration distribution due to the spatial extrusion of particles entering with the airflow, which makes the indoor pollutants unevenly distributed. While the roofless entrance lacks the collision and adsorption of particles by the shelter, the particles quickly enter the station hall space and do not stay at the entrance.

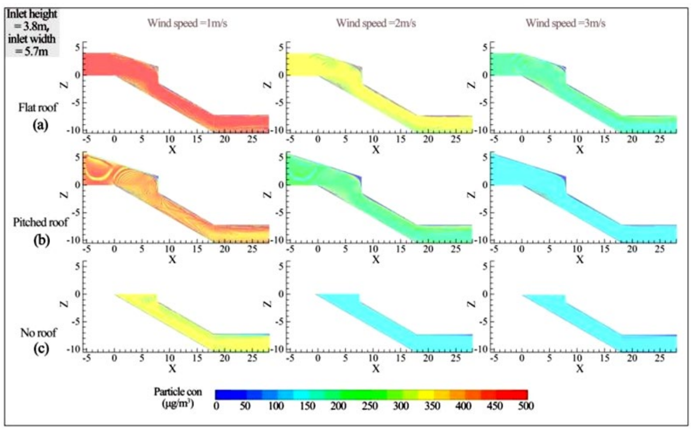


Figure 11: Contours of central X-Z plane's (i.e., Y = 2.85 m) particles distributed under different air curtain velocities with different wind speeds.[(a) plat roof; (b) Slopping roof; (c) no roof]

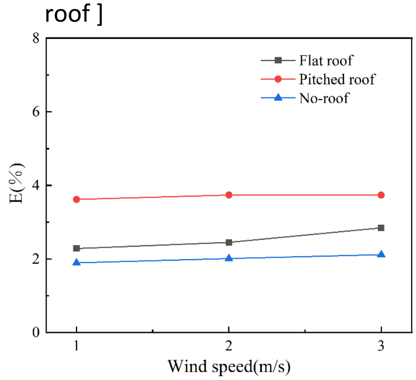


Figure 12: Comparison of the effect of subway opening roof form on the Interception efficiency of particles at different wind speeds.

We now turn to the study of the interception effect of different roof forms. Figure 12 shows the particle interception rates for different roof models at wind speeds of 1, 2, and 3 m/s. It can be seen that the subway entrance with the sloped roof form has the most important interception of outdoor particulate matter, followed by the flat roof, and the lowest interception rate of 1.89% for the roofless. Same as our understanding of Figure 11c, the roofless space has no shade to block the outdoor pollution source, and the particulate matter can directly settle into the room from the top.

In conclusion, without considering the complex outdoor airflow, the morphological design of the subway entrance roof shows that the sloped roof is the most favourable for indoor particulate matter abatement, followed by the flat roof and the worst without a roof.

5.Conclusions

The purpose of this study is to investigate the effect of different spatial forms of subway entrances on the abatement of outdoor atmospheric particles entering the subway stations. Through the survey of the Hefei subway, the spatial forms of existing subway stations were classified, from which three design indicators were selected as influencing factors. Numerical simulations were conducted using the validated turbulence model to study the corresponding effects of entrance orientation, roof morphology, entrance height to width ratio and atmospheric wind speed. The following conclusions were drawn.

(1) The interception rate of particles by the side-side entrance is 2-3 times higher than that of the front-side entrance. The lateral entrance to the subway station is easy to produce particle accumulation at the diagonal of the entrance and the middle of the canal; the forward entrance to the subway is easy to produce particle accumulation over the diagonal of the roof and the side of the canal.

(2) When the entrance height to width ratio is less than 1:1, the larger the entrance width is, the better the overall air quality of the subway station.

(3) From the morphological design of the roof of the subway entrance, the sloping roof is the most favourable to the abatement of indoor particulate matter, followed by the flat roof and the worst without a roof.

Acknowledgements

The authors would like to acknowledge the coordinated support from the National Natural Science Foun dation of China [51778001], the Open project of Key Laboratory of Built Environment and Health, Anhui J ianzhu University and the Graduate Scientific Research Project of Anhui Universities in 2021 [YJS2021050 1].

References

Aarnio, P., Yli-Tuomi, T., Kousa, A., Mäkelä, T., Hirsikko, A., Hämeri, K., Räisänen, M., Hillamo, R., Koskentalo, T. and Jantunen, M. (2005) The concentrations and composition of and exposure to fine particles (PM2.5) in the Helsinki subway system. *ATMOSPHERIC ENVIRONMENT*, 39 (28):5059-5066.

Genyin, C., Yifan, L., Song, P. and Yangqi, H. (2020) Measurement and analysis of PM2.5 in Beijing subway platform. *Journal of North China Institute of Science and Technology*, 17 (01):102-106.

Greenfield, C. and Quarini, G. (1998) A Lagrangian simulation of particle deposition in a turbulent boundary layer in the presence of thermophoresis. *APPLIED MATHEMATICAL MODELLING*, 22 (10):759-771.

Lu, K., Han, B., Lu, F. and Wang, Z. (2016) Urban rail transit in China: Progress report and analysis (2008–2015). *Urban Rail Transit*, 2 (3):93-105.

Martins, V., Moreno, T., Mendes, L., Eleftheriadis, K., Diapouli, E., Alves, C.A., Duarte, M., de Miguel, E., Capdevila, M., Querol, X. and Minguillón, M.C. (2016) Factors controlling air quality in different European subway systems. *ENVIRONMENTAL RESEARCH*, 146:35-46.

Moreno, T., Pérez, N., Reche, C., Martins, V., de Miguel, E., Capdevila, M., Centelles, S., Minguillón, M.C., Amato, F., Alastuey, A., Querol, X. and Gibbons, W. (2014) Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design. *ATMOSPHERIC ENVIRONMENT*, 92:461-468.

Querol, X., Moreno, T., Karanasiou, A., Reche, C., Alastuey, A., Viana, M., Font, O., Gil, J., De Miguel, E. and Capdevila, M. (2012) Variability of levels and composition of PM 10 and PM 2.5 in the Barcelona metro system. *ATMOSPHERIC CHEMISTRY AND PHYSICS*, 12 (11):5055-5076.

Ren, C., Feng, Z., Cen, D. and Cao, S. (2019) Study on the subway environment induced by moving train using Gaussian distributed momentum source theory method. *INDOOR AND BUILT ENVIRONMENT*, 28 (8):1083-1091.

Zhao, L. and Shen, L. (2019) The impacts of rail transit on future urban land use development: A case study in Wuhan, China. *Transport Policy*, 81:396-405.

Zhou, Y., Wang, H., Bi, H. and Wang, J. (2021) Experimental and numerical study of aerodynamic pressures on platform screen doors at the overtaking station of a high-speed subway. *BUILDING AND ENVIRONMENT*, 191:107582.

The role of education in the circular built environment: Analysis of Australian educational programs impact on construction and demolition waste management

Salman Shooshtarian[1], Savindi Caldera[2], Tim Ryley[3], Tayyab Maqsood[4], Atiq Zaman[5] and Peter SP Wong[6]

[1,4,6]RMIT University, Melbourne, Australia
{salman.shooshtarian[1], tayyab.maqsood[4], peterspwong[6]}@rmit.edu.au,
0000-0002-6991-8931[1], 0000-0001-7166-8110[4], 0000-0002-8429-2551[6]
[2,3] Griffith University, Brisbane, Australia
{s.caldera[2], t.ryley[3]}@griffith.edu.au, 0000-0002-1263-2924[2], 0000-0003-0878-5546[3]
[5]Curtin University, Perth, Australia
atiq.zaman@curtin.edu.au, 0000-0001-8985-0383[6]

Abstract: Resource circularity has become a necessity in the built environment sector. A significant amount of construction and demolition (C&D) waste is generated worldwide. This waste results from poor resource efficiency in the sector. Australia is among the lowest-ranked countries in the Organisation for Economic Co-operation and Development (OECD) regarding the sector's resource efficiency. A circular economy and resource efficiency can be achieved primarily through education, enforcement, and encouragement in the sector. Of these three elements, education is the focus of this paper. Education can generate attitudinal and behavioural change among stakeholders to move towards effective waste management (WM). This study aims to determine whether current Australian educational programs have successfully achieved circular economy objectives and improved resource efficiency. This paper provides an insightful overview of the programs and proposes a framework to evaluate the effectiveness of educational programs in a circular built environment. Lastly, it recommends a few practical suggestions to improve their effectiveness in the built environment sector.

Keywords: Construction and demolition waste, circular economy, behavioural change, Australia, training.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 548–558.*

1. Introduction

In the built environment (BE) industry, environmental and ecological problems linked with building operations have become a growing issue. The substantial quantity of waste created on construction sites is seen as a significant obstacle to the global expansion of the BE industry (Aslam *et al.*, 2020; Bao and Lu, 2020; Shooshtarian *et al.*, 2021b). Currently, the BE industry generates 35 percent of all garbage transported to landfills globally (Zheng *et al.*, 2017). In 2014, the United Kingdom created 49 million tonnes of construction and demolition (C&D) waste, of which more than half was landfilled (Menegaki and Damigos, 2018). China generates 2.36 billion tonnes of C&D garbage annually (Zheng *et al.*, 2017), whereas the United States generated 516 million tonnes in 2017 (US EPA, 2019). In Australia, housing, buildings, and transportation infrastructure development projects are being completed at an unprecedented pace. In this industry, the average annual growth rate between 2009 and 2019 was 3.33% (Kelly, 2021). According to the most recent statistics, Australians produced 27 metric tonnes of C&D waste, of which only 67 percent was recovered (National Waste Report, 2020). In response to this problem, three broad clusters of mitigation strategies, including enforcement, education, and encouragement, are offered. Education may play a crucial part in the 3R approach to waste management, which includes waste reduction, reuse, and recycling. Education has a significant impact on four primary domains in favor of waste management: increasing the awareness of industry stakeholders, improving organizational culture and changes in their attitudes and behaviors. Furthermore, recent efforts to implement circular economy (CE) concept in the BE industry place stress on education.

In Australia, the National Waste Policy (National Waste Policy, 2018) Strategy 3 (knowledge sharing, education and behaviour change), it is advised that coordinated knowledge sharing and education initiatives should be implemented to address the needs of governments, businesses and individuals, and to encourage the redesign, reuse, repair, resource recovery, recycling and reprocessing of products. Most Australian jurisdictions have formed teams dedicated to educating industry people and the wider community. Research and education are critical factors highlighted in all Australian waste strategy strategies and guideline documents. These documents have introduced initiatives to fund education programs to reduce waste disposal (Shooshtarian *et al.*, 2020a). A report by Senate Environment and Communications References Committee (2018) recommended that the Australian government should support state and local governments in providing effective recycling education initiatives. There is an ongoing debate about the individual role of education in promoting sustainable behaviour and attitudes in this context. For instance, Crocker and Lehmann (2013) highlight, that education alone has little or no effect when it comes to sustainable behaviour, concluding that improving knowledge and changing attitudes may not impact behaviour. Lingard *et al.* (2000) Lingard et al. (2000) suggested that if managers see a training program as successful and workers view it as irrelevant, it is unlikely that the training would have the intended impact. On the other hand, Chapman *et al.* (2013) observed that experiential learning results in new habits, and actively experiencing things is the most effective way to learn about environmental initiatives. Park and Tucker (2017) suggested that effective training can encourage the sharing of C&D waste responsibilities between contractors and professionals, and improve awareness and interest from would-be homeowners, clients and developers.

Several studies have highlighted the critical role of education in the Australian C&D waste context. Tam (2009) argued that inadequate private sector education on waste management technology investment is a crucial barrier to adopting C&D waste-related technologies in the Australian industry relative to its Japanese equivalent. A survey by Li and Yang (2014) showed that lack of knowledge and training of waste minimisation is the second most important waste management factor for building retrofit projects. Udawatta *et al.* (2015) study involving interviews of the sector professionals highlighted the importance of training and education for all stakeholders to enhance C&D was management performance. Park and Tucker (2017) identified attitudes towards reuse practices and training, lack of interest and demand are the major barriers to reusing recycled C&D waste materials in Australia. Newaz *et al.* (2020) interviewed 19 practitioners in NSW and found that knowledge, experience, and training of site operatives were one of the key factors influencing C&D waste management. Results of a survey showed that 'culture, poor education (attitude and behavior) and acceptance' is among the top four factors hindering a successful C&D waste management system (Shooshtarian *et al.*, 2021a). According to a survey of stakeholders' awareness of CE it was found that while over 70% of professionals grasped the essence of the CE concept, only 12.9% had enough expertise to implement CE in their organisations, (Shooshtarian *et al.*, 2022). Zhao et al. (2021) stated that to achieve state compliance standards, stakeholders must teach employers to change their attitude and awareness of WM. This will lead to effective WM behaviour from stakeholders over a project's life cycle. No studies have evaluated the impact of education on the C&D waste management system in Australia to yet. Consequently, the purpose of this study was to identify educational opportunities that would enhance the industry's capacity to alter the present C&D waste management status quo. This is the first effort to document such training initiatives in Australia, and it is part of a larger research project that seeks to discover the strategies to enhance the use of recycled C&D waste materials in Australian building projects. To achieve this aim, two objectives were set out: (1) to identify the main opportunities for educating the industry stakeholders on effective C&D waste management in Australia and (2) to provide suggestions for maximining the impact of education on C&D waste management.

2. Methodology

2.1. Research design

This study attempted to achieve research objectives by reviewing relevant literature. The literature used for this study included journal articles, conference papers, industry reports and other grey literature. Notably to achieve the first objective the primary educational providers and associated stakeholders were reviewed. The keywords used for extracting relevant literature included *'Australia', 'education', 'training',* '*construction and demolition waste', and 'circular economy.*

2.2. Study context

Australia's Commonwealth consists of six states and two self-governing territories. The Australian government, often known as the federal government, is the national government. The states and territories have a significant degree of autonomy; unless two conditions are met, the Australian government lacks the legal authority to influence many of state and territory governments' decisions, including waste regulations: (1) the regulations set by these governments conflict with international treaties that Australia is a party to (e.g., Agenda 21, Basel Conventions, and Stockholm Conventions) or (2) they impose threats to the environment that are of national concern. Furthermore, local governments and municipalities provide waste collection and recycling services, manage and operate or administrate landfill sites, deliver education and awareness programs, and provide and maintain recycling infrastructure (National Waste Policy, 2018). Therefore, the majority of legislation occurs at state and territorial government levels. The C&D waste stream is the largest source of waste in Australia. The waste management and resource recovery sector contributes 0.3% of Australia's GDP. Australian Bureau of Statistics for 2022 shows that over 1 million people work in the construction business and 656,000 in waste collection, treatment, and disposal (ABS, 2022). This organisation reported that the construction industry had spent $2 billion on waste collection, treatment, and disposal services among various sectors. These expenditures are calculated through the indicator of waste intensity, which quantifies the amount of waste generated per million dollars of value-added to the economy. This indicator for the construction industry is 87 tonnes per million dollars (ABS, 2020). These numbers simply imply the potential economic benefits obtained from educating employees in the construction and waste recovery industries.

3. Results and discussion

3.1. Educational opportunities

this section explores the extant educational opportunities for stakeholders involved [will be involved] in C&D waste supply chains. As illustrated in Figure 1, six common educational opportunities are provided by both the public and private sectors.

Figure 97. The most common educational opportunities in Australia

LinkedIn Learning- in recent years many universities and educational institutes across Australia are subscribed to this platform to unlock countless learning opportunities for their students and staff. LinkedIn Learning (LL), as a subsidiary of LinkedIn, is an online learning provider that offers video courses taught by industry experts in software, creative, and business skills. All the courses on LinkedIn fall into four categories: Business, Creative, Technology and Certifications and are designed for three levels: beginner, intermediate, and advanced. At the time of writing this article, the thirty-one courses on this platform are directly or indirectly linked to C&D waste management.

Tertiary education- The formal tertiary education system in Australia involves two primary levels: higher education (HE) and vocational education and training (VET, also known as TAFE: Technical and Further Education). HE focuses primarily on knowledge, theory, and critical thinking, and VET emphasises job-specific practical skills. The HE offers bachelor's degrees, graduate certificates, graduate diplomas, master's degrees, and doctoral degrees, and VET provides four levels of Certificates, diplomas and advanced diploma. Currently, the Australian tertiary education system advances the industry's understanding of effective C&D waste management in three ways: (1) providing waste management-specific courses in VET, (2) providing core or elective courses on sustainable construction management, technologies, practices and planning in HE and (3) providing opportunities for research activities focusing on C&D waste management in HE. NCVER (2022) reported that in 2021, 60.6% of VET qualification completers had an improvement employment outcome after training. Table 1 shows the current VET courses specific to waste management and their description.

Table 49. VET courses on waste management

Course title	**Duration**	**Course syllabus/description**
Certificate II in Waste Management	1 year	Students learn how to stay safe at work and then correctly sort waste and recyclables according to environmental protection laws. Students can choose electives that will enable you to drive forklifts and waste collection vehicles
Certificate III in Waste Management	1 year	The course includes identifying and segregating waste, conducting waste resource recovery, identifying hazards and responding to waste management emergencies, following WHS and site procedures, operating waste processing plant, carrying out waste assessments, operating waste collection vehicles, administration and leadership skills
Certificate IV in Waste Management	1 year	It teaches essential aspects of operations and safety management at waste processing facilities. Students will learn how to build relationships with staff and clients while implementing waste management plans—in accordance with environmental protection laws

With increased awareness of construction environmental impacts, Australian universities started to incorporate topics related to waste management, planning and practices in their course contents. The waste content is primarily included in courses that deal with construction sustainability. Also, few courses are offered that are specific to waste management, including 'Sustainable Waste Management' that covers C&D waste management. Some of these courses are also provided individually through Open Universities Australia (Crock *et al.*, 2013). Research activities provided via research programs or courses at three levels (i.e., undergraduate, master's and PhD programs) represent a further potential for the education of people about the C&D waste stream within HE. Students engaged in research-related courses at the undergraduate level may choose C&D waste management as their research topic, leading to Honours recognition from their host educational institutions. Students pursuing a Master's degree may undertake research on C&D waste management challenges via either the Masters by Research or Masters by Coursework programs. As the last point, there is a rising number of PhD candidates seeking to research C&D waste management for their doctoral theses. As shown in Figure 2, the number of thesis projects completed recently has seen a spike. According to Shooshtarian *et al.* (2021b), this might be due to increasing government funding possibilities for investigating C&D waste management challenges.

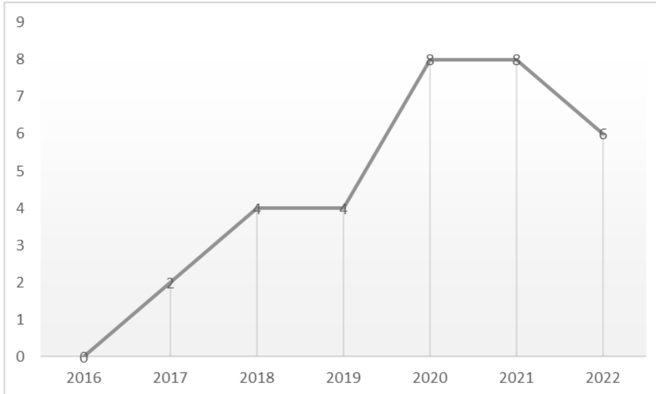


Figure 98. Number of research theses related to C&D waste recently completed in Australia. Source: Trove, National Library of Australia (2022)

Industry associations: Industry associations play an important role in providing a collective voice for individual businesses within an industry. Additionally, they attempt to educate their members on current industry-specific issues and solutions. In Australia, there are several associations that provide educational opportunities for stakeholders involved in C&D waste supply chains. Notably, the most active ones include Institute of Engineers Australia (IEA), Waste Management and Resource Recovery Association of Australia (WMRR), and Australian Council of Recycling (ACOR). These associations frequently arrange waste conferences and exhibits to offer networking and educational opportunities for industry stakeholders. WMRR has facilitated state-based waste education working groups to strategise waste education initiatives at the state and national level. These working groups consist of industry professionals, government representatives, and academics. ACOR designed a community-driven national recycling education program Recycle Mate, to increase public awareness of recycling issues and support recycling initiatives. Lastly, the Green Building Institute (GBI) provides some training course to minimise waste in the BE sector.

Sustainability rating organisations: these organisations primarily aim to improve sustainability in the Australian BE sector through their rating systems which recognize sustainability efforts in building and infrastructure sectors (Shooshtarian *et al.*, 2019). The main two organisations are Green Building Council of Australia (GBCA) and the Infrastructure Sustainability Council (ISC). In addition, they organise periodic professional development training to promote the awareness of sustainable construction among their members and other industry professionals. C&D waste management is one of the primary topics explored in these courses and activities. In a survey conducted by GBCA (GBCA, 2022), it was found that 91% of its members considered CE as ‘extremely important’ and ‘very important key are of focus for education.

Industry organisations: various organisations operating in waste recovery sector have launched educational programs that focus on behavioral change in the industry. Examples include Getting Wise About Waste and Greenius offered by Veolia and Cleanaway, respectively that are two major waste service providers in Australia. The former initiative is a fully interactive online learning portal for waste and recycling education– titled the EduPortal. The EduPortal provides clients with tailored information to help staff on-site across various positions, understand how to identify different waste streams and locate the correct receptacle within which to dispose of these materials. Lastly, Clean Site® is an industry education program created and executed by KESAB environmental solutions in collaboration with state and local governments and other industry associations delivers education and training embracing best practice on construction sites through onsite demonstration and information resource materials(KESAB, 2022).

Government educational programs: National and state governments have a pivotal role in providing and supporting educational programs for the BE sector. In most state waste strategy documents the role of education is highlighted (Shooshtarian *et al.*, 2020b). Some examples of these programs include ecologiQ that is a Victorian Government program that was designed in 2019 to help Victorians incorporate construction materials into transport projects. The ecologiQ offers educational opportunities for industry stakeholders in order to maximise the usage of recycled materials in infrastructure projects. In addition, the federal government, through Skilling Educators for Sustainability Australia (SESA), offered an opportunity for trainers in the waste sector to increase their skills and capabilities in order to better help their colleagues in responding to waste concerns. South Australian Green Industries has launched Circular360 (Global Centre of Excellence in Circular Economy) that will deliver training on the role of the CE in reducing Australia’s global carbon footprint through the smarter recovery, recycling and reuse of materials, with a focus on the benefits to business in becoming more circular (Waste Management Review, 2021). Lastly, each state's Environmental Protection Agency (EPA) offers professional educational opportunities. These opportunities that might be obligatory aim to enhance industry understanding of dealing with waste challenges.

3.2. Education's influence on C&D waste management: Analysis of evidence and way forward

In this section, the study analyses the impact of education on C&D waste educational programs. There is little evidence showing how the educational programs have led to increased sustainability in C&D waste management. However, it is documented that the quality of an educational programme may have a substantial influence on the attitudes and behaviours of industry professionals. For instance, a survey conducted by an Australian organisation (Alchemy Living & Learning, 2014) showed that waste educational programs would be more effective if there were primarily face-to-face, through networking and conferences and include onsite field studies. The research also attributed the success of waste education to providing accreditation or pathways into larger qualifications. The two main barriers to successful waste education included time and cost followed by the not knowing a course is running and lack of perceived value and relevance of an education program. Waste educational programs aim to influence attitudes and behaviours in the BE sector and waste recovery industry. To do this, educational programmes must be revamped and authorities must concentrate on maximising effect. This section offers strategies for achieving education providers' goals. These solutions rely on a framework by Michaela Zint of University of Michigan (Meera, 2022), as shown in Figure 3.

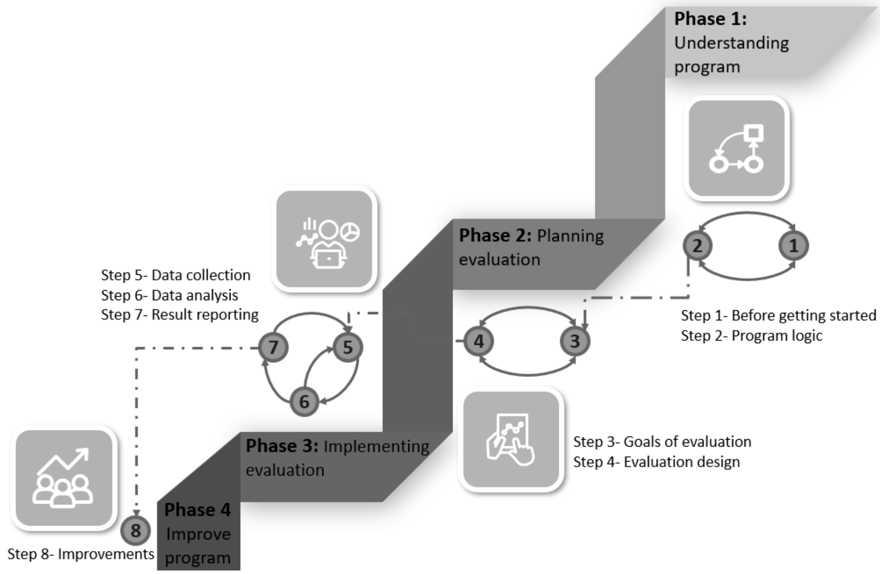


Figure 99. A framework to evaluate an educational program effectiveness.
Source: Adopted from Meera (2022)

This framework guides improvements in educational programs in four phases (understanding program, planning evaluation, implementing evaluation and improve program) and through eight steps. These eight steps are described in Table 2.

Table 50. Summary of strategies for successful design and implementation of waste educational programs

Step	Description of strategies	
1	• Engage external evaluator to conduct assessment activities • Create a forum to generate discussion and promote interaction among stakeholders	• Build organisational capacity and stakeholders' support to collaborate to evaluate program success measures
2	• Create a logic model to assist stakeholders understand the program's objectives and how it is accomplishing them	• Develop a logic model that shows your program's logic and the links between inputs (resources used), outputs (activities and audience), and benefits (outcomes and impacts in short, intermediate and long-term)
3	• Identify why evaluation is planned and who will use the evaluation's results which determine the method of evaluation • Develop indicators that help demonstrate whether program goals have been achieved	• Set evaluation questions based on the logic model components (created in Step 2), which also consider the concerns of multiple stakeholders
4	• Identify what type of data to collect and how to collect those data by reviewing the most effective methods	

5	• Devising a work plan with deadlines for all key aspects of the evaluation to keep the process manageable	• Identify expectations for staff and evaluation team members • Pilot-test instruments to ensure that directions are clear and that measures are appropriate for the target audience
6	• Ensure to analyse data at the appropriate level (e.g., intermediate or advanced)	
7	• To determine how results are shared based on target audience and program goals	
8	• Communicate the program's successful results to demonstrate the impact it has on your target audience or the community. • Address organization and planning problems to make the implementation of program more successful and increase participant satisfaction • Change content based on participants' feedback or other evaluation results	• Use what is learned from the evaluation to identify ways to increase awareness of your program's offerings • Consider investing in certain components of the program if some components provide less than ideal results than others • Learn from the mistakes and limitations of past evaluations to avoid these pitfalls in the future

In addition to evaluation, there are other strategies that may help program educational program achieve their goals. These strategies are provided below:

- Provide accreditation or pathways into larger qualifications
- Devise mandatory education for individuals engaged in C&D waste generation and handling
- Alignment between various waste educational initiatives
- Financial assistance from the government for participation in educational programmes
- Building capacity in organisations to enable individuals' participation in waste education

4. Conclusions

Education, enforcement, and encouragement are the three driving forces that enable the design and implementation of a successful C&D waste management system. In the Australian context, the role of education in advancing C&D waste is ill-studied. This study is the first attempt to capture the educational opportunities that will facilitate behavioural and attitudinal changes towards better waste management in the BE sector. The results showed that in the Australian context, there are six major channels for waste education. However, there is little evidence showing how these programs have been reflected in attitudinal and behavioral change in the BE sector. The present research contributes to the theory and practice of waste education in the Australian BE sector through providing suggestions that enable educational programs archive their intended goals. This review sets the springboard for the larger research project roadmap to evaluate how educational programs will lead to attitudinal and behavioral change resulting in minimization of C&D waste landfilling in the Australian BE sector.

Acknowledgements

This research has been developed with funding and support provided by Australia's Sustainable Built Environment National Research Centre (SBEnrc) and its partners. The authors also would like to thank RMIT Enabling Capability Platform (ECP) that provided funding under R&I - Strategic Investment - Research & Innovation Capability to support participation in ASA 2022 conference.

References

ABS (2020) *Waste Account, Australia, Experimental Estimates*, Australian Bureau of Statistics, Canberra, Australia.

ABS (2022) *Labour Force, Australia, Detailed*, Australian Bureau of Statistics, Canberra, Australia.

Alchemy Living & Learning (2014) *Report on professional development needs of waste and water industry trainers to educate for sustainability*.

Aslam, M. S., Huang, B. and Cui, L. (2020) Review of construction and demolition waste management in China and USA, *Journal of Environmental Management*, 264, 110445.

Bao, Z. and Lu, W. (2020) Developing efficient circularity for construction and demolition waste management in fast emerging economies: Lessons learned from Shenzhen, China, *Science of The Total Environment*, 724, 138264.

Chapman, J., Skinner, N. and Searle, S. (2013) Working towards sustainability: exploring the workplace as a site for pro-environmental behavioural change, in, *Motivating change: sustainable design and behaviour in the built environment*, Routledge, 88-102.

Crock, M., Baker, J. and Turner-Walker, S. (2013) Open Universities Australia: The evolution of open access and online education opportunities, in, *Global challenges and perspectives in blended and distance learning*, IGI Global, 83-98.

Crocker, R. and Lehmann, S. (2013) *Motivating change: Sustainable design and behaviour in the built environment*, ed., Routledge.

GBCA (2022) *Annual member survey ends 2021 on a high for GBCA*, Green Building Council of Australia Sydney, Australia

Kelly, A. (2021) *Construction in Australia.*, AU Industry (ANZSIC) Report E. IBISWorld Pty Ltd.

KESAB (2022) *Clean Site: Building a Better Environment* Available from: KESAB Environmental Solutions <http://www.kesab.asn.au/programs/clean-site/> (accessed 2022).

Li, M. and Yang, J. (2014) Critical factors for waste management in office building retrofit projects in Australia, *Resources, Conservation and Recycling*, 93, 85-98.

Lingard, H., Graham, P. and Smithers, G. (2000) Employee perceptions of the solid waste management system operating in a large Australian contracting organization: implications for company policy implementation, *Construction Management & Economics*, 18(4), 383-393.

Meera (2022) *My environmental education evaluation resource assistant*, University of Michigan, Michigan, US.

Menegaki, M. and Damigos, D. (2018) A review on current situation and challenges of construction and demolition waste management, *Current Opinion in Green and Sustainable Chemistry*, 13, 8-15.

National Waste Policy (2018) *Less Waste. More Resources*, in W. a. t. E. Department of Agriculture (ed.), Canberra, Australia.

National Waste Report (2020) *National Waste Report*, Department of Agriculture, Water and the Environment, Canberra, Australia.

NCVER (2022) *VET student outcomes 2021*, National Centre for Vocational Education Research.

Newaz, M. T., Davis, P., Sher, W. and Simon, L. (2020) Factors affecting construction waste management streams in Australia, *International Journal of Construction Management*, 1-9.

Park, J. and Tucker, R. (2017) Overcoming barriers to the reuse of construction waste material in Australia: A review of the literature, *International Journal of Construction Management*, 17(3), 228-237.

Senate Environment and Communications References Committee (2018) *Never waste a crisis: the waste and recycling industry in Australia*, Parliament of Australia Canberra, Australia

Shooshtarian, S., Caldera, S., Maqsood, T., Ryley, T. and Khalfan, M. (2021a) An investigation into challenges and opportunities in the Australian construction and demolition waste management system, *Engineering, Construction and Architectural Management*.

Shooshtarian, S., Hosseini, M. R., Kocaturk, T., Arnel, T. and Garofano, N. (2022) Circular economy in the Australian AEC industry: Investigation of barriers and enablers, *Building Research & Information*.

Shooshtarian, S., Hosseini, M. R., Kocaturk, T., Ashraf, M., Arnel, T. and Doerfler, J. (2021b) *The Circular Economy in the Australian Built Environment: The State of Play and a Research Agenda Prepared*, Deakin University.

Shooshtarian, S., Maqsood, T., Wong, P. S., Khalfan, M. and Yang, R. J. (2019) Green construction and construction and demolition waste management in Australia, *43rd AUBEA Conference: Built to Thrive: Creating Buildings and Cities That Support Individual Well-Being and Community Prosperity*, Noosa, Australia, 6 – 8 November 2019.

Shooshtarian, S., Maqsood, T., Wong, P. S., Yang, R. J. and Khalfan, M. (2020a) Review of waste strategy documents in Australia: analysis of strategies for construction and demolition waste, *International Journal of Environmental Technology and Management*, 23(1), 1-21.

Shooshtarian, S., Maqsood, T., Wong, S. P., Yang, J. R. and Khalfan, M. (2020b) Review of waste strategy documents in Australia: Analysis of strategies for construction and demolition waste, *International Journal of Environmental Technology and Management*, 23(1), 1-21.

Tam, V. W. (2009) Comparing the implementation of concrete recycling in the Australian and Japanese construction industries, *Journal of Cleaner Production*, 17(7), 688-702.

Udawatta, N., Zuo, J., Chiveralls, K. and Zillante, G. (2015) Improving waste management in construction projects: An Australian study, *Resources, Conservation and Recycling*, 101, 73-83.

US EPA (2019) *Advancing sustainable materials management: EPA 530-F-19-007.* , The US Environmental Protection Agency.

Waste Management Review (2021) *SA leading the world in circular economy*,Waste Management Review,, Waste Management Review,.

Zhao, X., Webber, R., Kalutara, P., Browne, W. and Pienaar, J. (2021) Construction and demolition waste management in Australia: A mini-review, *Waste Management & Research*, 0734242X211029446.

Zheng, L., Wu, H., Zhang, H., Duan, H., Wang, J., Jiang, W., Dong, B., Liu, G., Zuo, J. and Song, Q. (2017) Characterizing the generation and flows of construction and demolition waste in China, *Construction and Building materials*, 136, 405-413.

The walking tourist: How do the perceptions of tourists and locals compare?

Swarnali Dihingia[1], Morten Gjerde[2] and Brenda Vale[3]

[1, 3] Victoria University of Wellington, Wellington, New Zealand
(swarnali.dihingia, brenda.vale)@vuw.ac.nz[1]
[2] Norwegian University of Science and Technology, Trondheim, Norway
morten.gjerde@ntnu.no[2]

Abstract: Walking is known to be a healthy and sustainable way of moving about the city, particularly in comparison with motorised forms of transport. For these and other reasons, there is a growing interest amongst urban planners and policy makers in enhancing conditions for walkers. Growing the number of people walking makes sense from the perspectives of public health, reducing pollution and greenhouse gas emissions and social sustainability. This also applies to people visiting a city; tourists are increasingly walking to get to know the places they visit from the footpath. However, there is little known about their experiences. This research addresses the question of how visitors perceive and evaluate the city they are visiting when they walk. Comparisons are made with the experience of local residents. The paper examines the relatively overlooked domain of tourist walkability and investigates the extent to which accessibility and topography may influence walking experiences. Data was gathered from a Walk Diary in which respondents evaluated the environment along a single walk. Responses were received through convenience sampling from 132 people in two New Zealand cities: Christchurch and Wellington. The Walk Diary provided an effective way of capturing differences between locals and tourists when they walk. Insights from this study will be particularly useful to those tasked with enhancing people's urban walking experience.

Keywords: walking; tourists; accessibility; walking experience**.**

1. Introduction

Walking is recognized as an active transport mode that contributes to a wide range of benefits to both individual and society (Gehl 1987; Frank and Engelke 2001; Leyden 2003; Litman 2003; Forsyth and Southworth 2008; Ewing and Handy 2009; Hall, Le-Klähn and Ram 2017). Walking increases physical activity and thus improves health, well-being and quality of life and is accompanied by less vehicle travel and thus less traffic, air pollution, and other environmental impacts.

“Walkability” studies have measured and analyzed walking based on the time spent walking by individuals. Other research has dealt with pedestrian movement using empirical quantitative approaches that often deal with collective patterns of behaviour and their relationship to the physical environment (Cao, et al., 2006; Dihingia, et al., 2022). In terms of sustainable urban design, walkable places are regarded as preferable for locals and tourists alike (Ram & Hall, 2018). Nevertheless, a number of differences between locals and tourists walking have been identified (Hall, Le-Klähn and Ram 2017). Tourists are often found to wander about with an exploratory attitude at a lower speed in an unfamiliar environment, whereas, the walking behaviour of locals are characterised by frequently taken paths with ample knowledge about the topographical features of the city (Vojnovic 2006; Gorrini and Bertini 2018). However, there is still a lack of knowledge on the effects of walking environment on walking tourist in urban areas (Tong, Wang and Chan 2016; Vandenberg, et al. 2016; Gorrini and Bertini 2018; Yun, Kang and Lee 2018), especially a comparison between locals and tourists’ walking experience. Understanding and providing an appropriate level of walkability is a challenge for civic authorities, as they have to try to balance the demands of various users and uses of public space (Henderson 2018).

With the current literature on tourist walking, accessibility, connectivity, comfort, safety, aesthetics and appeal have been identified as significant factors for tourist walking behaviour (Samarasekara, et al., 2011; Ujang & Muslim, 2015; Mansouri & Ujang, 2016). Before a pedestrian proceeds to walk anywhere, these walking needs have to be catered for (Talavera-Garcia & Soria-Lara, 2015). Alfonzo (2005) developed a hierarchy of walking needs to be considered in the walking decision process. These needs ranged from the most basic, such as feasibility and accessibility to higher-order needs (related to urban form) and were based on priority of fulfilments. An individual would not typically consider a higher-order need in his or her decision to walk if a more basic need, such as accessibility was not already satisfied (Alfonzo, 2005). In their study of visitors in Kaula Lumpur, Mansouri & Ujang (2016) found that spatial features such as accessibility, connectivity and continuity strongly determine tourists’ expectation and satisfaction while walking. This supports the findings by Supitchayangkool (2012) who noted that accessibility to tourists spots is an indicator for tourists to revisit a destination.

Given the importance of accessibility and with the current effort of making cities walkable, this paper aims to understand whether there is a difference in how locals and tourists feel while walking in two New Zealand cities: Christchurch and Wellington. The two cities are popular with tourists yet differ in terms of their topography, building density, architecture, views, street characteristics and patterns. Hence, they provide different environments for walking. The city councils in each city have identified various walking routes with various themes to explore within and around the city. This paper particularly focuses on the attributes of accessibility and legibility: how easily a person is able to access their destination, and the physical barriers encountered. The working hypothesis is that the accessibility attributes have an effect on the tourists’ satisfaction with their route.

2. Methodology

A diary was adopted to capture the perceptions of locals and tourists about their walk experience. It was designed in the form of a A5 size booklet named the “Walk Diary” for the central city areas of Christchurch and Wellington. This Walk Diary was based on the idea of a walk with respondents filling it in while conducting the walk or soon after. The survey (lasting five and seven weeks in Christchurch and Wellington, respectively) was conducted in late summer to the start of autumn during the school holidays to capture visitors. Ultimately, 81 and 51 diaries were completed and returned with a response rate of 53% and 56% in Christchurch and Wellington respectively.

2.1. Data gathering tools

The data was gathered through convenience sampling by placing the Walk Diary on the front desks and counters of visitor accommodation, such as hotels, hostels and motels, cafés and restaurants, tourist attractions, educational institutions and student accommodation. As the target sample of the study was people visiting a place, these outlets seemed to be an effective way of recruiting them. The respondents were awarded with a coffee voucher after completing the Walk Diary. The protocol of the survey administration was based on the contact between the outlets' staff and the respondents rather than the respondents and the first author.

2.2. Walk Diary

The Walk Diary consisted of 14 A5 size portrait pages with a folded A3 size tourist map of each city centre with street names and labelled attractions. The diary was divided into sections with a set of instructions on how to fill it in and the estimated time it would take to complete each section. The first two sections consisted of close-ended questions probing individual and walk trip information. These sections obtained information about respondents' demographic details and information regarding the trip of the particular day. It was then followed by the route information about accessibility, safety, comfort, and pleasantness based on activities and built environment and for each walk conducted the respondents recorded their perceptions on a five-point agreement Likert scale. The respondents were left with space to write any additional feedback or to comment on any feelings about their walk.

Finally, the respondents were asked about their level of satisfaction with their walking trip, which was measured by the statement, *"I was satisfied with the route that I took".* This part also investigated the importance and their general expectations of walking.

2.3. Attributes selected for the study

As noted in Section 2.2, the walkability assessment criteria selected for the main study were accessibility, comfort, safety and pleasantness based on activities and built environment. In this paper, only the influence of the five sub-attributes of accessibility on the walking behaviour/route satisfaction will be discussed. The five sub-attributes for accessing accessibility were the presence of a sufficiently good and wide walkway condition, absence of closed roads (culs de sac), enough signs to understand the route, presence of a flat terrain, and universal design, such that people with baby buggies, wheelchairs, and older people could easily use the paths.

3. Walking experience

3.1 Personal information

The personal characteristics of the respondents in Christchurch and Wellington are summarised in Table 1. The respondents were of mixed ages and the percentage of females was slightly higher than that of males in both cities. A wide range of age groups was captured from under 25 to 70 years and above. However, almost half of the respondents in both cities were between 25-39 years old, again with a higher percentage of women respondents in this age group. The next highest group were respondents under 25 years with a slightly higher percentage of women in Wellington. This meant the survey data was somewhat skewed to younger age groups, particularly women. The final participation rates were different

(Christchurch, n=81; Wellington, n=51), and the two cities also differed in the split between locals and tourists. The Christchurch survey captured more tourists than locals (55.6% were tourists), while in Wellington only one-third of the respondents were tourists (27.5%). City resident respondents in both cities were asked about their familiarity with the city with 3.7% and 2.7% in Christchurch and Wellington respectively being not at all familiar (Table 2). For tourists, in Christchurch most were somewhat or not at all familiar with the city with only 6.3% being familiar with it. Interestingly, in the case of Wellington, most visitors were not at all familiar with the city.
These differences should reflect the attitudes and the perception of walking in two major cities.

Table 51: Respondent demographic comparisons for Christchurch and Wellington

		Christchurch		**Wellington**	
Variable					
Age		**Frequency (n)**	**Share (%)**	**Frequency (n)**	**Share (%)**
	Under 25	21	25.9	12	26.3
	25-39	33	40.7	29	50.9
	40-54	8	9.9	3	6.2
	55-69	14	17.3	6	13.5
	70 and above	5	6.2	1	3.1
Gender					
	Female	42	51.9	29	55.7
	Male	38	46.9	22	44.3
	Others	1	1.2	0	0.0
Type of visitor					
	Locals	36	44.4	41	72.5
	Tourists	45	55.6	10	27.5
Familiarity					
	Very familiar	28	34.6	23	36.3
	Somewhat familiar	31	38.3	19	41.0
	Not at all familiar	22	27.2	9	22.0
Total		81	100.0	51	100.0

Table 2: Familiarity of locals and tourists with Christchurch and Wellington

		Christchurch		**Wellington**	
		Frequency (n)	**Share (%)**	**Frequency (n)**	**Share (%)**
Locals	**Very familiar**	23	28.4	23	36.3
	Somewhat familiar	10	12.4	16	33.6
	Not at all familiar	3	3.7	2	2.7

Tourist	**Very familiar**	5	6.2	0	0
	Somewhat familiar	21	25.9	3	7.5
	Not at all familiar	19	23.5	7	20.0

Total		81	100.0	51	100.0

3.2 Analysis Approach

The differences in the walking behaviour of locals and tourists emerge from the descriptive analysis. The study was able to capture different age groups from under 25 to above 70 with a dominance of respondents between 25-39 years old, and more females than males.

The aim was to understand the influence of the attributes on the walking route satisfaction of locals and tourists. Because of the ordinal polytomous nature of the dependent and the independent variables, ordinal logistic regression was adopted to estimate satisfaction with the attributes for both cities. Using the PersonMean imputation in RStudio the few missing values were filled for the estimation data set. Imputation methods are used to fill missing data with the variable mean score (Glaw 2010). Imputing the row mean (PersonMean) is mainly used in sociological or psychological research, where data sets often consist of Likert scale items (Schork 2019), as in the case of the Walk Diary. In order to analyse the data, a numerical code (from 1 to 5) was assigned to each point on the ordinal scale, based on direct determined quantification (De Luca, 2006). Specifically, a value equal to 1 was assigned to “Strongly Disagree”, and a value of 5 to “Strongly Agree”.

3.3 Respondents satisfaction

Table 3 lists the accessibility sub-attributes and the respondents’ satisfaction with their walking routes in both cities. The mean of the satisfaction level of the respondents differed city wise and on whether they were locals or tourists. A good condition of walkway was seen throughout Christchurch and Wellington by both locals and tourists. City wise, in Christchurch, both locals and tourists enjoyed their route due to the flat terrain and the absence of culs de sac. In Wellington, locals were moderately satisfied with the level terrain whereas the mean score for tourists was considerably lower at 3.00. This may reflect Wellingtonians’ familiarity with and acceptance of the city’s often steep topography surrounding the flatter central area. On the other hand, a proportion of the tourists experienced these steeper conditions as their walks took them further afield.

The Wellington responses to questions about the universal design attributes respondents may have encountered along their walks suggest that tourists expect public spaces to provide more opportunities for people with different abilities. This was the only mean score to fall below the neutral line, and it was significantly below that number in this survey.

Table 3: Respondent satisfaction with route attributes

	Christchurch		**Wellington**	
	Mean		**Mean**	
Attributes	**Locals**	**Tourists**	**Locals**	**Tourists**
Good walkway condition	4.33	4.42	4.07	3.80
Absence of cul de sac	4.16	4.02	3.58	3.10
Signs to create understandable route	3.97	3.64	3.82	3.10
Flat terrain	4.69	4.53	3.95	3.00
Universal design	3.72	3.95	2.95	2.30
Route satisfaction	4.48	4.18	4	4.3
Total	**36**	**45**	**41**	**10**

3.4 Estimation results

In the model, the dependent variable is the route satisfaction, while the independent variables are the respondent specific categorial variables and their satisfaction with the accessibility sub-attributes of the route. A two-way ANCOVA was used to determine if there was a statistically significant two-way interaction effect between the sub-attributes and the respondents being tourists on the overall route satisfaction. The results of the final estimates are shown in Tables 4. Ordinal logistic regression was estimated for the 81 respondents in Christchurch and 51 respondents in Wellington.

The main effects of the sub-attributes on the overall route satisfaction in Christchurch were not significant. The two-way ANCOVA revealed that for tourists, absence of culs de sac showed a positive correlation on the overall route satisfaction. The main effect of the presence of signs for understanding the route was significant in Wellington, however, we could not run the interaction with tourists due to the inadequate sample size (n=10). In this case, for Wellington, we are forced to conclude that the data do not support the hypothesis that the walking behavior of locals and tourists are different.

Even then, the different effects of the sub-attributes on locals and tourists were apparent from the respondents' feedback. Most of the sub-attributes were positive, but there was a weak correlation between tourists' satisfaction with the route and their overall satisfaction. Some tourists in Christchurch mentioned that the walkways were wide, however, for some, the footpaths in the city center were too narrow. This was rather surprising, as Christchurch has aimed to be a walkable city as it has been rebuilt following the 2010-11 earthquake sequence. The dissatisfaction with Christchurch footpaths was echoed by locals who reported that there were constructions which obstructed the footpath connectivity. Opinions differed between tourists regarding signs for understanding the route. Some tourists felt that there were enough signs, whilst the majority voiced their concern about lack of signage, especially at intersections. One tourist mentioned the presence of excessive billboards and advertisements was rather displeasing.

In Wellington, the presence of signs to help understand the route had an effect on the route satisfaction for both locals and tourists. This was a major concern voiced by locals as there were no signs, especially in areas connecting the motorways and in places of roadworks and construction sites. The majority of locals mentioned that they disliked the construction sites, which eventually led to narrower walkways. One local reported that they did not particularly liked walking through the temporary shipping container protecting the footpath and the presence of scaffoldings seemed threatening for another. A minority of locals mentioned that the footpaths were well connected and wide, however, the condition of the walkways received negative comments. A number of issues were identified by the locals who noted that the footpaths were damaged in areas and overflowed with surface water, thus creating unpleasant puddles and slippery surfaces. A few locals mentioned that their route satisfaction was affected due to their route being uphill.

Table 4: Estimation results

	Christchurch (n=81)			Wellington (n=51)		
Intercepts	**a_j**	**SE**	**Odds ratio**	**a_j**	**SE**	**Odds ratio**
Strongly Disagree to Disagree	-2.38	2.25	-	-	-	-
Disagree to Neutral	-1.25	2.20	-	-0.39	2.15	-
Neutral to Agree	0.41	2.19	-	1.41	2.15	-
Agree to Strongly Agree	2.83	2.21	-	3.80	2.20	-
Attributes						
Good walkway condition	-0.18	0.70	0.83	0.51	0.37	1.67
Absence of cul de sac	-0.80	0.49	0.45	-0.24	0.24	0.79
Signs to understand route	0.28	0.34	1.32	**0.83****	0.37	**2.30****
Universal design	0.57	0.36	1.77	-0.19	0.27	0.83
Flat.terrain	0.82	0.62	2.28	-0.29	0.30	0.75
Tourist	-4.56	4.00	0.01	1.02	0.80	2.77
Tourist * Good walkway condition	0.67	0.92	1.96	-	-	-
Tourist * Absence of cul de sac	**1.33****	0.63	**3.79****	-	-	-
Tourist * Signs to understand route	-0.25	0.55	0.78	-	-	-
Tourist * Universal design	-0.21	0.63	0.81	-	-	-
Tourist * Flat terrain	-0.67	0.82	0.51	-	-	-

***p<0.1; **p<0.05; ***p<0.01**

4. Discussion

The general findings from this study suggest both locals and tourists walk, with tourists in Christchurch and locals in Wellington being more vocal about their likes and dislikes. A possible explanation in the case of Christchurch might be that the Christchurch survey captured more tourists than locals. The locals were well acquainted and comfortable with the ongoing rebuilding of the city after the 2010-11 earthquake, which was not the case for the tourists who were in an unfamiliar environment. In the case of Wellington, the locals were more outspoken which might be due to their familiarity and regular usage of the public spaces.

It is interesting to note that despite the issues raised, the majority of locals and tourists were satisfied with their overall route in both cities. As the tourist sample in Wellington was small, statistical information could not be derived from the population of tourists and a comparison between locals and tourists was not possible. However, in Christchurch, there were significant differences in the walking behaviour of locals and tourists. Comparing both the cities, respondents found better overall quality of walking conditions in Christchurch than Wellington. The likely cause for the better conditions in Christchurch could be due to the flat terrain, and hence it meeting the needs for universal design. At the same time, the positive correlation of being a tourist on the absence of culs de sac could be attributed to the fact that Christchurch has been rebuilt in a grid layout. Considering previous literature which stated that tourists wander around with an exploratory attitude (Gorrini & Bertini, 2018; Davies, 2018), the benefit of having a serial vision, a concept conceived by Cullen (1961), proved helpful.

The resources for wayfinding include signage and information systems, point-of-decision cues and aids, such as street name signs, and indications of accessible pedestrain access. Surprisingly, past research on walking and walkability has given limited attention to wayfinding (Vandenberg, et al., 2016). In unfamiliar places, pedestrains often use mobile navigation tools or maps (Laurier & Brown, 2008). Based on the comments of the locals and tourists, the lack of signage surfaced due to temporary narrow passages with no indication of an alternative route owing to undergoing construction works in both cities. As researchers and practitioners both acknowledge that signage cannot compensate for poor design and, as a matter of practice, should be considered in the context of overall design and movement patterns and integrated with other information resources (Arthur & Passini, 1992; Passini, 1996), care should also be taken over signage for temporary events.

A view commonly expressed by locals and tourists in both cities was the absence of signs to help them understand how to get to where they wanted to walk. This finding is consistent with that of Farkic, et al. (2015) and Gorrini and Bertini (2018) who found that the level of tourist walkability was deeply affected by the lack of basic services, such as scarcity of road signs in their studies in Serbia and Venice respectively. However, the mean preference scores for understanding the route, aided by signage, were overall positive for the whole respondent group as well as in each of the distinct categories set out in Table 3 above. This could be an indication of the reliabilty of Lynch's (1960) concept of imageability. Lynch found that people develop mental images of the places they inhabit aided by five key physical attributes. Nodes and districts describe the imageability of neighbourhood centres and other urban clusters or punctuations in cities, whereas paths and edges relate to the influence boulevards and large natural features such as streams/rivers or harbours might have on mental images. Landmarks are the fifth element, with towers and mountains as examples. Both Wellington's and Christchurch's central areas are blessed with vivid examples of each; in Wellington it could be the clear edge of the harbour, the silhouette of the hills forming the amphitheature around the city or it could be one of several landmark buildings. Christchurch has the Avon River tracing an organically shaped ribbon through an otherwise gridiron plan, the Port Hills to the south and key pathways such as Worcester Boulevard and Manchester Street. Further investigation of the influence urban form may have had on people's ability to navigate the city in the absence of wayfinding signage is warranted given these results.

5. Conclusion and Future research

As accessibility is the highest order walking needs, this paper aimed to report the findings of research looking into differences and similarities in the walking behaviour of locals and tourists in the central city areas of Christchurch and Wellington. To make these findings it was necessary to distinguish between tourists, daily visitors, and locals when interrogating their walking behaviours. The comparisons were made between two New Zealand cities, each with distinct physical geographies. It could also be argued that societal characteristics of the local populations are reasonably similar. This enabled the researchers to draw comparisons based on differences between local and tourist respondents and to look for possible explanations in the physical characteristics of the places people were walking.

The key findings of this part of the research are that both locals and tourists appreciated well designed level walkways with good signage to aid wayfinding. Connectivity is also important as this aids the exploration of a new place for tourists. When events like construction works disrupt normal footpaths much greater consideration needs to be given to alerting walkers to alternative routes so they can avoid these places, just as motorists are given detours when roads are disrupted. With this information, we recommend these issues be looked at carefully by urban planners and traffic engineers. Further research will involve analysis of other attributes that affect the walking experience of locals and tourists that formed part of this survey.

Acknowledgements

This research is funded by a Victoria University of Wellington Doctoral Scholarship and the data collection was funded by a Victoria University of Wellington Research Grant. The authors would also like to thank the outlets that carried the survey and the respondents for their participation.

References

Alfonzo, M. A., 2005. "To walk or not to walk? The hierarchy of walking needs." *Environment and Behaviour,* pp. 808-836.

Arthur, P. & Passini, R., 1992. *Wayfinding, People, Signs and Architecture.* New York: NY: McGraw Hill.

Cao, X., Handy, S. L. & Mokhtarian, P. L., 2006. The influences of the built environment and residential self-selection on pedestrian behavior: evidence from Austin, TX. *Transportation,* Volume 33, p. 1–20.

Cullen , G., 1961. *Concise Townscape.* 1st ed. London: Architectural Press.

Davies, N. J., 2018. Who walks, where and why? Practitioners' observations and perspectives on recreational walkers at UK tourist destinations. *Annals of Leisure Research,* 21(5), pp. 553-574.

Dihingia, S., Gjerde, M. & Vale, B., 2022. Walking Tourist: Review of Research to Date. *Journal of Urban Planning and Development,* 148(2), p. 04022017.

Ewing, R. & Handy , S., 2009. Measuring the Unmeasurable: Urban Design Qualities Related to Walkability. *Journal of Urban Design,* 14(1), pp. 65-84.

Farkic, J., Lesjak, M., Peric, D. & Petelin, M., 2015. Urban walking: Perspectives of locals and tourists. *Geographica Pannonica,* 19(4), pp. 212-222.

Forsyth, A. & Southworth, M., 2008. Cities afoot – pedestrians, walkability and urban design. *Journal of Urban Design,* pp. 1-3.

Frank, L. D. & Engelke, P. O., 2001. The built environment and human activity patterns: exploring the impacts of urban form on public health. *Journal of Planning Literature,* 16(2), p. 202–218.

Gehl, J., 1987. *Life between buildings.* New York, NY: Van Nostrand-Reinhold.

Glaw, C. W., 2010. Missing Data. In: P. Peterson, E. Baker & B. McGaw, eds. *International Encyclopedia of Education.* Third ed. s.l.:Elsevier.

Gorrini, A. & Bertini, V., 2018. Walkability assessment and tourism cities : the case of Venice. *International Journal of Tourism Cities.*

Hall, C. M., Le-Klähn, D. T. & Ram, Y., 2017. *Tourism, Public Transport and Sustainable Mobility.* Bristol: Channel View.

Henderson, J., 2018. Making cities more walkable for tourists: a view from Singapore's streets. *International Journal of Tourism cities,* 4(3), pp. 285-297.

Laurier, E. & Brown, B., 2008. Rotating maps and readers: praxiological aspects of alignment and orientation. *Transactions of the Institute of British Geographers,* 33(2), p. 201–216.

Le-Klähn, D. T., Roosen, J., Gerike, R. & Hall, C. M., 2015. Factors affecting tourists' public transport use and areas visited at destinations. *Tourism Geographies,* 17(5), p. 738–757.

Leyden, K. M., 2003. Social capital and the built environment: the importance of walkable neighborhoods. *American Journal of Public Health,* p. 1546–1551.

Litman, T. A., 2003. Economic value of walkability. *Transportation Research Record,* Volume 1828, p. 3–11.

Lynch, K., 1960. *The image of the city.* Cambridge: MIT Press.

Mansouri, M. & Ujang, N., 2016. Tourist's expectation and satisfaction towards pedestrian networks in the historical district of Kuala Lumpur, Malaysia. *Asian Geographer,* 5706(33:1), pp. 35-55.

Passini, R., 1996. Wayfinding design: logic, application and some thoughts on universality. *Design Studies,* 17(3), pp. 319-331.

Samarasekara, G. N., Fukahori, K. & Kubota, Y., 2011. Environmental correlates that provide walkability cues for tourists: An analysis based on walking decision narrations.. *Environment and Behavior, ,* 43(4), pp. 501-524.

Schork, J., 2019. *Mean Imputation for Missing Data (Example in R & SPSS).* [Online] Available at: https://statisticsglobe.com/mean-imputation-for-missing-data/ [Accessed 20 June 2022].

Supitchayangkool, S., 2012. The Differences Between Satisfied/Dissatisfied Tourists Towards Service Quality and Revisiting Pattaya, Thailand. *International Journal of Business and Management ,* p. 30–39.

Talavera-Garcia, R. & Soria-Lara, J. A., 2015. Q-PLOS, developing an alternative walking index. A method based on urban design quality. *Cities,* Volume 45, pp. 7-17.

Tong, X., Wang, Y. & Chan, E. H. W., 2016. International research trends and methods for walkability and their enlightenment in China. *Procedia Environmental Sciences,* Volume 36, pp. 130-137.

Ujang, N. & Muslim, Z., 2015. Walkability and attachment to tourism places in the city of Kuala Lumpur, Malaysia.. *Athens Journal of Tourism,* 2(1), pp. 53-65.

Vandenberg, A. E. et al., 2016. Walking and walkability: is wayfinding a missing link? Implications for public health practice. *Journal of Physical Activity and Health,* 13(2), pp. 189-97.

Vojnovic, I., 2006. Building Communities to Promote Physical Activities: a multi scale geographical analysis.. *Journal Compilation of Geographical Analysis,* 88 (B)(I), pp. 67-90.

Yun, H. J., Kang, D. J. & Lee, M. J., 2018. Spatiotemporal distribution of urban walking tourists by season using GPS-based smartphone application. *Asia Pacific Journal of Tourism Research,* 23(11), pp. 1047-1061.

Thermal performance of student-built naturally ventilated remote accommodation in Fish River, NT

David Kroll[1], Joti Weijers-Coghlan[2] and Arianna Brambilla[3]

[1] University of Adelaide, Adelaide, Australia
david.kroll@adelaide.edu.au, 0000-0003-3447-0775,
[2] University of South Australia, Adelaide, Australia
joti.weijers-coghlan@unisa.edu.au, 0000-0003-0047-0136,
[3] University of Sydney, Sydney, Australia
Arianna.brambilla@sydney.edu.au, 0000-0002-8494-7861

Abstract: Remote accommodation in tropical Australia is often characterised by poor thermal performance and enormous energy costs when mechanical cooling systems are installed. Fish River Station, located in the Northern Territory, features a series of bala balas; tent-like structures to host aboriginal rangers working on-site, offering only a roof to shed beds from the rain and no additional features to provide thermal comfort. This paper is part of the Fish River project, a 3-year-long student design-build project to retrofit two of the bala balas to improve living conditions for the rangers. This paper reports on the thermal performance of one of the comprehensively retrofitted bala balas, enhanced with roof insulation and other upgrades to reduce radiant heat and improve overall thermal comfort inside. The retrofitted bala bala and an original, unmodified bala bala were monitored simultaneously (temperature/humidity/radiant heat). The authors expected to find significant improvements in thermal comfort due to the upgrades. The data shows that the upgrades resulted in overall improvements in indoor comfort. However, they also caused a thermal lag and heat retention at nighttime and during the early morning hours. The study shows that the effectiveness of roof insulation needs to be considered carefully depending on the local climate and how the accommodation is used.

Keywords: building performance, thermal comfort, natural ventilation, indoor environmental quality.

1. Introduction

The Indigenous Land Corporation (ILC), now the Indigenous Land and Sea Corporation (ILSC), contacted the Design Construct program of the University of South Australia in 2016 to help with the improvement of accommodation for Aboriginal rangers on a remote station in Australia's Northern Territory. Fish River station employs four to eight rangers from the nearby Daly River community and encourages Aboriginal rangers and their families to work and spend time on their traditional land. The previous ranger station

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 570–579. © 2022 and published by the Architectural Science Association (ANZAScA).*

accommodation was made up of rudimentary tent structures that became unbearably hot when exposed to direct sunlight due to scorching radiant heat. They also lacked insect screening and basic amenities such as shelves, lighting, ceiling fans, beds, and privacy. To address these shortcomings, the ILC obtained funding (AUD 100,000) for the construction of upgraded ranger accommodations. Over the next two years, the project was designed and built with students from a variety of design and construction disciplines (Figure 1).

Figure 100: Fish River Aboriginal ranger accommodation

Design-build programs have long offered an opportunity for integrating applied environmental design awareness and research into the architectural curriculum and to create new knowledge through their built projects. Hinson, for example, highlights the importance of design-build studios to “serve as an effective base for the synthesis, integration, and transformation of knowledge through teaching” and to be “research-driven” (Hinson, 2007). The Design Construct program at the University of South Australia has a long history of creating built projects with students. The program has typically been engaged by non-for-profit organisations and local communities, in particular indigenous communities. Previous work includes completed projects for indigenous communities in Patjarr, Alukuru and Mimili in Australia to provide accommodation and other facilities (Morris and Weijers-Coghlan, 2017).

The Design Construct program aims to expand student learning beyond the formal core design stages. Students take part in design, costing, construction and are also involved in the early briefing stages, for example by engaging with end-users and clients. More recently, the team has also begun evaluating the long-term performance of its projects once in use. Our notion of this more comprehensive, circular approach to the architectural process is illustrated in Figure 2. This expanded approach has been important for integrating practical environmental design knowledge into all these stages and is inspired by Kieran’s method for ‘Research in Design’ through evaluating and learning from previous projects (Kieran, 2007). It means that an understanding of environmental performance can be informed, not only by software simulations and best practice guidance, but also by an exposure to real-world practicalities and contexts. This circular process was first implemented in the Fish River Aboriginal Rangers Accommodation project with a post-occupancy thermal performance study.

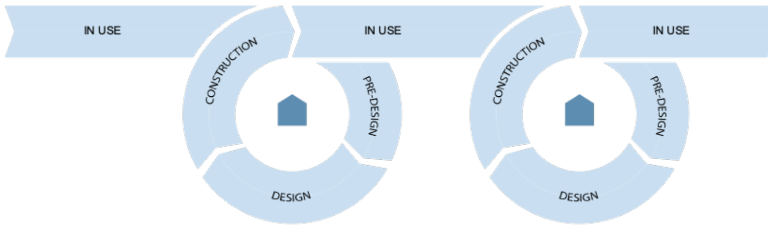


Figure 101: Circular model of project workflow where post-construction, in-use evaluation informs follow-on projects.

2. Construction of retrofit

Fish River Station originally had four bala balas built in close proximity to house rangers. Due to staffing requirements, it was only considered necessary to upgrade two of the bala balas, thus leaving two bala balas in their original state (Figure 3). All bala balas shared similar orientation and tree cover, providing the opportunity to undertake a synchronous thermal comparison of the upgraded and original bala balas.

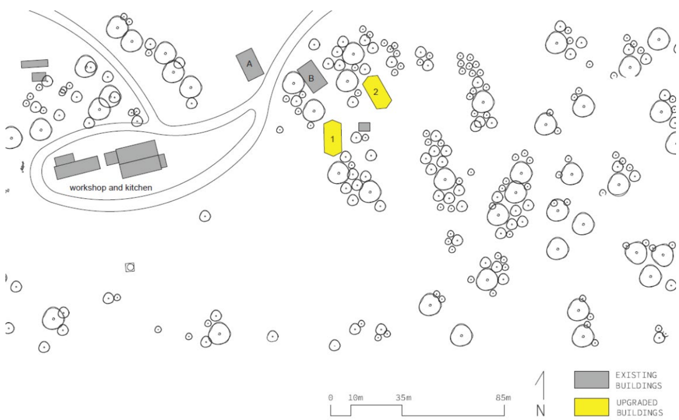


Figure 102: Site plan showing the location of the retrofitted bala balas (1 and 2) and the original bala balas (A and B) used for synchronous thermal performance analysis.

The original bala balas are constructed in a tent like manner, consisting of a tarpaulin roof stretched over a steel frame, assembled from prefabricated components. Steel columns on a 4.5m x 3m grid, support a steel sub-floor structure of bearers and joists, which carry a timber deck floor, elevated approximately 500mm above the ground. The steel columns carry a pitched roof frame consisting of steel rafters placed at 3m intervals. These rafters carry a steel ridge beam and two edge purlins, that support a heavy-duty PVC tarpaulin, which is stretched over the structure and tethered to steel horizontal rails running along either side of the building (Figure 4).

Figure 103: One of the original bala balas, consisting of a steel frame, raised timber deck floor and tarpaulin roof.

The bala bala retrofit was designed to take advantage of the existing rigid steel frame, re-using as much of the original buildings as possible while improving thermal comfort for the occupants. In addition, the retrofit also provided insect screening, improved visual privacy and greater protection from wind driven rain (Figure 5). These improvements were achieved by making the following changes:

- Tarpaulin roof replaced with corrugated metal roof
- Addition of an insulating, vapour barrier with thermal break below the roof sheeting
- Addition of plywood ceiling to indoor and outdoor habitable spaces
- Addition of corrugated metal eaves lining
- Extension of the roof coverage in all directions.
- Addition of floor to ceiling mesh screening on all sides.
- Deck flooring was replaced with solid plywood flooring for internal habitable spaces.
- Addition of ceiling fans and lighting

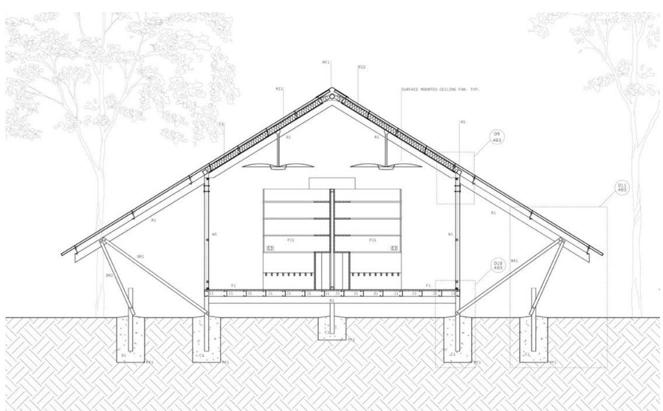


Figure 104: The upgraded accommodation was designed to make use of its natural environment without artificial cooling or heating

These modifications required additional steel framing to brace the structure and carry the additional internal linings and exterior cladding (Figure 6). It should be noted that while improved thermal comfort of the occupants was the priority of the retrofit, this objective was compromised by other, competing demands, particularly that of keeping insects out. The high level of natural ventilation afforded by the original bala bala, was not matched by the retrofit, which exchanged the porous condition of the decking boards for a solid floor and further reduced airflow by means of continuous insect screening. Such compromises were an inevitable part of the design process which addressed thermal comfort in tandem with other objectives, including safety, personal and cultural preferences, construction method and budget.

Figure 105: Ranger's accommodation under construction. The existing steel structure and foundations have been reused and incorporated into the new buildings. The roof has been updated with reflective insulation (AIR-CELL Insulbreak) and a ventilated cavity to provide better protection from the sun.

3. Materials and methods

This study aimed to evaluate the thermal advantages of the bala bala retrofit, especially in relation to the roof performance. It is important to note that the site is occupied only during the dry season (May to November), not the wet season. A series of sensors were installed to study the thermal performance of the retrofit in relation to the design aims and objectives. Two sensor networks have been installed in the site: one for the monitoring of the retrofitted accommodation and the other on the original configuration (Figure 7). The buildings are generally used only during night-time for sleeping or reading, as rangers usually gather around the fire or around the workshop and kitchen area during their free time and until sleeping time. For this reason, the sensors log environmental data monitoring the indoor temperatures temperature and stratification, the radiant temperature beneath the roof, the air velocity, and the CO2 concentration.

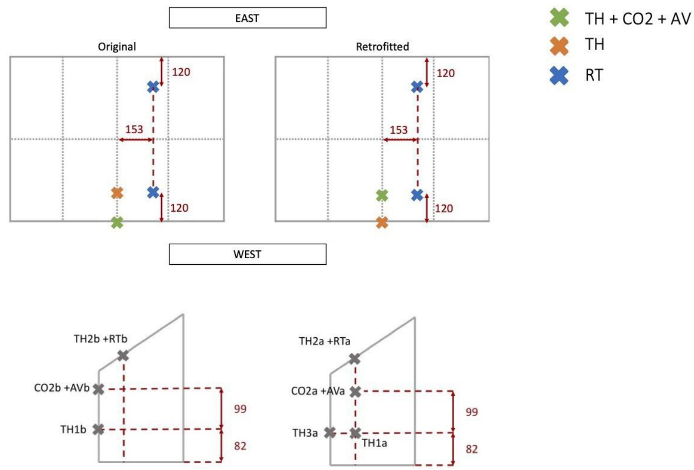


Figure 106: Sensor placement in original and retrofitted accommodation

Table 1 reports the data specification of the sensors employed and that could be retrieved at the end of the monitoring campaign, corresponding to the locations TH2b and TH2a of Figure 7. Unfortunately, due to the remoteness of the locations and the delay in the collection caused by bushfires, Covid19 and consequent border enforcements, several of the sensors were lost, damaged, or disposed.

Table 52: Data specification of the sensor

Type of sensor	Temperature and humidity
Model	HOBO MX2300
Accuracy	± 0.2°C; ± 2.5 % (range 10 % to 90 %); ± 5 % (> 90 %)
Logging time steps	30 minutes

While on site for the installation of the sensors, a first exploration of the thermal performance of the roof was undertaken. Spot temperature measurements were taken with a handheld infrared thermometer in the morning, mid-day and afternoon of 24th August 2018 on the internal roof surface of both the retrofitted and original bala balas. The original bala balas have different roof colours and the initial exploration was undertaken for all typologies: retrofitted, green and white. It is important to note that the original balas were roofed with the same heavy duty PVC tarpaulin material, and the only difference was the colour of the tarpaulin. This first test was by no means conclusive, but it showed significant improvements of over 20 degrees at certain times, particularly midday and afternoon when the roof was exposed to direct sunlight (Figure 8). Temperatures have been taken at morning, mid-day and afternoon on the internal roof surface for the retrofitted shed, the old one (green) and the improved configuration (white). Temperature was taken in the middle of the section.

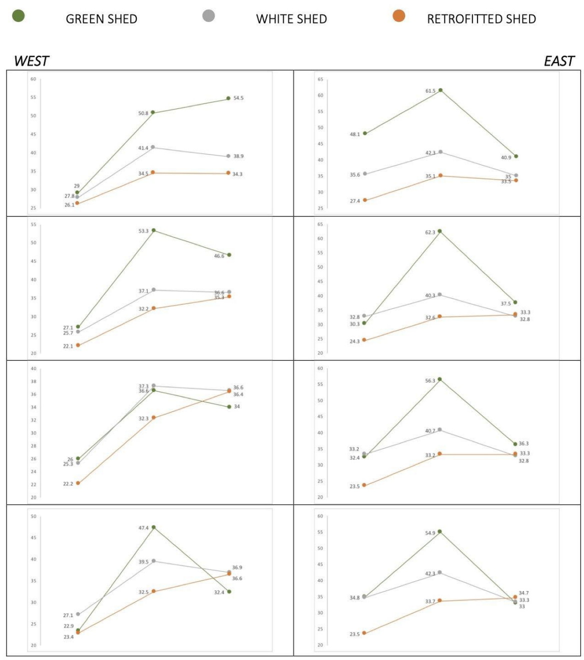


Figure 107: Preliminary study on the roof underside surface temperature

4. Results

Figure 9 displays the outdoor temperature, as logged by the weather station, and the indoor temperatures monitored in both buildings. The location is characterised by a typical tropical climate, with warm nights and hot days, hence the biggest difference between the indoor and the outdoor temperatures is registered during the day, with up to 7°C difference. During these peaks, it appears that the retrofitted solution maintains lower indoor temperature compared to the original, suggesting that the indoor thermal variations is higher inside the original accommodation.

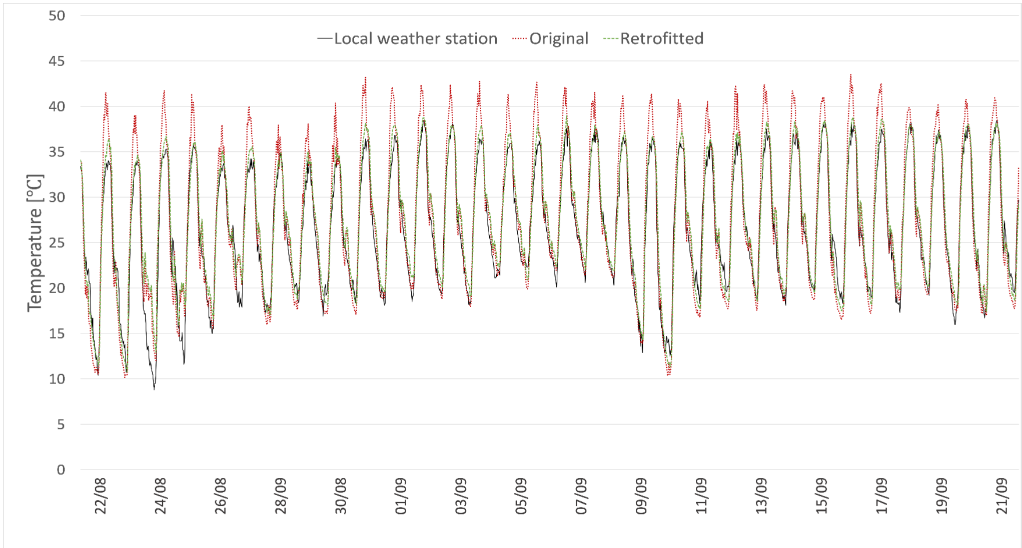


Figure 108: Indoor temperatures registered in the retrofitted and original bala bala, and outdoor temperature as logged by the closest weather station.

To further explore these differences, in Figure 10, the vertical axis displays the temperature difference between the original design and the retrofitted (original indoor temperature minus retrofitted indoor temperature), expressed in degree Celsius, while the horizontal axis represents the outdoor temperature. This means that points resting on the horizontal axis are representative of a situation where the indoor temperatures of the two accommodations were equal (difference is 0), points on the upper part of the graph indicate a situation where the retrofitted accommodation was cooler than the original one (difference is positive, hence original accommodation indoor temperature is higher), and points in the lower part represent a situation where the retrofitted accommodation was warmer (difference is negative, hence original accommodation indoor temperature is lower). The graph is colour coded, where red dots represent day hours (red is midday) and blue dots represent night hours.

The graph demonstrates that, during the day, the retrofitted accommodation maintains a lower indoor temperature, with a difference of up to nearly 7°C, compared to the old tent structures that the rangers lived in. Furthermore, it shows that the warmer it is outside, the greater is the difference to the original accommodation, demonstrating a higher resilience to increasing temperatures during peak hours. The retrofitted accommodation registered a slightly higher temperature during the night (by up to 3°C), which may affect comfort. However, the retrofitted accommodation overall shows a more stable and constant temperature, providing a more stable indoor thermal environment throughout the day and less fluctuation during the 24-hours. The retrofitted accommodation allows temperature to stabilise during the day, which may be an advantage under extreme weather events, as underlined by the better performance during the day and peak hours. The more stable indoor environment of the retrofitted accommodation is important since it is intended to be used as a passive design without air-conditioning.

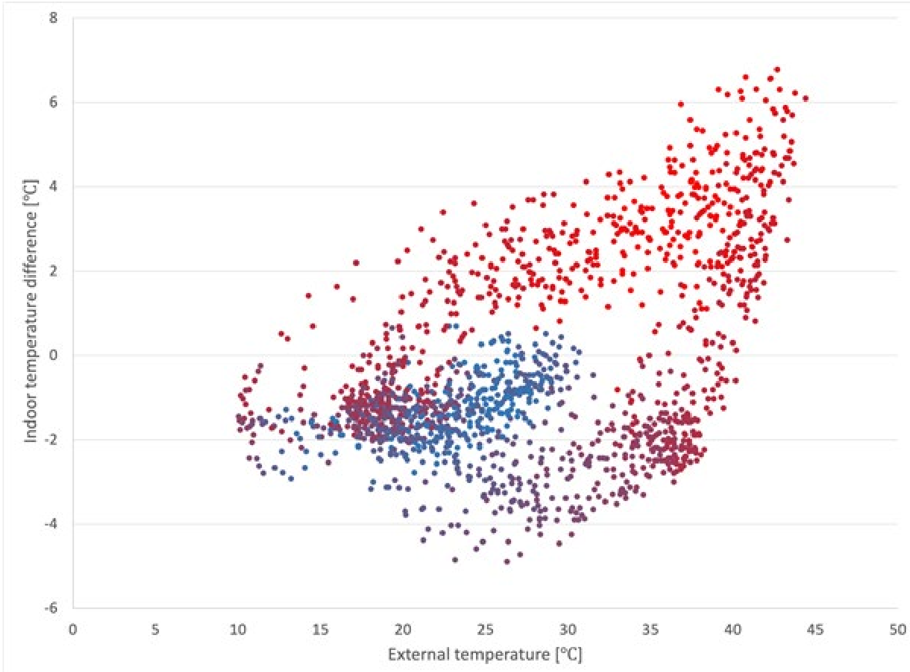


Figure 109: Indoor temperature difference between the original and retrofitted accommodation expressed as function of the external temperature. Colours indicate the time of the day, where red is midday and dark blue midnight.

5. Discussion

The objective of achieving thermal comfort for occupants of accommodation in tropical climates that uses passive design strategies demands consideration of occupation patterns and a compromise between often competing demands. As this case demonstrates, achieving improved thermal comfort during the day may have the unwanted consequence of reduced comfort at nighttime. The thermal analysis of the Fish River bala bala retrofit suggests the addition of insulative material to the roof, ceiling lining and steel roof cladding all contributed to greater insulation against radiant heat and immediate heat gain in the occupied space during the day. However, it is reasonable to conclude that this additional material, coupled with increased steel framing to support it, has brought an increased thermal mass to the roof structure, which has created a thermal lag in the rate of cooling for the occupied space at night. In addition, the requirement to seal the space from insects has reduced the potential for natural airflow, which may further contribute to this lag. Ceiling fans were added to respond to the reduced airflow, but it is not known if these were used and if this would have impacted the internal temperature or simply created a perception of improved comfort.

Acknowledgements

ILSC provided funding for the project to the value of $110,000. UniSA URIPA funding provided hardware and costs associated with post occupancy thermal analysis to the value of $12,000. Stanbond SA and Crimsafe kindly provided discounted material and in-kind assistance, and Kingspan provided discounted insulation material.

References

Hinson, D. (2007) 'Design as research: learning from doing in the design-build studio', *Journal of Architectural Education*, 61(1), pp. 23–26.

Kieran, S. (2007) 'Research in design: planning doing monitoring learning', *Journal of Architectural Education*, 61(1), pp. 27–31.

Morris, D. and Weijers-Coghlan, J. (2017) 'Making do: enhanced architectural education through pedagogical, cultural, and environmental contrasts', in. *Architecture Connects, aae 2017 conference*, Oxford Brookes School of Architecture, Oxford, UK.

Tools to assess internal surface mould growth: dynamic vs static

Griffin Cherrill[1], Michael Donn[2], Nigel Isaacs[3] and Stephen McNeil[4]

[1, 2, 3]School of Architecture, Victoria University of Wellington, Wellington, New Zealand
{griffin.cherrill[1], michael.donn[2], nigel.isaacs[3]}@vuw.ac.nz, 0000-0001-6890-6843[1], 0000-0002-4716-4286[2], 0000-0002-1348-4644[3]
[4]Building Research Association of New Zealand (BRANZ), Judgeford, New Zealand
steve.mcneil[4]@branz.co.nz

Abstract: The paper reports on research to identify a reliable tool to take account of thermal bridging. This will allow designers to evaluate the performance of timber-framed construction and the potential for internal surface mould growth. The Isothermal Planes method required by New Zealand Building Code Clause E3/AS1 to avoid internal moisture is too simplistic, therefore a more reliable tool is required. This paper compares the results from the static (moment in time) tool THERM and the dynamic tool WUFI 2D. Internal conditions were estimated by following Appendix A.1 of ISO 13788:2012 and calculated using a calibrated whole building simulation, WUFI Plus. The Temperature Factor and VTT Mould Growth Index were used to interpret the results from the static and dynamic tools, respectively. When ISO 13788:2012 is used to estimate the internal conditions, the risk of mould growth concluded from the static and dynamic tools is inconsistent with the measured data. The reason is that ISO 13788:2012 assumes internal relative humidity (RH) does not exceed 70% RH, yet mould growth commences at 80%. When internal conditions from the calibrated whole building simulation were used in WUFI 2D, the risk of mould growth was consistent with the measured data. Although using a dynamic tool over a static tool is preferred to simulate over time and account for the changing external climate, the results also highlight the importance of applying correct internal conditions, especially when assessing risk.

Keywords: Simulation; mould; static; dynamic.

1. Introduction

The method in Clause E3/AS1 of the New Zealand Building Code (NZBC) used to avoid internal surface moisture in habitable spaces requires the overall R-value of a timber-frame wall to exceed R-1.5. This method ignores the impact of multiple timber studs (thermal bridges) that cause cooler surface temperatures, which potentially lead to an increased risk of condensation and mould growth. Clause E3/AS1 states “fungal growth (mildew) is avoided by minimising internal condensation”, when in reality, mould can grow with a surface relative humidity (RH) of 80% but condensation forms at a surface RH of

100% (Standards New Zealand, 2017). This method may still permit local internal surface temperatures to drop below the critical temperature and encourage mould growth and condensation. It has already been identified as inadequate (Cherrill & Donn, 2020); therefore, this research aims to identify a more reliable tool that can be used to calculate surface conditions and assess the risk of mould growth and condensation in the New Zealand situation.

A range of simulation tools are available that can be used to calculate the conditions inside a building and on the surface. Simulation tools allow a designer to assess the performance of their building considering the material properties of constructions used, as well as accounting for other activities, such as ventilation, space conditioning and internal loads. But the tools available are not all equal, especially when used to calculate the internal surface conditions rather than the energy demand. A literature review, reported in Cherrill and Donn (2020), found there are various factors that dictate the abilities of a tool and the reliability of the results it produces.

In a broad sense, there are two types of simulation tools which can be used to understand the surface conditions to be found in a building: Building Component Simulation (BCS) and Whole Building Simulation (WBS). WBS are usually used to estimate the energy demand of a building while a BCS gives a clear idea of the internal surface conditions of a construction in a specific area of the building. A BCS can simulate a specific part of the building, for example a junction where a wall intersects with a floor, whereas a WBS simulates on a larger scale, treating each room of the building as a thermal zone. A BCS can usually produce more reliable results of the internal surface conditions as it can model heterogeneous constructions, including thermal bridges, but a WBS can account for the wider context of the building, including external climate conditions, building geometry, internal loads, space conditioning and external shading. Where a WBS can calculate the hygrothermal conditions inside a zone, a BCS will require the user to estimate internal conditions or use measured data.

Within BCS, there are multiple factors that dictate the complexity of the tool, the time it takes to simulate a given construction detail and the reliability of results. These factors include the simulation conditions (static or dynamic), the number of dimensions the tool simulates in (1-Dimension, 2D or 3D) and the material properties used (thermal or hygrothermal).

To get a realistic idea of the conditions on the surface of a point thermal bridge, where three building surfaces intersect and the risk of condensation and mould growth is at its greatest, Cherrill and Donn (2020) argued for the use of a 3D dynamic hygrothermal tool, the most comprehensive tool. But when going along the spectrum of tools from the least detailed 1D static thermal tool to the most comprehensive 3D dynamic hygrothermal tool, the simulation time potentially increases from a few seconds to a number of weeks, and the required inputs increase significantly.

Therefore, the aim of the wider research, of which part is reported here, is to identify how far along the spectrum of tools lies a tool that produces results that are good enough to assess the risk of mould growth and condensation, while minimising the time and experience required to get results. This paper explores the initial research findings, comparing the results from the static simulation tool THERM (Lawrence Berkeley National Laboratory, 2019) and the dynamic simulation tool WUFI 2D (Fraunhofer Institute for Building Physics, 2019).

2. Static and dynamic tools

A significant difference between static and dynamic tools is the time period which they simulate. Both tools require the modeller to electronically 'build' the construction detail, apply correct material properties and surface resistance values. A static tool takes user entered external and internal conditions to calculate the internal surface temperature for a single point in time. A dynamic simulation tool uses a climate file for the external conditions to calculate the internal surface temperature for period of time, usually one year. The internal conditions used in a dynamic tool are not calculated by a BCS and have to be manually entered. These can be obtained from measured data, calculated data from a WBS, or estimated using indoor climate assumptions, such as those from ISO 13788:2012 which is built into WUFI 2D.

This paper assesses results for internal surface mould growth produced by a static tool and a dynamic tool for the same thermal bridge detail. Monitored internal hygrothermal data for the 2015 year was made available by BRANZ for a research house. External conditions were obtained from New Zealand's National Climate Database CliFlo for the 2015 year (National Institute of Water and Atmospheric Research, 2007). Measured data for the building and thermal bridge detail were compared against the results from the tools. ISO 13788:2012 was used to estimate the internal conditions of the building using the measured external data. The results from the two tools will be used to assess the risk of internal surface mould growth.

Figure 1 shows the wall-to-wall linear thermal bridge (LTB) junction case-study, with timber studs built up in the corner, insulation between, plasterboard on the internal surface and fibre-cement cladding on the external surface. The details are drawn in THERM and WUFI 2D.

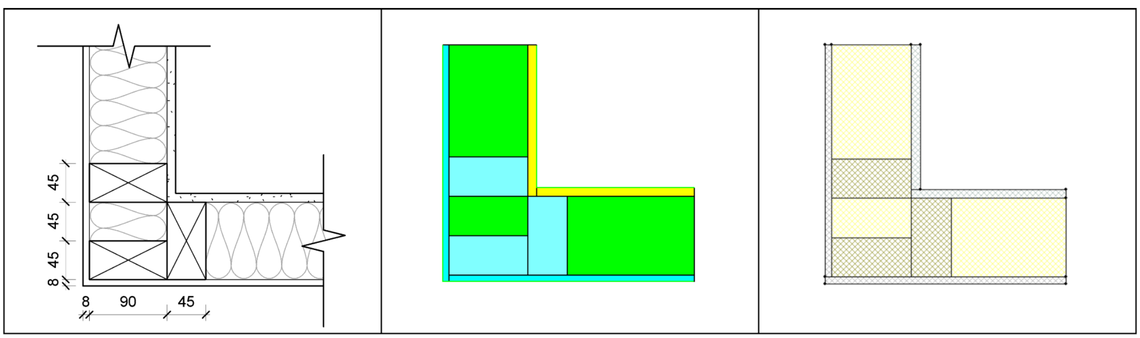


Figure 110. Wall-to-wall thermal bridge detail in (a) Revit drawing, (b) THERM and (c) WUFI 2D. (Source: Authors, 2022)

2.1. Boundary conditions for static tool

The standard ISO 13788:2012 outlines “simplified calculation methods” to assess the risk of mould growth on the internal surface of buildings using a static simulation tool. Appendix A.1 and Section 4.2.3 (b) of ISO 13788:2012 use the monthly mean external air temperature to estimate monthly mean internal air temperature, internal RH and ground temperature. ISO 13370:2001 can be used to estimate the monthly mean subfloor temperature with a static thermal balance equation in Appendix F.1, using the monthly mean external air temperature and estimated internal air temperature.

Section 4.4.1 of ISO 13788:2012 also provides surface resistance values to be used when calculating the risk of mould growth. It suggests the external surface resistance should be 0.04 $m^2 \cdot K/W$, which is consistent with the values used in Table E2 of NZS 4214:2006 and Table 1 of Chapter 25 in ASHRAE

Handbook 2001. However, it suggests the internal surface resistance should be 0.25 $m^2 \cdot K/W$ on opaque surfaces "to represent the effect of corners, furniture, curtains or suspended ceilings" (International Organization for Standardization, 2012, p. 6). This value is double the values found in NZS 4214:2006 and ASHRAE Handbook 2001, which range from 0.11 to 0.16 $m^2 \cdot K/W$, depending on the direction of heat flow. ISO 13788:2012 gives no evidence to support the use of this value, or how it chances the risk of mould growth.

The equations used in Appendix A.1 of ISO 13788:2012 use the external air temperature to estimate the internal temperature and RH. There is an assumption that the internal air temperature is always between 20°C to 25°C and the internal RH does not exceed 70%. Although these conditions could be considered as ideal for all houses, they are unrealistic in the New Zealand setting.

The HEEP Study conducted by BRANZ in 2010 found the national mean summer daytime living room temperature was 21.8°C, which aligns with the assumption made with ISO 13788:2012. However, in the standard, the critical month, usually in winter, is used to assess the risk of mould growth. The HEEP Study found the national mean winter evening living room temperature was 17.9°C.

A later study, conducted by Plagmann et al. (2021) in 2016 and 2017, agrees with these findings from the HEEP Study. Their study found the national mean annual evening bedroom temperature was 17.3°C, with 100% of the houses recording a temperature lower than 21°C for 96% of the time in 2016 and 94% in 2017. The study also measured bedroom RH over the year of 2016 and 2017. The results show 86% of the houses had an RH greater than 70% for 23% of the time in 2016, and 83% of the houses had a RH greater than 70% for 28% of the time in 2017. In more than 4/5 of the houses, the RH exceeded 70% for around 1/4 of the year (Plagmann et al., 2021).

During the time when the RH is over 70% the risk of mould growth is at its highest, but the ISO 13788:2012 assumptions are that the RH cannot exceed 70%. For this risk assessment, the conditions should be the worst-case scenario in order to ensure adequate building performance most of the time.

2.2. Boundary conditions for dynamic tool

Unlike a static tool which gives a snapshot at one instant of time, a dynamic tool simulates over a period of time, usually every hour for one year. It requires a set of values with the external and internal air temperature and RH. The external conditions can be obtained from measured data specific to the location of the building, or a representative weather file. For this research, a custom weather file with hourly temperature, humidity, solar radiation, rain and wind data was created for the 2015 year using measured data from NIWA CliFlo.

The internal conditions are not calculated by the dynamic BCS as it only simulates a single junction, rather than the whole building. Therefore, the internal conditions can be obtained from measured data if available or calculated using a WBS. Using the WBS tool WUFI Plus, a model of the case study house was calibrated against internal measured data for the 2015 year. The model results were within the tolerance bands for calibrating internal conditions, identified by Huerto-Cardenas et al. (2020). As the measured data was recorded when the house was unoccupied, once the model was calibrated an internal moisture load was added to represent an occupied house. Some tools, such as WUFI 2D, can use indoor climate assumptions, such as those from ISO 13788:2012, to estimate the internal conditions. Again, this climate model assumes the temperature cannot fall below 20°C and the internal RH does not exceed 70%.

In WUFI 2D, the internal surface resistance is 0.12 $m^2 \cdot K/W$, which is consistent with ASHRAE Handbook 2001 and the external surface resistance is wind dependent, calculated with the weather file.

3. Metrics for mould growth risk

The VTT Mould Growth Index (VTT Index), developed by Hukka and Viitanen (1999) based on empirical data, can be used to estimate the growth of surface mould. To assess the risk of mould growth from the results from a dynamic tool, the equations from the VTT Index are used to produce a value between M = 0 (no mould growth), to M = 6 (surface 100% covered in toxic mould) (Hukka & Viitanen, 1999). The original equations are were developed to estimate the growth of mould on pine, but adjustable variables have since been added to the equations to change the material and its properties (Ojanen et al., 2010). Therefore, the assessing mould growth, the sensitivity class was set to 'Sensitive' to represent "wall paint for indoor use", with a mould growth decline of 0.5 and a "cleaned" surface.

The results from a static tool are not sufficient to use with the VTT Index as it calculates the change in mould growth over time, but a static tool produces a result for a single point in time. ISO 13788:2012 provides guidance to assess the risk of mould growth using the temperature factor with the results from a static tool. The temperature factor, calculated with Equation 1 from the standard, uses the external air temperature, internal air temperature and internal surface temperature to calculate what proportion of the temperature drop across the building element occurs at the internal boundary layer.

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_i - \theta_e} \qquad (1)$$

Where:

f_{Rsi} = temperature factor; θ_{si} = internal surface temperature; θ_e = external air temperature; θ_i = internal air temperature.

The equation produces a dimensionless value within 0 to 1, where a greater value indicates a lower risk of mould growth. To assess the risk of mould growth, the temperature factor is compared against the critical temperature factor, calculated following Section 5.3 of ISO 13788:2012 using the conditions of the critical month and a critical surface RH of 80%. If the temperature factor is below the critical temperature factor, the construction detail will encourage mould growth (International Organization for Standardization, 2012).

The metrics are used to assess the risk of mould growth but the extent of the outputs differ. Both metrics will identify whether the results from the tools indicate a risk of mould growth or not, but the VTT Index provides further information to illustrate the severity of the risk.

4. Results

Two tools are used to calculate the surface temperature of a wall-to-wall LTB junction. The static tool THERM uses measured external conditions data from 2015 and internal conditions estimated with indoor climate assumptions in Appendix A.1 of ISO 13788:2012. The dynamic tool WUFI 2D was used to produce two sets of results. The first set, similar to THERM, uses internal conditions estimated with ISO 13788:2012, and will help to identify the impact on the risk of mould growth when using a dynamic tool rather than a static tool. The second set use the calculated internal conditions from a calibrated WBS model of the building in WUFI Plus. These results will help to identify the impact on the risk of mould growth when internal conditions are calculated using a WBS and measured data rather than estimated using indoor climate assumptions.

4.1. Results from static tool (THERM)

Section 4.2.2 of ISO 13788:2012 states the mean monthly external air temperature is to be used to calculate all internal conditions. To test the impact of the external air temperature on the risk of mould growth, the same process also was followed using the minimum (rather than mean) monthly external air temperature. Table 1 shows the calculated temperature factor at the wall-to-wall LTB for July (the worst month), when the mean and minimum monthly external temperatures are used to estimate internal conditions and calculate the surface temperature in THERM.

Table 53. LTB critical temperature factor and temperature factor for mean and minimum external air temperature.

	Critical Temperature Factor	Temperature Factor
Minimum External Temperature	0.64	0.70
Mean External Temperature	0.56	0.70

Regardless of whether the mean or minimum external air temperature is used, the calculated temperature factor at the LTB is 0.70. However, the use of the minimum external air temperature results in a higher critical temperature factor, which changes the critical threshold at which the risk of mould growth becomes apparent. Regardless, the results from THERM indicate there is no risk of mould growth at the LTB as the calculated temperature factor is greater than the critical temperature factor.

The risk of mould growth is largely dictated by the surface temperature and also by the RH of the air directly in contact with the surface (Hukka & Viitanen, 1999). The temperature factor attempts to account for surface RH by calculating the critical temperature factor with 80% of the saturation pressure. THERM calculates the surface temperature and allows for the surface RH to be specified, but this does not change the calculated surface temperature.

4.1.1. Impact of external air temperature

Figure 2 illustrates the calculation of the temperature factor for the wall construction, with a minimum monthly external air temperature -1.8°C and mean of 8.8°C in July 2015. As the external air temperature is below 10°C, ISO 13788:2012 assumes the internal air temperature is 20°C.

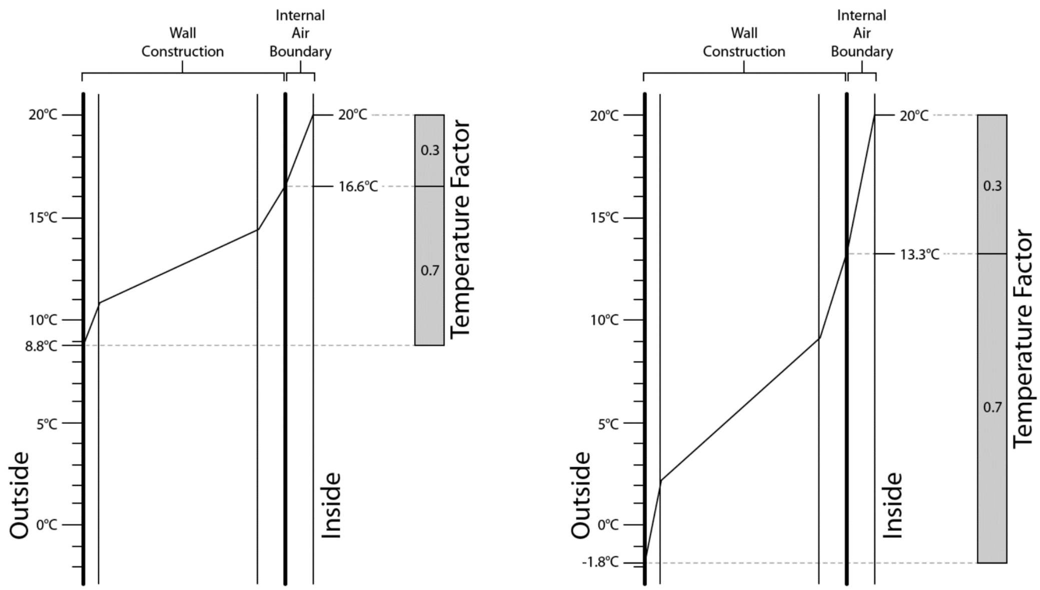


Figure 111. Temperature factor calculation with different external air temperature. (Source: Authors, 2022)

Regardless of the external air temperature, Figure 2 shows the temperature factor is the same, as it calculates what proportion of the temperature drop across the building element occurs at the internal air boundary. Therefore, with the same wall construction and internal surface resistance, the temperature factor will be the same even if the conditions used to calculate are different. However, Table 1 shows the monthly external air temperature influences the critical temperature factor and therefore affects the threshold at which mould risk becomes apparent.

4.1.2. Impact of internal surface resistance

In addition to Equation 1 from ISO 13788:2012, which uses the surface and air temperatures, Equation 2 from Appendix B of EN ISO 10211-2:2001 can calculate the temperature factor using the thermal resistance of the construction and the surface resistance values.

$$f_{Rsi} = \frac{R_{value} + R_{se}}{R_{si} + R_{value} + R_{se}} \quad (2)$$

Where:

f_{Rsi} = temperature factor; R_{value} = thermal resistance of construction; R_{se} = external surface resistance; R_{si} = internal surface resistance.

Section 4.4.1 of ISO 13788:2012 states the internal surface resistance should be 0.25 $m^2 \cdot K/W$ when assessing risk, rather than the value used for vertical surfaces of 0.12 $m^2 \cdot K/W$ suggested in ASHRAE Handbook 2001. Equation 2 shows the impact of a greater R_{si} value will lower the calculated temperature factor. Therefore, the higher internal surface resistance acts as a safety margin, to lower the performance of the building detail and increase the perceived risk of mould growth

4.2. Results from dynamic tool (WUFI 2D)

Figure 3 graphs the measured surface temperature and absolute humidity against the results from the dynamic tool WUFI 2D.

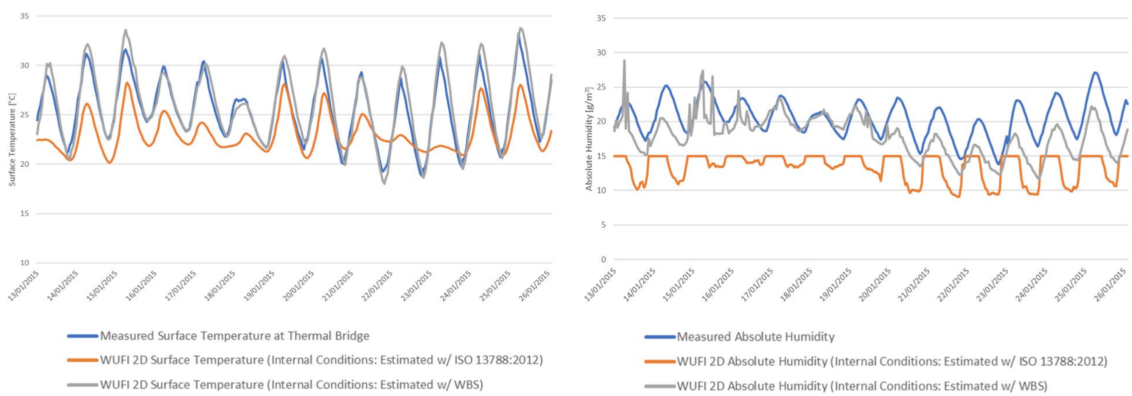


Figure 112. Measured and calculated results from WUFI 2D for (a) surface temperature and (b) absolute humidity (Internal conditions: Estimated with ISO 13788:2012 & calculated with WBS).

WUFI 2D simulated two scenarios. The first used the same conditions used in THERM, with 2015 external measured conditions and internal conditions estimated using WUFI 2D, based on ISO 13788:2012. The second scenario used the same external conditions but with internal conditions calculated from a calibrated WBS. Figure 3a (left) compares the measured LTB surface temperature (blue line) with the WUFI 2D surface temperatures using estimated (orange) and calculated (grey) internal conditions. Figure 3b (right) compares the absolute humidity for the same analyses.

Figure 3 shows a clear difference between the results from WUFI 2D when the internal climate is estimate and calculated. The ISO 13788:2012 results from WUFI 2D follow the same diurnal pattern as the measured data, but the absolute values differ. Additionally, the impact of the ISO 13788:2012 assumptions on the internal air temperature and RH is evident where the absolute humidity does not exceed 15 g/m^3 in Figure 3b. With the maximum internal RH set to 70%, the risk of mould growth is reduced and therefore may not be representative of the true risk.

Results from WUFI 2D more closely align to the measured data internal conditions are calculated using the WBS. This was confirmed with the Root Mean Square Error (RMSE) of the residuals, with the surface temperature RMSE of 3.5°C estimated with ISO 13788:2012 and 1.0°C calculated with WBS. The absolute humidity residuals RMSE are 5.5 g/m^3 (ISO 13788:2012) and 3.2 g/m^3 (WBS).

This comparison suggests the use of a dynamic BCS tends to be more realistic than the results obtained from a static tool, as the dynamic tool can account for a changing external climate. A dynamic BCS tool alone may not be adequate if internal conditions are simply estimated. The calculated surface temperature and absolute humidity align to the measured data better when the internal conditions are calculated with the WBS, but it is unknown how these differences can impact the risk of mould growth.

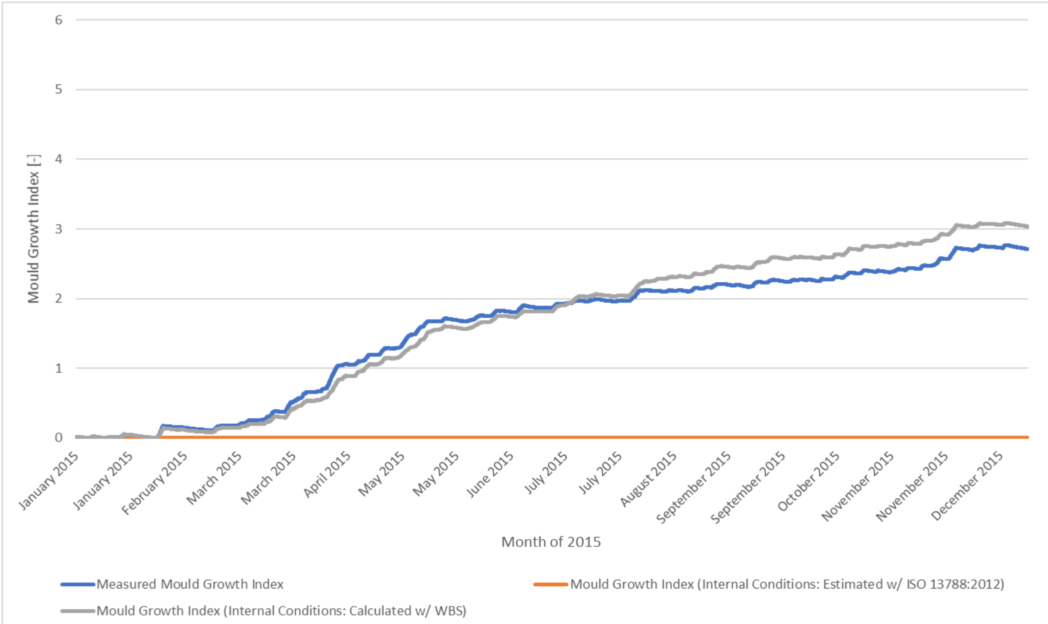


Figure 113. Mould growth index calculated with results from WUFI 2D (Internal conditions: Estimated with ISO 13788:2012 & calculated with WBS).

Figure 4 graphs the VTT Mould Growth Index, the potential for mould growth over the year using measured data, and the results from WUFI 2D. When the internal conditions calculated from the WBS are used in WUFI 2D, the growth of mould closely follows the measured mould growth index. However, when internal conditions are estimated with ISO 13788:2012, WUFI 2D predicts a mould index growth of M = 0 (mould will not grow). ISO 13788:2012 assumptions do not permit surface RH to exceed 70% but equations from the VTT Index show the critical surface RH for mould growth is 80%. Hence, mould will not grow with this limit, regardless of the reliability of the surface temperature calculations.

5. Discussion

The results from the static tool when ISO 13788:2012 is used to estimate the internal conditions indicated there is no risk of mould growth. These results do not align with the measured data which shows the conditions will lead to a mould growth index of M = 3 after one year. Due to the nature of the static tool, which produces a temperature factor value to represent each month of the year, it is possible a static tool can produce unreliable results, although this will be is unknown.

A sensitivity analysis found internal surface resistance and external air temperature were the main variables to affect the risk of mould growth using the static tool and temperature factor. The external air temperature changes the critical temperature factor and hence the threshold at which the risk of mould growth becomes apparent. The higher-than-normal internal surface resistance acts as a safety margin, producing a lower temperature factor which leads to an increased possibility of mould growth. The results from the static tool found no risk of mould growth, even with the additional safety margins.

Using the same indoor climate assumptions from ISO 13788:2012 in the dynamic tool WUFI 2D, the internal surface temperature was again calculated. The comparison of the results from WUFI 2D and THERM show a dynamic tool is required to produce usable results, as the static tool THERM and its assumptions do not provide a realistic assessment of the risk of mould growth. But a dynamic tool alone may not be adequate. The data the modeller inputs into the tool has a significant effect on the reliability of the results. The results from WUFI 2D, using internal conditions estimated using ISO 13777:2012 and calculated using WBS, are different. This is evident when the VTT Mould Growth Index is used to assess the risk, where the measured data and results using the internal hourly conditions from the WBS produce an VTT Index of M = 3, compared to the static indoor climate assumptions index of M = 0.

5. Conclusion

The findings from this study suggest the static tool (THERM) is unreliable compared to the dynamic tool (WUFI 2D) and measured data, even when additional safety margins are added. Due to the lack of useful outputs from the static tool, the temperature factor needs to be used. But this metric and the static tool do not account for the RH, which is one of the main drivers of mould growth on the internal surface.

Not only is a dynamic tool helpful to account for the temperature fluctuations of the changing external climate and the thermal inertia of the materials, but this highlights the importance of correct input data. Ideally the temperature does not drop below 20°C and the RH does not exceed 70%, but studies have found this is unrealistic for most New Zealand houses, especially for worst-case scenarios.

When using WUFI 2D with the internal conditions calculated with the WBS, the VTT index aligns closely to the measured data. But this method requires two simulations to be built in a WBS and BCS. The static tool THERM simulates results almost instantly, whereas the dynamic tool WUFI 2D can take upwards of 40 minutes. Furthermore, the WBS WUFI Plus used to obtain the internal conditions requires additional information of the building. Therefore, the question still remains whether a different tool can be identified that produces reliable results that align with the measured data but requires less time and experience from the modeller.

Acknowledgements

This research is funded by a Victoria University Doctoral Scholarship and a BRANZ Doctoral Scholarship.

References

American Society of Heating, Refrigerating and Air-Conditioning Engineers (2001) *2001 ASHRAE Handbook Fundamentals*, ASHRAE, Atlanta, GA.

Cherrill, G. and Donn, M. (2020) Methods to assess the risk of condensation from thermal bridges in timber-framed houses: a systematic literature review, in A. Ghaffarianhoseini, A. Ghaffarianhoseini and N. Naismith (eds.), *Imaginable Futures: Design Thinking, and the Scientific Method*, (54th International Conference of the Architectural Science Association (ANZAScA)), pp. 735–744.

Fraunhofer Institute for Building Physics (2019) *WUFI 2D.* Available from: <https://wufi.de/en/software/wufi-2d> (accessed 2 July 2022).

Huerto-Cardenas, H. E., Leonforte, F., Aste, N., Del Pero, C., Evola, G., Costanzo, V. and Lucchi, E. (2020) Validation of dynamic hygrothermal simulation models for historical buildings: State of the art, research challenges and recommendations, *Building and Environment*, 180.

Hukka, A. and Viitanen, H. A. (1999) A mathematical model of mould growth on wooden material, Wood Science and Technology, 33(6), 475-485.

International Organization for Standardization (2001) *Thermal bridges in building construction — Calculation of heat flows and surface temperatures — Part 2: Linear thermal bridges (EN ISO 10211-2:2001)*, ISO, Geneva.

International Organization for Standardization (2001) *Thermal performance of buildings — Heat transfer via the ground — Calculation methods (UNI EN ISO 13370:2001)*, ISO, Geneva.

International Organization for Standardization (2012) *Hygrothermal performance of building components and building elements — Internal surface temperature to avoid critical surface humidity and interstitial condensation — Calculation methods (ISO 13788:2012)*, ISO, Geneva.

Isaacs, N. (ed.), Camilleri, M., Burrough, L., Pollard, A., Saville-Smith, K., Fraser, R., Rossouw, P. and Jowett, J. (2010) *Energy Use in New Zealand Households: Final Report on the Household Energy End-use Project (HEEP)*, BRANZ Study Report 221, BRANZ Ltd, Judgeford, New Zealand.

Lawrence Berkeley National Laboratory (2019) *THERM - Two-Dimensional Building Heat-Transfer Modeling.* Available from: <https://windows.lbl.gov/software/therm> (accessed 2 July 2022).

National Institute of Water and Atmospheric Research (2007) *The National Climate Database.* Available from: <https://cliflo.niwa.co.nz> (accessed 12 July 2022).

Plagmann, M., White, V. and McDowall, P. (2021) *Indoor climate and mould in New Zealand homes*, BRANZ Study Report SR452, BRANZ Ltd, Judgeford, New Zealand.

Standards New Zealand (2006) *Methods of Determining the Total Thermal Resistance of Parts of Buildings NZS 4214:2006*, Standards New Zealand, Wellington.

Standards New Zealand (2017) *Acceptable Solutions and Verification Methods for New Zealand Building Code Clause E3 Internal Moisture*.

Tuomo Ojanen, Hannu Viitanen, Ruut Peuhkuri, Kimmo Lähdesmäki, Juha Vinha and Kati Salminen (2010) *Mold Growth Modeling of Building Structures Using Sensitivity Classes of Materials*, Thermal Performance of the Exterior Envelope of Whole Buildings XI, ASHRAE, Clearwater Beach, Florida.

Towards a Post-Occupancy Evaluation linking occupant behaviour and energy consumption to mitigate the energy performance gap in residential retrofitted buildings: a literature review

Luis E. Medrano-Gómez[1], Paola Boarin[2] and Alessandro Premier[3]

[1, 2, 3] *The University of Auckland, Auckland, New Zealand*
{lmed585 [1], p.boarin [2], alessandro.premier [3]}@auckland.ac.nz

Abstract: Building retrofit has become a leading sustainable action in the built environment and is expected to deliver the most energy savings by 2050. However, an Energy Performance Gap (EPG) has been identified in literature and practice related to occupant behaviour. Although links between EPG and occupant behaviour are being increasingly investigated, a lack of mixed-method studies in the field and technocentric approaches have not delivered the expected energy savings. Post-Occupancy Evaluations (POE) have proven to evaluate performance effectively, thus providing critical information to face the EPG. However, unravelling the impact of physical parameters and occupant behaviour on energy consumption requires new perspectives integrating contextual, societal and physical elements. Although current POE practice and recertification schemes consider occupant behaviour, it is evaluated simplistically and subjectively, resulting in a lack of assessment of Occupant-Building Interactions (OBI). This paper reviewed previous studies on EPG in retrofitted buildings, occupant behaviour and energy consumption, POE and rating systems, OBI, and socio-technical approaches to identify gaps in knowledge and opportunities for an innovative POE framework assessing behaviours leading to EPGs in retrofitted residential buildings. It was found that despite an increasing interest in the impact of occupant behaviours on energy consumption in buildings, there is a critical need for research assessing energy-related behaviours, magnitudes, and resulting energy savings from behavioural interventions.

Keywords: Energy performance gap; occupant behaviour; post-occupancy evaluation; retrofit.

1. Introduction

The Paris Agreement (UNFCCC, 2015) urged the need to reduce greenhouse gas emissions, limit the rise in temperatures, and increase the ability to adapt to the impacts of climate change. In this regard, improving energy efficiency in buildings has become a critical strategy (Yoshino *et al.*, 2017), as the building sector is responsible for over 30% of the final energy consumption and close to 40% of total CO_2 emissions in its entire life cycle (IEA, 2020).

It is estimated that the existing building stock will compose 70% of buildings in 2050 (Visscher *et al.*, 2016), and currently, about 61% of the construction projects are renovations (Regnier *et al.*, 2018). Thus, building retrofit must be the leading strategy to achieve projected energy savings and emissions reductions. In this regard, the residential sector has emerged as a crucial niche for building retrofit and climate change mitigation (Ahern and Norton, 2020). The impact of occupants' behaviours on energy consumption in this sector is critical as occupants have more interactions with energy-consuming systems (e.g. HVAC and appliances), and behaviours are highly variable and uncertain compared to other sectors (Mo and Zhao, 2021).

Studies have demonstrated a discrepancy between estimated and actual energy savings (Zou *et al.*, 2018b), known as the Energy Performance Gap (EPG), representing risk in tackling climate change challenges. Although several factors contribute to the EPG, occupant behaviour is increasingly recognised as crucial for achieving efficient buildings (Hong *et al.*, 2017; Salvia *et al.*, 2020). Therefore, interdisciplinary studies and holistic methodologies are needed to understand better the links between occupants and buildings (D'Oca *et al.*, 2017; Day *et al.*, 2020).

This paper aims to gather, review and discuss extant literature about EPG in retrofitted buildings, occupant behaviour and energy consumption, POE and rating systems, OBI, and socio-technical approaches to identify gaps in knowledge and opportunities for an innovative POE framework assessing behaviours leading to EPGs in retrofitted residential buildings.

2. Building retrofit and Energy Performance Gap

Building retrofit has become one of the principal actions toward sustainability in the built environment (Xing *et al.*, 2011). However, it must meet the predictions as many governments have set energy conservation goals and strategies based on performance to face the growth in energy demand and consumption (Zou *et al.*, 2018b). A margin of error is perhaps inevitable between predicted and measured energy consumption due to uncertainties in the design and operation of buildings, limitations of measurement systems (van Dronkelaar *et al.*, 2016), simulation errors, and variations in observations (Wilde, 2014). However, such a margin goes beyond the acceptable boundaries (i.e. ±10% according to Van den Brom *et al*. (2019)) and can be as much as 2.5 times higher than predicted (Wilde, 2014).

The EPG in the residential sector has still not been well understood due to some peculiarities, such as the impact of occupant behaviour, privacy issues blocking data collection, and the variety of building characteristics (Swan and Ugursal, 2009). Studying the EPG in this sector is vital because identical dwellings with similar installations have shown significant energy use variations (Rinaldi *et al.*, 2018). Such variations are characteristic of residential buildings due to the diversity of occupant behaviours (Rouleau *et al.*, 2018) and, more specifically, the interaction between these behaviours and the building technology (Bauer *et al.*, 2021). Although it is evident that occupants' behaviours play a critical role in residential energy consumption, assessing such energy-related behaviours (e.g. profiles and patterns) and their magnitude remain a crucial challenge (Osman and Ouf, 2021) and a significant research and knowledge gap.

2.1 Rebound and prebound effects

The EPG phenomenon leading to significantly fewer energy savings cannot be understood entirely without two critical concepts: the rebound and prebound effects. The rebound effect may be defined as the increased demand for a building energy service as a direct consequence of improving its efficiency (Calì, Osterhage, *et al.*, 2016). Therefore, it is an induced demand in energy consumption primarily affected by occupant behaviour. In turn, the prebound effect is the underconsumption of energy services before a retrofit is done or in the total absence of it (Cozza *et al.*, 2020). Sunikka-Blank and Galvin (2012) introduced the concept after finding that the energy performance rating considered greater energy consumption pre-retrofit, hence driving fewer energy savings post-retrofit "as retrofits cannot save energy that is not actually being consumed" (Sunikka-Blank and Galvin, 2012, pp. 270). Occupant behaviour is also critical for the prebound effect, as demonstrated by Teli *et al*. (2016). They conducted a pre-retrofit study in a UK social housing building where they gathered thermal information and created occupant behaviour profiles to be used in the simulations. The simulation results showed that the actual energy savings would be around 40% less than predicted when using standard guidelines rather than actual occupants' behaviour. The researchers concluded that more studies assessing OBI in social housing are needed to inform carbon reduction programmes and reduce the EPG.

3. Occupant behaviour and energy consumption

The strong influence of occupant behaviour on energy consumption in buildings is now well recognised (Yan *et al.*, 2015), and several researchers determined that one of the main reasons for the EPG is occupant behaviour. Occupant behaviour is critical for energy consumption in residential buildings as this sector presents a high variability of actions like occupancy patterns, control of windows and doors, lifestyle, thermal comfort preferences, or interaction with building systems (Stazi *et al.*, 2017; Rouleau *et al.*, 2019). While improvements in the building's characteristics and materials, like those made in retrofits, substantially affect the energy performance in dwellings, such a techno-centric approach does not necessarily affect occupants' behaviour (Miller *et al.*, 2021). Despite all of this, only a few studies have focused on proposing and testing a solution based on energy-related occupant behaviour even though it seems crucial for closing the EPG, and that focusing on occupant behaviour is more cost-effective than merely technological approaches (Sunikka-Blank and Galvin, 2012).

Chen *et al*. (2021) classify energy-related occupant behaviour into three groups: occupancy, interactions, and behavioural efficiency. Occupancy refers mainly to the physical presence of occupants in buildings with parameters such as number, location, and duration of stay. In turn, the interactions group is more complex, referring to how occupants interact with systems and building technologies such as HVAC, lighting, and windows. Finally, behavioural efficiency refers to a qualitative group with parameters related to education and training. This group can jeopardise the building's energy efficiency but, at the same time, hosts the most cost-effective actions for new and retrofitted buildings, focusing on detecting and resolving inefficient energy behaviours through occupant awareness. In this regard, the authors acknowledge that more studies assessing energy savings achieved by behavioural interventions are needed.

Zou *et al*. (2018a) conducted a literature review of energy-related occupant behaviour from peer-reviewed papers published between 2007 and 2017. The papers were classified according to the research methodology adopted: quantitative (83.48%), qualitative (0.87%), mixed (5.22%), and review or conceptual (10.43%). The results show that although the nature of the topic is multidisciplinary, there is a lack of mixed-method studies explaining why and how energy-related occupant behaviours are generated. The following section discusses how commonly-used evaluation schemes address the impact of occupants' behaviour on energy consumption in new and retrofitted buildings.

4. Post-occupancy evaluation and green building rating systems

POE is an alternative to facing the EPG by providing designers with factual information about buildings' performance during the operational stage (Menezes *et al.*, 2012). Its importance has grown in the last few years as the data collected can be compared against estimates (Miller *et al.*, 2021). However, it has been acknowledged that, aside from energy performance and occupant satisfaction, other aspects, such as occupant behaviour and systems operation, can and should be assessed in POEs (van Dronkelaar *et al.*, 2016). The link between POE and building retrofit was introduced by Chiu *et al*. (2014). According to them, the building retrofit practice is currently limited by a black-boxing effect (i.e., the more technological development, the more blurred and obscured it gets) that will only succeed from the associations between physical elements of buildings, technology, and occupants, while effective POEs allow that option. In other words, unravelling the impact of physical parameters of the buildings and occupant behaviour on energy consumption requires POEs adopting a new perspective with close integration of contextual, societal and physical elements. However, most POE projects published mainly focus on indoor environmental parameters and energy use without exploring the links with occupant-related parameters such as driving factors and comfort (Colclough *et al.*, 2022).

Green Building Rating Systems (GBRSs) are other assessment tools used in the built environment with increasing interest in occupant-related parameters and retrofitted buildings. The official manuals from some of the most commonly used GBRSs (e.g. LEED, BREEAM, Green Star, WELL, Living Building Challenge) show that versions have been created to evaluate the performance in existing and retrofitted buildings (e.g. LEED O+M, BREEAM In-Use, Green Star Performance, WELL Performance Verification) and that parameters such as occupants' satisfaction, occupant's comfort, and occupants' feedback have been incorporated. However, there is still more to do to move from satisfaction evaluation and training to objective correlations highlighting wasteful behaviours.

5. Occupant-building interaction

The Occupant-Buildings Interaction (OBI) was not recognised and investigated until the last decade, going from 156 papers published in 2009 to 475 in 2019 (Harputlugil and de Wilde, 2021). Such interaction with buildings is necessary to preserve and enhance occupants' productivity, health, and well-being, but at the same time, it significantly impacts the performance of buildings (Harputlugil and de Wilde, 2021), which can be pretty significant even if parameters such as weather conditions, building materials, and system characteristics are accurate (Yan *et al.*, 2015). For instance, buildings with higher temperature setpoints or higher levels of window operation consume more energy than others (Calì, Andersen, *et al.*, 2016). In other words, it is not the occupant behaviour alone that causes the EPG but the conscious and unconscious occupant practices developed from the interaction with the building's elements (Bauer *et al.*, 2021).

There is still a lack of understanding of the complexity of the OBI (Harputlugil and de Wilde, 2021), and the way occupants behave while controlling the building's systems is very different from the modelled one (Stazi *et al.*, 2017). Moreover, only a few building elements are intuitive; therefore, learning how to use them is crucial to ensuring the correct building energy performance (Glad, 2012). The elements and systems that have been identified as part of the OBI are luminaires, windows, blinds, domestic hot water, thermostats, fans, electrical appliances, and doors (Yan *et al.*, 2015; Rouleau *et al.*, 2019; Chen *et al.*, 2021; Mahdavi *et al.*, 2021).

5.1 Classification and driving factors for the occupant-building interaction

Mahdavi *et al*. (2021) classified OBI into four categories: envelope (i.e., operation of elements directly in contact with the exterior), mechanical systems (i.e., interaction with HVAC controls), plug loads and lighting (i.e., interaction with appliances and lighting controls), and internal heat gains (i.e., occupant density and schedules that lead to internal heat gains). Many driving factors can influence the OBI, and researchers have no universal agreement on the specific factors (Stazi *et al.*, 2017). For instance, Van Den Brom *et al*. (2019) identified demographics such as income, employment, and occupancy to impact energy consumption in the residential sector. Alternatively, Rinaldi *et al*. (2018) and Day *et al*. (2020) divide them into internal (e.g., biological and psychological aspects) and external factors (e.g., contextual and environmental conditions).

In turn, Stazi *et al*. (2017) gathered from a literature review a more robust classification of driving factors, including environmental factors (e.g., air temperature), time-related factors (i.e., actions repeated in specific periods), contextual factors (e.g., ease of control), physiological factors (e.g., sensitivity to brightness), psychological factors (e.g., need for privacy), social factors (e.g., organisation policy), and random factors (i.e., actions depending on uncertain factors). However, it is acknowledged that among these factors, the physical ones are objectives and strongly affect occupants, whereas the contextual, psychological and physiological factors are subjective and are rather influential.

5.2 Personality traits, profiles and patterns

Personality traits can be a compelling parameter for predicting energy consumption (Milfont and Sibley, 2012), particularly considering that the classifications of driving factors include psychological and social factors. The most accepted classification for personality traits is based on the 'Big five personality traits' theory, divided into neuroticism, agreeableness, conscientiousness, openness to experience and extraversion (Shen *et al.*, 2020). According to Milfont and Sibley (2012), the agreeableness trait refers to cooperative, pleasant and compliant occupants seeking their well-being. Conscientiousness refers to organised, responsible and meticulous occupants tending to long-term planning. The openness trait refers to imaginative and intelligent occupants engaged with novel endeavours. The extraversion trait refers to active, outgoing, and confident occupants tending to maximise social interactions, and the neuroticism trait refers to insecure and anxious occupants.

Occupancy profiles and patterns are other important concepts for OBI. Occupant profiles group people according to demographics based on parameters previously identified as driving factors. According to Yoshino et al. (2017), simulations tend to use standard occupancy profiles to simplify reality with fixed values concerning energy-related behaviours such as setpoints or control of windows and blinds (Yoshino, Hong and Nord, 2017). Although more complex and dynamic simulation tools are increasingly used to accurately predict thermal comfort and energy use, more information on OBI is needed to benefit further from simulations. For instance, methodologies incorporating sensitivity and uncertainty analysis have highlighted the importance of model calibration in existing buildings (Yoshino, Hong and Nord, 2017). Such calibration requires more and more detailed assessment tools gathering information on occupant behaviours and their interaction with building elements. Moreover, the simulation output is the result of assumed behaviours (aside from technical and environmental parameters); thus understanding behaviours in different contexts is also critical as it cannot be assumed that individual personality traits can apply to broad generalisations in profiles between cultures (Milfont and Sibley, 2012).

Occupancy patterns are long-term behavioural effects that characterise actions and reactions on a specific time scale (Harputlugil and de Wilde, 2021). Such patterns are directly linked to the behavioural efficiency classification and can be redefined over time due to improved awareness or training, and their definition requires comprehensive monitoring. Both characteristics indicate that incorporating the assessment of occupant behaviours into POE frameworks would allow the definition of occupancy patterns and how they change over time. Previous attempts to classify patterns include Galvin (2013), who used a simple pattern classification based on the energy-use intensity dividing consumers into light, medium or heavy consumers. In contrast, Vogiatzi *et al*. (2018) proposed six patterns based on data gathered through surveys applied to residents of Athens, grouping them into environmentally friendly, adopting energy-saving practices, having economic motivation behind energy-saving practices, environmentally uninvolved, and environmentally unaware.

6. Socio-technical and cognition-centred approaches

Given the contextual and environmental nature of the topic, socio-technical and interdisciplinary studies are now conducted, integrating multiple theories around energy efficiency in buildings and OBI (D'Oca *et al.*, 2017). However, a paradigm shift is crucial to stop seeing the occupant as a source of heat gain content in a standardised indoor space (O'Brien *et al.*, 2020) and to start defining the OBI as mutually constitutive, shaping and changing each other (Salvia *et al.*, 2020). In this regard, Gupta et al. (2015) presented the intent and outcomes of a deep retrofitting social housing programme in the UK. They found an EPG and concluded that future retrofitting programmes must adopt a socio-technical approach considering building and occupants addressing social and physical factors influencing energy performance. It is estimated that a socio-technical approach coupling technical infrastructure and behavioural change could result in over half a reduction of the final energy demand from the entire building sector by the end of this century (Levesque *et al.*, 2019) and around a 20% reduction in the US residential sector (Hong *et al.*, 2017).

Behavioural change has proven to result in more benefits than installing new technologies. Therefore, guiding occupants to identify energy-related harmful behaviours and applying other strategies, such as financial incentives, can promote informed occupant-building interactions in residential and non-residential buildings (Chen *et al.*, 2021). According to Sangalli *et al.* (2020), future directions and current efforts for this approach require identifying occupancy patterns, needs, perceptions, and cultural values, which can provide valuable information about the variation in energy use in residential buildings. Thus, the need to have POE methodologies gathering data on energy-related occupant behaviours is evident.

According to Khani et al. (2021), although behavioural change in buildings is challenging and unsteady, it can be achieved with systematic monitoring of behaviours and savings. Moreover, researchers from engineering and psychology have also agreed that understanding and influencing behavioural change is firmly dependent on culture and context, as different applications may be practical on different occupants even within countries (Milfont and Sibley, 2012). These perspectives support the implementation of POEs from a socio-technical approach accounting for the interaction between social practices and physical elements, something critical to understanding the EPG and practical issues in residential retrofit (Chiu *et al.*, 2014). Opportunities for socio-technical approaches come from the expertise of social sciences, architecture, and technological development, capturing objective and subjective aspects of OBI (D'Oca *et al.*, 2017). Thus, interdisciplinarity represents an alternative to merging knowledge in novel ways to have holistic research connecting occupants and energy systems (D'Oca *et al.*, 2017). However, it is required to benefit from historically-informed theories and problem-oriented thinking for sustainable transitions (Smith *et al.*, 2010).

An alternative route for behavioural change is to focus on cognition. A multidisciplinary project supporting this was introduced by Schoot Uiterkamp and Vlek (2007). The project called "HOusehold Metabolism Effectively Sustainable" (HOMES) was active between 1994 and 2000, analysing occupants' energy consumption in the residential sector while connecting the data to environmental impacts. Findings revealed that occupants generally decide about energy-related behaviours based on their cognitive system; thus, interventions using feelings and cognition are a promising direction to obtaining pro-environmental behaviours (Habib *et al.*, 2021). Authors like Mitchell (2021) have indicated that one of the challenges for behavioural change comes from traditional epistemology separating mind and body to resolve sustainability challenges such as the EPG. Instead, technical infrastructure must promote behavioural change through user-friendly, stimulating, easy-to-adopt, culture and context-focused building elements (Barthelmes *et al.*, 2019) while perceived as self-decided.

7. Conclusions

This paper reviewed previous studies on EPG in retrofitted buildings, occupant behaviour and energy consumption, POE and rating systems, OBI, and socio-technical approaches to identify gaps in knowledge and opportunities for an innovative POE framework assessing behaviours leading to EPGs in retrofitted residential buildings. This study highlights that, despite an increasing interest in the impact of occupant behaviours on energy consumption in buildings, there is a critical need for research assessing energy-related behaviours, magnitudes, and resulting energy savings from behavioural interventions. In this context, an innovative approach for POEs assessing behaviours leading to EPGs in buildings emerges as a viable solution for closing several gaps in knowledge, such as the lack of mixed-method studies explaining why and how energy-related occupant behaviours are generated or the need for assessment tools gathering information on occupant behaviours and their interaction with building elements. Despite this, it was found that most of the published POE projects mainly focus on indoor environmental parameters and energy use without exploring the links with occupant-related parameters such as driving factors and comfort, and GBRSs only consider parameters such as occupants' satisfaction and feedback.

Focusing on residential retrofitted buildings is also of great importance as building retrofit has become a leading sustainable action towards tackling climate change, and occupant behaviours have a critical impact in residential buildings due to the increased interaction with building elements and high variability of actions, even within contexts and cultures. In this regard, researchers have highlighted the need for POEs to adopt socio-technical approaches to identify occupancy patterns, needs, perceptions and cultural values. Such an approach can provide valuable information about the variation in energy use in residential retrofitted buildings to be used in other innovative approaches linking occupant behaviour and energy consumption, such as dynamic simulation tools based on adaptive behaviours, behavioural interventions or future directions like cognition-centred approaches and usability of building systems.

Acknowledgements

This research has been carried out within the Future Cities Research Hub at Te Pare School of Architecture and Planning of the University of Auckland, New Zealand.

References

Ahern, C. and Norton, B. (2020) 'Energy Performance Certification: Misassessment due to assuming default heat losses', *Energy and Buildings*, 224, p. 110229. doi:10.1016/j.enbuild.2020.110229.

Barthelmes, V., Fabi, V., Corgnati, S., and Serra, V. (2019) 'Human Factor and Energy Efficiency in Buildings: Motivating End-Users Behavioural Change', in Bagnara, S. et al. (eds) *Advances in Intelligent Systems and Computing 825 - Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)*, pp. 514–525. doi:https://doi.org/10.1007/978-3-319-96068-5_58.

Bauer, A., Möller, S., Gill, B., and Schröder, F. (2021) 'When energy efficiency goes out the window: How highly insulated buildings contribute to energy-intensive ventilation practices in Germany', *Energy Research and Social Science*, 72, p. 101888. doi:10.1016/j.erss.2020.101888.

Van Den Brom, P., Meijer, A. and Visscher, H. (2019) 'Actual energy saving effects of thermal renovations in dwellings-longitudinal data analysis including building and occupant characteristics', *Energy & Buildings*, 182, pp. 251–263. doi:10.1016/j.enbuild.2018.10.025.

Calì, D., Andersen, R. K., Müller, D., and Olesen, B. W. (2016) 'Analysis of occupants' behavior related to the use of windows in German households', *Building and Environment*, 103, pp. 54–69. doi:10.1016/j.buildenv.2016.03.024.

Calì, D., Osterhage, T., Streblow, R., & Müller, D. (2016) 'Energy performance gap in refurbished German dwellings: Lesson learned from a field test', *Energy and Buildings*, 127, pp. 1146–1158. doi:10.1016/j.enbuild.2016.05.020.

Chen, S., Zhang, G., Xia, X., Chen, Y., Setunge, S., and Shi, L. (2021) 'The impacts of occupant behavior on building energy consumption: A review', *Sustainable Energy Technologies and Assessments*, 45, p. 101212. doi:10.1016/j.seta.2021.101212.

Chiu, L. F., Lowe, R., Raslan, R., Altamirano-Medina, H., and Wingfield, J. (2014) 'A socio-technical approach to post-occupancy evaluation: Interactive adaptability in domestic retrofit', *Building Research and Information*, 42(5), pp. 574–590. doi:10.1080/09613218.2014.912539.

Colclough, S., Hegarty, R. O., Murray, M., Lennon, D., Rieux, E., Colclough, M., and Kinnane, O. (2022) 'Post occupancy evaluation of 12 retrofit nZEB dwellings: The impact of occupants and high in-use interior temperatures on the predictive accuracy of the nZEB energy standard', *Energy and Buildings*, 254, p. 111563. doi:10.1016/j.enbuild.2021.111563.

Cozza, S., Chambers, J., Deb, C., Scartezzini, J. L., Schlüter, A., and Patel, M. K. (2020) 'Do energy performance certificates allow reliable predictions of actual energy consumption and savings? Learning from the Swiss national database', *Energy and Buildings*, 224, p. 110235. doi:10.1016/j.enbuild.2020.110235.

D'Oca, S., Chen, C. F., Hong, T., and Belafi, Z. (2017) 'Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings', *Energy Research and Social Science*, 34, pp. 240–251. doi:10.1016/j.erss.2017.08.002.

Day, J. K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., O'Brien, W., Rajus, V. S., De Simone, M., Kjærgaard, M. B., Pritoni, M., Schlüter, A., Peng, Y., Schweiker, M., Fajilla, G., Becchio, C., Fabi, V., Spigliantini, G., Derbas, G., and Pisello, A. L. (2020) 'A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort', *Building and Environment*, 178, p. 106920. doi:10.1016/j.buildenv.2020.106920.

van Dronkelaar, C., Dowson, M., Spataru, C., and Mumovic, D. (2016) 'A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings', *Frontiers in Mechanical Engineering*, 1, pp. 1–14. doi:10.3389/fmech.2015.00017.

Glad, W. (2012) 'Housing renovation and energy systems: The need for social learning', *Building Research and Information*, 40(3), pp. 274–289. doi:10.1080/09613218.2012.690955.

Gupta, R., Gregg, M., Passmore, S., and Stevens, G. (2015) 'Intent and outcomes from the Retrofit for the Future programme: Key lessons', *Building Research and Information*, 43(4), pp. 435–451. doi:10.1080/09613218.2015.1024042.

Habib, R., White, K., Hardisty, D. J., and Zhao, J. (2021) 'Shifting consumer behavior to address climate change', *Current Opinion in Psychology*, 42, pp. 108–113. doi:10.1016/j.copsyc.2021.04.007.

Harputlugil, T. and de Wilde, P. (2021) 'The interaction between humans and buildings for energy efficiency: A critical review', *Energy Research and Social Science*, 71, p. 101828. doi:10.1016/j.erss.2020.101828.

Hong, T., Yan, D., D'Oca, S., and Chen, C. fei. (2017) 'Ten questions concerning occupant behavior in buildings: The big picture', *Building and Environment*, 114, pp. 518–530. doi:10.1016/j.buildenv.2016.12.006.

IEA (2020) *Tracking Buildings 2020*, *Paris*. Available at: https://www.iea.org/reports/tracking-buildings-2020 (Accessed: 21 April 2021).

Khani, S. M. R., Haghighat, F., Panchabikesan, K., and Ashouri, M. (2021) 'Extracting energy-related knowledge from mining occupants' behavioral data in residential buildings', *Journal of Building Engineering*, 39, p. 102319. doi:10.1016/j.jobe.2021.102319.

Levesque, A., Pietzcker, R.C. and Luderer, G. (2019) 'Halving energy demand from buildings: The impact of low consumption practices', *Technological Forecasting and Social Change*, 146, pp. 253–266. doi:10.1016/j.techfore.2019.04.025.

Mahdavi, A., Berger, C., Amin, H., Ampatzi, E., Andersen, R. K., Azar, E., Barthelmes, V. M., Favero, M., Hahn, J., Khovalyg, D., Knudsen, H. N., Navarro, A. L., Roetzel, A., Sangogboye, F. C., Schweiker, M., Taheri, M., Teli, D., Touchie, M., and Verbruggen, S. (2021) 'The role of occupants in buildings' energy performance gap: Myth or reality?', *Sustainability (Switzerland)*, 13(6), pp. 1–44. doi:10.3390/su13063146.

Menezes, A. C., Cripps, A., Bouchlaghem, D., and Buswell, R. (2012) 'Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap', *Applied Energy*, 97, pp. 355–364. doi:10.1016/j.apenergy.2011.11.075.

Milfont, T.L. and Sibley, C.G. (2012) 'The big five personality traits and environmental engagement: Associations at the individual and societal level', *Journal of Environmental Psychology*, 32(2), pp. 187–195. doi:10.1016/j.jenvp.2011.12.006.

Miller, W., Sodagar, B., Whaley, D., Bamdad, K., and Zedan, S. (2021) 'Mind the gap : A comparison of socio-technical limitations of national house rating systems in the UK and Australia', *Journal of Building Engineering*, 43, p. 102570. doi:10.1016/j.jobe.2021.102570.

Mitchell, A.S. (2021) 'Rethinking theories of change in the light of enactive cognitive science: Contributions to community-scale local sustainability initiatives', *Systems Research and Behavioral Science*, 38(4), pp. 448–458. doi:10.1002/sres.2678.

Mo, Y. and Zhao, D. (2021) 'Effective factors for residential building energy modeling using feature engineering', *Journal of Building Engineering*, 44(March), p. 102891. doi:10.1016/j.jobe.2021.102891.

O'Brien, W., Wagner, A., Schweiker, M., Mahdavi, A., Day, J., Kjærgaard, M. B., Carlucci, S., Dong, B., Tahmasebi, F., Yan, D., Hong, T., Gunay, H. B., Nagy, Z., Miller, C., and Berger, C. (2020) 'Introducing IEA EBC annex 79: Key challenges and opportunities in the field of occupant-centric building design and operation', *Building and Environment*, 178, p. 106738. doi:10.1016/j.buildenv.2020.106738.

Osman, M. and Ouf, M. (2021) 'A comprehensive review of time use surveys in modelling occupant presence and behavior: Data, methods, and applications', *Building and Environment*, 196(February), p. 107785. doi:10.1016/j.buildenv.2021.107785.

Regnier, C., Sun, K., Hong, T., and Piette, M. A. (2018) 'Quantifying the benefits of a building retrofit using an integrated system approach : A case study', *Energy & Buildings*, 159, pp. 332–345. doi:10.1016/j.enbuild.2017.10.090.

Rinaldi, A., Schweiker, M. and Iannone, F. (2018) 'On uses of energy in buildings: Extracting influencing factors of occupant behaviour by means of a questionnaire survey', *Energy and Buildings*, 168, pp. 298–308. doi:10.1016/j.enbuild.2018.03.045.

Rouleau, J., Gosselin, L. and Blanchet, P. (2018) 'Understanding energy consumption in high-performance social housing buildings: A case study from Canada', *Energy*, 145, pp. 677–690. doi:10.1016/j.energy.2017.12.107.

Rouleau, J., Gosselin, L. and Blanchet, P. (2019) 'Robustness of energy consumption and comfort in high-performance residential building with respect to occupant behavior', *Energy*, 188, p. 115978. doi:10.1016/j.energy.2019.115978.

Salvia, G., Morello, E., Rotondo, F., Sangalli, A., Causone, F., Erba, S., and Pagliano, L. (2020) 'Performance gap and occupant behavior in building retrofit: Focus on dynamics of change and continuity in the practice of indoor heating', *Sustainability (Switzerland)*, 12(14), pp. 1–25. doi:10.3390/su12145820.

Sangalli, A., Pagliano, L., Causone, F., Salvia, G., Morello, E., and Erba, S. (2020) 'Behavioural Change Effects on Energy Use in Public Housing: A Case Study', in *Smart Innovation, Systems and Technologies*. Springer Singapore, pp. 759–768. doi:10.1007/978-981-32-9868-2.

Schoot Uiterkamp, A.J.M. and Vlek, C. (2007) 'Practice and outcomes of multidisciplinary research for environmental sustainability', *Journal of Social Issues*, 63(1), pp. 175–197. doi:10.1111/j.1540-4560.2007.00502.x.

Shen, M., Lu, Y., Wei, K. H., and Cui, Q. (2020) 'Prediction of household electricity consumption and effectiveness of concerted intervention strategies based on occupant behaviour and personality traits', *Renewable and Sustainable Energy Reviews*, 127, p. 109839. doi:10.1016/j.rser.2020.109839.

Smith, A., Voß, J.P. and Grin, J. (2010) 'Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges', *Research Policy*, 39(4), pp. 435–448. doi:10.1016/j.respol.2010.01.023.

Stazi, F., Naspi, F. and D'Orazio, M. (2017) 'A literature review on driving factors and contextual events influencing occupants' behaviours in buildings', *Building and Environment*, 118, pp. 40–66. doi:10.1016/j.buildenv.2017.03.021.

Sunikka-Blank, M. and Galvin, R. (2012) 'Introducing the prebound effect: The gap between performance and actual energy consumption', *Building Research and Information*, 40(3), pp. 260–273. doi:10.1080/09613218.2012.690952.

Swan, L.G. and Ugursal, V.I. (2009) 'Modeling of end-use energy consumption in the residential sector: A review of modeling techniques', *Renewable and Sustainable Energy Reviews*, 13(8), pp. 1819–1835. doi:10.1016/j.rser.2008.09.033.

Teli, D., Dimitriou, T., James, P. A. B., Bahaj, A. S., Ellison, L., and Waggott, A. (2016) 'Fuel poverty-induced "prebound effect" in achieving the anticipated carbon savings from social housing retrofit', *Building Services Engineering Research and Technology*, 37(2), pp. 176–193. doi:10.1177/0143624415621028.

UNFCCC (2015) *The paris agreement*. Paris.

Visscher, H., Sartori, I. and Dascalaki, E. (2016) 'Towards an energy efficient European housing stock: Monitoring, mapping and modelling retrofitting processes: Special issue of Energy and Buildings', *Energy and Buildings*, 132, pp. 1–3. doi:10.1016/j.enbuild.2016.07.039.

Vogiatzi, C., Gemenetzi, G., Massou, L., Poulopoulos, S., Papaefthimiou, S., and Zervas, E. (2018) 'Energy use and saving in residential sector and occupant behavior: A case study in Athens', *Energy and Buildings*, 181(2018), pp. 1–9. doi:10.1016/j.enbuild.2018.09.039.

Wilde, P. De (2014) 'The gap between predicted and measured energy performance of buildings : A framework for investigation', *Automation in Construction*, 41, pp. 40–49. doi:10.1016/j.autcon.2014.02.009.

Xing, Y., Hewitt, N. and Griffiths, P. (2011) 'Zero carbon buildings refurbishment - A Hierarchical pathway', *Renewable and Sustainable Energy Reviews*, 15(6), pp. 3229–3236. doi:10.1016/j.rser.2011.04.020.

Yan, D., O'Brien, W., Hong, T., Feng, X., Burak Gunay, H., Tahmasebi, F., and Mahdavi, A. (2015) 'Occupant behavior modeling for building performance simulation: Current state and future challenges', *Energy and Buildings*, 107, pp. 264–278. doi:10.1016/j.enbuild.2015.08.032.

Yoshino, H., Hong, T. and Nord, N. (2017) 'IEA EBC annex 53: Total energy use in buildings—Analysis and evaluation methods', *Energy and Buildings*, 152, pp. 124–136. doi:10.1016/j.enbuild.2017.07.038.

Zou, P. X. W., Xu, X., Sanjayan, J., and Wang, J. (2018a) 'A mixed methods design for building occupants' energy behavior research', *Energy and Buildings*, 166, pp. 239–249. doi:10.1016/j.enbuild.2018.01.068.

Zou, P. X. W., Xu, X., Sanjayan, J., and Wang, J. (2018b) 'Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives', *Energy and Buildings*, 178, pp. 165–181. doi:10.1016/j.enbuild.2018.08.040.

Urban dwellers’ view on hazards and disasters; and, the COVID-19 pandemic: implications for resilient urban housing in the post-pandemic period

Minerva Rosel[1] and Isidoro Malaque III[2]

[1,2]*University of the Philippines Mindanao, Davao City, Philippines*
{mcrosel1 [1], irmalaqueiii [2]}@up.edu.ph

Abstract: This paper aims to assess the housing needs and conditions of the city population, particularly in the central business district (CBD), as a pre-requisite for design intervention towards urban resiliency and enhanced quality of life. In the southern part of the Philippines, a comprehensive study was conducted in Davao City on urban dwellers’ view towards hazards and disasters, through a survey covering more than 1,000 respondents from the CBD’s daytime population, that was carried out in the latter half of 2019 prior to the community quarantine restrictions due to COVID-19 pandemic. Study shows that most city dwellers belong to the working population who prefer co-living arrangements, whether transient or permanent. This implies a need for new design parameters in urban housing design, as an alternative to conventional configurations. Furthermore, learning from the current pandemic, utmost consideration for health protocols in shared spaces must also be considered. With the onset of the pandemic, the real estate industry saw a shift in market preferences, particularly in high-density housing. Considering other urban hazards and disasters concerning the city dwellers as identified in the comprehensive study, new design insights and parameters are hoped for resilient infrastructure and housing developments in the post-pandemic period.

Keywords: Mindanao urbanization; mass housing; urban resilience; resilient cities.

1. Introduction

The growing number and concentrations of populations exposed to hazards make cities as the most vulnerable areas in our rapidly urbanizing world, and most of them are in Asia. In a ranking of urban centers’ exposure to a range of environmental and climate-related threats, data revealed that 99 of the world’s 100 riskiest cities are in Asia, and over a billion city dwellers facing environmental risk (Nichols, 2021). For years, Philippine authorities are concerting efforts to be prepared for the “Big One” – a worst case scenario of a 7.2-magnitude earthquake, deemed to be inevitable in a country along the Pacific Ring of Fire – in Metropolitan Manila, the most densely population region in the country. In the southern islands cluster of Mindanao, the center of urban development is Davao City. Metropolitan Davao is rapidly urbanizing, currently expanding towards its neighboring local government units in the region. While Davao

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 601–609.*

City is less congested than the major cities such as Manila and Cebu in the Luzon and Visayas islands clusters respectively, the aggressive housing and infrastructure developments created an emerging concern towards the natural environment and risks for disasters.

City planning traces its roots from the need to address societal problems during the industrial revolution. The poor housing conditions for workers in the city were at the core of various planning theories and concepts, giving birth to urban and regional planning principles and movements. These include the invention of complex road networks and popularization of suburban living, as introduced by early town planners from the west. The resulting urban sprawl and creation of car-centric societies, however, are now among the subjects concerning sustainable development, particularly in rapidly urbanizing regions in Asia. As rapid urbanization continues to shape the global economy, finding ways to provide the right infrastructure and services in cities will be a crucial problem to solve for communities and organizations (Ghosh, 2019). On one hand, suburban living may offer a better alternative to housing in the city but requires additional travel time and transportation cost. On the other hand, housing options may be available in the city, but are cramped and/or expensive. Neither option provides a better quality of life for low-income urban workers.

Communal living, an arrangement that has been in place for centuries in western societies (Kopec, 2006), is one solution that addresses affordable housing needs of urban dwellers. In the Philippines, living in dormitories and boarding houses is very common, not only to students but to young urban professionals as well, as typically provided by the private sector, such as families with spare residential spaces. As land value and construction costs continue to rise, real estate specialists are beginning to consider “co-living” spaces as a major player in the residential sector (JLL, 2019). With the emergence of a sharing economy and shift of traditional workforce to collaborative digital nomads, co-living spaces are seen to gain popularity as a sustainable alternative to underused but excessive traditional housing configurations. Prior to the COVID-19 pandemic, the demand for co-living spaces was expected to rise in the United States and drastically change design and urban development parameters (Grozdanic, 2016). Today, co-living has become more than just a housing model; it has become a solution for the market demands of a growing younger generation (Mahl, 2021).

The COVID-19 pandemic, a hazard that affected the whole world, highlighted some parameters that are crucial in urban space planning and design, more so on shared areas such as co-living spaces. Co-living spaces’ popularity comes from the fact that many people want to be around others and form connections (Di Risio, 2022). Community lockdowns may have temporarily reduced workers mobility, but greatly increased capacities for remote work. Humankind's ability to adapt to virtual platforms has paved ways for more technological advancements and virtual collaboration in the new normal. Health protocols requiring social distance made physical space even more valuable socialized housing program are favorable to the private developers and not to the intended beneficiaries.

2. Background

As pointed out by Habitat for Humanity in 2021, adequate and affordable housing leads to benefits in health, education, and economic opportunities. Having one’s own place to live is not just an accomplishment but is also an enforcement of resilience against economic and natural disasters. Unfortunately for Filipinos, the country's huge housing backlog is yet to be addressed despite the existence of several key shelter agencies (KSA) in the Philippines (Fernandez, 2021).

Socialized housing projects are typically located away from people's livelihoods, increasing the need for transportation, and reducing land for food production. Meanwhile in the CBDs, high density residential developments and townships are proliferating for the rich minority (see Figure 1).

Figure 114: Residential area along the Pasig River in Manila, with upscale condominiums in the background and residential community in the foreground that are providing housing units for transient residents. (photo by Dolly Anne Zoluaga, 2016).

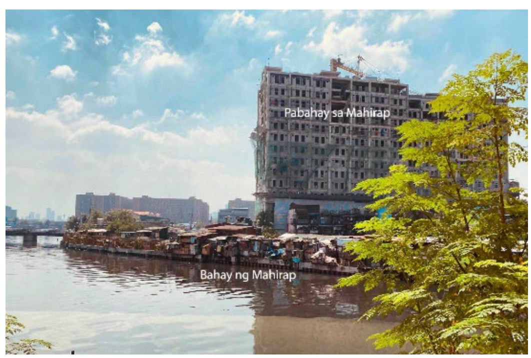


Figure 2: Residential area along the Pasig River in Manila, with existing informal settlement in the foreground and socialized housing project in the background (image by Joy Dawis-Asuncion, 2022).

The creation of the Department of Human Settlements and Urban Development (DHSUD) in 2019 aims to streamline government bureaucracy and ultimately deliver decent and affordable housing units to the Filipino masses. This includes high density residential buildings located in the CBD (see Figure 2). In the photo, "Bahay ng Mahirap" means "house of the poor", while "Pabahay sa Mahirap" means "housing for the poor". Similarly in Clark, a freeport and special economic zone north of Manila, authorities are already eyeing the establishment of workers' housing, for continuity of the manufacturing industry, as key to economic recovery (Silverio, 2020).

In Davao City, low-cost housing is provided through subdivision developments, none of which is in the CBD. Typical dwelling units are single detached, duplex and row house configurations, wasting valuable vertical space for higher density and horizontal space for parks and gardens. Moreover, the so-called socialized housing packages can hardly be considered affordable, with the government prescribed price range of PhP 0.45-1.25 Million (My Davao Property, 2022). These housing packages are available through bank loans, that the poor do not have access to. In 2021, a case study was conducted in Davao City, to probe if the government's socialized housing program truly addresses the needs of low-income households (Yares 2021). Results of the study showed that housing units are overpriced, and the socialized housing program is prone to abuse, as the majority of the socialized housing owners do not really belong to the low income sector. Furthermore, the study supports criticisms that the development outputs of the socialized housing program are favorable to the private developers and not to the intended beneficiaries.

3. Aims and objectives

Considering that the Philippines ranks third among the countries with highest disaster risks in the world (World Risk Report, 2018, as cited in Malaque III and Golimlim 2019), there is a need to integrate the COVID-19 pandemic implications on housing, as a pre-condition for resilience of urban dwellers of Davao City, through the daytime population of its CBD. The study aimed to profile the urban dwellers from the daytime population of the CBD and to sieve the perceptions of those who are living in from those who live outside of the CBD. Furthermore, the study aimed to compare the respondents' confidence in disaster resilient public infrastructure. The final objective is to compare how much time and money the respondents spend on transportation and housing, as inputs on design parameters for resilient workers' housing. For the discussion, this paper recommends and enumerates the benefits of an alternative configuration for city housing.

4. Case study areas and sampling

Davao City as the case study area, the comprehensive survey was conducted at Poblacion District as the urban area within the political boundary of the city. A ten-question survey questionnaire was designed covering three components, other than respondents' profile, to include: housing; transportation; and, disaster risk awareness. For the distribution of surveys, the study area was divided into eight zones. Fifty (50) research enumerators were deployed to conduct the survey all the zones covering a total of 1,026 respondents who participated in the survey. Research respondents include the daytime population, when the survey was actually conducted, in the Poblacion District who either lived within or outside of the case study area. For this article, results were analyzed from the two (2) cohorts to represent the city and non-city dwellers, respectively. The survey was conducted from November to December 2019, most of which were gathered in the first half of November. Incidentally, the region experienced a phenomenal swarm of earthquakes around the same period from September to December 2019.

5. Research results

To profile the respondents, we asked what they were doing in the CBD, anticipating that majority are students, with the number of schools and university campuses in Davao City. Results show that majority (54%) of the respondents are workers, and only seventeen percent (17%) are there to study. Almost a quarter (23%) stated that they are just visiting, and a few (5%) are merely residents. Majority of the respondents also live in the CBD. 52% declared that they are Poblacion residents, while an additional 6% consider themselves as transient residents. The 42% reside outside the CBD. Integrating these data, we found out that majority 362 out of 532 (68%) of the respondents are workers who are living within the CBD. It is interesting to note that there is a substantial number 274 out of 464 (59%) of worker and student respondents are not living in the CBD (Figure 3).

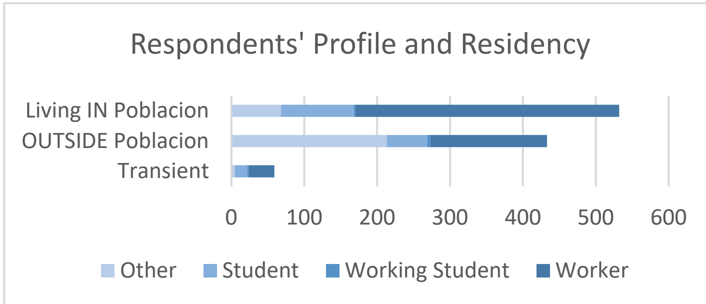


Figure 3: Respondents' profile and residency.

To get an overview of the respondents' monthly transportation expenses and compare the results from the two cohorts, the third question on the survey was "How much do you spend on transportation?". For those living within the CBD, majority spent the least amount ranging from 0 to 500 pesos. For those living outside the CBD, majority are spending up to 2,000 (Figure 4). As to their daily travel time, majority of those living within the CBD were only spending up to 30 minutes on the road each day. For those living outside the CBD, the top response was up to 1 hour of commute, with a notable number of responses revealing up to 4 hours of daily commute (Figure 5). Even if travel time is not computed with monetary value in this study, research results show that those living outside the CBD are already spending more as compared to those living within the CBD.

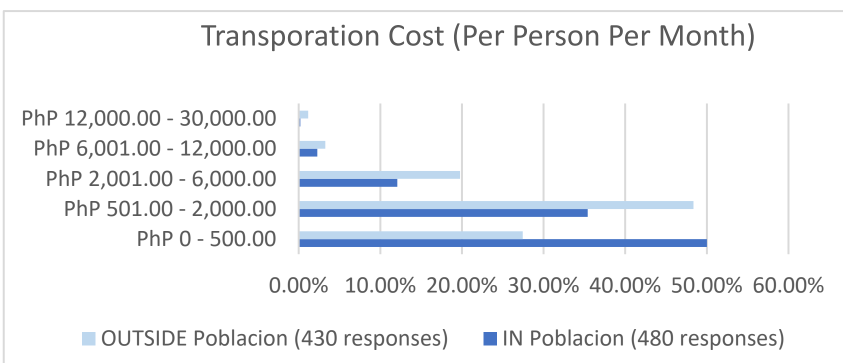


Figure 4: Transportation cost (per person per month).

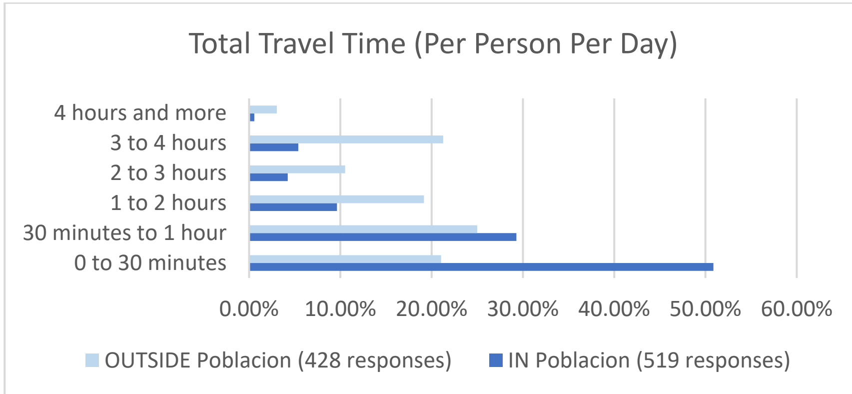


Figure 5: Total travel time (per person per day).

The study aimed to compare the cohorts' perceptions on hazards and their confidence on their respective community's resilient infrastructure. Asked if they were aware of public infrastructure to protect their houses from hazards, there were more respondents from those living outside the CBD who admitted that they do not know. In general, only a minority of the respondents, from both cohorts, are aware of such infrastructure. As to the hazards, "fire" is a concern for more city-dwellers than non-city dwellers. On the other hand, more non-city dwellers are concerned of "typhoons" and "landslides", than city-dwellers. For both cohorts, "flood" was equally identified, and "earthquake" was the most identified hazard (Figure 6). For evacuation areas, while majority (59%) of the respondents from both cohorts believe they have access to one, many (41%) are not aware of their availability or accessibility (Figure 7).

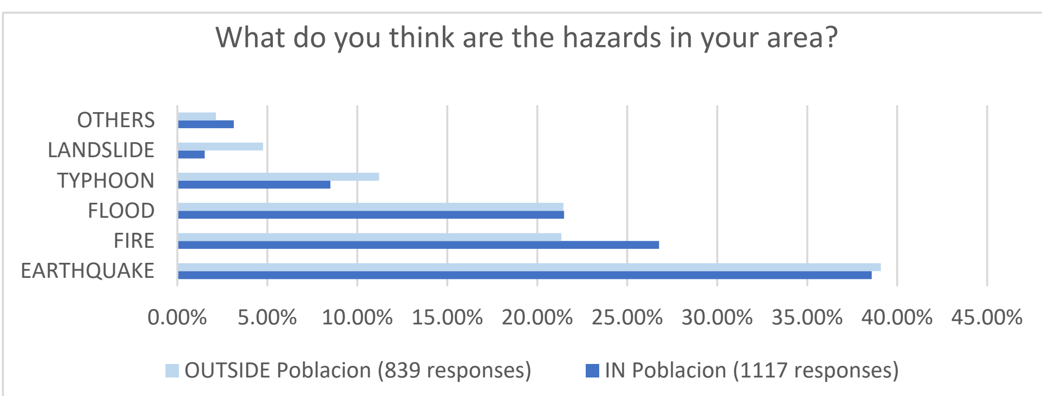


Figure 6: The perception of the population who live in, and outside the CBD with respect to the hazards in their area.

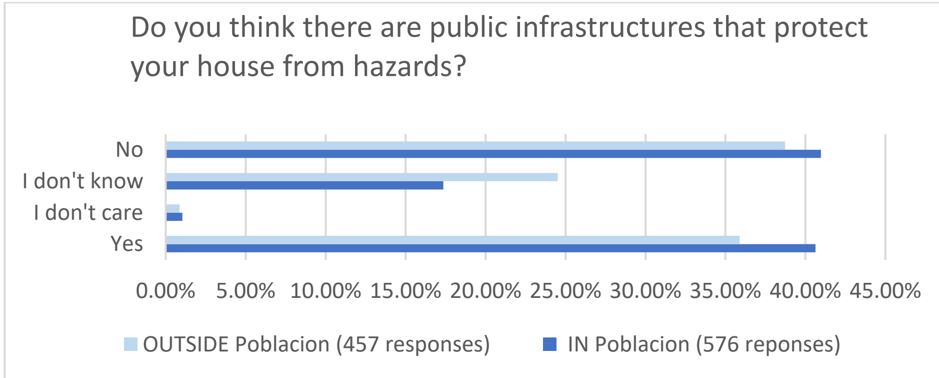


Figure 7: The perception of the population who live in, and outside the CBD with respect to public infrastructures in protecting their house from hazards.

As part of the respondents' profile, the survey also probed on the household size, or the number of persons living in the same housing unit. Of the total respondents, we filtered the responses to the city-dwellers, with the addition the transient city residents, resulting to 480 total responses. A considerable number (217 or 45%) of respondents belong to a household size of 5 and more, indicating that majority of the city-dwellers are co-living or sharing their dwelling unit. Only 48 respondents or a mere 10% of choose to live alone (Figure 8).

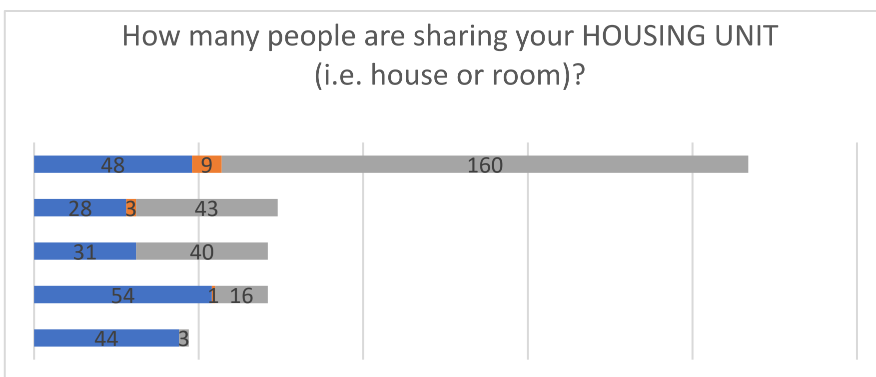


Figure 8: The number of people sharing their housing unit, whether it is through rental, amortization, or free/owned.

As we investigated the housing expense of city dwellers, majority (55%, or 262 out of 480 respondents) claimed to have no expenses spent on housing. For purposes of determining the affordability of city housing, we further filtered the data to consider only the figures for housing payments, both rental and amortization, from the remaining 45% (or 218 out of 480 respondents). Majority of the respondents spend between PhP 1,000.00 to PhP 3,000.00 per person per month on housing in the CBD (Figure 9).

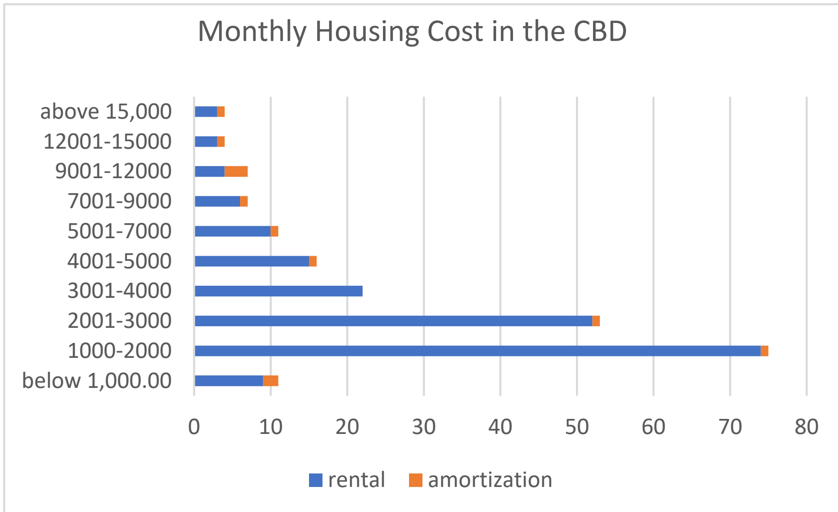


Figure 9: Monthly housing cost in the CBD.

6. Conclusion and Recommendations

There is a demand for housing in the CBD as evident the respondents' profile, as only 52% of the respondents permanently live in the CBD. Workers, students, and working students are potential market for housing in the CBD. Vehicular and pedestrian traffic volume as well as budget for transportation can be reduced by providing housing for workers and students. Considering other design parameters for resilient infrastructure, housing should particularly address resilience to earthquake, fire, and flood, to attract as an added value to city dwellers. Housing should cater to a household size of 5 and more to be marketable. The housing cost to be borne by an individual city dweller, is ideally within the affordability range of PhP 1,000-3,000 (in 2019), to be marketable, and ultimately sustainable. The benefits and practicalities of co-living arrangements may be introduced to city housing design, as an alternative to conventional configurations of individual or single-family housing unit, with utmost consideration for health protocols in shared spaces. The definition of socialized housing should be revised and expanded to include vertical developments that is appropriate in a CBD.

References

Chandran, R. (2018) [online] Manila's homeless set to move into more empty homes if official handover delayed. Reuters. https://www.reuters.com/article/us-philippines-landrights-lawmaking/manilas-homeless-set-to-move-into-more-empty-homes-if-official-handover-delayed-idUSKBN1H41L7?fbclid=IwAR3wdQoaJgnwSahjYwGkyCfL0tHXZdNaRYpSU9TRS_eFyRdyQEFcAEBCW-A (Accessed 15 July 2022)

Di Risio, A. (2022) Global Coworking Growth Study 2020 | Market Size & Industry Trends. [online] Coworkingresources.org. https://www.coworkingresources.org/blog/key-figures-coworking-growth (accessed 14 July 2022)

Fernandez, D., 2021. Robes says PH needs P50B to solve 'worsening housing backlog'. [online] INQUIRER.net. Available at: <https://newsinfo.inquirer.net/1514753/robes-says-ph-needs-p50b-to-solve-worsening-housing-backlog> [Accessed 15 July 2022].

Grozdanic, L. (2016) How Coworking and Coliving are Redefining Space as a Service. [online] ArchDaily. <https://www.archdaily.com/785550/how-coworking-and-coliving-are-redefining-space-as-a-service> (Accessed 15 July 2022)

Ghosh, I. (2019) Mapped: The Dramatic Global Rise of Urbanization (1950–2020). [online] Visual Capitalist. https://www.visualcapitalist.com/map-global-rise-of-urbanization/ (accessed 14 July 2022)

Habitat.org. (2021) Housing and the Sustainable Development Goals, The transformational impact of housing. https://www.habitat.org/sites/default/files/documents/Solid-Ground-SDG_booklet-update-2021.pdf (accessed 14 July 2022)

Ilo.org. 2022. Recommendation R115 - Workers' Housing Recommendation, 1961 (No. 115). [online] https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:R115#:~:text=As%20a%20general%20principle%2C%20the%20competent%20authority%20should%2C,and%20take%20appropriate%20measures%20to%20enforce%20these%20standards.

JLL.com. (2019, July 23) Co-Living: A Viable Alternative to Metro Manila Living Experience. https://www.jll.com.ph/en/newsroom/co-living-a-viable-alternative-to-metro-manila-living-experience (accessed 14 July 2022)

Kopec, Dan. (2006) Environmental Psychology for Design. First. New York: Fairchild Publications, Inc.

Mehl, B. (2021) Global Coworking Growth Study 2020 | Market Size & Industry Trends. [online] Coworkingresources.org. https://www.coworkingresources.org/blog/key-figures-coworking-growth (accessed 14 July 2022)

Nichols, W. (2021) Asian Cities in Eye of Environmental Storm – Global Ranking. [online] Verisk Maplecroft. https://www.maplecroft.com/insights/analysis/asian-cities-in-eye-of-environmental-storm-global-ranking/ (accessed 14 July 2022)

Visual environments for people living with dementia: a review of building performance criteria

Jane Waterhouse[1], Alessandro Premier[2] and Paola Boarin[3]

[1, 2, 3] Future Cities Research Hub, The University of Auckland, Auckland, New Zealand
{j.waterhouse[1], alessandro.premier[2], p.boarin[3]}@auckland.ac.nz,
0000-0002-6131-6354[1], 0000-0002-2565-9923[2], 0000-0003-3252-5699[3]

Abstract: Globally, there is an increased incidence of dementia correlated with aging populations and growing efforts toward diagnosis. This effort is accompanied by a movement to create more therapeutic built environments for people living with dementia to help promote a better quality of life. Due to the complex implications and consequences of this population's visual and cognitive impairments, the visual environment can be hugely impactful. This paper provides a review of the literature on the relationship between lighting and health for the population living with dementia. The review provides insights into the current approaches for designing indoor visual environments to improve the health of people living with dementia and examines the level of evidence underlying these recommended approaches. Literature review results showed that appropriate visual environments could help alleviate the dementia-related decline in visual perception and spatial ability, as well as sleep, mood, and behaviour disturbances. However, the existing evidence does not yet provide conclusive building performance metrics and thresholds for designing appropriate visual environments for people living with dementia. Accordingly, the review indicates the future research priorities towards improving building performance for design and research into visual environments for people living with dementia in healthcare and residential settings.

Keywords: Dementia, Health and Wellbeing, Visual Environment, Building Performance.

1. Introduction

The World Health Organisation (WHO) has estimated that, with the increasing incidences of dementia, 132 million people worldwide may have this condition by 2050 (World Health Organisation, 2017). Due to the high burden of disease and inadequacy of existing support levers, WHO's current dementia strategy signalled for greater intersectoral collaboration for dementia prevention, diagnosis, treatment, and care (World Health Organisation, 2017). This includes the building sector, which plays a significant supportive role as people living with dementia (PLwD) spend great amounts of time indoors and have higher sensitivities to environmental stimuli due to their dementia condition (van Hoof *et al.*, 2010). Hence, in

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 610–619.*

recent decades, there have been increasing endeavours to push for more humane and therapeutic environments and develop evidence-based design practices for this population (Fleming *et al.*, 2020).

In particular, the indoor visual environment has been identified by previous scholars as a domain within the built environment in need of further research and being highly impactful on PLwD's wellbeing (Torrington and Tregenza, 2007; van Hoof *et al.*, 2010). Past research has shown the correlation between aspects of the visual environment with visuospatial dysfunction, behavioural and sleep disturbances, among other symptoms (Torrington and Tregenza, 2007). Therefore, this paper reviews the literature on the relationship between the visual environment and dementia, with the following objectives:

- Reviewing existing research on the visual environment and dementia.
- Understanding dementia-specific concerns within designing visual environments.
- Identifying gaps and limitations with existing knowledge to establish future priorities for architectural research.

2. Human factors within visual environment design for PLwD

The visual environment is constituted by light sources, building geometry, surface finishes, daylighting and electrical lighting systems (Lechner, 2015). Human factors within visual environment design are concerned with people's psychological and physiological responses to this (Boyce, 2003). The main human responses to the indoor visual environment result from neuroprocessing via the visual or non-visual pathways following ocular reception of light stimuli (Houser and Esposito, 2021) (Figure 1).

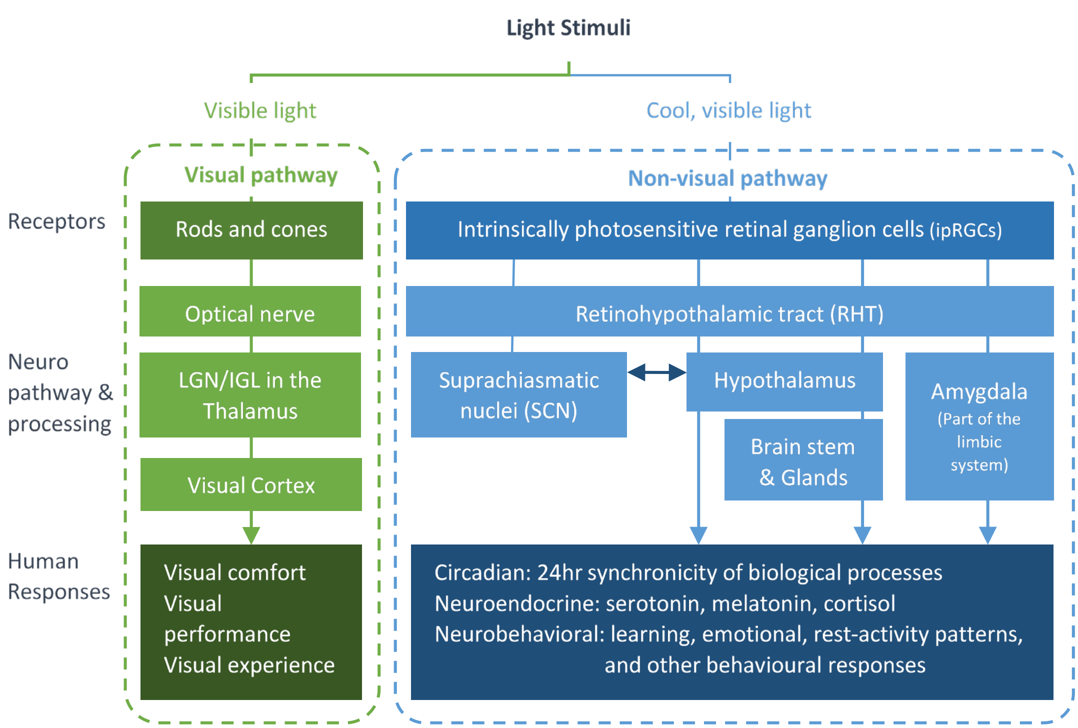


Figure 115: Neuro processing and human responses of the visual and non-visual pathways following ocular reception of light (adapted from Houser and Esposito (2021) and Houser *et al.* (2021))

Light processed through visual pathways leads to image-forming responses, impacting people's visual performance, comfort, and experience (Houser and Esposito, 2021). However, poor lighting conditions will impact PLwD's visual responses more than a healthy adult, as many will likely experience some form of age-related vision decline (Torrington and Tregenza, 2007). Aging eyes can have (Boyce, 2003; van Hoof *et al.*, 2010):

- Decreased adaptivity to light and increased sensitivity to glare due to atrophy of the ciliary muscles holding the lens and greater lens rigidity
- Decreased visual acuity and night vision, need for higher contrast as the density of retinal photoreceptors lowers
- Reduced colour sensitivity due to the yellowing of the lens
- Reduced ability for depth perception due to decreased size of pupils
- Restricted field of vision or visual disturbance due to shrinkage or floaters in the vitreous

It is also common for PLwD to experience other pathological visual impairments such as cataracts, macular degeneration, glaucoma, tunnel vision and pigmentosa, which will disturb their vision or increase their glare sensitivity (Brawley, 2006). However, beyond ocular degeneration, poorer perceptual abilities for interpreting visual stimuli are also caused by neurological dysfunction in older PLwD (van Hoof *et al.*, 2010). While older populations experience some difficulties with perception as neurons in the visual cortex decrease in density, visuospatial dysfunctions are more apparent in PLwD (Boyce, 2003; van Hoof *et al.*, 2010). Therefore, poor lighting conditions can easily exacerbate other cognitive issues associated with dementia, leading to confusion, misperceptions, disorientation, visual hallucinations, and social isolation (Boyce, 2003; van Hoof *et al.*, 2010).

Light can have non-image forming consequences, leading to circadian, neurobehavioral, and neuroendocrine responses (Illuminating Engineering Society, 2018). These non-visual responses are connected to sleep, alertness, behaviour, mood and wellbeing, and other biological functions (Ticleanu, 2017). Like their visual abilities, older PLwD will likely have compromised sensitivities to light via the non-visual pathway due to both dementia and old age. Age-related declines in ocular and neural physiology can shorten the circadian cycle with a phase advance (Boyce, 2003) and limit the amount of circadian-potent, cool light entering the eyes as the lens becomes more yellow and opaque (van Hoof *et al.*, 2010). These issues are compounded by dementia-specific atrophies in the suprachiasmatic nuclei (SCN), which play a vital role in circadian and hormone regulation (van Hoof *et al.*, 2010). As a result, affective disorders, behavioural and sleep disturbances can be common for dementia populations (Torrington and Tregenza, 2007).

3. Review of literature on the visual environment and dementia

3.1. Support for visual performance for PLwD

Visual environment literature that reported its effect on the visual performance of PLwD consisted of low evidence studies, making up a smaller portion of existing publications. Amongst reviews, qualitative, correlation, or case studies, was one experimental study by Yong *et al.* (2020) in spatial settings; others only used 2-dimensional prompts for inquiry into the visual perceptual abilities of PLwD (Wijk *et al.*, 1999).

However, despite the limited evidence base, there was high agreement among existing publications on how visual environments should be designed to support the visual and spatial perception of PLwD (Bowes *et al.*, 2016). It was found that adequate daytime and night-time illumination, especially natural lighting, was essential for this goal (Torrington and Tregenza, 2007). Sufficient lighting levels were crucial for enabling vision and correlated with reduced falls (Jäntti *et al.*, 1993) and increased caloric intake (Brush *et al.*, 2002; Douglas and Lawrence, 2015). Task-specific lighting in dark corners can also be helpful for vision and supporting activities of daily living (ADL) (Bowes *et al.*, 2016). Dim lighting environments increased confusion and lessened wayfinding abilities for PLwD (Netten, 1989). Hence, upgrades to electrical lighting were relatively common in dementia facilities (Neylon *et al.*, 2019), as low light levels can be typical for these settings. Due to the lack of dementia-specific illuminance thresholds, existing publications usually referred to design standards for older adults and low vision populations: a threshold of 50 fc (approx. 538 lux) (McDaniel *et al.*, 2001) or twice the standard illuminance was suggested (Dewing, 2009). Publications have also used other non-dementia-specific lighting recommendations to improve visual and depth perceptions such as with an illuminance uniformity of 3:1 or a colour rendering index of 80 to determine the placement and colour of lighting respectively (Brush *et al.*, 2002; Brawley, 2006).

Inadequate contrast in the visual environment was detrimental to PLwD as it reduced the ability of PLwD to distinguish objects or level changes (Torrington and Tregenza, 2007; Bowes *et al.*, 2016) and may lead to higher dependency when eating (Douglas and Lawrence, 2015). Low contrast can, however, be used advantageously to de-emphasise visual clutter, and in turn, contrasting elements can be used for cueing to limit unsafe movement, support perception, wayfinding, and memory decline (Torrington and Tregenza, 2007; Bowes *et al.*, 2016). Contrast, in this context, refers to both the colour and reflectance of surface finishes. Wijk *et al.* (1999) found that utilising red or yellow colours may be more effective as PLwD can more easily discriminate these hues. However, significant luminous ratios in ambient lighting can be hazardous due to slower eye adaptation to illuminance changes in PLwD (Torrington and Tregenza, 2007). Additionally, there may also be limited visual cueing functions associated with a localised light (Yong *et al.*, 2020). However, natural contrasts in daylighting or view conditions across rooms were suggested to improve spatial recognition and orientation for PLwD (Torrington and Tregenza, 2007).

Beyond lighting and contrast, Day *et al.* (2000) also emphasised the need to reduce glare and minimise surface patterns or shadows. An experimental study by Yong *et al.* (2020) found that highly shadowed floors can lead to confusion and hesitation while walking for PLwD. Dementia populations may misperceive shadows and dark patterns as holes in the floor or floor level change (Bakker, 2003). Glare and veiling reflections on reflective surfaces can also be misperceived by PLwD, leading to frightening experiences (Wong *et al.*, 2014). Additionally, lighting glare correlates with an increased risk of falls for PLwD (Bicket *et al.*, 2010). However, Bowes *et al.* (2016) note that efforts to reduce glare through minimising luminous ratio may contradict the need in PLwD for adequate contrast.

3.2. Support for visual comfort and experience for PLwD

Few visual comfort surveys or qualitative studies on the PLwD's experience of the visual environment were identified by this review. Existing studies rely on proxy reports from caregivers (Wong *et al.*, 2014) or correlations between lighting conditions with behavioural observations (Garre-Olmo *et al.*, 2012).

The literature indicates that windows contribute positively to PLwD's visual comfort, as caregivers have reported that natural lighting conditions are enjoyed by PLwD (Brawley, 2006; Wong *et al.*, 2014; van Vracem *et al.*, 2016). Similarly, Torrington and Tregenza (2007) have suggested maintaining access to a glare-free view, especially to nature, for its therapeutic value. However, care should be taken to control glare from low-elevation and afternoon sunlight, which can be problematic for PLwD (La Garce, 2004; Wong *et al.*, 2014).

There are contradicting understandings about dim light and visual comfort within the literature for PLwD. A correlation study by Garre-Olmo *et al.* (2012) found an association between the low lighting levels (85.2 – 134.6 lux) in bedrooms with poorer mood compared to shared spaces (250.5 – 493 lux). In contrast, Wong *et al.* (2014) found that some PLwD in residential facilities preferred dimmer lighting environments; dim light only proved a problem at dusk when residents felt confused, insecure, and agitated. As correlations cannot determine causality, lower moods found in dimmer conditions could also be due to social factors, as a significant difference in mood was not detected between different lighting conditions of the common spaces (Garre-Olmo *et al.*, 2012). Another explanation for the contradictions may be normative or individual preferences for lighting. PLwD's satisfaction with lighting conditions may be related to previous expectations and personalised control (Bowes *et al.*, 2018).

The visual environment also plays an essential role in creating a comfortable aesthetic within residences, such as utilising calming colour schemes (Wong *et al.*, 2014). However, related to the earlier point, place-identity theories may apply as PLwD can prefer familiar aesthetics for lighting or surface which are congruent with their expectations of the activity setting (Torrington and Tregenza, 2007). For example, a warm correlated colour temperature around 2700 – 3000K may be more suitable for residential settings (Brawley, 2006).

3.3. Support for non-visual responses for PLwD

Most studies investigated the non-visual effects of lighting on PLwD, especially light therapy experiments to ameliorate sleep and behavioural disturbances. Early research tended to use short morning exposures (1-2hr) to high or very high illuminances from static, electrical lighting in laboratory settings (Mishima *et al.*, 1998). Although these interventions continue to be trialled with PLwD (Chen *et al.*, 2020), later studies also experimented with longer exposures (4 hr to all day) to cool or biodynamic lighting in residential facilities (Figueiro *et al.*, 2015; Wahnschaffe *et al.*, 2017a). Biodynamic lights mimic daylight by changing intensities and correlated colour temperatures (CCT) throughout the day (Wahnschaffe *et al.*, 2017a).

Table 54: Categorisation of lighting interventions (adapted from Houser and Esposito (2021))

Illuminances (Lux)		Correlated Colour Temperature (K)	
Very High > 1000		Warm	1700 - 3200
High	600 - 1000	Neutral	3200 - 4200
Moderate	300 - 600	Cool	4200 - 6200
Low	50 - 300	Very Cool	6200 - 9500
Very Low < 50		Extremely Cool > 9500	

Sleep-related outcomes were the most prevalent among studies. Despite this, there is no clear consensus on a therapeutic illuminance threshold that consistently ameliorates sleep outcomes for PLwD. Studies that used high and very high illuminances yielded mixed results on PLwD's rest-activity patterns (Mishima *et al.*, 1998; Skjerve *et al.*, 2004; Riemersma-van der Lek *et al.*, 2008), with improvements primarily for nocturnal restlessness (Goudriaan *et al.*, 2021). In contrast, the review found limited evidence to show the efficacy of low to moderate illuminances, often as experimental controls or within biodynamic lighting, for improving measured sleep outcomes in PLwD (Mishima *et al.*, 1998; Wahnschaffe *et al.*, 2017a). However, improvements in sleep quality and circadian entrainment were found when high moderate vertical illuminances were used with cool CCT (Figueiro *et al.*, 2015). Similarly, comparison studies found warm or neutral CCT to be less effective than cool (5000K) or very cool CCT (6500K) for improving sleep outcomes in PLwD (van Hoof *et al.*, 2009a; Chen *et al.*, 2020). Despite the limited number of studies carried out, the greater potency for cooler CCT to ameliorate sleep disturbances in PLwD aligns with the scientific understanding of the peak spectral sensitivity in ipRGCs. However, findings from another study by van Hoof *et al.* (2009b) casts doubt on the efficacy of CCT as a metric for biologically potent light, as findings show no significant differences between warm and extremely cool CCT of 17000K on sleep outcomes in PLwD.

Behavioural disturbances such as agitation and sundowning are other symptoms of dementia of concern within light therapy studies for PLwD. So far, insufficient research has been conducted with low to high illuminances to reveal any notable trends for these thresholds in ameliorating behavioural disturbances. Existing experiments seem to suggest some therapeutic potential with very high illuminances (> 1000 lux) on behavioural symptoms, as the administration of these thresholds on PLwD has shown a decrease in agitated behaviours across several studies (Skjerve *et al.*, 2004; van Hoof *et al.*, 2009a). However, a comparison study by Barrick *et al.* (2010) found moderate illuminances 500 – 600 lux more effective than high illuminances for reducing agitation in PLwD. Beyond differences in experimental protocol and lighting, it is difficult to fully divulge the underlying cause of this contradiction due to the reliance on observation scales to measure agitation. The literature reported similar effects of CCT on agitation to sleep: cool (5500K) or very cool (6500K) CCT yielded improvements in agitation (La Garce, 2004; van Hoof *et al.*, 2009a), while warm or extremely cool CCT did not (van Hoof *et al.*, 2009b).

It was difficult to understand the effects of light therapy on depression, cognitive function, quality of life and performance of ADL for PLwD due to the limited number of studies measuring these outcomes with comparable lighting interventions. Other uncertainties within the field include the development of circadian lighting metrics and their association with health outcomes for PLwD. Figueiro *et al.* (2018) have indicated that a Circadian Stimuli (CS) > 0.3 is the threshold needed for sleep amelioration, while Konis *et al.* (2018) showed that Melanopic illuminance (mLux) may be a better metric than photic illuminance in predicting the therapeutic potency of light stimuli for depressive symptoms. However, insufficient research with PLwD has been conducted using either metric to gain significant insight. Limited research has also studied the utilisation and management of daylight in light therapy for PLwD. Figueiro (2008) makes a strong case for the importance of electrical sources in light therapy due to the inconsistency of daylight due to weather, distribution and glare. However, studies have shown that daylight still has a relationship with nocturnal restlessness (Brawley, 2006; Wahnschaffe *et al.*, 2017b), agitated sundowning behaviours (La Garce, 2004) and depressive symptoms in PLwD (Konis *et al.*, 2018).

Overall, the evidence level for bright light therapy for people with dementia to improve health outcomes is considered promising but low due to conflicting evidence and methodological flaws, which make the comparison difficult (Goudriaan *et al.*, 2021; Harrison *et al.*, 2022). These flaws include the inconsistency with intervention type, light intensity and CCT, duration of exposure and study, small cohorts which generally do not differentiate between different types of dementia (Day *et al.*, 2000), and lacking daylight, building and photometric descriptions (Aarts *et al.*, 2016).

4. Discussion

The review found limited research on dementia and the visual environment. The current understanding of how the visual environment affects the visual performance of PLwD is underpinned by low-evidence studies. However, there is consensus within the literature for using adequate lighting, contrasting surface reflectance and hue, and minimising shadows and glare to improve visual performance. This is consistent with the need to compensate for reduced vision, contrast sensitivity, adaption and perceptual ability and increased potential for hallucination in PLwD. For visual responses, the literature suggests that moderate illuminances may be appropriate for PLwD. Garre-Olmo *et al.* (2012) found better moods associated with 250.5 – 493 lux in PLwD, while 538 lux as specified by lighting standards for the elderly was used by McDaniel *et al.* (2001) and Brush *et al.* (2002) in the refurbishment of a dementia facilities. Due to limited dementia-specific studies addressing different cohorts and contexts, this finding cannot be conclusive. Hence, future studies are needed to identify new thresholds, or to validate existing ones, for light intensity, spectrum, distribution, and surface quality for PLwD's visual performance, comfort, and experience. PLwD's visual comfort and experience remain a significant research gap as much of the existing research was conducted by proxy of the caregiver or through observation. However, this reflects broader issues within dementia research; counter developments using innovative research and design methods involving PLwD are being adopted (Fleming *et al.*, 2020). Current research themes suggest that salutogenic principles related to coherence and comprehensibility, familiarity and meaning, and personal management may be significant for the visual comfort and experience of PLwD due to cognitive impairments.

In comparison, more efforts have been invested into the non-visual effects of light on PLwD with, notably, continuous experimentation with light therapy to ameliorate common sleep, behavioural and psychiatric symptoms of dementia. However, consistent with previous reviews (Goudriaan *et al.*, 2021), it was found that light therapy research on PLwD has been conducted with inconsistent protocols and interventions with mixed outcomes, leaving little certainty as to the light stimuli and exposures needed. Other explanations for inconsistent outcomes could be related to the unsuitability of photic metrics for describing biological light (Konis *et al.*, 2018) or the limitations of existing observation scales in differentiating environmental and social causes of behavioural and psychiatric symptoms of dementia. Thus far, the literature can only indicate that cool to very cool CCT (4200 – 9500K) and moderate to very high illuminance (> 600Lux) has the most potential to ameliorate sleep disturbance. Some inference can be made to suggest that very high illuminance (>1000 lux) and cool to very cool CCT may be therapeutic to agitation in PLwD. Other outcomes such as depression, cognition, functional independence, and observable quality of life measures were understudied or did not yield any observable trends.

However, there is limited application of these findings for architects and building researchers due to the lack of comprehensive descriptions of building performance in most of the publications on the visual environment and dementia reviewed. This is particularly relevant to research on visual responses for which there is a greater dependency on the acute experience of specific lighting conditions and spatial distribution, as opposed to the emphasis on temporality and history of exposure to biological light (Illuminating Engineering Society, 2018). The limited built environment perspectives found in this review align with Burke (2003) and Aarts *et al.* (2016)'s findings. Burke (2003) suggested that the dominant approach from nursing professions to visual environment research were related to the need for care-supportive environments, the availability of dementia expertise, and the lack of experienced design professionals within an emerging field. There may be some relationship between the historical lack of involvement of architectural research and the greater reliance within the literature on electrical lighting interventions for visual and non-visual responses despite understanding the benefits of natural lighting. Besides Konis *et al.* (2018)'s study showing the efficacy of 230 mLux of daylight for improving depressive symptoms in PLwD and the association of 1345.5 – 3767.4 lux at eye level with fewer sleep complaints in descriptive studies by Brawley (2006), no other thresholds or light intervention associated with daylight was found within the literature. This is a significant finding as daylight management has more implications on architectural design and practice than electrical lighting (Lechner, 2015).

Previously, notable reviews were either framed by health measures for PLwD (Goudriaan *et al.*, 2021; Harrison *et al.*, 2022), dementia symptoms and outcomes (Torrington and Tregenza, 2007) or aspects of the care environment (Day *et al.*, 2000; Bowes *et al.*, 2016). To the best of the authors' knowledge, this is the first review on dementia and the visual environment framed around architectural concepts within visual environment design, such as visual performance, comfort, and building performance. In doing so, this review identified significant gaps within the literature around dementia-specific building performance thresholds, understanding of visual comfort and the provision of daylight on PLwD.

5. Conclusion

A literature review has been carried out to understand how the design of the visual environment can impact and support the health and wellbeing of PLwD. Results from the review have shown that different aspects of the visual environment are associated with ocular and neurological impairments, as well as other symptoms of dementia such as visuospatial dysfuction, affective disorders, sleep and behavioural distubances experienced by PLwD. Hence, there is potential for lighting and architectural design to create supportive environments which can ameliorate these symptoms of dementia to improve the quality of life within this population. Currently, there is still uncertainty as to how this should be achieved. This review has highlighted the need for future research to establish dementia-specific building performance thresholds for the visual environment and investigate the relationship between indoor daylight and dementia, as well as understand the visual comfort needs of PLwD.

Acknowledgements

Include any acknowledgements to people, funding bodies etc.

References

Aarts, M. P. J., Aries, M. B. C., Diakoumis, A. and van Hoof, J. (2016) Shedding a Light on Phototherapy Studies with People having Dementia, *American Journal of Alzheimer's Disease & Other Dementias*, 31(7), 551-563.

Bakker, R. (2003) Sensory Loss, Dementia, and Environments, *Generations*, 27(1), 46-51.

Barrick, A. L., Sloane, P. D., Williams, C. S., Mitchell, C. M., Connell, B. R., Wood, W., Hickman, S. E., Preisser, J. S. and Zimmerman, S. (2010) Impact of ambient bright light on agitation in dementia, *International Journal of Geriatric Psychiatry*, 25(10), 1013-1021.

Bicket, M. C., Samus, Q. M., McNabney, M., Onyike, C. U., Mayer, L. S., Brandt, J., Rabins, P., Lyketsos, C. and Rosenblatt, A. (2010) The physical environment influences neuropsychiatric symptoms and other outcomes in assisted living residents, *International Journal of Geriatric Psychiatry*, 25(10), 1044-1054.

Bowes, A., Dawson, A., Greasley-Adams, C. and McCabe, L. (2016) Design of residential environments for people with dementia and sight loss: A structured literature review, *British Journal of Visual Impairment*, 34(3), 225-237.

Bowes, A., Dawson, A., Greasley-Adams, C. and McCabe, L. (2018) Developing best practice guidelines for designing living environments for people with dementia and sight loss, *Ageing and Society*, 38(5), 900-925.

Boyce, P. (2003) *Human Factors in Lighting*, 2 ed., Taylor & Francis, London.

Burke, T. J. (2003) Significance of tonal contrast in dementia accommodation, *Geriaction*, 21(3), 11-15.

Brawley, E. C. (2006) *Design Innovations for Aging and Alzheimer's: Creating Caring Environments*, ed., John Wiley & Sons, New York.

Brush, J. A., Meehan, R. A. and Calkins, M. P. (2002) Using the Environment To Improve Intake for People with Dementia, *Alzheimer's Care Quarterly*, 3(4), 330-338.

Chen, C. Y., Chen, H. W., Luo, M. R., Fang, C. C. and Hu, G. Y. (2020) A Study of Lightings for Elder with Dementia, *2020 Fifth Junior Conference on Lighting (Lighting)*, 1-3.

Day, K., Carreon, D. and Stump, C. (2000) The Therapeutic Design of Environments for People With Dementia, *The Gerontologist*, 40(4), 397-416.

Dewing, J. (2009) Caring for people with dementia: noise and light, *Nursing Older People*, 21(5), 34-38.

Douglas, J. W. and Lawrence, J. C. (2015) Environmental Considerations for Improving Nutritional Status in Older Adults with Dementia: A Narrative Review, *Journal of the Academy of Nutrition and Dietetic*s, 115(11), 1815-1831.

Figueiro, M. G. (2008) A proposed 24 h lighting scheme for older adults, *Lighting Research and Technology*, 40(2), 153-160.

Figueiro, M. G., Hunter, C. M., Higgins, P. A., Hornick, T. R., Jones, G. E., Plitnick, B., Brons, J. and Rea, M. S. (2015) Tailored lighting intervention for persons with dementia and caregivers living at home, *Sleep Health*, 1(4), 322-330.

Figueiro, M. G., Kalsher, M., Plitnick, B., Rohan, C. and Rea, M. S. (2018) 0295 Tailored Lighting Intervention For Alzheimer's Patients And Its Effects On Sleep, Mood And Agitation, *Sleep*, 41, A113-A114.

Fleming, R., Zeisel, J. and Bennett, K. (2020) *World Alzheimer Report 2020: Design, dignity, dementia: Dementia-related design and the built environment*, Alzheimer's Disease International, London.

Garre-Olmo, J., López-Pousa, S., Turon-Estrada, A., Juvinyà, D., Ballester, D. and Vilalta-Franch, J. (2012) Environmental Determinants of Quality of Life in Nursing Home Residents with Severe Dementia, *Journal of the American Geriatrics Society*, 60(7), 1230-1236.

Goudriaan, I., van Boekel, L. C., Verbiest, M. E. A., van Hoof, J. and Luijkx, K. G. (2021) Dementia enlightened?! a systematic literature review of the influence of indoor environmental light on the health of older persons with dementia in long-term care facilities, *Clinical Interventions in Aging*, 16, 909-937.

Harrison, S. L., Dyer, S. M., Laver, K. E., Milte, R. K., Fleming, R. and Crotty, M. (2022) Physical environmental designs in residential care to improve quality of life of older people, *Cochrane Database of Systematic Reviews*, 2022(3).

Houser, K. W., Boyce, P. R., Zeitzer, J. M. and Herf, M. (2021) Human-centric lighting: Myth, magic or metaphor?, *Lighting Research and Technology*, 53, 97-118.

Houser, K. W. and Esposito, T. (2021) Human-Centric Lighting: Foundational Considerations and a Five-Step Design Process, *Frontiers in Neurology*, 12.

Illuminating Engineering Society (2018) *ANSI/IES TM-18-18 Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioural Responses*, Illuminating Engineering Society, New York.

Jäntti, P. O., Pyykkö, V. I. and Hervonen, A. L. J. (1993) Falls among elderly nursing home residents, *Public Health*, 107(2), 89-96.

Konis, K., Mack, W. J. and Schneider, E. L. (2018) Pilot study to examine the effects of indoor daylight exposure on depression and other neuropsychiatric symptoms in people living with dementia in long-term care communities, *Clinical Interventions in Aging*, 13, 1071-1077.

La Garce, M. (2004) Daylight interventions and Alzheimer's behaviors - A twelve-month study, *Journal of architectural and planning research*, 21(3), 257-269.

Lechner, N. (2015) *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*, 4 ed., John Wiley & sons Inc., New Jersey.

McDaniel, J. H., Hunt, A., Hackes, B. and Pope, J. F. (2001) Impact of dining room environment on nutritional intake of Alzheimer's residents: A case study, *American Journal of Alzheimer's Disease & Other Dementias*, 16(5), 297-302.

Mishima, K., Hishikawa, Y. and Okawa, M. (1998) Randomized, Dim Light Controlled, Crossover test of Morning Bright Light Therapy for Rest-Activity Rhythm Disorders in Patients with Vascular Dementia and Dementia of Alzheimer's type, *Chronobiology international*, 15(6), 647-654.

Netten, A. (1989) The effect of design of residential homes in creating dependency among confused elderly residents: A study of elderly demented residents and their ability to find their way around homes for the elderly, *International Journal of Geriatric Psychiatry*, 4(3), 143-153.

Neylon, S., Bulsara, C. and Hill, A.-M. (2019) Improving Australian Residential Aged Care Facilities: A Review of Minor Refurbishment Elements, *Journal of Housing for the Elderly*, 33(3), 227-243.

Riemersma-van der Lek, R. F., Swaab, D. F., Twisk, J., Hol, E. M., Hoogendijk, W. J. G. and Van Someren, E. J. W. (2008) Effect of Bright Light and Melatonin on Cognitive and Noncognitive Function in Elderly Residents of Group Care Facilities, *JAMA*, 299(22), 2642-2655.

Skjerve, A., Holsten, F., Aarsland, D., Bjorvatn, B., Nygaard, H. A. and Johansen, I. M. (2004) Improvement in behavioral symptoms and advance of activity acrophase after short-term bright light treatment in severe dementia, *Psychiatry and Clinical Neurosciences*, 58, 343-347.

Ticleanu, C. (2017) *Literature review on circadian lighting*, Building Research Establishment, London.

Torrington, J. M. and Tregenza, P. R. (2007) Lighting for people with dementia, *Lighting Research and Technology*, 39(1), 81-97.

van Hoof, J., Aarts, M. P. J., Rense, C. G. and Schoutens, A. M. C. (2009a) Ambient bright light in dementia: Effects on behaviour and circadian rhythmicity, *Building and Environment*, 44(1), 146-155.

van Hoof, J., Kort, H. S. M., Duijnstee, M. S. H., Rutten, P. G. S. and Hensen, J. L. M. (2010) The indoor environment and the integrated design of homes for older people with dementia, *Building and Environment*, 45(5), 1244-1261.

van Hoof, J., Schoutens, A. M. C. and Aarts, M. P. J. (2009b) High colour temperature lighting for institutionalised older people with dementia, *Building and Environment*, 44(9), 1959-1969.

van Vracem, M., Spruytte, N., Declercq, A. and Van Audenhove, C. (2016) Agitation in dementia and the role of spatial and sensory interventions: Experiences of professional and family caregivers, *Scandinavian Journal of Caring Sciences*, 30(2), 281-289.

Wahnschaffe, A., Nowozin, C., Haedel, S., Rath, A., Appelhof, S., Müch, M. and Kunz, D. (2017a) Implementation of Dynamic Lighting in a Nursing Home: Impact on Agitation but not on Rest-Activity Patterns, *Current Alzheimer Research*, 14(10).

Wahnschaffe, A., Nowozin, C., Rath, A., Floessner, T., Appelhoff, S., Münch, M. and Kunz, D. (2017b) Night-time activity forecast by season and weather in a longitudinal design – natural light effects on three years' rest-activity cycles in nursing home residents with dementia, *International Psychogeriatrics*, 29(12), 2071-2080.

Wijk, H., Berg, S., Sivik, L. and Steen, B. (1999) Colour Discrimination, Colour Naming and Colour Preferences Among Individuals with Alzheimer's Disease, *International Journal of Geriatric Psychiatry*, 14(12), 1000–1005.

Wong, J. K.-W., Skitmore, M., Buys, L. and Wang, K. (2014) The effects of the indoor environment of residential care homes on dementia suffers in Hong Kong: A critical incident technique approach, *Building and Environment*, 73, 32-39.

World Health Organisation (2017) *Global action plan on the public health response to dementia 2017–2025*, World Health Organisation.

Yong, K. X. X., McCarthy, I. D., Poole, T., Ocal, D., Suzuki, A., Suzuki, T., Mengoudi, K., Papadosifos, N., Boampong, D., Tyler, N., Frost, C. and Crutch, S. J. (2020) Effects of lighting variability on locomotion in posterior cortical atrophy, *Alzheimer's and Dementia: Translational Research and Clinical Interventions*, 6(1).

What can academic research do for city-building practitioners?

Fanni Melles[1], Jeni Paay[2] and Ian Woodcock[3]

[1, 2] Swinburne University of Technology, Melbourne, Australia
{fmelles@swin.edu.au[1], 0000-0001-6664-1183[1]}
[3] The University of Sydney, Sydney, Australia

Abstract: Cities are where we need to begin solving global and local urban challenges by changing how we approach urban management, planning and design. Academic research, like the smart city field, currently focuses more on informing urban policy-makers than city-building practitioners such as architects, urban planners and designers, and engineers. These professions directly affect urban fabric, systems and behaviour through their practice. However, there is a disconnect between academic theories on achieving urban sustainability and city-building practices. In this article, we analyse 43 semi-structured interviews with practitioners based in Melbourne, Australia, to understand their perceptions about academic research related to the future of cities and its relevance for and relationships with practice. According to the participants, academic research rarely connects with practice, and research outcomes do not reach practitioners as they are not in an easily accessible form. The interviewees felt that academic research discounts the value of practical knowledge. These practitioners advocated for more innovative research and risk-taking in academic research with adequate proof and translation, making findings more applicable to practice. They praised collaboration across disciplines and stakeholders. Insights from this research indicate the need for pathways for translating academic research findings into practical advice for city-building practitioners.

Keywords: academic research; practical implementation; city-building practitioners.

1. Introduction

Cities are the constantly changing manifestation of humanity and collaborative networks of social, natural and built infrastructures (Komninos, 2011; Budde, 2013; Cocchia, 2014; Albino et al., 2015; Murgante and Borruso, 2015; Bansal et al., 2017; Musa, 2018; United Nations, 2018; Juniper Research, 2019; Katz, 2019). However, they are in crisis due to global and local factors. The global population is ever-increasing, and they increasingly live in cities, creating overpopulation, sanitation and health pressures, and economic challenges (The State of Victoria, 2006; European Commission, 2012; International Organization of Standardization, 2017; United Nations, 2018). Cities are known to consume around 70 per cent of resources, produce the same ratio of waste, while emitting more than 71 per cent of greenhouse gases

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 620–629.*

(International Organization of Standardization, 2012; Cocchia, 2014; Albino et al., 2015; International Organization of Standardization, 2017; United Nations, 2018). Local issues are partially the consequences of the global ones, with cities losing their uniqueness in the global competition or being endangered due to global warming effects (Morris, 1992; Belanche et al., 2016). For example, urban heat islands make cities uncomfortable and potentially hazardous to health, urban sprawl creates low density and fragile infrastructure, and nature and biodiversity seem to be missing from the built environment (Walt et al., 2014; Bansal et al., 2017; Musa, 2018; Shelton and Lodato, 2019).

Urban areas are increasingly acknowledged as the key to solving global challenges, such as climate change; therefore, urban management, planning and design need to take on this challenge in practice (Budde, 2013; Murgante and Borruso, 2015; Madden, 2019; Vanolo, 2019). Academia and science research into solutions for a better future (United Nations, 2015; Vanolo, 2019), such as the smart city concept (Komninos, 2011; Cocchia, 2014; Kunzmann, 2014; Albino et al., 2015; Murgante and Borruso, 2015; Aina, 2017; International Organization of Standardization, 2017). However, the research outcomes focus more on urban decision-makers and providing them with information (Giffinger et al., 2007; Angelidou, 2014; 2015; 2017; Angelidou et al., 2018). The smart city concept usually targets policy-makers and tries to help them transform their urban areas with global ideas (Giffinger and Gudrun, 2010; Kunzmann, 2014; Murgante and Borruso, 2015). However, the decision-makers are just part of the urban agent landscape. City-building practitioners, such as architects, urban planners and designers, and engineers, who can influence the urban fabric through their designs, are usually left out of the latest research (Giffinger et al., 2007; Giffinger and Gudrun, 2010; Giffinger et al., 2010; Walt et al., 2014). Even when their work is included, it highlights practitioner aspects from the point of view of the policy-makers instead of giving advice or providing practical knowledge directly to the city building practitioners (Walt et al., 2014).

Additionally, there seems to be a gap between academic theory and professional practice concerning the design of future cities (Komninos, 2011; Angelidou, 2014; Taylor and Hurley, 2016; Bansal et al., 2017; Arundel et al., 2018). The concepts for better urban futures rarely flow into practice or are seldom operationalisable and in a form useful for the city-building practitioners; they do not translate well to reality, even though the researchers highlight the need for bridging this gap (Giffinger et al., 2010; Taylor and Hurley, 2016; Fernandez-Anez et al., 2018). Academia continues to produce new ideas and approaches from their research that do not reach the design practitioners (Taylor and Hurley, 2016), even though the research aims to influence future design (Fernandez-Anez et al., 2018).

To bridge this gap, this paper investigates how city-building practitioners perceive academic research as being applicable to them and what role they see it playing in their practice. We present what city-building practitioners as participants of this study see academia's responsibility in establishing the future of cities and answer the question of what academic research can do for them. Our findings are based on semi-structured interviews with 43 city-building practitioners. Our outcomes include identifying opportunities for academic research to become more practical and valuable to the professions, which influence the design of the city, and hence its future, through their work.

The following sections introduce the research methodology and the interview participants, clarifying limitations. The findings and discussion sections present the advantages and disadvantages of academic research, according to the interviewees. The paper concludes by restating how best to translate academic research for practitioner use based on the participants' answers.

2. Methodology

The research involved 43 city-building practitioners residing in Melbourne, interviewed on their views on the future of cities and smart cities and their specific views on academia and its role in their practice. These professions were architecture, urban planning and design, and engineering, as these influence the urban fabric through their work.

With ethics approval, semi-structured interviews were conducted online between 2020 and 2021. The ethics application contained 14 starting questions for the average 60-minute interviews, but the semi-structured format implied the opportunity to follow the potential participants' answers to understand them more in detail. The questions were about the smart city and the future of cities' concepts' operationalizability in city-building practices and the connection between theory and practice. Questions like 'Do you read research?' and 'Whose responsibility is to initiate or establish the smart city or the future of cities?' helped to understand the participants' views on different urban segments, including academia.

A total of 179 practitioners were contacted with a list of starting questions, from which 43 agreed to the interview (Table 1). In total, 44,75 hours were spent interviewing online, using Microsoft Teams or Zoom. The recordings were transcribed with the Otter.ai service, checked manually and then sent to the participants for their approval. Afterwards, the transcripts were de-identified, resulting in 660 pages of material. These de-identified materials were loaded into NVivo to create the 5432 codes for thematic network analysis based on Attride-Stirling (2001). The thematic network analysis helps identify basic, organising and general themes and outliers across the investigated materials and visualises them in a network. The thematic networks were created from the codes using Cytoscape to organise them. The networks provided insights into overarching patterns and outlier ideas throughout the analysis. Figure 1 presents the thematic network for the interview question 'Do you read research?' – even though it was a yes-no question, the answers varied widely, providing insights into the practitioners' research reading habits and academic research connections, among others.

Table 55 – Disciplinary background of interviewed city-building practitioners

Profession	**Number of participants**
architect	16
architectural engineer	2
engineer	13
urban planner and designer	12
Sum	**43**

There are limitations to the findings. The research was not focused on the academic role but on how theoretical concepts can be used in city-building practices. Therefore, if the interviewees were explicitly asked about the academic research aspect, there might be additional roles for academia. The interview questions mitigated this shortcoming by asking broad questions, such as 'Whose responsibility is to initiate or establish the future of cities?' allowing participants to talk about any responsible party. Additionally, the 'Do you read research?' question immediately connected their thinking to academia.

Moreover, the findings can be seen as Melbourne-specific because of the participants' location. This limitation was chosen to have a physical boundary for the research and allow face-to-face meetings. These were later cancelled due to the COVID-19 pandemic, but the inclusion criteria had already been established. This limitation was mitigated by the interviewees' international attachments through educational, working or personal experiences. Therefore, although the participants were Melbourne-based, the findings can be useful for a wider audience.

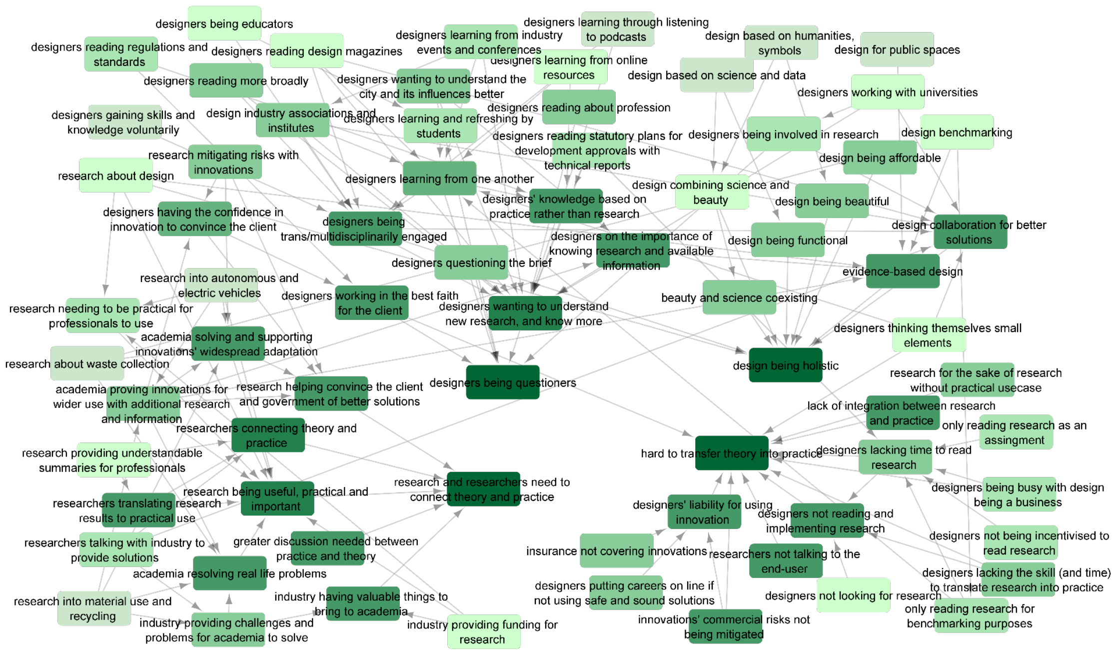


Figure 116 - Thematic network for the question 'Do you read research?' with the global - organising - basic themes gradient

3. Findings and discussion

City-building practitioners (identified only with their profession and plural pronouns for their safety) highlighted the advantages and disadvantages for academic research, according to the participants, their use (or non-use) of it, and specific roles which seemed helpful for them in their practice.

3.1. Academic research advantages and roles for the interviewees

Regardless of the disadvantages, the participants saw great opportunities, responsibilities and roles for academia to help them in their practice. They advocated for scientific innovation to evolve in urban areas and proof generation for innovation to be reliable and defendable. They also admitted the need for research to flow into practice, with more appropriate translation and collaborative efforts between researchers and practitioners to make this happen. Advantages were found in innovation and risk-taking, research translation, collaboration and bringing together different agents.

Innovation and risk-taking

Academic innovative research seemed essential for the participants as creators and managers for knowledge innovation. Academic research was said to be crucial as long as it could service practitioners with real solutions to real, industry-provided challenges, such as new materials or building methods. The interviewees had fewer resources and less time to create scientific innovation, even though they did practical innovation. They argued that academia has the means to do innovation and take risks because of their connections, facilities, and generally trans- and multidisciplinary approaches. Furthermore, academics can risk researching something and then finding it unsuitable for broader use – the practitioners do not have this luxury.

Many stated their will and need to know and understand more about the urban environment and its academic research. They mentioned that if academic research can prove and provide more information about proposed innovations, the practitioners are more confident in using that research, even or especially with their obligation to their clients to act in the best faith. One urban planner advocated for university research pushing boundaries:

> "I think it's really important, I think it's pretty good the way … that it currently happens ... I do think though it's important for academia to be able to push the boundaries and that they should be pushing … and pushing hard because … pushing thing's quite hard."

Investigation and proving

Participants also highlighted the crucial role of academic research in helping innovation become widespread. One of the difficulties in implementing academic research and theory in practice is that the practitioners are legally liable for any solution they provide; therefore, they risk their career and reputation when using a solution that is not adequately documented and supported by research. This notion also includes the insurance companies, which prefer to support tried-and-tested solutions, and avoid the commercial risks associated with new and novel ones. If academic research can provide the necessary proof to convince clients, governments, decision-makers, and insurance companies about better and more innovative solutions being reliable and valuable, then it is more likely to be used by practitioners. When academic research provides sufficient and convincing information for practitioners, they can mitigate and manage the risks involved while using innovative solutions in their practice. An engineer advocated for more proof coming from academia, helping the construction industry adopt innovative solutions:

> "The industry ... is so reluctant to commit to something unless there is proof ... And that burden of proof is quite extensive … [university] has done a lot of … practical lab testing where you could like simulate any environment … how that thing might perform or meet the current standards, using recycled content instead the usual virgin material."

As an example, an architect explained how innovation, in their specific case, the use of timber, was introduced:

> "How do we utilise this material [timber] better to make it a more predictable material because that was the other problem. Structural engineers hated timber because it wasn't predictable. … Now that they have engineered timbers that they can predict how they're going to perform, they're quite comfortable going up to 20 storeys, and more importantly, their insurance companies are quite comfortable with them going up to 20 stories."

Research translation

Academic researchers need to improve their research communication with the practitioners. Academic research needs to be tied more closely to practice for it to be useable, and the results need to be appropriately translated for the practitioners to understand and operationalise in their practices. Researchers could present their findings where the practitioners could reach them more easily. Theory translation also included research summaries to let the practitioners know about the innovations using more understandable language. Research awareness benefited the practice, but interviewees also highlighted the need for the wider public to learn about such innovations and breakthroughs. Thus, translation needs to happen in a broader context.

A direct connection between industry and academia was also praised for the possibility of finding real solutions to real problems. An engineer expressed appreciation for researchers who try to understand industrial challenges, finding answers to those and then giving practical outcomes in an easily understandable format:

> "I worked with some other great researchers where you could sort of take a problem to them, and then they would help you … work through what the right path would be. Or they researched at least where they really try to understand the industry – [this is] where we got more of the practical outcomes. … Research is very important in terms of stepping stone, but it's got to be practical."

Collaboration and bringing together the different agents

Interviewees also supported the need for academic collaborations, either across universities and fields or with outside agents. They valued how academia can bring the different stakeholders together and facilitate discourse among decision-makers. With this approach, researchers can also show how better urban understanding for designers, policy-makers and citizens leads to a better future for cities. The participants wished for collaboration with academic research groups, and some were fortunate enough to experience that positively when they were researching some specific parts of the urban fabric. An engineer praised the connecting role of academia:

> "I think that the solutions lie within research …, and I guess that those conversations need to be facilitated between our decision-makers and whether the world research lies."

The practitioners strongly believed in the role that academia and industry could play together. An architect expressed that both parties have an essential role to play:

> "I think there needs to be a greater integration between the two because the industry has valuable things to bring to academia … that need to be resolved. And, … testing things that academia is actually producing or things that are being research … and can be adapted."

3.2. Academic research disadvantages for the interviewees

Although the participants admitted the importance and advantages of academic research, they highlighted specific shortcomings. These included the rare connection between theory and practice and the missing translation of research for them to be easily consumable and practical. There was also a need for academia to acknowledge the practitioners' practical knowledge and let go of the urge to tell them how to do their job.

Rare connection between academic theory and practice

There seems to be a limited flow of knowledge from academic research into practice, although integrating the two is crucial for finding the best solutions. According to the interviewees, academic research is rarely linked from the beginning to the end-user, to answer pragmatic questions, or help real users. They experienced on several occasions that researchers created outputs and then tried to find a good use for them in reality. Doing research for the sake of doing research was also problematic for them. Moreover, participants also mentioned that they are unaware of what is happening in academic research, even though they acknowledged the need to keep up with innovation.

A striking example was around research being misused in practice. One practitioner used specific research, even referencing the name of the writers, but admitted never reading the research itself. Thus, they misrepresented the particular findings and the intended use of that research, which were highlighted in the research output but which never reached this specific practitioner.

Other interviewees described their specific experiences of researchers starting their research without trying to find a practical use for it but campaigning at organisations to support them financially. An engineer expressed the lack of connection between theory and practice for research:

> “They need to connect at the start to understand all of those things that are going to be a barrier at the end. So, there is no point just doing research for the sake of research without understanding what those needs and requirements are of the industry that will actually enable it to be rolled out on a large scale to make the research more worthwhile.”

Missing translation

The interviewees admitted not having the time and skills to follow and understand research outputs. Many advocated for researchers to disseminate their outcomes to a broader audience beyond the research community and specific conferences because practitioners are not usually part of such events. Additionally, the formal written output is challenging for the practitioners. They don’t have the time to read through lengthy articles with scientific language and then have to translate that into real-world applications. Therefore, they argued that researchers should translate their findings to more legible platforms and formats for the everyday user to reach and understand them. Even participants with research backgrounds admitted that they need to use different languages depending on their audience being academic or pragmatic. An urban planner required academia to translate their outputs and communicate them without jargon:

> “I think that certainly academics have responsibility to … translate what they're on about to the general public. But also I think that some disciplines might be a bit more naturally inclined to stepping outside of the subdiscipline than others.”

Interviewees admitted they could do more to reach, read and implement research because academic innovation does not flow into practice without that. Many said they don’t have the time to find and understand the articles, as they are occupied in their businesses, where they are not incentivised to read academic research. Others advocated for broader discussions for the research outputs to challenge or validate them properly for real-world application. When they read for their profession, they admitted that most research they read is related to specific tasks or benchmarking exercises for a current design project. One engineer admitted their lack of time and incentive to reach out to research:

> “There is a level of ability to use somehow research findings and plug them into the actual work of the practitioner. The reason being you are not asked to do that. So, it is something that you have on top of your activity. And that’s because you want to provide that more

> valuable work that reflects the needs of the community and that embeds the latest thinking. But it's on top of what you are asked to do."

Missing acknowledgement of practical knowledge

The interviewees did not resent the missing academic acknowledgement of the value of practical knowledge; however, the need for practice and academia to learn from each other, constantly urging evolution and development, was highlighted. Practitioners create investigations during their processes of analysing the urban fabric. They try to find the best spatial solution, root causes and perfect answers to urban challenges through questioning the urban situation, status quos, challenges, stakeholders and other elements. They also talked about how they are engaged with other disciplines and learn from each other. This trans- and multidisciplinarity was present in their information gathering as well. They mentioned reading magazines, being part of different and multidisciplinary institutions and associations, participating and attending industry events and conferences, being educators and learning from and with students, and even taking the time to gain new skills and knowledge through online resources. Additionally, they also mentioned that their reading is wider than the design profession itself, thus increasing their knowledge's multi- and transdisciplinary attributes. This knowledge could be utilised in updating academic research, which could help practitioners answer their current problems.

One example of this is the academic establishment of the smart city concept. Academic researchers try to create a global definition for it (with respect to honourable exceptions, such as Angelidou (2017)) as a solution to urban problems. However, practitioners know from their practice that cities need differences worldwide; therefore, one specific urban future will not suit all cities. Many participants questioned the idea of creating one global concept because, based on their wisdom and experiences, they found that each urban situation requires a specific answer suited to the local characteristics.

The smart city concept is also a good example of how academia shows a lack of value in practice. Smart city designs started to emerge in the 1990s in practice. However, the first scientific articles were about such case studies in the 90s, according to Cocchia (2014). Then, academia tried to help practice with researching the topic, producing increasing research outputs (Cocchia, 2014). Now, academia creates smart cities and urban futures in theory, but without connection to the practice itself, which was disturbing to the practitioners. One even stated that they don't need academia to teach them how to do their job:

> "I think it's very easy to start getting prescriptive, and I notice a lot of academics will start saying you should design in this way or there are rules to design. And when I think of myself as designer, I don't follow any rules."

4. Conclusion

Cities need transformation to achieve a better future and solve the current challenges caused by global or local problems. Academic research has produced theories on accomplishing this, like the smart city concept. Still, these seem separate from how practice can influence the urban fabric through their work. Based on semi-structured interviews, this article presented how 43 city-building practitioners – architects, urban planners and designers, and engineers – see academic research and its role in their practice.

The participants expressed their disappointment over the disadvantages they experienced with academic research, particularly that academic research seems disconnected from practice and that researchers are producing outcomes that are unusable for the interviewed practitioners. They admitted lacking the time and incentive to reach out and translate research findings and apply them in practice. Furthermore, their practical knowledge seems not to be acknowledged in academic research, which results in a feeling that academics try to teach the practitioners their professions rather than evolve their findings in a form useful for practice.

On the positive side, the interviewees identified beneficial roles and responsibilities for academia. Academic innovation and risk-taking remain crucial input to their work, and deep investigation and proof generation can help to spread such innovation. This makes it easier for practitioners to apply the knowledge with good conscience and to convince decision-makers on innovative designs. Translating research into a usable and understandable form could help with implementing and understanding knowledge for a wider audience. Academia's role as collaborators was also praised for bringing the different stakeholders together and finding transdisciplinary answers to presented challenges.

Further investigations can enhance the practitioners' understanding of and requirements for academic research with targeted investigations, as these findings were only a by-product of professional-focused research. Additionally, future research in this area should include a wider group of participants to discover the global differences in academic and practitioner collaboration.

References

Aina, Y. A. (2017) Achieving smart sustainable cities with GeoICT support: The Saudi evolving smart cities, *Cities*, 71, 49-58.

Albino, V., Berardi, U. and Dangelico, R. M. (2015) Smart Cities: definitions, dimensions, performance, and initiatives, *Journal of Urban Technology*, 22(1), 3-21.

Angelidou, M. (2014) Smart city policies: A spatial approach, *Cities*, 41, S3-S11.

Angelidou, M. (2015) Smart cities: A conjuncture of four forces, *Cities*, 47, 95-106.

Angelidou, M. (2017) Smart city planning and development shortcomings, *TeMA*, 10(1), 77-94.

Angelidou, M., Psaltoglou, A., Komninos, N., Kakderi, C., Tsarchopoulos, P. and Panori, A. (2018) Enhancing sustainable urban development through smart city applications, *Journal of Science and Technology Policy Management*, 9(2), 146-169.

Arundel, J., Lowe, M., Hooper, P., Roberts, R., Rozek, J., Higgs, C. and Giles-Corti, B. (2018) *Creating liveable cities in Australia: Mapping urban policy implementation and evidence-based national liveability indicators*, ed., Centre for Urban Research (CUR).

Attride-Stirling, J. (2001) Thematic networks: an analytic tool for qualitative research, *Qualitative Research*, 1(3), 385-405.

Bansal, N., Mukherjee, M. and Gairola, A. (2017) *Smart Cities and Disaster Resilience*, Springer Singapore, Singapore, 109-122.

Belanche, D., Casaló, L. V. and Orús, C. (2016) City attachment and use of urban services: Benefits for smart cities, *Cities*, 50, 75-81.

Budde, P. (2013) Smart cities of tomorrow, in S. T. Rassia and P. M. Pardalos (eds.), *Cities for smart environmental and energy futures*, Springer, Berlin, Heidelberg, 9-20.

Cocchia, A. (2014) Smart and digital city: A systematic literature review, in R. P. Dameri and C. Rosenthal-Sabroux (eds.), *Smart City: How to Create Public and Economic Value with High Technology in Urban Space*, Springer International Publishing, Cham, 13-43.

European Commission (2012) *The European Innovation Partnership on Smart Cities and Communities*. Available from: European Union <https://eu-smartcities.eu/> (accessed 09/01).

Fernandez-Anez, V., Fernández-Güell, J. M. and Giffinger, R. (2018) Smart City implementation and discourses: An integrated conceptual model. The case of Vienna, *Cities*, 78, 4-16.

Giffinger, R., Fertner, C., Kramar, H., Kalasek, R., Milanović, N. and Meijers, E. (2007) *Smart cities - Ranking of European medium-sized cities*, ed., Vienna University of Technology.

Giffinger, R. and Gudrun, H. (2010) Smart cities ranking: An effective instrument for the positioning of the cities, *ACE: Architecture, City and Environment*, 4.

Giffinger, R., Haindlmaier, G. and Kramar, H. (2010) The role of rankings in growing city competition, *Urban Research & Practice*, 3(3), 299-312.

International Organization of Standardization (2012) *ISO/TC 268 Sustainable cities and communities*. Available from: ISO <https://www.iso.org/committee/656906.html> (accessed 05/09).

International Organization of Standardization (2017) *ISO and smart cities*, in International Organization of Standardization (ed.), ISO, 1-20.

Juniper Research (2019) *Smart cities - What's in it for citizens?*, Juniper Research Ltd, Juniper Research.

Katz, I. (2019) Urban recalibrations and radical potentials, *City*, 23(1), 128-132.

Komninos, N. (2011) Intelligent cities: Variable geometries of spatial intelligence, *Intelligent Buildings International*, 3(3), 172-188.

Kunzmann, K. R. (2014) Smart cities: A new paradigm of urban development, *CRIOS*, 2014, 9-20.

Madden, D. (2019) Editorial: City of emergency, *City*, 23(3), 281-284.

Morris, R. W. (1992) Economic development, technology transfer, and venture financing in the global economy, in D. V. Gibson, G. Kozmetsky and R. W. Smilor (eds.), *The Technopolis Phenomenon: Smart Cities, Fast Systems, Global Networks*, Rowman & Littlefield Publishers, Lanham, Maryland, USA, 179-192.

Murgante, B. and Borruso, G. (2015) Smart cities in a smart world, in S. T. Rassia and P. M. Pardalos (eds.), *Future city architecture for optimal living*, Springer, Cham, Switzerland, 13-35.

Musa, S. (2018) Smart cities - A road map for development, *IEEE Potentials*, 37(2), 19-23.

Shelton, T. and Lodato, T. (2019) Actually existing smart citizens, *City*, 23(1), 35-52.

Taylor, E. J. and Hurley, J. (2016) “Not a Lot of People Read the Stuff”: Australian Urban Research in Planning Practice, *Urban Policy and Research*, 34(2), 116-131.

The State of Victoria (2006) *Victorian Planning Authority*. Available from: Victoria State Government <https://vpa.vic.gov.au/about/> (accessed 10/03).

United Nations (2015) *Sustainable Development Goals*. Available from: United Nations <https://www.un.org/sustainabledevelopment/> (accessed 10/10).

United Nations (2018) *World urbanisation prospects, the 2018 revision*, Department of Economic and Social Affairs, United Nations, 1-126.

Vanolo, A. (2019) Scenes from an urban outside, *City*, 23(3), 388-401.

Walt, N., Doody, L., Baker, K. and Cain, S. (2014) *Future cities: UK capabilities for urban innovation*, ARUP.

Zeroing in: A community-based approach to the design of public space for zero-carbon living

Susan J. Wake[1] and Pippa Sommerville[2]

[1, 2] Unitec Institute of Technology, Auckland, New Zealand
[1]swake@unitec.ac.nz, 0000-0002-1837-7581
[2]sommerville.pippa2@gmail.com

Abstract: This paper addresses our need to shift to a net-zero (zero-carbon) lifestyle. It begins by considering how public space can contribute to this and what other cities are doing about it. A case is then made for a community-based participatory approach, as it will empower people within the process of climate change mitigation. The results from participant surveys in the study area of Rānui, an outer suburb of Auckland, were followed by consultation workshops with community members. These were incorporated into a research-by-design process that has identified some key ways this community would like to see public space adapt in pursuit of a net-zero lifestyle. This research presents a holistic, integrated approach to emissions reduction which is meaningful and relevant for communities, and puts landscape architecture at the centre of the solution.

Keywords: zero emissions; net-zero, community participation; public space design.

1. Introduction

The Intergovernmental Panel for Climate Change (IPCC) has advised that limiting global warming to 1.5 degrees Celsius above pre-industrial levels is essential to reduce the extremity of weather events and avoid a collapse of essential ecosystems. They conclude that to achieve this, being carbon neutral by mid 21st century at the latest, is essential (IPCC, 2022).

20th Century urban design has assumed that fossil-fuel consumption will continue to support people's lives and the reliance on cars has undermined the close relationship between open spaces and the buildings around them (Madanipour, 2010). The drive for zero-emissions will lead to more localised living, which will create an opportunity to bring the human scale back to our cities.

There are several case studies from global cities that are tackling the zero-carbon goal, however there is a lack of small-scale community-based examples. This research therefore investigates emissions reduction behaviour through engagement of residents in Rānui, West Auckland, via surveys and participatory design. The resulting design of public space in Rānui embraces significant aspects of the required change to a zero-carbon lifestyle within this local community over the next 30 years.

Architectural Science and User Experience: How can Design Enhance the Quality of Life: 55th International Conference of the Architectural Science Association *2022,* P. Izadpanahi and F. Perugia (eds.), *pp. 630–640.*

2. Literature Review

Climate change can be defined as long term shifts in temperature and weather patterns, largely attributable to human activity since the 19th Century, especially the burning of fossil fuels (United Nations, n.d.). The definition of 'zero-carbon' for the purpose of this research is the balancing of carbon emissions with sequestration within a predetermined geographical area (Climate Council, 2020). 'Public space' is defined as all streets, parks, footpaths, cycleways and public car parks.

Urban public space provides multiple and diverse functions in a city and public space contributes to the preservation of biodiversity, the reconciliation of people and nature and promotes the health and well-being of the population (Pinto and Remesar, 2009). Twentieth Century urban design has assumed that fossil-fuel consumption will continue to support people's lives and the reliance on cars has undermined the close relationship between open spaces and the buildings around them. This has resulted in the development of public space which has little or no local network connection with other spaces in the city (Madanipour, 1999). In addition, in Auckland (Tāmaki Makaurau), regional public space planning for emissions reduction is currently considered and implemented in emissions-based silos. For example, walking and cycling planning is not aligned with public transport plans and waste and recycling plans and strategy is not aligned with food and consumption-based initiatives.

For this reason, a community-based approach, considering the behaviours, needs and limitations of the people and their streets and neighbourhoods is needed to allow a multi-functional and interdependent approach for all aspects of emissions (Kellett *et al*., 2013). Furthermore, a participatory design approach is necessary to ensure design interventions have a positive effect for the people living in the community and, therefore, the greatest chance of success due to the community having a vested interest in the outcome (Whitmarsh *et al*., 2011).

There are many theoretical models being developed and tested globally to grow and adapt cities to a low-carbon environment. The theory is diverse as solutions differ depending on the model and stage of development for each city. It is of relevance to this research that a study analysing four European cities that were each developed using a sustainable low-carbon model, observed that radical transformation of the urban landscape is necessary for such development to be successful (Fraker, 2013). Fraker proposes such radical transformation of public space could completely change the sensory experience of the city, and impact favourably not only on energy, CO_2 emissions and climate, but also on health and well-being.

The New Zealand Government passed the Climate Change Response (Zero Carbon) Amendment Act in 2019, with a commitment to invest $14.5 billion into better public transport, walking and cycling infrastructure over the next 10 years. Much of this funding will be invested into cities, with the largest investment likely to be in Auckland (Ministry for the Environment, 2019). Auckland Council have shown commitment to reducing emissions and have prepared an action plan (Te Tāruke-ā-Tāwhiri: Auckland's Climate Action Framework). The plan aims to reduce emissions by 50% by 2030 which will have major implications, especially for transport, which is currently responsible for 40% of Auckland's carbon emissions (Wilson, 2020).

Te Tāruke ā Tāwhiri interweaves a te ao Māori world view with a te ao Pākehā perspective on climate change and outlines key shifts incorporating this dual world view required to achieve the goals of: 1. Reducing greenhouse gas emissions by 50% by 2030 and achieving net zero emissions by 2050 and 2. Adapting to the impacts of climate change by ensuring we plan for the changes we face under our current emissions pathway (Auckland Council, n.d.). Te Ao Māori sees people and the environment as one living system, each interdependent on one another. Fundamental to this is the understanding that poor health of the environment and its natural systems will lead to poor health and wellbeing of the people (Lyver *et al*., 2019). Te ao Māori recognises sustainability of one system being interdependent on another, so views the natural systems making up the entire world as interdependent – meaning sustainability for all.

2.1. Case Studies

In Melbourne, the Victoria State Government have launched a 20-Minute Neighbourhood Pilot Program to test the theory that living locally reduces the use of carbon. Twenty-minute neighbourhoods are mixed-use places defined by a well-connected active transport network and a high-quality public realm with good access to employment, essential services, and community infrastructure (Harper, 2019). The premise is that essential goods (eg supermarkets, chemists) and services (eg doctors, public transport) can be reached within 20 minutes of walking.

In Auckland, a similar idea for a 15-minute city has been applied by Abley Consultants, as developed by Carlos Moreno, a Human Smart City expert (Abley, 2021). Abley mapped the locations of amenities and services that support a range of essential community requirements (defined as living, working, supplying, caring, learning, enjoying) and highlighted suburbs that provided these within a 15-minute walking radius.

3. Site Selection & Research Method

3.1. Site selection

The outer West Auckland suburb of Rānui was identified in Abley Consultants mapping as having 15-minute city potential. This along with being a diverse community that are engaged in their local area, having an existing public transport service (trains and buses) and open space offerings led to Rānui being selected as the study area for this research. Other key aspects that made Rānui ideal for this research was the presence of a well-established community garden, active community centre and a social services organisation called the Rānui Action Project, all which are well connected with the community.

Rānui has a population of 7,500 people with a higher-than-average proportion of Māori (23-25%), Pacific Peoples (28-35%) and young people (24% 15- to 25-year-olds), according to the New Zealand 2018 census (Stats NZ, 2020). Te Kawerau ā Maki and Ngāti Whātua ki Kaipara tribes are mana whenua (indigenous guardians) for Rānui. Consultation was undertaken with them in the early stage of this research and advice on priority areas for mana whenua, such as restoration of the awa (streams), ngahere (forest) and provision for whānau (wider family) accessibility to local taonga (treasures) has been woven into the design.

3.2. Research method

As a research-by-design project it was important to do a detailed site analysis, followed by other data collection, ahead of an iterative design process that folds in site specific data with information from the literature review and associated case studies (Roggama, 2016). Note that all images are the authors unless otherwise indicated.

A site within Rānui was selected with an area that one researcher could survey and engage with. This site takes in the train station, shops, key arterial routes and the two largest parks in the neighbourhood. Around 1000 homes are in the study area, which are largely single dwellings on small to medium sections. This area was extensively mapped and analysed – see Figure 1.

To understand the places that the community needs to focus on emissions reduction, it was important to establish a localized emissions profile. Surveying the community for some basic information on

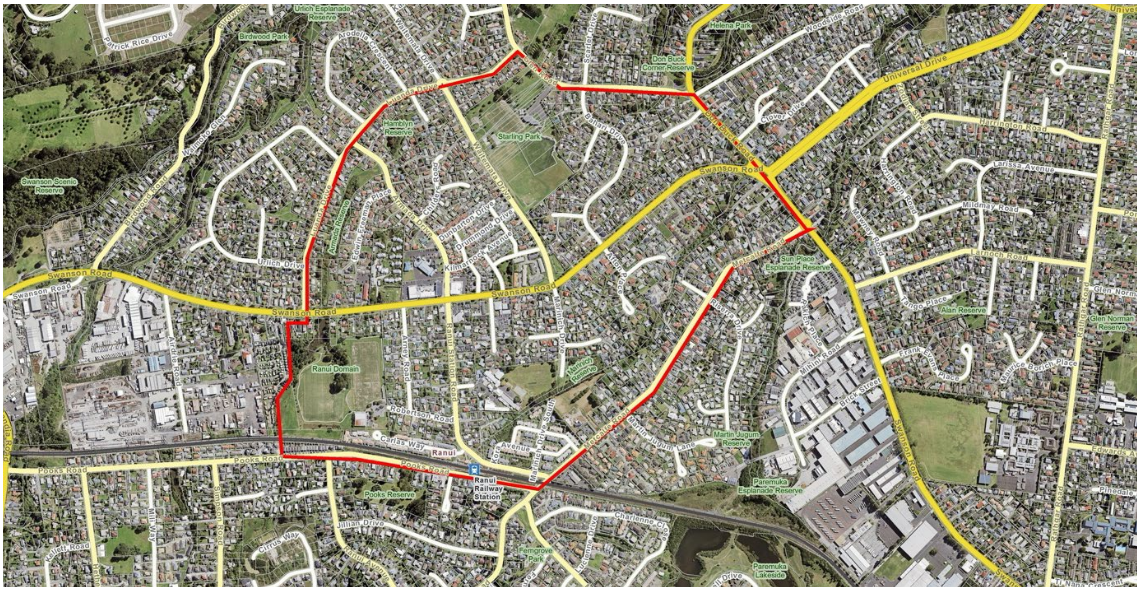


Figure 1: Study area in the West Auckland suburb of Rānui. (Source: Auckland Council GeoMaps)

emissions-producing activities was undertaken in late 2020. Approximately 2000 people living in the study area were delivered a paper survey, which they could either complete by hand and return to a box at the community centre or complete online and email results to the researcher. The 'Future Fit' survey was designed by Auckland Council for Auckland residents and was determined to be the best tool for emissions data collection in this research. Future Fit has been designed for individuals to understand where their emissions are being generated, as encouragement to reduce them (https://www.futurefit.nz/).

The survey asks 20 multi-choice or dropdown questions that are related to emissions-generating activities. The survey then generates an emissions profile, categorizing emissions per annum into four areas – Move (generated by transport), Eat (generated by food consumption choices), Shop (generated by consumption and waste), Power (generated in the home). There are limitations to how the data in the survey translates into emissions calculations and some assumptions are made for the purpose of this research, particularly in the areas of consumption and waste. The survey revealed key areas where emissions are being generated, which was then presented back to participants at a community workshop.

This is a participatory design approach, which involves user participation and a democratic process of design. Participatory design empowers the user to own the solutions, drives motivation for design implementation and leads to tangible benefits realisation and project success (IAP2, n.d.). At the workshop, people were asked to vote for the suggested solutions which would best support emissions reduction activities and lifestyles in their suburb. Further research and interviews with groups involved in key areas relevant to this research was then conducted before public space design solutions were drafted for discussion with the community.

4. Findings

4.1. Future fit survey

While the rate of survey return was low (2%) due to surveys conducted over summer, a lack of resources to encourage participation and covid-19 related complications, results did reveal that the average Rānui resident emits 1.4 tonnes less carbon than the average Auckland resident (7.2 tonnes in Rānui compared with 8.6 tonnes for the average Aucklander). The low socio-economic demographic of Rānui, along with good local access to services and public transport including the train and bus network may have contributed to this finding.

From the analysis it was determined that transport, food consumption and waste were emission sources with the greatest potential for positive impact due to public space design. This focus was therefore taken into the participatory design workshop to garner community feedback.

4.2. Carbon sequestration

To discover how much carbon is being sequestered in the study area, land coverage for trees, shrub and grass on public space were quantified and the sequestration rates for these areas calculated using the Ministry for the Environment tool for sequestration (MFE, 2020). It was estimated that the vegetated public space areas sequester 70 tonnes of carbon per annum which is equal to the emissions of about seven people. With an estimated 2000 residents in the study area it is clear that emissions need to be drastically reduced and tree cover greatly increased for the community to reach net zero.

4.3. Participatory design workshop

At the first workshop, in July 2021, in collaboration with the Rānui Action Project, participants were asked to indicate from a series of questions which would best support emissions reduction activities and lifestyles in the three identified key areas of transport, food, consumption and waste. The questions were accompanied by a set of solutions, and participants were asked to vote by sticking a dot on the solution they would most support (see Figure 2). For example, under 'consumption and waste' they were asked "Which things would make it easier for you to buy less stuff and recycle/compost more?" Solutions included:

- Having local places to share and swap things that everyone uses?
- Having local places outside of your home for composting food or garden waste?
- Having places where people can get together to fix things (or learn how)?

Figure 2: Community participants indicate their preferences to suggestions of ways to reduce carbon.

The following pie graph (Figure 3) shows the results of this participatory process for ‘Food’

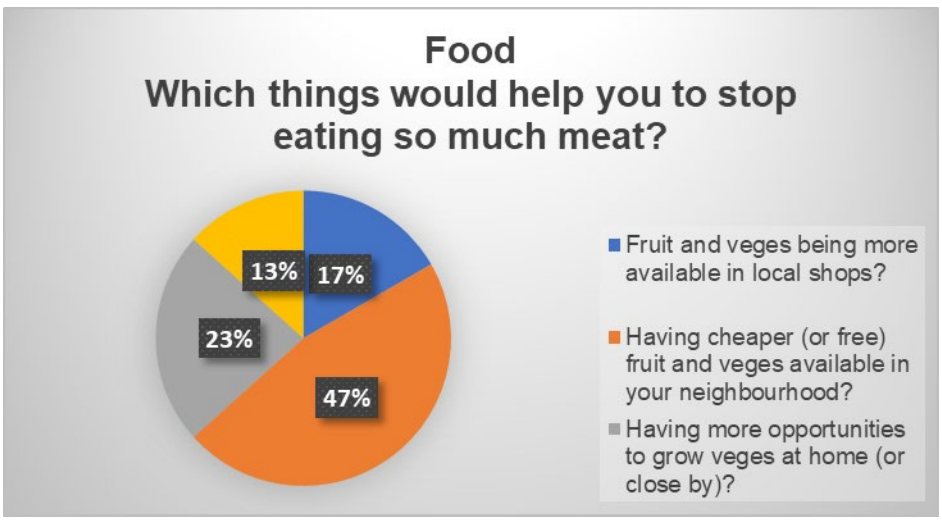


Figure 3: Pie graph showing community preference (from Workshop 1) for actions to do with food.

It is planned to go back and canvas community-members’ feedback on the designs that have developed from this data. Further research was also undertaken to investigate other local initiatives that aligned with the suggested solutions – eg community gardens, bike hubs, recycling centres, repair cafés. Advice and learnings from people running these initiatives was invaluable in informing the design process.

4.4. Design process

Taking all the information and collected data into a design process has been an exciting exploration of possibilities. After mapping the current landscape character and function of the research area, design layers were created, driven by the most popular chosen options (see Figures 4 and 5) of the community participants that attended Workshop 1 (approx. 25 people).

Figure 4: Design layer showing possible areas in the research site for increased food production.

Figure 5: Design layer showing possible areas for ‘fixing’ things.

The views of local Māori iwi (tribes) were also folded in (see Figure 6) to increase the mauri (health or life force) of the area through forest and stream restoration. The key to this development towards a carbon zero-focused master-plan is that change should be radical and transformative, in the words of Fraker (2013). It is important to think differently in terms of the way we will be living in future and not to let small (present) detail dictate large (future) change.

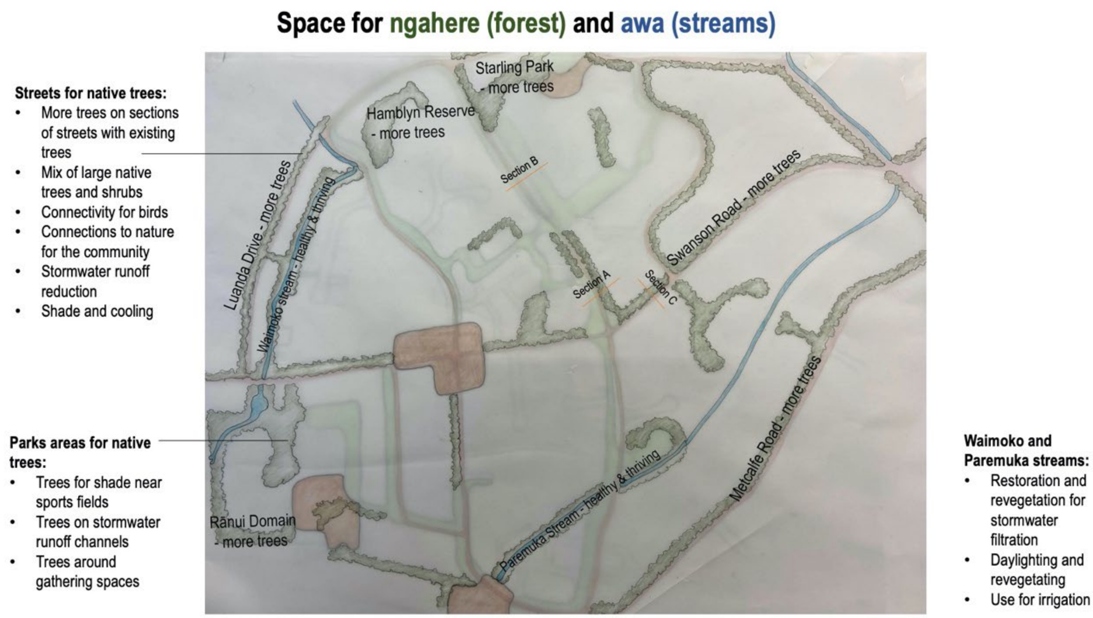


Figure 6: Design layer showing increased native planting along streets, pathways and streams

Figure 7: Existing arterial road layout in Rānui

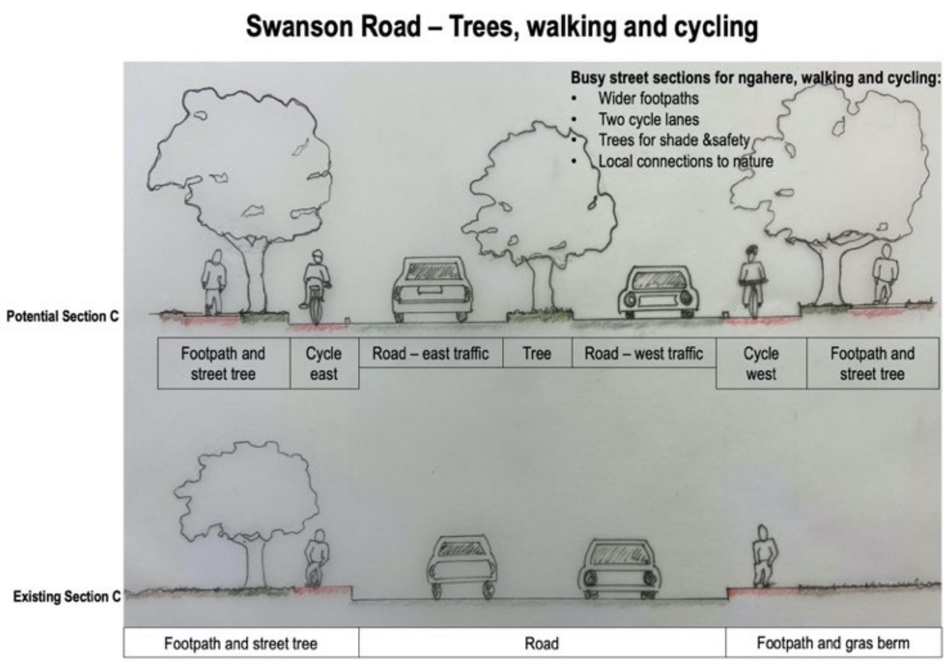


Figure 8: Cross section of proposed layout for an arterial street in the research site

Figure 7 shows an existing arterial street photo that reflects our past and current fixation with car transport while Figure 8 shows a cross section of a modified arterial street with cycle paths and extra shade trees to reduce heat island effects and create shade and nature experiences for pedestrians. In Figure 9 the possibility is shown of turning a non-arterial road into a one-way street with cycle and walking lanes, fruit and shade trees, raised vegetable beds and storage sheds for garden maintenance tools. The existing car-focused streetscape is shown in the bottom half of the image.

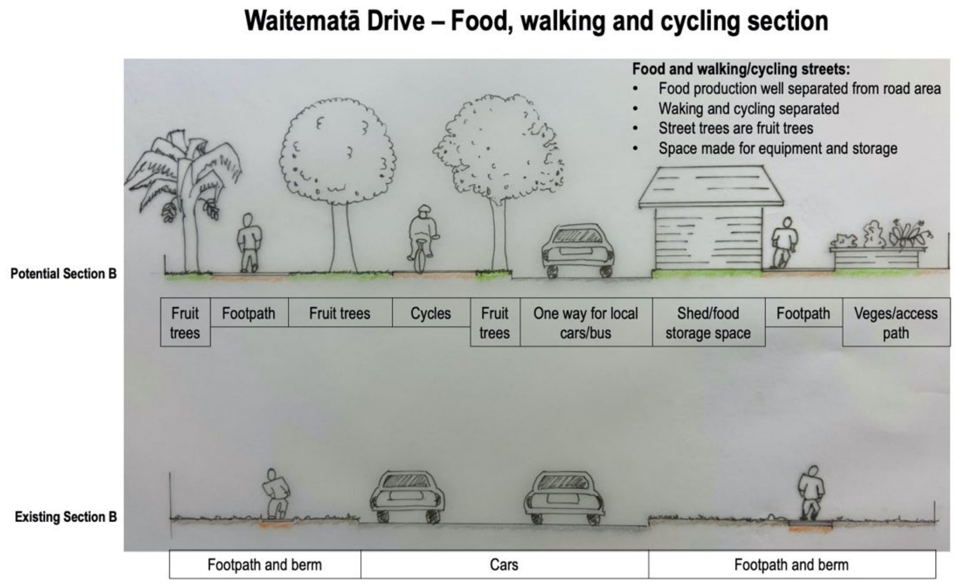


Figure 9: Cross section of proposed layout for a local or non-arterial road.

To enable such an ambitious plan as this to work in a way that could supply community members with significant amounts of fresh fruit and vegetables there would need to be garden staff employed to maintain plants and manage production and distribution. This could not be done on a volunteer basis. There would also need to be skilled staff in bike hubs and repair cafes. It is suggested that this could be the radical rethinking that Fraker (2013) refers to.

6. Conclusion

This research aims to put into practice the government-drafted plans and policies intended to reduce our reliance on fossil fuels for energy through testing their effectiveness at a neighbourhood scale for a community in suburban West Auckland. It is hoped that the penultimate design will guide sustainable, low impact public space development that supports emissions reduction activities and behaviours. The project is not quite complete as there is a further round of participatory design to occur, with community invited to give feedback and the plans then revised according to this and other feedback from industry. It is planned to incorporate this in the final paper.

The outcomes of this research, if implemented, will help reach the Auckland Climate Plan goal of reducing greenhouse gas emissions by 50 per cent by 2030 and achieving net zero emissions by 2050. It will also provide a precedent for neighbourhood-scale planning in other Auckland suburbs and highlight the need for a participatory approach, with solutions co-designed with the community for them to be supported and effective.

Acknowledgements

Auckland Council, Resource Management Law Association, Unitec Institute of Technology

References

Auckland Council (n.d.) *Auckland's climate plan*. Available from https://www.aucklandcouncil.govt.nz/plans-projects-policies-reports-bylaws/our-plans-strategies/topic-based-plans-strategies/environmental-plans-strategies/aucklands-climate-plan/Pages/default.aspx (accessed 15 July 2022).

Climate Council (2020) What does net zero emissions mean? Available from https://www.climatecouncil.org.au/resources/what-does-net-zero-emissions-mean/ (accessed 15 July 2022).

Fraker, H. (2013) *The hidden potential of sustainable neighbourhoods: Lessons from low-carbon communities*, Washington D.C.: Island Press.

Harper, L. (2019). *Neighbourhood Living*. Report prepared for Resilient Melbourne. Available from https://www.planning.vic.gov.au/__data/assets/pdf_file/0023/450275/Mambourin-Report-Staging-Community-Infrastructure.pdf (accessed 12 July 2022)

IAP2, (n.d.) International Association for Public Participation. *The three pillars of public participation*. Available from https://www.iap2.org/page/pillars (accessed 15 July 2022)

IPCC, (2022) *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press. Available from https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ (accessed 15 July 2022).

Kellett, R., Christen, A., Coops, N. C., van der Laan, M., Crawford, B., Tooke, T. R., & Olchovski, I. (2013) A systems approach to carbon cycling and emissions modeling at an urban neighborhood scale. *Landscape and Urban Planning*, 110(1), 48–58. https://doi.org/10.1016/j.landurbplan.2012.10.002

Lyver, P. O. B., Ruru, J., Scott, N., Tylianakis, J. M., Arnold, J., Malinen, S. K., Bataille, C. Y., Herse, M. R., Jones, C. J., Gormley, A. M., Peltzer, D. A., Taura, Y., Timoti, P., Stone, C., Wilcox, M., & Moller, H. (2019) Building biocultural approaches into Aotearoa–New Zealand's conservation future. *Journal of the Royal Society of New Zealand*, 49(3), 394–411. https://doi.org/10.1080/03036758.2018.1539405

Madanipour, A. (1999) Why are the design and development of public spaces significant for cities? *Environmental and Planning B: Urban Analytics and City*, Planning and Design, 26(6), 879–891. https://doi.org/10.1068/b260879

Madanipour, A. (Ed.). (2010). *Whose public space? International case studies in urban design and development*. Chapter 1 – Introduction, 1-16, London: Routledge.

Ministry for the Environment. (2019) *Climate Change Response (Zero Carbon) Amendment Bill: Summary*. Wellington: Ministry for the Environment.

Ministry for the Environment. (2020) *Measuring Emissions: A Guide for Organisations: 2020 Detailed Guide*. Wellington: Ministry for the Environment.

Pinto, A. J., & Remesar, A. (2009). *Thinking Public Spaces for Low Carbon Cities*. Presented at 45th ISOCARP Congress 2009, 11pp. Available from https://www.isocarp.net/Data/case_studies/1538.pdf (accessed 12 July 2022)

Roggema, R. (2016) Research by design: Proposition for a methodological approach. *Urban Science*, 1(2), 1-19.

United Nations (n.d.) *What is climate change?* Available from https://www.un.org/en/climatechange/what-is-climate-change (accessed 12 July 2022).

Stats NZ (2020) *2018 Census.* Available from https://www.stats.govt.nz/2018-census/ (accessed 15 July 2022).

Whitmarsh, L., Seyfang, G., & O'Neill, S. (2011). Public engagement with carbon and climate change: To what extent is the public "carbon capable"? *Global Environmental Change*, 21(1), 56–65. https://doi.org/10.1016/j.gloenvcha.2010.07.011