School of Design and the Built Environment

Circular Economy of Advanced Prefabricated Buildings

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Author's Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Timothy Michael O'Grady

14 April 2022

Statement of contributors

The research within this PhD and the hereafter proposed hybrid thesis was conceived and undertaken by me, Timothy Michael O'Grady. I also wrote, gathered and analysed the data as reported in the produced manuscripts.

Timothy Michael O'Grady

14 April 2022

Abstract

The building sector generates the greatest percentage of waste globally. Construction and demolition waste is believed to be the single most adversely impacting industry on the environment in developed countries. Construction waste is produced across the life cycle of a building, from the mining and production of materials, the construction process itself, maintaining the building through its occupation, and most impacting, the demolition of the building. The materials and components that result from decommissioned buildings could either be disposed to landfill, or recycled, remanufactured and reused in their second life.

The circular economy approach aims to turn waste construction materials into new resources. This concept has been successfully applied to many industry sectors, but research reported for buildings and empirical studies have been relatively limited. To investigate possible solutions to this issue, this research has combined theory with design and practice, by building a circular economy prototype as a case study, and exploring the related empirical implications.

Specifically, in this thesis, three literature reviews have been published. The first, provided insight into the circular economy strategies that have been established in other industries, and allowed a proposal for a model to create reusable, circular economy buildings. The second provided an in depth review of the tools and measurement units used to quantify material and buildings environmental impact. The third provided a technological analysis of building automation systems which would enable the prototype building to be adaptable for future industry 4.0 developments and incorporate energy efficient technology. By applying these strategies to a modular building, a disassemblable and reusable building prototype, namely the Legacy Living Lab, was manufactured and built on-site. Further, a study into the buildings connection systems was published to show how a building can be designed for disassembly, deconstruction and resilience. The latter publication is closely linked with a virtual reality model so that the circular economy benefits could be experienced globally to share the lessons learned.

A life cycle assessment was carried out to calculate the environmental benefits of applying the circular economy to buildings. It was shown that, in so doing, up to 88% of greenhouse gas equivalent emissions could be avoided for Legacy Living Lab. Through our research we have proposed a method to calculate a circular economy index, named 3DR (design for deconstruction, disassembly and resilience) which may be used to calculate the degree of circularity of a building. The 3DR index of the Legacy Living Lab demonstrates that Legacy Living Lab is 69% circular, whereas a traditionally built modular building scores a 3DR index of just 37%.

Within this PhD seven peer reviewed research papers are appended, and the research also concludes with the creation of the Curtin University asset, the Legacy Living Lab. This relocatable research

facility is intended to be the place and space for further research, innovation and prototyping on the circular economy of buildings. L3 has already demonstrated success in enabling networking strategies between research institutes or universities, creating new knowledge; industry partners, pushing the boundaries of new product development; and society, influencing the market and policies.

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Finally to Greg and Bobby. We have created a legacy. Well done.

Dedication

To Nanna and Grandad, I wish you could have seen this.

Publications and submitted manuscripts included in the thesis

The following publications and manuscripts are the foundation of this thesis and are provided as appendices to the exegesis.

I. Minunno, R., **O'Grady, T**., Morrison, G.M., Gruner, R.L. and Colling, M., 2018. Strategies for applying the circular economy to prefabricated buildings. *Buildings*, 8(9), p.125. doi.org/10.3390/buildings8090125.

II. Minunno, R**.**, **O'Grady, T**., Morrison, G.M., Gruner, R.L., 2020. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. Published in *Renewable and Sustainable Energy Reviews,* vol. 143. doi.org/10.1016/j.rser.2021.110935

III. **O'Grady, T**., Chong, H.Y., Morrison, G.M., 2021. A systematic review and meta-analysis of building automation systems. *Building and Environment*, vol. 195. doi.org/10.1016/j.buildenv.2021.107770

IV. **O'Grady, T**., Minunno, R., Chong, H.Y., Morrison, G.M., 2021. Interconnections: An analysis of joint systems used in a Circular Economy building. Published in *Buildings,* 11(11) p. 535. https://doi.org/10.3390/buildings11110535

V. Minunno, R., **O'Grady, T**., Morrison, G.M., Gruner, R.L., 2020. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resources, Conservation & Recycling*, vol. 160. doi.org/10.1016/j.resconrec.2020.104855.

VI. **O'Grady, T**., Minunno, R., Chong, H.Y., Morrison, G.M., 2020. Design for disassembly, deconstruction and resilience in construction: A circular economy index. Published in *Resources, Conservation and Recycling*, vol 175. doi.org/10.1016/j.resconrec.2021.105847

VII. **O'Grady, T**., Minunno, R., Chong, H.Y., Morrison, G.M., 2021. Virtual reality in BIM based Circular economy prefabricated construction. Published in *Energies* 14(13) 4065. doi.org/10.3390/en14134065

Co-authors' statements

Publication I (published)

I, Timothy O'Grady, contributed 30% to the publication:

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Table of Contents

List of Figures

List of Tables

Glossary and acronyms explanation*

BoQ	Bill of Quantities	List of materials, components, machinery and labour involved in producing a building.
CE	Circular Economy	Theory which posits, if waste could be reused as a new resource and without external input of non-renewable energy or materials, that waste would have improved environmental and anthropogenic value.
3DR	Design for disassembly, deconstruction and reuse	New approach developed in this PhD to quantify the level of disassemblability, reusability and recyclability of components.
GHG	Greenhouse Gas	Combination of gases which contribute to the greenhouse effect and related global warming.
L3	Legacy Living Lab	The modular building prototype that has been conceptualized and built within this PhD to test the Circular Economy of buildings.
LCA	Life Cycle Assessment	Established method to quantify the environmental impact of products and services.
SLR	Systematic Literature Review	Method to collect and review literature in a structured way.

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* To facilitate the reading of this thesis, these terms are re-explained the first time they are mentioned in each chapter.

Chapter 1. Introduction

This research is focused on the environmental sustainability of the construction industry (Minunno, O'Grady et al. 2020) – buildings being a significant source of global greenhouse gas emissions and waste. This PhD aims to provide a contribution to solving the emissions and waste issues by integrating and distilling the findings of seven published peer reviewed articles to form a hybrid thesis. The reviewed literature provides a fundamental setting on which a building could be designed and constructed, following the principles of circular economy (Morseletto 2020), and turning waste into new products. The design and manufacture of a full scale building prototype, Legacy Living Lab, is central to this PhD. The prototype provides a case study by which comparisons can be made with the traditional building industry processes; the intention being to provide an environmental assessment of the advantages (and possibly disadvantages) of a circular economy approach. This PhD has a perspective of a client-side project management position, where the design, industry partnership, construction and documentation will be discussed within the PhD. This chapter sets out the structure of the PhD in terms of research context and organization.

1.1 Research context: The environmental impact of buildings and their materials

Typically, buildings conform to the linear economy (Salama 2017). Traditionally, their raw materials are mined and manufactured to be joined in one place until such time as the building is not needed and is disposed into landfill. The first deliberate realisation of the linear economy model followed the great depression where goods were designed with a reduced life expectancy in order to stimulate the economy (London 1932). The linear economy is considered by researchers to be unsustainable for the environment and subsequently, a circular economy concept has been proposed as an alternative to reduce environmental impact (Benachio, Freitas et al. 2020). The circular economy concept advocates that business' and policy makers could and should have a more profitable and sustainable relationship with the environment by turning waste into new resources (Morseletto 2020).

Individual industries have attempted to stem the flow of waste in an effort to adopt the circular economy. The illumination industry is a stand out with Phillips now offering light as a service, as opposed to a product. This example has seen product costs fall by 14% and the environmental impact of the business fall by 46% (Wang, Su et al. 2021). The electronic waste industry has attracted significant attention by repurposing and recycling its waste, as well as switching to modular product design to facilitate optimised recycling of computer parts (Sarc, Curtis et al. 2019). The construction industry faces its own challenges in the transition to the circular economy as traditional buildings are built in a monolithic fashion and cannot easily be refurbished without the creation of waste (Allwood 2014). As a result practical applications of circular economy in the built environment are in their infancy. This chapter outlines the current problem and how this research has proposed to address the problems faced by the industry.

1.1.1 Background

The pressure exerted on nature as a result of the built environment can be attributed to the raw materials consumed and their high embodied energy, the traditional monolithic built form and inflexibility of existing structures, energy consumption of the existing building stock and finally, material depletion and pressure on landfills caused by construction and demolition waste at the end of life (Chan, Bachmann et al. 2020).

Raw materials and embodied energy

Globally, 60% of raw materials by mass are used in the building sector (Hossain and Poon 2018). Embodied in this lies 6% of global energy use, which in the future will release 11% of related CO_2 into the atmosphere (Dean, Dulac et al. 2016, Hu 2019, Sedláková, Vilčeková et al. 2020). The most common construction materials used include concrete, steel, bricks, tiles, insulation and timber. During the construction, operation and demolition process, materials such as steel and timber are produced and discarded (Zabalza Bribián, Valero Capilla et al. 2011). This adds to additional material depletion and pressure on landfills (Hölzle 2019). In an effort to quantify the level of impact caused on the natural environment the Life Cycle Assessment (LCA) method has been increasingly used (Hoxha, Habert et al. 2017, Minunno, O'Grady et al. 2021). Related LCA articles reveal that producing 1 kg of concrete, for example requires ~1.1 MJ and emits ~0.16 kg of greenhouse gas (expressed in CO_2 equivalent — the units of measures are defined in Section 5.1.1; (Sicignano, Di Ruocco et al. 2019)). Similarly, producing 1 kg of steel requires ~21.5MJ and emits ~1.5 kg of greenhouse gas equivalent (Ahmed and Tsavdaridis 2018).

Traditional building design and inflexibility

Typically, buildings are designed to be static monolithic structures (Salama 2017). Traditional construction methods do not adequately consider the future uses of structures and buildings are designed for one purpose, rather than a flexible myriad of purposes. This leads to additional waste during the lifecycle of a building, particularly if this includes refurbishment (Gontia, Thuvander et al. 2020). Refurbishment can include a spatial or physical layout restructure of the building, but more frequently structures are internally refitted due to technology changes and improvements to indoor air quality. The traditional building methodology needs to be reconsidered as the construction industry generates the largest percentage of waste globally, creating a significant environmental impact (Solís-Guzmán, Marrero et al. 2009, Ajayi, Oyedele et al. 2015).

Energy consumption and industry 4.0

Buildings account for about 40% of total global energy consumption (Babu, Zhou et al. 2019, Bakhtiari, Akander et al. 2019). Refurbishment of buildings has been expedited by the introduction of global energy targets to deal with the current climate emergency (He, Hossain et al. 2021). It is estimated that 9 Gt of carbon dioxide needs to be reduced from the building sector to limit global warming to 1.5 °C (Wang, Chen et al. 2018). In an attempt to reduce the impact that buildings have on the environment, Building Automation Systems (BAS) were introduced in the 1970's to control Heating Ventilation and Air Conditioning (HVAC) and LED lighting systems and keep buildings at set temperatures (Bellido-Outeirino, Flores-Arias et al. 2012, Pellegrino, Lo Verso et al. 2016). As these systems have evolved, the continuing refurbishment of buildings has been necessary, while research into energy reduction and solutions for sick building syndrome has led to the advancement of building quality (O'Grady, Chong et al. 2021).

Demolition waste

Waste is created at all stages of the life cycle of a building (construction, operation and demolition), however the largest proportion of this waste is generated at demolition (Vefago and Avellaneda 2013). Over the past 50 years scholars have studied construction and demolition waste and have focused on the sizeable units and large volumes of waste components (Cullham 1975). A possible solution to the volume and weight of building components could be reducing them into smaller parts through design for disassembly (Rios, Chong et al. 2015). Reported research that has attempted to solve the large volumes of construction and demolition waste typically focuses on material recycling (Ginga, Ongpeng et al. 2020). Material recycling can be an advantageous strategy, but in the case of construction materials, the preferred solution is introducing them as a replacement feedstock for remanufacturing of components, a practice referred to as down-cycling (Blengini and Garbarino 2010, Allwood 2014, Minunno, O'Grady et al. 2018). Design for disassembly would also enable potential reuse of the deconstructed components, allowing not only to save materials from landfill but also to avoid additional resource consumption through the production of new components (Minunno, O'Grady et al. 2021).

Circular economy

To put an end to the environmental impact of landfill and down-cycling, scholars and practitioners should consider buildings at end-of-life as valuable resources rather than waste, as suggested by the circular economy approach (Jimenez-Rivero and Garcia-Navarro 2017, Minunno, O'Grady et al. 2018, Eberhardt, Birgisdóttir et al. 2019). Circular economy in construction can be defined as the economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in the production/distribution and consumption process (Kirchherr and van

Santen 2019). As such, and following a circular economy approach, the reuse of components would be enabled primarily by design for disassembly (Akinade, Oyedele et al. 2015), allowing the rescue and restoration of components at the end of buildings' service life, thereby limiting demolition waste to a minimum (Kibert, Chini et al. 2000, Guy, Shell et al. 2006).

The environmental benefits of reusing building components have been demonstrated through a limited number of recent case studies (Minunno, O'Grady et al. 2020). Further, technological innovation fosters the disassemblability of structural components, such as concrete columns, floor systems and roof structures (Brambilla, Lavagna et al. 2019, Eberhardt, Birgisdottir et al. 2019, Minunno, O'Grady et al. 2020, O'Grady, Minunno et al. 2021). However, many barriers hinder the reuse of building components. For example, demolition and recycling are often more financially feasible than disassembly (Densley Tingley, Cooper et al. 2017), while deconstruction remains complex and inconvenient. Additionally, in many countries, a lack of a market for reusable components represents a substantial barrier towards a closed-loop of the construction industry's supply chain (Cooper and Gutowski 2017, Arora, Raspall et al. 2019).

Nevertheless and due to its many benefits, design for disassembly and reuse is gaining traction (Tingley, Cooper et al. 2017, Akanbi, Oyedele et al. 2018, Hopkinson 2018, Akanbi, Oyedele et al. 2019), although the limited knowledge on reuse building components presents a noticeable literature gap (Ghaffar, Burman et al. 2020). Despite the number of initiatives to unlock the potential reuse of building materials, there remains a lack of reported empirical studies (Iacovidou and Purnell 2016, Kirchherr and van Santen 2019).

Research into the circular economy (CE) of buildings is in its infancy with a limited documentation on CE buildings in existence at the outset of this project. Previous research indicates that the physical application of CE to the construction industry was the most noticeable gap in the literature. In order to fill this research gap, there was a clear understanding within the research team that a physical building prototype would have to be designed and constructed to prove the proposed framework, quantify its benefits and investigate barriers towards its scaleability (scaleability implies innovation take up by practitioners in the built environment). This PhD examines a building typology that could represent a straightforward and close to market solution for disassembly and reuse, *via* prefabricated buildings. Prefabricated buildings stand to overcome the three main barriers which hinder the application of CE to buildings. The three barriers being; typically buildings are monolithic, they are built without standardised measurements, and have a lack of closed loop supply chains (Allwood 2014). Buildings that are designed for transport lend themselves to be transported a second and possibly multiple times, enabling components and modules to be moved and repurposed with maximum transport dimensions creating a standardised spatial boundary. These characteristics could facilitate closing the material loop allowing the integration of old components into new projects (Stahel 1997, Allwood 2014, Stahel 2016).

One sub-category of prefabricated construction is volumetric modular buildings, buildings with box-like structures which are built offsite to be transported and assembled on-site (Hwang, Shan et al. 2018). Volumetric modular buildings are widely used in many northern European countries and the United States (Dave, Watson et al. 2017, Jin, Gao et al. 2018). However, in other countries, including Australia, their adoption is hindered by an overall negative perception. In such countries, volumetric modular construction has been used in mining camps, emergency accommodation and social housing projects which has created a customer perception of temporary and inelegant buildings (Blismas and Wakefield 2009). For this reason, the production of high-quality prefabricated buildings might improve the quality brand associated with modular buildings. Such high-quality buildings could begin to shift the public's perception of prefabricated buildings through new anecdotal learnings (Blismas and Wakefield 2009).

After these considerations it was decided that an important aspect of this PhD was the construction of a modular, commercially viable building based on the principles of Circular Economy.

1.2 Research positioning

This PhD has its theoretical foundation in the CE. The practical application of circular economy in the construction industry has not been successful to date. Therefore, the reviewed literature used provided insights into the design and construction of a circular economy modular building which considers each stage of building life cycle.

The research presented within this thesis contrasts with the traditional *modus operandi* of the construction industries linear economy and presents an alternative by way of the circular economy. This positioning can be visualised in Figure 1 which has been adapted from publication V.

This research investigates the opportunities for the construction industry to minimise its significant impact by adopting the circular economy framework. The building methodology most suited to the integration of CE is prefabricated modular construction. Modular prefabrication allows the building to be built off-site and transported and assembled as volumetric components (Alembagheri, Sharafi et al. 2020). This research is positioned to consider the academic literature in terms of business management (practice of planned obsolesce and the linear economy), ecology and the restorative biological process (circular economy) and civil engineering, architecture and industrial manufacturing (modular building and design). The design of prefabricated modular construction also draws from project management to implement the CE and the technology sector in an attempt to design an adaptable building.

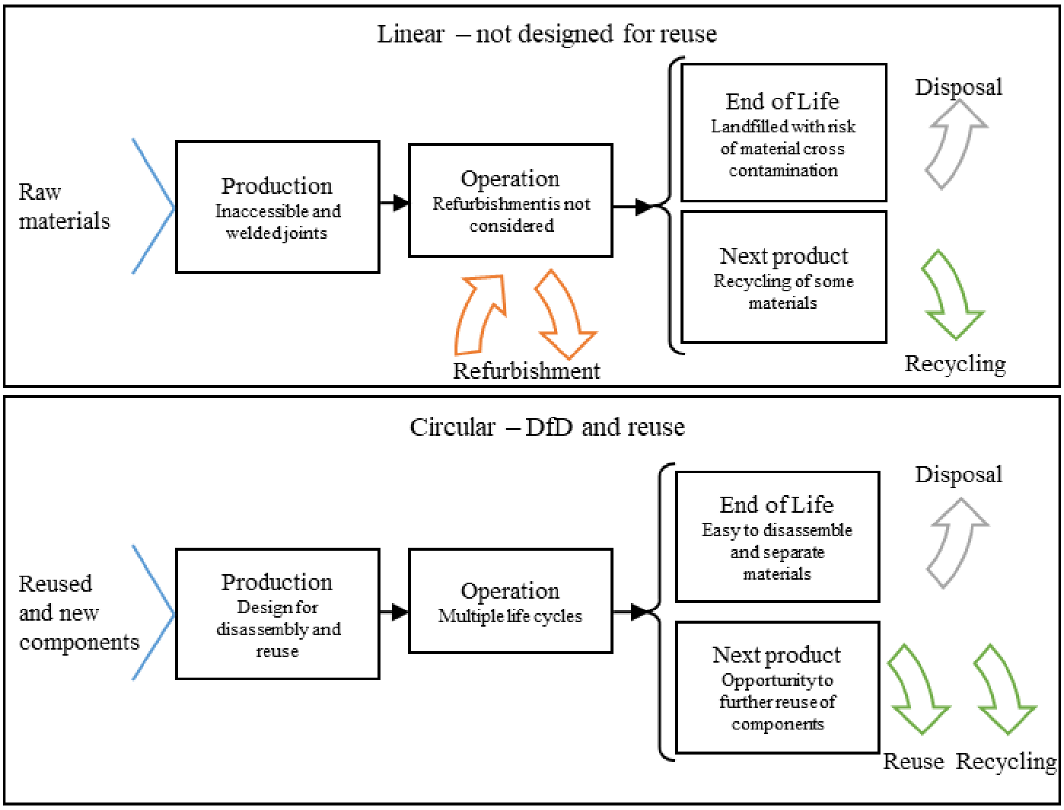

Figure 1.1 – Research framework adapted from Publication V.

To achieve this, three review methods were applied to the literature. The first, investigated the environmental impact of the industry and related assessment tools through a systematic literature review. The second, narrative literature review uncovered the strategies adopted by other industries to achieve the circular economy business model. Third, technological advances were reviewed to assess the reduction of energy consumption in buildings, and also to review the technological changes that would have to be anticipated when designing a circular economy building. From this review process a number of important works have focused specifically on different sections of sustainability of the built environment for example, Allwood (2014) proposed a focus on reduction of material use through life extension, while Stahel (1997) proposed a focus on sharing spaces.

Design for disassembly and recycling of construction materials have been the focus of research by (Tingley and Davison 2011, Rios, Chong et al. 2015, Crowther 2018, Akanbi, Oyedele et al. 2019). However, throughout the body of knowledge a gap exists concerning the implementation of theory into practice through the design and construction of a circular economy building that would allow for continued life cycles of varying technology and usages. Additionally, the environmental impact of the traditional and circular building methodologies have also not yet been investigated.

The aim of this PhD research was to design a building guided by the existing body of knowledge to solve the barriers of implementing circular economy in the construction industry. In order to achieve this, the modular construction methodology was implemented and the impacts of this change assessed and published. For this PhD the author (a licensed builder) not only designed the building, later named Legacy Living Lab, based on CE theory and principles, but also contacted and engaged the industry sponsors, managed the construction off-site and coordinated the process to create a unique Curtin University building on the DevelopmentWA East Village (Innovation through demonstration) precinct.

1.3 Research questions, sub-questions & objectives

The research question guiding this PhD is:

Can a building be designed and constructed in-line with the circular economy framework, and if so, what would be the environmental benefits?

The resolution of this research question requires further research sub-questions. The sub-questions are linked to methodological, empirical and practical barriers. These sub-questions can be summarized as follows:

1. What are the main strategies that have fostered the application of the circular economy, and how can these strategies be adapted to the building context?
2. What can be learnt by collecting and summarizing individual environmental impact studies of buildings to foster environmental impact reduction towards a circular economy?
3. What are the limits related to the quantification of the environmental impact of second life buildings? what are the assessment tools? and how can these limits be overcome?
4. What is the current state of building automation with respect to user input, automation, energy saving and demand response toward the minimisation of their operational energy?
5. What physical boundaries hinder the installation and maintenance of building automation systems? And what access and space will be needed in future industry 4.0 developments?
6. How can buildings be designed and assembled so their connections are accessible and disassemblable?
7. How can these connections be disguised so occupants perceive a familiarity with traditional construction types?
8. What are the environmental advantages of applying the circular economy to a building purposely built following circular economy strategies?
9. How can the circularity —disassemblability and reusability —of a building be measured?
10. How can materials and components be advertised digitally, thereby implementing a digital market for second life construction products?
11. What design features can be implemented to ensure that materials and components can be safely assembled and disassembled?

Within this PhD, I investigated the research question and sub-questions and attempted to resolve them through seven published peer-reviewed articles. The related articles, objectives and research sub-questions are summarized in Table 1.

1.4 Thesis organization

The research undertaken in this thesis is presented in the format of a thesis by publication, with the seven published peer reviewed papers (appendices I to VII) providing the data and evidence that is then integrated *via* this exegesis. A synthesis of the literature review is presented in Chapter 2 (extracted from articles I-III). Chapter 3 presents the overall research methodologies. Chapter 4 summarises the results from articles IV-VII and Chapter 5 discusses how these results contribute to the body of knowledge on the focused research topics. Chapter 6 provides conclusions and discusses future research opportunities in the field of the circular economy of buildings.

Table 1.1 – Summary of the produced articles and manuscripts, related research sub-questions and objectives.

Title	***Research sub-question***	***Objective***
I. Strategies for Applying the Circular Economy to Prefabricated Buildings. ***Peer-reviewed article published.***	What are the main strategies that have fostered the application of the circular economy? And how can these strategies be adapted to the building context?	Review the circular economy strategies that have been applied in various industry sectors and formulate and adapt these for the construction sector
II. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. ***Peer-reviewed article published.***	What can be learnt by collecting and summarizing individual environmental impact studies of buildings to foster environmental impact reduction towards a circular economy?	Collect and summarize the existing data on the environmental impact of buildings into a ranking benchmark.
	What are the limits of environmental impact assessment tools and how can these limits be overcome?	Create procedural guidelines to assist LCA practitioners in their LCAs.
III. A Systematic review and meta-analysis of building automation systems. ***Peer-reviewed article published***	What is the current state of building automation with respect to user input, automation, energy saving and demand response?	Identify current trends in building automation systems aimed at reducing energy consumption and improving occupant comfort.
IV. Interconnections: An Analysis of Disassemblable Building Connection Systems towards a Circular Economy. ***Peer-reviewed article published.***	How can buildings be designed and assembled so their connections are accessible and disassemblable?	Design a functional connection system that would foster the circular economy of buildings without affecting the visual presentation of buildings
V. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. ***Peer-reviewed article published.***	What are the environmental advantages of applying the circular economy to a building purposely built following the circular economy strategies?	Calculate the environmental impact of the circular economy building, the prototype L3. Compare the L3's impact to the impact of a similar linear economy building.
VI. Design for disassembly, deconstruction and resilience in construction: A circular economy index. ***Peer-reviewed article published.***	How can the circularity — disassemblability and reusability — of a building be measured?	Create and validate a method to calculate the degree of disassemblability, reusability, and recyclability of any building.
VII. Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction. ***Peer-reviewed article published.***	How can materials and components be advertised digitally, thereby implementing a digital market for second life construction products? What design features can be implemented to ensure that materials and components can be safely assembled and disassembled?	Link a Building Information Model with gaming software to document the assembly and disassembly procedures and allow potential buyers the opportunity to view components for the potential of purchase at the end of life.

Chapter 2. Literature Review Summary

This chapter provides a synthesis of the literature reviewed for this thesis. An extended literature review is presented in full in the Appendix (Publications I-III) and outlined in Table 2.1.

Section 2.1 outlines a narrative literature review on the strategies to apply the circular economy to buildings. It was evident through this preliminary review that the CE of buildings was not thoroughly investigated with a limited number of niche works available in the field of study. Having identified a research gap a comprehensive review on the methods and tools used to quantify the environmental impact of buildings was needed to understand the parameters and evaluation for the proposed building prototype (Section 2.2). The review into embodied energy and carbon identified a third gap in the research which was the energy consumption of the building after the construction process had been evaluated. Operational energy was found to be equally as important as embodied energy and a holistic view on the project life cycle dictated that the technology of a building could not be ignored looking towards the future. This review investigated methods of automation aimed at reducing the energy consumption of the building, whilst also evaluating the physical aspects of the installed system so that provisions could be designed into the building prototype to help future proof the project (Section 2.3).

Table 2.1 – Literature reviewed in three of the published articles.

Title of publication	***Literature reviewed***
I. Strategies for Applying the Circular Economy to Prefabricated Buildings. ***Peer-reviewed article published.***	Literature on applications of the circular economy to several industry sectors.
II. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. ***Peer-reviewed article published***	Comprehensive review of the literature on environmental impact of construction materials and buildings.
III. A Systematic review and meta-analysis of building automation systems. ***Peer-reviewed article published***	Systematic review of building automation systems aimed at reducing the energy consumption of buildings.

2.1 Literature on Circular Economy strategies

To identify current CE strategies and how they are applied to other industries, an early and exploratory literature review was conducted. The findings revealed seven strategies commonly applied to other industries which were then used to help influence the design of the case study prototype (Table 2.2). The proposed strategies are linked to the 3 R's concept of reduce, reuse and recycle although they go further by identifying focal points needed in the design phase such as design for adaptability and disassembly.

Table 2.2 – Seven strategies found in the literature review along with opportunities, Barriers and solutions to the adoption in the construction industry (adapted from Publication I).

Strategy	*Opportunity*	*Barrier*	*Solution for adoption*
1. Reduction of construction waste and the lean production chain	Integrate lean production in the prefabrication phase of building components.	Complexity and variability of traditional buildings.	Increase the use of prefabricated components and optimisation of design to consider standardised construction material available. This strategies finds justification in the 'R' reduce.
2. Integration of scrap, waste, and by-products into new components	The use of concrete fosters the second life of by-products.	Strategy limited to the use of concrete, which, by itself, is highly carbon intensive.	Integrate by-products into concrete production. High potential in traditional buildings, where more concrete is typically used. By-product reintegration allows waste minimization, as it increases the value of such by-products in the production chain. The benefit is double: it avoids by-products from landfill and limits the need for new materials, as by-products are their substitutes.
3. Reuse of replacement parts or entire components	Through reuse of parts, waste can be reduced, giving a second life to building components. Supply chain could be integrated in business planning.	Technological barrier of disassembling a monolithic building; economic barrier if components are not designed toward reuse. Supply chain for reused components is yet to be developed in the building sector.	Design for disassembly facilitates the reuse of components. Preferring visible joints, steel frames, and standard measures, components can be disassembled and reused, fostering the market of reused parts. This strategy is not limited to building material, but also components with high embodied energy such as fixed appliances. This strategy is directly linked to the 'R' reuse.
4. Design toward adaptability (reduction through life extension) during operational stages	Planning of flexible spaces and design of adaptable elements to reduce the waste due to modifications in the operational stage of buildings.	The degree of adaptability is proportional to the mobility degree of the building. Traditional buildings are built on-site to be	Prefabricated building components could be designed to be movable, increasing the adaptability of both traditional and modular buildings. Adaptability helps reduce the need for new materials, spaces, products. It is linked to the 'R' reduce through life extension.

		permanent, and thus, are not adaptable.	
5. Design toward disassembly of goods into components to be reused	The use of BIM in prefabrication allows for material tracking, identification, and cataloguing.	Cost effectiveness and technological feasibility hinder the practical application of disassembly.	BIM stores instructions on components and their relationship to the structure, enabling methodical deconstruction. In turn, deconstruction fosters second use of materials and components, linking to the 'R' material reuse. Also, a facilitated deconstruction helps decrease material contamination, which, in turn, improves recyclability.
6. Design for recycling of construction materials	Steel can be recycled, and concrete is commonly down-cycled. Building with steel would then increase the material saving.	Transport of recycling components and the recycling processes themselves are carbon-intensive for both concrete and steel.	Whenever possible, the use of recycled concrete and steel should be preferred. Steel in particular maintains its mechanical characteristics. Strategy 6 is directly linked to the 'R' recycle.
7. Systems to track materials and components within their supply chain	Track materials and components throughout the life cycle of buildings.	Location of materials and time when those would become available.	Prefabricated buildings designed with BIM could allow the information to be shared in the forthcoming deconstruction. This strategy could help create a database of material and component stock, fostering a closed-loop of building materials towards reuse or recycle.

Strategy 1 – Reduction of construction waste

Reduction of construction waste starts in the design phase of a project. Designing with the knowledge of the material size you have available will help to limit off cuts and waste (Haeusler, Gardner et al. 2021). The generation of waste in the primary stages of a construction project are not limited to design with large amounts of waste being created from over production, delays and inventory issues of damage during transport (Fercoq, Lamouri et al. 2016). With traditional buildings being constructed on site, materials are typically ordered before they are needed, delays to installation caused by inclement weather, labour shortages and other site-based constraints lead to further waste creation for materials damaged or stolen from site (Poon, Yu et al. 2004). To solve these issues manufacturers are increasingly focused on optimizing their supply chain towards material savings (Lan 2007). Among the new supply chain innovations to improve efficiency the introduction of lean production and paralleled line manufacturing were found to be superior approaches for diminishing waste during the manufacturing phase (Browning and Heath 2009, Lin, Chang et al. 2012).

The published literature assessing the waste created at the production phase of a construction project highlighted steel reinforcement offcuts, lack of precision in concrete elements and loss of sand during transport to be highly significant (Formoso, Soibelman et al. 2002). To increase precision and reduce human error in construction projects Building Information Modelling (BIM) has been adopted to assist the documentation of construction projects, which has the potential to reduce a significant amount of waste (Sacks, Radosavljevic et al. 2010). However, the complexity of traditional buildings does not often allow the full benefit of BIM or other lean supply chain tools, or worse BIM tools are used, but design inputs are not completed which can lead to service clashes, missed structural members and incorrect overlay of plans resulting in increased waste (Yu, Tweed et al. 2009). Further, the traditional building method can be viewed by some as the only method, thereby the construction industry stands as a barrier to innovative systems, such as volumetric prefabricated housing where lean production systems are common (Höök and Stehn 2008).

Strategy 2 – Integration of waste

Integration of waste or by-products is considered by many to be one of the leading strategies in closing the waste-resource loop (Brown and Buranakarn 2003, Allwood, Cullen et al. 2012, Stahel 2016) and in most cases is more efficient than recycling (Allwood, Ashby et al. 2011).

Most of the waste generated by the construction industry is inert material and can be reused to create new recycled concrete and crushed rock for backfill, bedding and road base (Formoso, Soibelman et al. 2002). Another material which can be added to recycling streams to create new materials includes ceramic tiles that have been used to create paving blocks (Penteado, de Carvalho et al. 2016). Brick and concrete down cycling have been used as aggregate to create recycled concrete (Demir and Orhan 2003, Tabsh and Abdelfatah 2009), while other industries by-products such as geo-polymer slurry and fly ash and blast have been introduced to concrete production (Meyer 2009, Junak and Sicakova 2018). When 35% of fly-ash is substituted for cement in a concrete mix, up to 33% of both embodied energy and carbon can be saved without endangering the properties of the product (Gan, Cheng et al. 2017).

Strategy 3 - Reuse of Components

Reusing disassembled components is a fundamental step towards CE in any industry (Aye, Ngo et al. 2012, Bocken, Olivetti et al. 2017). The construction industry is hindered by the traditional design of buildings which make the disassembly of components, whilst keeping them intact, difficult and often unfeasible (Cullen 2017). This is most commonly due to chemically bonded joints, toxic material contamination, and time and cost constraints. Disassembly falls in favour of the more cost effective demolition (Guy and McLendon 2000). However, using examples from other industries, such as the technology industry, the standardisation and accessibility of joints can enable increased component separation at the end of life and lead to increased material circularity (Go, Wahab et al. 2011). Unfortunately, the construction industry faces additional barriers; one example is the deconstruction of feasible designs as parts will require storage, testing and recertification if they are to enter a new market of second life building components (Gorgolewski 2008, Galle, De Temmerman et al. 2017).

Strategy 4 – Design for Adaptability

Renovation and refurbishment create significant volumes of waste although theoretically extending the life cycle of a building throughout its operational phase (Hardie, Khan et al. 2007). Refurbishment and life extension share a common barrier, and in terms of construction: if the cost to renovate is the same or more expensive than the cost to demolish and build new, the latter is preferred (Hirschl, Konrad et al. 2003). To counter this trend, strategies are being applied to extend life by creating flexible spaces and adaptable building elements (Allwood 2014). The flexibility and adaptability of buildings is largely tied to standardised measurements and the degree of their moveability (Arge 2005, Galle, De Temmerman et al. 2017). It follows that, both the environmental (in terms of CO_2-equivalent emissions) and the economic cost of disassembly of steel components is less than the disassembly cost of concrete components; thus, off-site construction systems, such as modular prefabricated buildings potentially play a fundamental role in adaptability (Sanchez and Haas 2018). Despite the potential of prefabricated buildings, there is a recognised knowledge gap around the adaptability and reuse of building components which has caused resistance from building designers (Sanchez and Haas 2018).

Strategy 5 – Design towards disassembly

Design for disassembly (DfD) should consider a holistic approach to the construction and deconstruction of a building and its components (Desai and Mital 2005). Wheaton describes the process as pre-emptive, aiming to include serviceability and adaptability in its methodology (Wheaton 2017). Buildings designed with mechanical connections, rather than chemically bonded joints are more likely to foster easy separation at end of life (Crowther 2000). Mechanical connections should be accessible to increase the likelihood of disassembly and facilitate the disassembly process (Catalli 2001). BIM holds the key to DfD as it enables a buildings components to be tracked and the information can reveal the relationship between a particular element and the overall structure (Ashcraft 2008). Components can be tracked from procurement to handover ensuring tracking extends over the buildings life cycle which will enable the materials to be recovered at end of life through a material passport (Merrild, Jensen et al. 2016).

Strategy 6 – Design for Recycling

Following the 3R’s hierarchy (reduce, reuse, and recycle) of CE, building components which cannot be maintained in the material supply chain should ultimately be recycled. While designing with the intention of incorporating recyclable materials it is worth defining some terminology. Recycling is the term defining a product that, if managed correctly, can be reintroduced into the material supply chain without losing its mechanical properties and hence its value (Haas, Krausmann et al. 2015). In contrast, while concrete is often viewed as a recyclable material, the quality and value of recycled concrete is lower than new, hence concrete can only be down-cycled (Ravindrarajah and Tam 1987, Blengini 2009, Braungart, McDonough et al. 2012). With the consideration of recyclability it is therefore more beneficial to CE that steel be used in favour of concrete to increase circular material flow and avoid the additional inputs required to maintain concrete in the loop (Knoeri, Sanyé-Mengual et al. 2013).

Strategy 7 – Track Materials and Components within the Supply Chain

Organisations can use inventory technology to track the movement of materials and components throughout their business with the aid of radio-frequency identification and barcodes (Power and Gruner 2017). BIM technology allows materials to be tracked through the procurement, installation and handover process enabling the data to be viewed, with structures then becoming Buildings As Material Banks BAMB (discussed further in Section 5.6.7) at the end of life (Ahmadian F.F, Rashidi et al. 2017). Prefabricated construction enables increased tracking of materials as a centralised process, rather than each site having its own materials procurement and installation process (Zhong, Peng et al. 2017).

2.2 Literature on the Impact of Buildings

Understanding the strategies that have been applied to other industries to invoke a CE, it was critical to review the current body of knowledge with regard to impact assessment in the construction industry. Publication II is a systematic literature review (SLR) and meta-analysis of the environmental impact of construction industries materials (individually), and buildings themselves (as an assembled product). Due to the incremental number of articles published each year it is clear that the subject is gaining traction. More than 50% of the collected articles studied materials or buildings located in Asia (Figure 2.2).

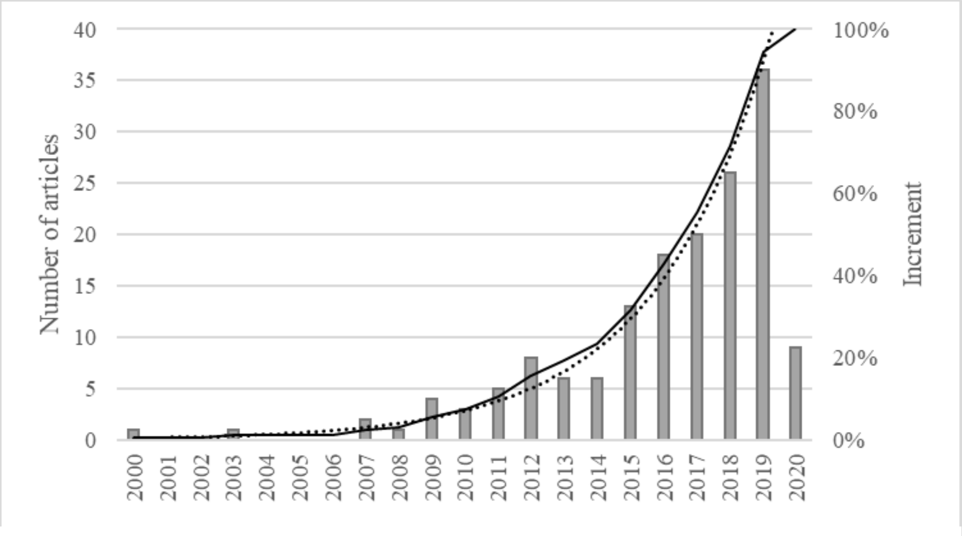

Figure 2.1 – Distribution of the shortlisted articles across the years and comparison with the exponential trend.

Through the SLR process, 8 main construction materials were prevalent across the published articles; concrete, reinforcement bars, steel, timber, bricks, tiles, insulation and plaster (Minunno, O'Grady et al. 2021). The terms in the field of research are embodied energy and embodied carbon. Embodied energy is defined as the sum of primary renewable and non-renewable energy that has been employed to extract raw material sources, transport, and process them to then produce and dispose of the selected construction materials (Ajayi, Oyedele et al. 2019). Hence, the overall embodied energy of a building is the amount of energy that is derived from renewable and non-renewable resources to produce building materials and components (Wen, Siong et al. 2015).

The SLR investigated the findings from 338 LCAs of construction materials and 292 LCAs of buildings in terms of both embodied energy and embodied carbon. The literature suggests that the most popular life cycle accounting software is SimaPro, whilst the most popular database is Ecoinvent. The researched construction materials which impact in terms of embodied energy and embodied carbon are presented in Figure 2.3 and Figure 2.4 respectively.

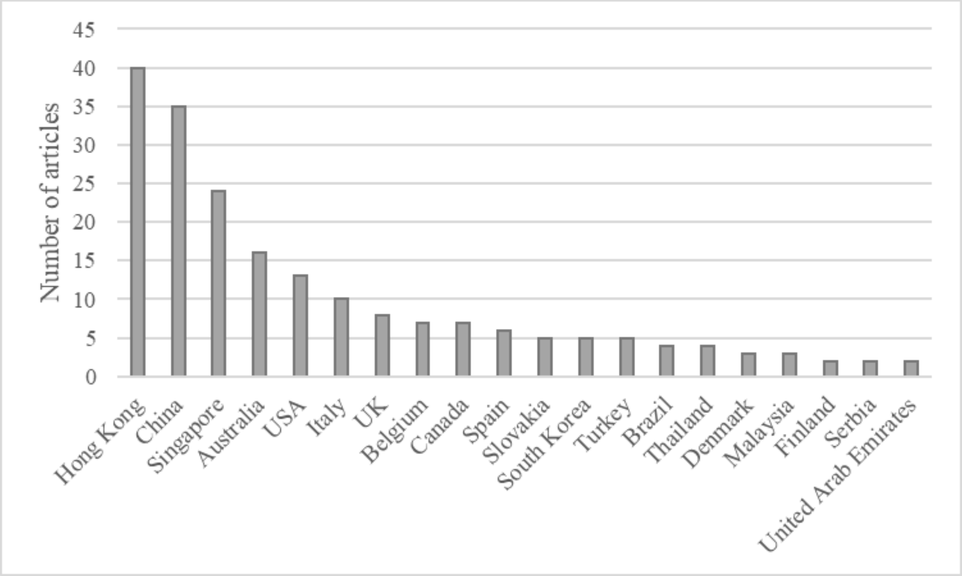

Figure 2.2 – Distribution of the shortlisted articles across the countries.

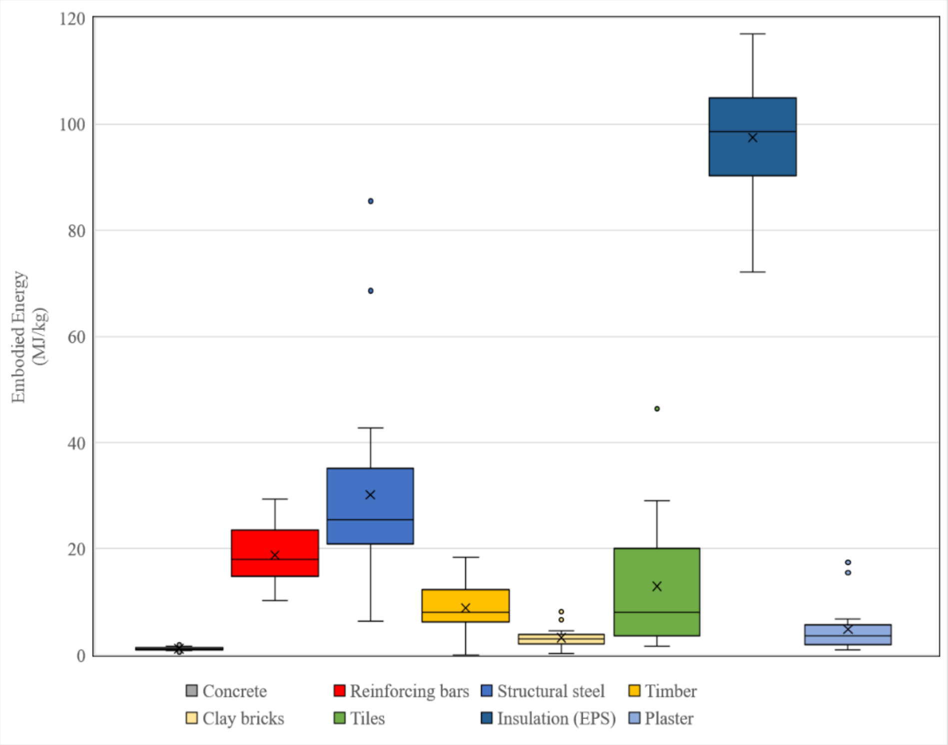

Figure 2.3 – Environmental impact of the studied materials, in terms of embodied energy. Outliers are represented by dots outside the fences, and the crosses mark the mean values. Extracted from Publication II.

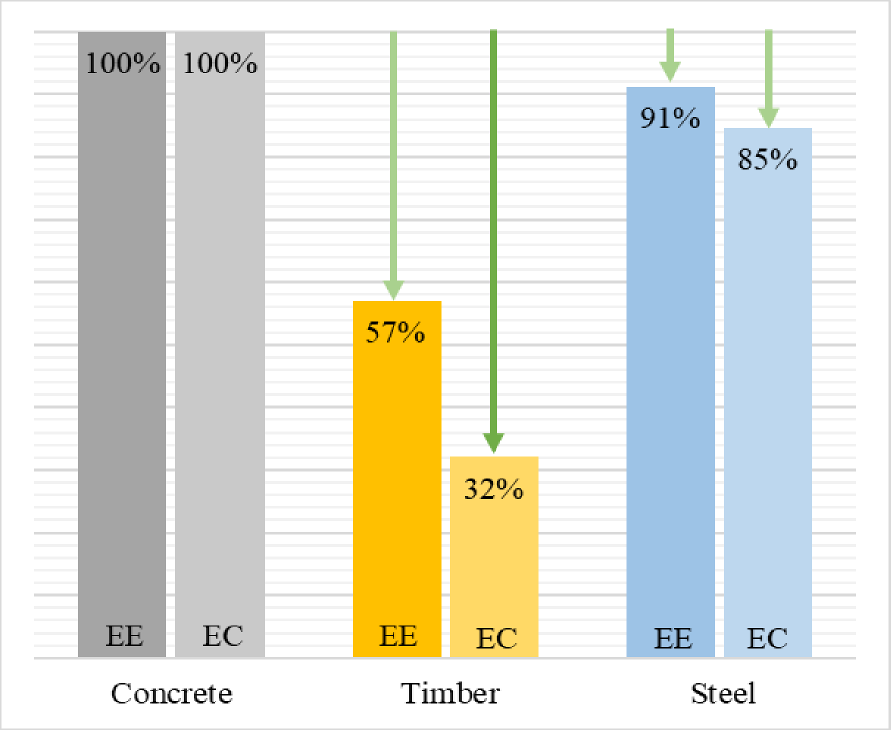

Figure 2.4 – Medians of embodied energy and carbon of the timber and steel buildings relative to concrete buildings over the whole life cycle.EE= embodied energy, EC=embodied carbon. Extracted from Publication II.

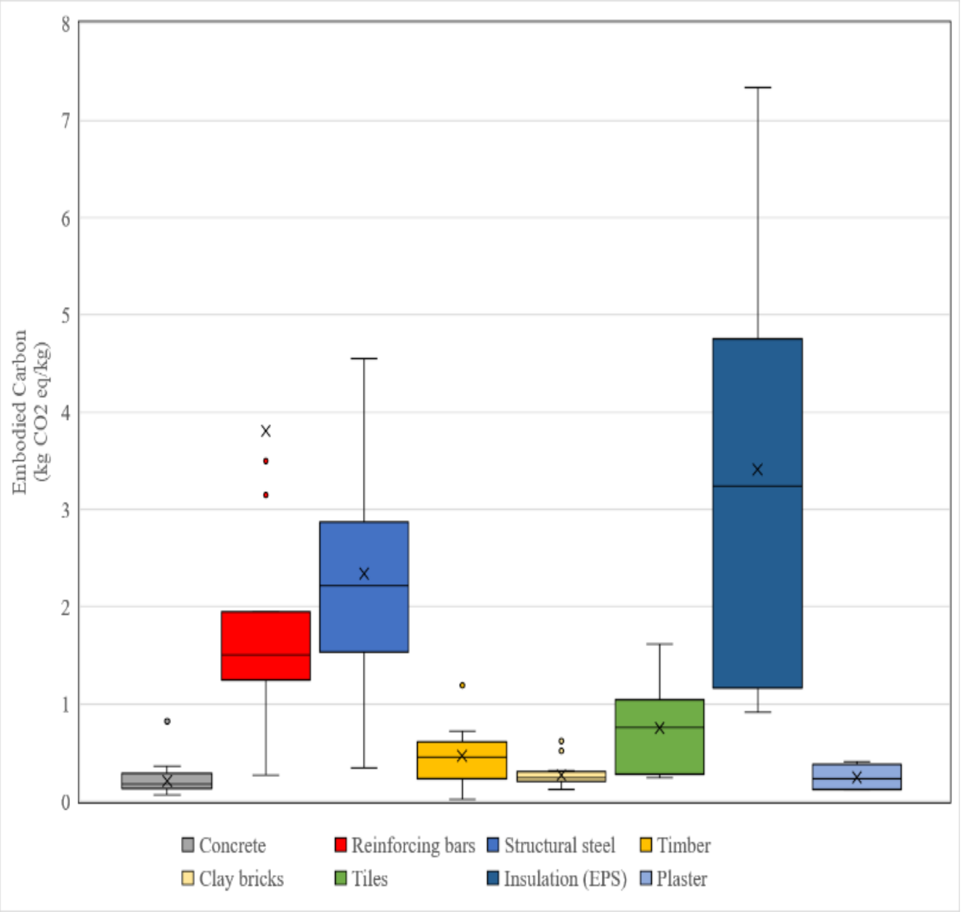

Figure 2.5 – Environmental impact of the studied materials, in terms of embodied carbon. Outliers are represented by dots outside the fences, and the crosses mark the mean values. The reinforcing bar series shows its mean value outside of the interquartile range. Extracted from Publication II.

2.3 Literature on Building Automation Systems

With the assessment for material and building impact reviewed, the final step was to undertake a literature review to understand the operational energy consumption of buildings. This SLR was conducted in an effort to first, plan for the installation (and potential future upgrade) of systems in a CE prototype, and second to assist in the decision making around the Building Automation Systems (BAS) that would lead to reduced energy consumption during the buildings operational life.

BAS can be described as technology that can aid the user in controlling the electrical peripheral of a house, shifting inputs from a static aggregation of resources into an active asset that can support its users (Harun, Onn et al. 2011). BAS have been thoroughly researched in recent years (Figure 2.6), with the research being clearly divided into two distinct paths; energy reduction and quality improvement (Figure 2.7 adapted from (O'Grady, Chong et al. 2021)).

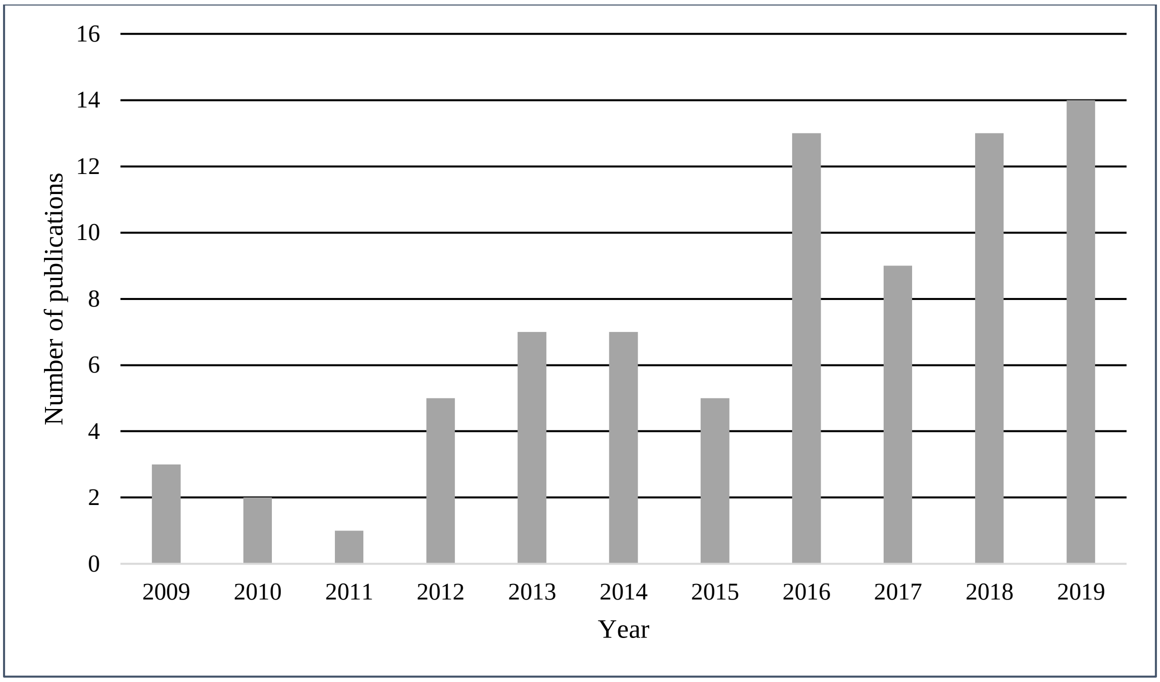

Figure 2.6 – Distribution of number of articles published per year within last 10 years.

The review uncovered four main target areas; energy (Chaiwiwatworakul, Chirarattananon et al. 2009), human comfort (Ahmadi-Karvigh, Ghahramani et al. 2017), cost savings (Nezamdoost, Van Den Wymelenberg et al. 2018) and CO_2 reduction (Hoyo-Montaño, Valencia-Palomo et al. 2019) as the reasons for implementing some level of building automation (Figure 2.7).

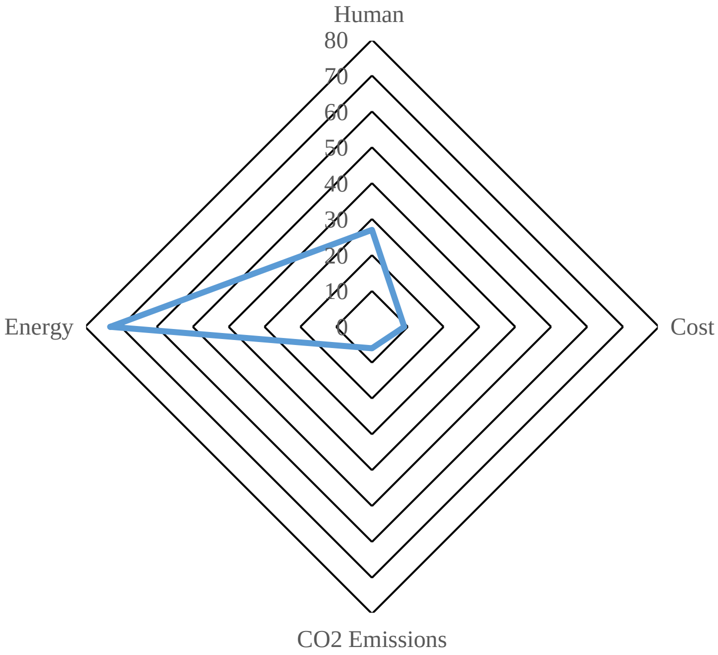

Figure 2.7 – Distribution of focus areas and overlapping target areas.

Daylighting of office buildings through the use of horizontal blinds and other fenestration techniques proved to be the most researched with 15 articles claiming to reduce energy consumption between 54% and 80% (Chaiwiwatworakul, Chirarattananon et al. 2009, Chen, Yang et al. 2019). The use of automated blinds can be categorised into two main energy saving techniques, first to reduce lighting demand and second to prevent solar heat gain, thus reducing HVAC demand (Babu, Zhou et al. 2019, Karjalainen 2019). The review highlighted that human interaction with BAS systems was under-represented and presented a knowledge gap.

Furthermore, the geographical locations of the research were heavily skewed towards three geographical locations: USA with 30% (26 articles), Europe with 29% (25 articles) and Asia with 26% (23 articles). There were outliers in the Oceania region, South America and Africa that comprised the remaining geographical case study locations. The focus of the study was dependent on geographical location as energy use in the built environment is primarily affected by whether the location was heating or cooling dependent and the types of structure the BAS was deployed within. The need for modelling based on geographical location is evident, as daylight hours, angle of penetration and sun intensity have a dramatic impact on the function of the built structure (Babu, Zhou et al. 2019).

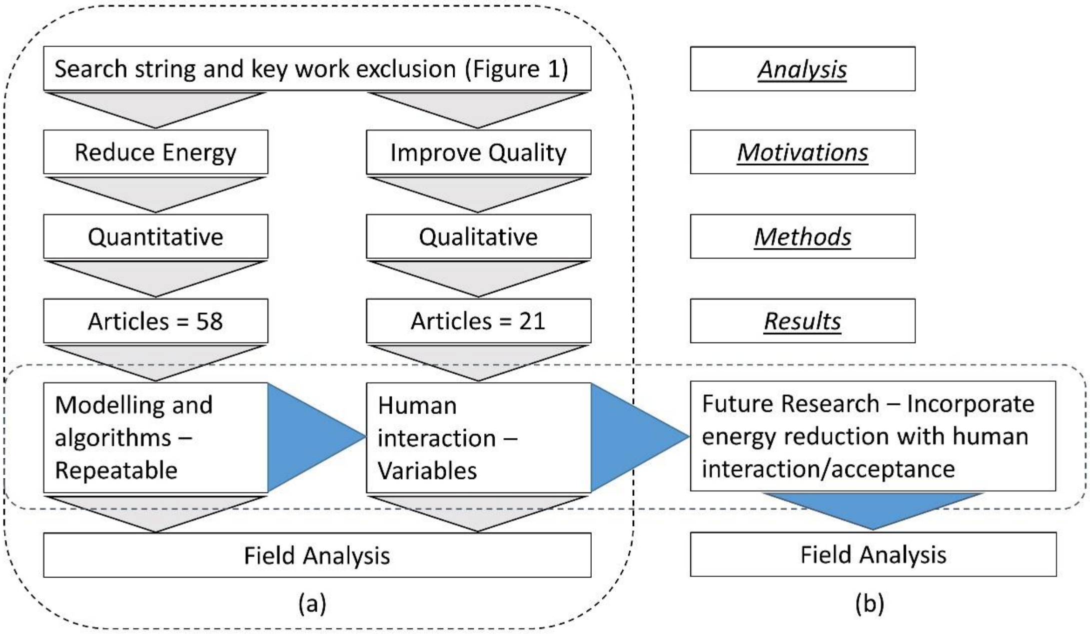

Figure 2.8 – Research analysis of building automation. Two distinct paths were present in (a) Current researched trends and (b) Blue arrows which identify the knowledge gap in research which requires a lateral shift from the existing vertically integrated research. Adapted from publication III.

Features and benefits of BAS—building modelling software and building automation architecture

Building modelling software

Academic research into the effects of automation in the built environment has largely been based on computational modelling. A number of advantages of simulation modelling over field experimentation have been identified (Yang, Pan et al. 2016, Wan Mohd Nazi, Royapoor et al. 2017);

1. allows evaluation of performance where field experiments are not feasible
2. permits estimation of energy saving prior to implementation
3. reduces time and expense
4. allows tasks to be performed repeatedly to check the effect of a parameter
5. permits control measures such as weather
6. is non-intrusive for building occupants
7. simplifies the output of performance indicators that are difficult to measure
8. provides results that are easily interpreted.

The SLR determined that the complexity of the software is increasing. Specific software is used to evaluate specific metrics of the building system at different stages of the buildings life cycle (Lazim, Sarip et al. 2015). Tools such as Revit and AutoCAD are used in the design of most buildings and have the ability to perform basic functions throughout the design phase (Kamel and Memari 2018). Existing buildings require their envelopes to be modelled from drawing registers and existing documentation to model their energy use through modern software applications (Yeon, Yu et al. 2019). The modelling software identified as used in academic research is shown in Figure 2.9.

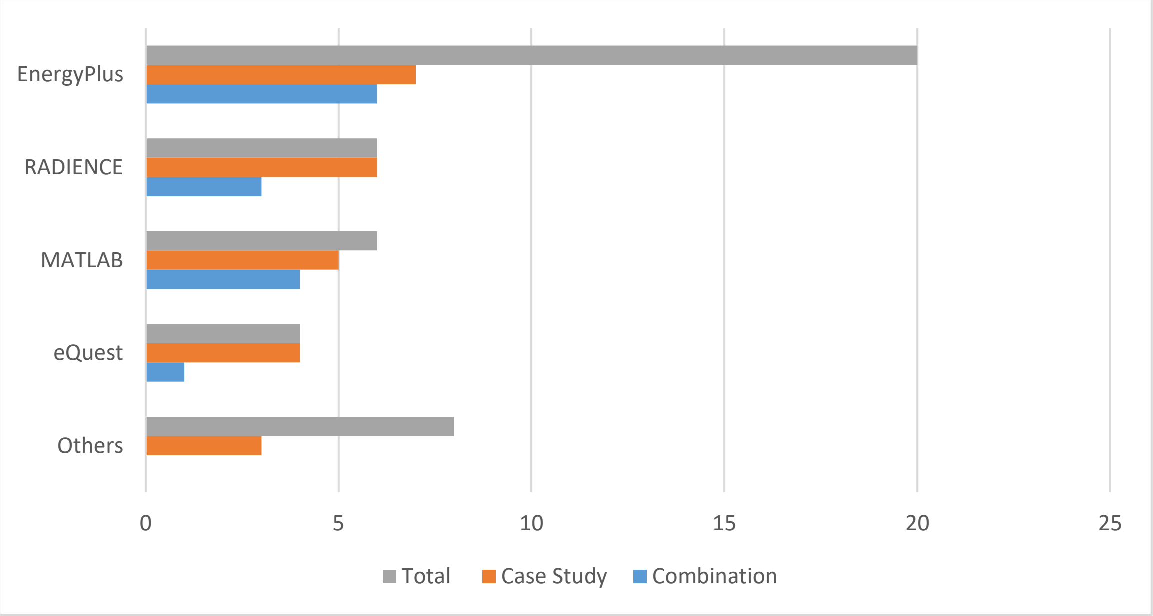

Figure 2.9 – Modelling software—the four most commonly used software programs for determining the energy use of the building, occupancy loads and internal–external heat gain.

Building automation architecture

BAS involve the computer-based measurement, control and management of building services (Dajiang 2009). Generally, BAS begin with the control of mechanical, electrical and plumbing systems as these are the largest energy consumers for a building (Government 2013), with lighting and HVAC being the most heavily researched (Tesiero, Nassif et al. 2014). The SLR uncovered a research trend, as most articles focused on one niche area of the building automation levels described by (Marinakis, Doukas et al. 2013). The literature in Table 2.3 is organised to correspond with the level of automation chosen as the focal point in each study.

Table 2.3 – Surveyed literature distilled into levels of automation architecture

Level	Contribution	No. articles	References
1. Component	Sensors, switches & relays can be used to save energy. These act by detecting pre-set parameters and reporting to BAS of devices, creating a feedback loop.	6	(Chaiwiwatworakul, Chirarattananon et al. 2009, Aghemo, Blaso et al. 2014, Eltaweel and Yuehong 2017, Iwata, Taniguchi et al. 2017, Bakhtiari, Akander et al. 2019, Wu, Kämpf et al. 2019)
2. Device	The device level includes counters and timers that store, display and control the sequence of events involving a controlled device e.g. blinds, windows, lights. Manipulating blinds to block or allow light to permeate a space has been shown to have the strongest influence on HVAC and lighting energy consumption.	15	(Bonnema, Pless et al. 2010, Lee, Claybaugh et al. 2012, Olbina and Hu 2012, Tesiero, Nassif et al. 2014, Van Den Wymelenberg 2014, Fazel, Izadi et al. 2016, Meerbeek, de Bakker et al. 2016, Sotehi, Chaker et al. 2016, Kandasamy, Karunagaran et al. 2018, Nezamdoost, Van Den Wymelenberg et al. 2018, Soltanaghaei and Whitehouse 2018, Babu, Zhou et al. 2019, Chen, Yang et al. 2019, Karjalainen 2019, Yeon, Yu et al. 2019)
3. Process and communication	Programmable logic controllers are a process control system based on a set of digital and analogue I/O (on/off) signals received from the assigned sensors and actuators at the component level. Computers are used in complex systems to log, display and transmit the status of operational systems. Improvements to this process have reduced the energy consumed in buildings, with advanced fuzzy logic controls giving increased decision making parameters to BAS.	28	(Shu, Halgamuge et al. 2009, Glass, Brannon et al. 2010, Hu and Olbina 2011, Oldewurtel, Parisio et al. 2012, Lehmann, Gyalistras et al. 2013, Marinakis, Doukas et al. 2013, Osello, Acquaviva et al. 2013, Romero, Hermosillo et al. 2013, Xiong, Li et al. 2013, Gunay, O'Brien et al. 2014, Leal, Zucker et al. 2014, Costa and La Neve 2015, Chaudhary, New et al. 2016, Kim, Andonova et al. 2016, Martirano, Parise et al. 2016, Pellegrino, Lo Verso et al. 2016, Chan, Othman et al. 2017, Salamone, Belussi et al. 2017, Adhikari, Pipattanasomporn et al. 2018, Bellia, Borrelli et al. 2018, Homod 2018, Kwon, Yeon et al. 2018, Zhang, Zhong et al. 2018, Gomes, Ramos et al. 2019, Hoyo-Montaño, Valencia-Palomo et al. 2019, Lin, Yang et

Level	Contribution	No. articles	References
			al. 2019, Lin, Luo et al. 2019, Mataloto, Ferreira et al. 2019)
4. Macro	The macro system includes modelling simulations and software used to predict the sequence and actions taken to reduce consumption. Research at this level has contributed to an in-depth understanding of building performance. Predictions made by modelling programs allow designers to calculate sun angle, glare and light distribution during the design phase to greatly enhance the energy savings achieved by installed BAS. Modelling software allows new energy saving technology to be analysed without the need for physical implementation.	30	(Kolarik, Toftum et al. 2009, Bellido-Outeirino, Flores-Arias et al. 2012, Ritter 2012, Oldewurtel, Sturzenegger et al. 2013, Song, Zhen et al. 2013, Dhalluin and Limam 2014, Yang, Becerik-Gerber et al. 2014, Dorizas, Assimakopoulos et al. 2015, Lazim, Sarip et al. 2015, Miciu and Ogescu 2015, Perepelitza, Petterson et al. 2015, Abdallah, El-Rayes et al. 2016, Aksamija 2016, Lawrence, Boudreau et al. 2016, Sehar, Pipattanasomporn et al. 2016, Yang, Pan et al. 2016, Yin, Kiliccote et al. 2016, Ahmadi-Karvigh, Ghahramani et al. 2017, Chen, Hong et al. 2017, García-Sanz-Calcedo and López-Rodríguez 2017, Sehar, Pipattanasomporn et al. 2017, Wan Mohd Nazi, Royapoor et al. 2017, Ahuja and Khosla 2018, Bisadi, Akrami et al. 2018, Hyemi, Kyung-soon et al. 2018, Kamel and Memari 2018, Thyer, Thomas et al. 2018, Heim and Pawłowski 2019, Kim, Song et al. 2019, López, Pouresmaeil et al. 2019)

BAS have developed into an important field of control systems and have a tendency to standardise their communication processes. The hierarchy above was further teased apart with research trends uncovered in each level of the system stack.

Component level

Sensors are responsible for the transmission of data to controllers. At the lowest level of the system stack these components are crucial inputs for the decision making in energy saving as they create feedback loops (Chan, Othman et al. 2017, Soltanaghaei and Whitehouse 2018). Important sensors uncovered in the review included motion detection, light sensors and thermostats.

Device Level

As most energy is consumed in the existing building sector, energy efficiency in retrofitting BAS systems is considered an essential strategy for reducing GHG emissions (Chen, Hong et al. 2017)**.** Therefore, technology companies must offer devices to incorporate into existing markets (Osello, Acquaviva et al. 2013, Pellegrino, Lo Verso et al. 2016, Hoyo-Montaño, Valencia-Palomo et al. 2019). The devices uncovered included: blinds and louvres, efficient lighting, and optimised HVAC systems.

Communication systems and protocols

BAS can be described as centralised, interlinked networks of hardware and software that monitor and control the built environment (Tesiero, Nassif et al. 2014). Traditional BAS use wired technologies that require complex cabling from the management layer to the sensor and actuator device level (Dajiang 2009, Marinakis, Doukas et al. 2013). Running cables to install sensor networks accounts for 50–90% of the installation cost; therefore wireless sensor networks have become preferable as the technology has improved (Kim, Andonova et al. 2016). Understanding that future applications may require advanced design redundancy for installation, the communication systems reviewed were both wired and wireless. While wireless systems save on installation cost, they often require batteries, adding to ongoing maintenance costs.

Human interaction

The most evident gap in research present in this review is the lack of research focused on the human interaction with the system. With the installation of BAS a significant degree of control has been removed from the occupant to satisfy fiscal and energy targets (Song, Zhen et al. 2013). This problem is compounded, as most energy modelling is carried out prior to installation, failing to account for human interaction and risking lack of occupant adoption (Bisadi, Akrami et al. 2018, Pan, Lin et al. 2018, Lin, Yang et al. 2019). Metrics investigated to monitor occupant satisfaction with installed systems included the monitoring of indoor environment quality, daylighting and glare.

Chapter 3. Methods

This chapter outlines the various methodologies used to address the research question and sub-questions in this thesis as well as the data collection and analysis methods. First, a narrative literature review enabled the topic of circular economy (CE) in construction to be explored broadly. Second, two separate systematic literature reviews were conducted to obtain an in-depth understanding of the environmental impact assessment methods and the systems available to reduce the energy consumption of buildings.

These three different reviews distilled the necessary knowledge to inform the design and documentation of a full-scale prototype building which would become a case study through which to investigate and report on the application of the circular economy by comparative life cycle assessment and, to propose a new method to quantify the circularity index of buildings. The published articles which form this hybrid thesis and their associated research methods are listed in Table 3.1.

Table 3.1 – Summary of the produced articles, related research methods and data analysed adapted from the publications

Title	*Methods applied or studied*	*Data analysed*
I. Strategies for Applying the Circular Economy to Prefabricated Buildings. ***Peer-reviewed article published.***	Narrative literature review and synthesis.	Literature on circular economy initiatives across several industries to find those which could be used in the construction industry
II. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. ***Peer-reviewed article published.***	Systematic literature review Meta-analysis Life cycle assessment	Literature on life cycle assessment of buildings. Review of construction materials' embodied energy and embodied carbon
III. A Systematic review and meta-analysis of building automation systems. ***Peer-reviewed article published***	Systematic literature review Meta-analysis	Literature review of building automation systems
IV. Interconnections: An Analysis of Disassemblable Building Connection Systems towards a Circular Economy. ***Peer-reviewed article published.***	Case study method	To assess a functional connection system that would foster the circular economy of buildings without affecting the visual presentation of buildings
V. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. ***Peer-reviewed article published.***	Comparative life cycle assessment.	Data obtained from the Legacy Living Lab: Bill of quantities. Construction technologies. Material inflow and outflow. End-of-life and next product practices.
VI. Design for disassembly, deconstruction and resilience in construction: A circular economy index. ***Peer-reviewed article published.***	Design for disassembly, deconstruction & resiliency (3DR) — new method proposed, developed and assessed	Data obtained from the Legacy Living Lab: Bill of quantities. Construction technologies. Material inflow and outflow. End-of-life and next product practices.
VII. Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction. ***Peer-reviewed article published.***	Case study method linked to game design technology	Digital twin to unlock CE inventory and explore buildings as material banks through VR experience. Links BIM with BoQ and material resiliency

3.1 Narrative Literature Review Method

To begin the research, a broad scoping survey of the two key themes: circular economy and construction was needed, with the aim to discover the barriers that prevent the adoption of CE in construction. The specific research question to be answered was "What are the main strategies that have fostered the application of the circular economy, and how these strategies can be adapted to the building context?" and for this the narrative literature review method was employed. The narrative literature review method was used to answer this question due to the limited amount of research available. This method allowed papers to be entered from outside the construction sector so that practices from other industries could be evaluated and potentially applied to the construction industry.

The narrative literature review method unfolded in four main steps (Figure 3.1). In the first step, starting from the research question, keywords were selected (circular economy, buildings, reuse, reduce, recycle and construction waste). In the second step these were entered into four selected databases: ScienceDirect, Scopus, Web of Science and ProQuest. We then selected the most relevant academic studies (articles containing relevant literature to answering the research questions).

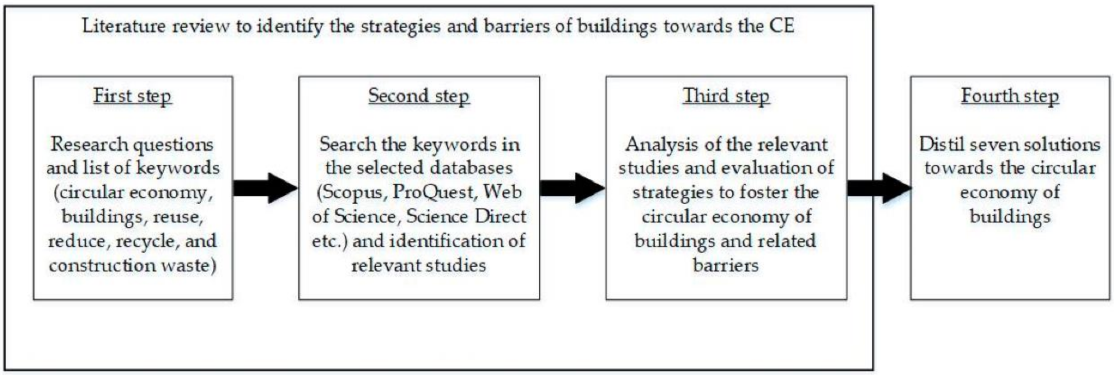

Figure 3.1 – Steps of the narrative literature review method. Adapted from publication I.

The third step required detailed analysis of the articles selected to evaluate those which could have results and methods that were transferrable to the construction industry. The author of this thesis has 10 years' experience in the construction industry which helped enable the identification of overlap potential across sectors. The fourth step was the formalisation of the seven strategies which were identified as being applicable to the construction industry.

The main outcome of this research (Publication I) was the clear result that modular building technology could indeed be used to apply the CE to the construction industry. Now that the applicable strategies had been identified, the next step was to understand the metrics used to quantify the improvement of applying CE to the construction industry. This lead to the SLR methodology used in Publications II and III.

3.2 Systematic Literature Review Method

The SLR is a stringent methodology that provides rigorous, repeatable and unbiased results (Cook 2009, Siddaway, Wood et al. 2019). A review performed following predefined steps with results quantitatively analysed is termed a meta-analysis (Cleophas and Zwinderman 2017, Hernandez, Marti et al. 2020). I combined the SLR method with a meta-analysis to analyse the results within publications II and III in this thesis. Publication II is a detailed review of the life cycle assessment method (LCA), used to calculate the environmental impact of a building. Publication III is a review of building automation systems (BAS) components and how they can be used to save operational energy throughout the lifecycle of a building. The separate review of these two fields was necessary as the case study design was subsequently impacted by the findings (more in Chapter 4).

3.2.1 Systematic Literature Review – Life Cycle Assessment

The SLR method was selected to address the research questions “What can be learnt by collecting and summarizing individual environmental impact studies of buildings to foster environmental impact reduction towards a circular economy?” and “What are the limits of the environmental impact assessment tools and how can these limits be overcome?”. In addition to the SLR a meta-analysis approach was adopted to analyse the quantitative data extracted from the literature. This SLR methodology unfolded in four steps which have been summarised in Figure 3.2.

Step 1 – Keyword and search string determination. Key words were taken from the focus areas to attempt to answer the research question set forth in Publication II (Table 1.1), then added into the following Boolean search string:

(life cycle assessment OR lca) AND (embodied energy OR carbon emissions) AND building.

If keywords contained two words they were retained with quotation marks, and the string engine automatically searched for plural spelling of the same words.

Step 2 – Data base search, extraction and copies elimination. The search string was applied to four selected databases: ScienceDirect, Scopus, ProQuest and Web of Science, searching in the titles, abstracts or articles’ keywords (search date: January 2021). The search criteria were not limited to cut-off year, and only articles in English were retrieved. The search retrieved 1181 articles which were then extracted as source meta-data.

Step 3 –Article exclusion and shortlist creation. Exclusion criteria was determined at this stage to minimise search bias. Two of the authors independently surveyed 618 of the searched articles and decided to retain or reject the articles. Cohens kappa was used to measure the level of agreement on articles to be excluded (Cohen 1960). On a scale of 0-1 the Cohen’s kappa was 0.84. Articles that were rejected lacked information regarding the accounting of LCA, used incompatible functional units or were irretrievable. This brought the search down to 181 articles.

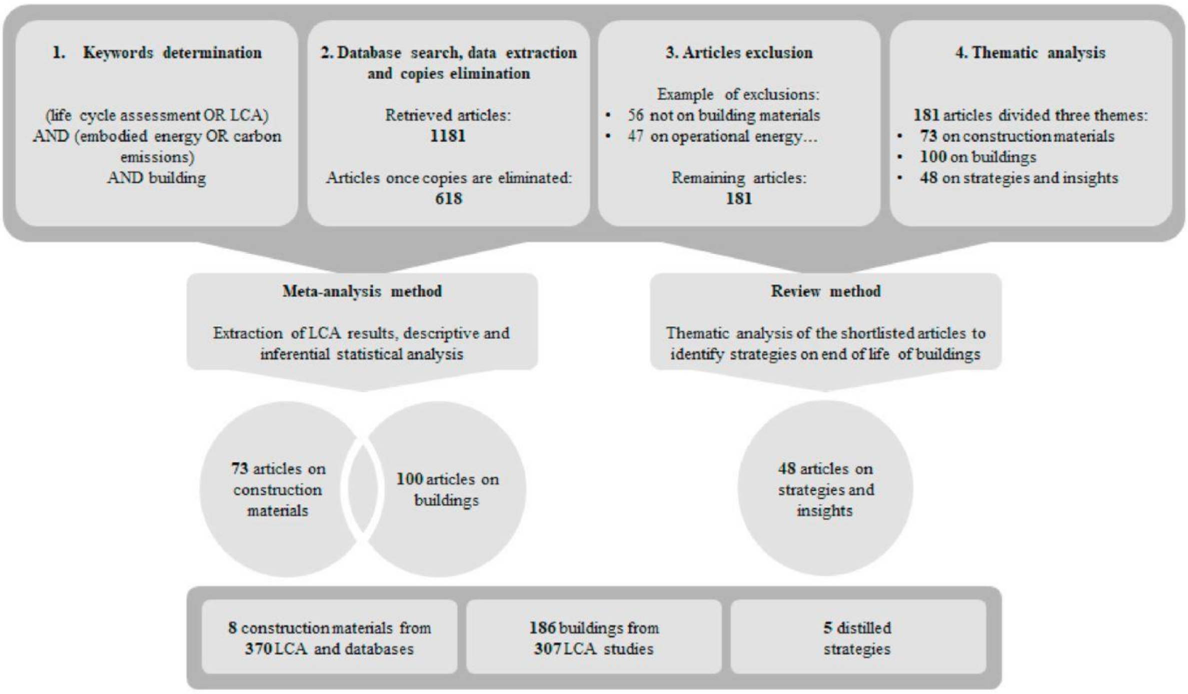

Figure 3.2 – Systematic Literature Review and meta-analysis flowchart and results adapted from Publication II

Step 4 –Thematic analysis. The 181 articles were separated into two distinct categories: works containing LCA of building materials (73 articles) and works containing LCA on Building structures (100 articles). Furthermore 48 articles were included for their insights on end of life and next product strategies.

3.2.2 Systematic Literature Review of Building Automation Systems

The research question informing the SLR process and subsequent meta-analysis was, ‘What is the current state of building automation with respect to user input, automation, energy saving and demand response?’. In attempting to answer the overarching research question, insights regarding system installation, maintenance and adaptability would also be highlighted. Information on physical systems, and component architecture allowed trends to be tracked in the BAS field. This knowledge in turn informed the physical and spatial design of the case study, as well as the specification of the BAS components used.

This SLR unfolded in four steps identified above (section 3.2.1).

Step 1 – Keywords and search string. I identified three distinct themes aimed at answering the research question: controller, benefit and device (Table 3.2). Then I identified a list of relevant keywords associated with the themes and synonyms that would expand the search results. The search was limited to keywords, titles and abstracts. To ensure the search identified the intended article content words were separated by ‘OR’ returning both AND/OR results. Again, keywords made up of two or more words were bound by quotation marks.

Table 3.2 – Search terms established within three distinct research themes to highlight the intended research area Extracted from Publication III.

Controller	**Benefit**	**Device**
Home energy management system	Energy savings	Window shade
Smart homes	Power savings	Louvre
IoT	Energy savings	Awning
Intelligent buildings	Cost savings	Sunshade
Interconnected device	Environment	Curtain
Sensors and actuators	DR	Shutter
Automation	Experience	Window covering
Voice control		Window protection
Human inputs		HVAC
		Light
		Air conditioning

*Step 2 – Database search***.** The search was entered into Scopus, Web of Science and ProQuest data bases which actively search for plural spelling of the same word. The thematic group lines were separated by AND meaning that one word from each line would be returned in the searches. The search string was entered as follows:

("home energy management system" OR "smart home" OR "internet of things" OR "intelligent building" OR "interconnected device" OR "sensors and actuators" OR automation OR "voice control" OR “human input”)

AND

("energy saving" OR power OR energy OR Environment OR "Cost saving" OR "power saving" OR "demand response" OR experience)

AND

("window shade" OR louvre OR awning OR sunshade OR curtain OR shutter OR "window covering" OR "widow protection" OR "heating ventilation air conditioning" OR HVAC OR "air conditioning" OR blinds OR blind)

AND

(Lighting OR lights OR light)

There were 201 articles identified through the database search which was reduced to 142 after duplicates were identified and discarded.

Step 3 – Shortlist creation. A criterion was established to limit articles closely related to the research topic. Hence articles not published in English, not peer reviewed, or considered to be grey literature were removed at the first stage of screening (32 articles, Figure 3.3). The second stage of screening removed articles that, although containing the correct search terms, were not related, or applicable to the construction industry, for example studies into hospital, nursing or aged care and medically implanted controllers (31 articles, Figure 3.3).

Step 4 – Categorisation. The remaining articles were categorised into two separate categories based on their research methods. Qualitative studies were represented by 21 articles and 58 were researched through quantitative research methods (Figure 3.3).

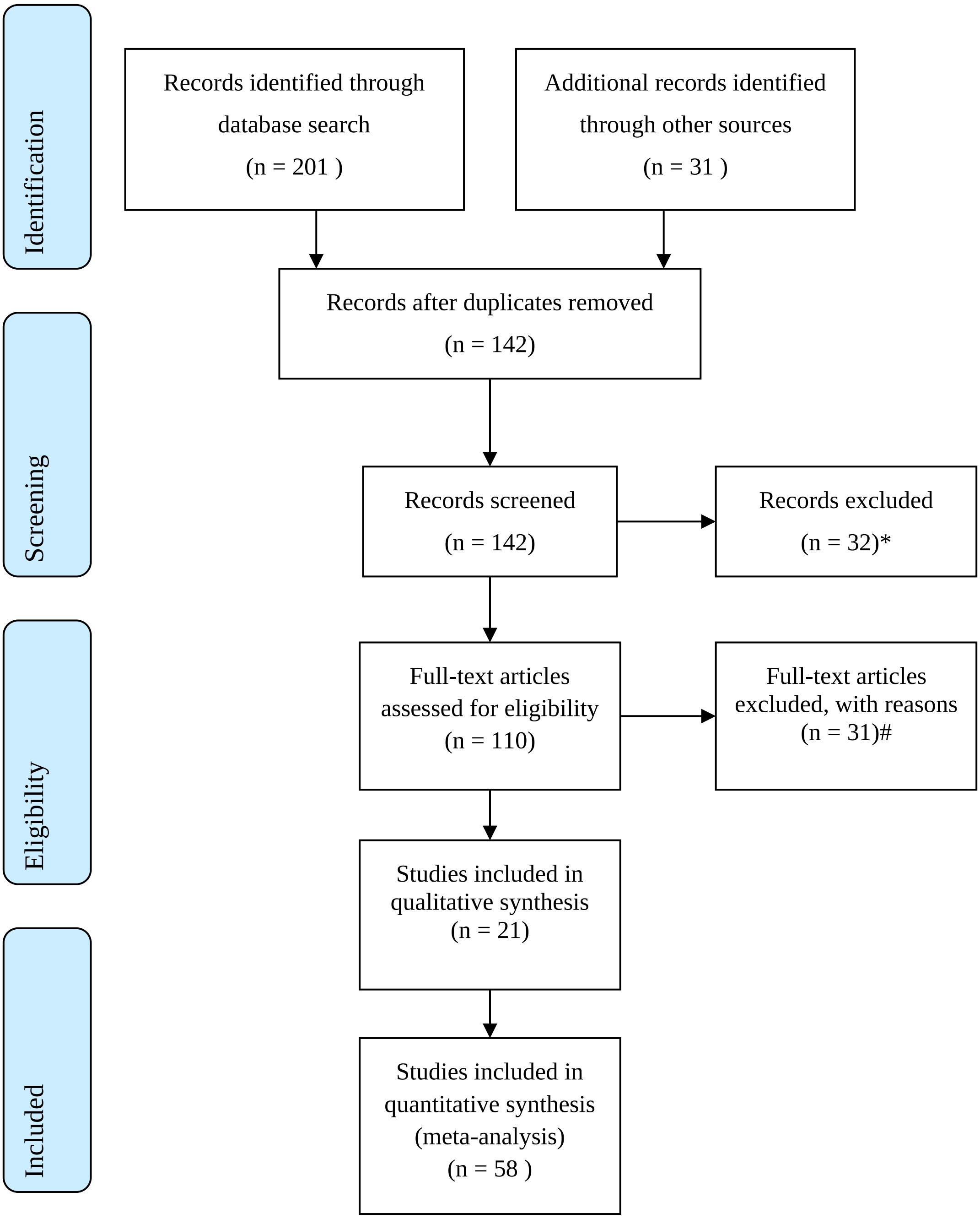

*Figure 3.3 – PRISMA diagram. * indicates records excluded in the first stage. These were papers published in a foreign language or grey literature; for example, conference reports, committee publications and industry flyers. # indicates full-text articles excluded*

With a comprehensive literature review process of three relevant focal areas, I believed I had understood the existing body of knowledge, and could practically apply the distilled learnings to a full size case study. This design, guided by the relevant knowledge would test the limit of theoretical application of CE principles and their practical effect on the construction industry.

3.3 Case study method

The case study method is widely regarded as the best tool to observe a research phenomenon in its practical context and empirical endeavour (Yin 1992, Yin 1994, Yin 2012, Sovacool, Axsen et al. 2018). Three main reasons make the case study method an essential tool for research into the design and manufacture of a CE prefabricated building. First, the case study method allows for the design and construction based on the reviewed literature. Second, it is evident that the most significant gap in all referenced research is a lack of empirical studies, therefore, a full scale construction to test the applied theory allows for accurate reporting of building documentation (Publication IV-VII). Third, a full size case study enables direct future research on emerging topics and a continuation of theory through practice.

Therefore a thorough analysis of a case study can demonstrate the strengths and weaknesses of the proposed CE theory and its adaption to the construction industry. This method unfolded in 4 steps adapted from Tellis (1997).

Step 1 - Case study design and construction. In this step we designed the L3 case study as a representation of the extreme case of a circular economy building. To achieve this I drew on my building experience to design disassemblable joints, flashings and wall systems whist incorporating a number of materials and products that were reused, or contained recycled content. The building also used novel prototype fixing methods to further push the boundaries (more in Section 4).

Step 2 – Detailed design. The selected design details were collated and reported according to their assembly process and detailed photographs and videos. Once the joints were collated they were categorised according to material type. Once the grouped materials were sectioned they were further examined for the reusability of the material.

Step 3 – Sample analysis. On completion, the physical and technical characteristics of the building were analysed. I applied several varied methods to conceal joints or have them exposed as features. Distinctive features of accessible joints is their feasibility for disconnection. For example, if a structural component has a born load on it, which must be removed before disconnection, another is the watertightness of a join in a practical context.

Step 4 – Reporting. Once the building was complete, recommendations and implications of the adopted joints were reported. This step was crucial as it allowed for best practice alternatives when designing and assembling a building based on the success of a case study.

The Legacy Living Lab (L3) is a modular prefabricated building located in Fremantle, Western Australia. The building has been conceptualized to practically examine the limitations and possibilities of applying the circular economy to the construction industry and was built as a case study to validate my research (Figure 3.4). The strategies from Publication I have been applied to the design of the building, the life cycle assessment method has been applied to the Bill of Quantities (BoQ) of L3 for Publication II. Building automation and energy saving and monitoring technology have been installed, based on the SLR findings in Publication III and design details reported in Publication IV.

Figure 3.4 – The case study selected for this research, the Legacy Living Lab (photo taken by author). The building consists of 8 modules is 250m^2 in area and is complemented by an electric vehicle.

The quantification of LCA results and the 3DR methods reported below are detailed in Publications V and VI with the digital distribution and VR opportunities explored in VII. The case study designed and reported on in this research is described in Chapter 4 in full detail.

3.4 Life Cycle Assessment Method

The Life Cycle Assessment method has been used to quantify the impact of products and services on the natural environment (Nwodo and Anumba 2019). This process tracks impact from production to disposal and includes recycling and reuse to follow the impact into next product systems (Finkbeiner, Inaba et al. 2006). Traditionally, an LCA of construction is focused on material production, construction and disposal, however as research investigates the second life of building components and the CE of buildings, LCA is considered a key approach to evaluating the environmental benefits of this research. The comparative LCA was performed on the case study building (L3) using SimaPro 9.0 and the database Econinvent 3.5. This LCA was performed in accordance with the European international standards 14040 and 14044 (Chomkhamsri, Wolf et al. 2011). The LCA method was used to evaluate the impact of the L3 case study, and a building of the same dimensions built to the typical specifications of the building contractor engaged for construction. The traditional *modus operani* was taken to be a control case study, as the building documentation and Bill of Quantities were created for both case buildings.

The life cycle of the L3 case study is divided into 4 life cycle stages (Table 3.3). In the production stage (A), the components are manufactured and the materials are assembled. As this LCA forms a comparative assessment for two building typologies, transport has been excluded for both materials and modules being delivered to site. The operational stage (B) incorporates the materials needed throughout the operation of the building to maintain its function. Operational consumption, such as energy and water have been excluded to focus on the building materials themselves. One important consideration is that the application of CE principles contribute to a lower waste created during operation, as refurbishment with accessible wall designs, such as plywood and steel cladding enable access for upgrades and modification. In the end of life stage (C) the materials sent to landfill were accounted and transport of these materials was excluded. Finally, the next product stage (D) accounts the materials which can be recycled.

Life Cycle Inventory Analysis. The data collected from the BoQ (Bill of Quantities) during the design of L3 and its linear case study are detailed in Table 3.4. The amounts of different materials used were given as weights in kilograms and enabled a comparative study between the two building designs. All steel used in the L3 building is recyclable, however according to the fundamental principles of CE, all effort should be made to reuse the material in its current form. In line with this suggestion, 16 139kg of steel is reused in the CE version of the L3. To further incorporate CE principles, 19 848kg of concrete was avoided, as it can only be down cycled, in favour of using steel foundations in the CE case study.

Table 3.3 – Life cycle stages of the L3 included and excluded from this study. Adapted from Manuscript II.

	LCA stage	***Process***	***Code***	***Included***
Material input	Production (A)	Raw materials input	A1	Yes
		Transport of raw materials	A2	No
		Production	A3	Yes
		Transport of modules to site	A4	No
		Craning	A5	Yes
	Operation (B)	Refurbishment/repair	B1	Yes
		Energy and water consumption for operation	B2	No
Material output	End-of-life (C)	Deconstruction/demolition	C1	Yes
		Transport to landfill	C2	No
		Waste recovery	C3	Yes
		Landfill disposal	C4	Yes
	Next product system (D)	Reuse, recovery or recycle	D	Yes

Table 3.4 – Life cycle inventory, materials input to produce the L3. Adapted from Manuscript II.

Material	***Description***	***Amount (kg)***
Steel	Chassis and load bearing structure, internal walls structure, and external cladding.	21 335
Timber	Stairway steps, cladding plywood, flooring pressed timber and external cladding pressed timber.	9 406
Concrete foundations	Concrete foundations composed of concrete discs and footings[1].	19 848
Steel foundations	Pile driven lightweight steel foundations[2].	735
Plasterboard	Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	140
Others (carpet, vinyl and insulation)	Floor covering and insulation.	3 413
Openings	Aluminium windows and glazed doors, and internal timber doors.	63 (m^2)

[1] Concrete foundations are only used in the linear version.

[2] Steel foundations are included as an alternative design choice in the prototype only.

The amounts of materials calculated during the life cycle inventory analysis were measured as primary data and therefore a sensitivity analysis of the LCA was not necessary (see Toniolo, Mazzi et al. (2017), Wei, Larrey-Lassalle et al. (2015)). Indeed, sensitivity — or uncertainty — analyses are used in LCAs when some of the data cannot be precisely calculated. Some examples include the adoption of sensitivity analysis to calculate the impact of different transport scenarios (for example see Hossain, Poon et al. (2016) and Brambilla, Lavagna et al. (2019)).

Life Cycle Impact Assessment and Results Interpretation. These remaining two modules are explained in the Results (section 5.4).

3.5 3DR Method – Building Circularity Index

From previous research it was evident that methods existed to calculate the impact of the materials used in the building, and that the impact of construction materials is connected to their waste management. However, the literature reviews revealed a clear research gap on a method to quantify the level of circularity (circular economy of the buildings material parts and components) (Mesa, González-Quiroga et al. 2020, Munaro, Tavares et al. 2020). To address this, publication VI proposes a novel method aimed at calculating the circularity of a building in terms of circular economy. The method assesses the degree to which a building applies the CE framework by examining the design, disassemblability, deconstructability and resilience (3DR) of the materials and design methods selected for a project.

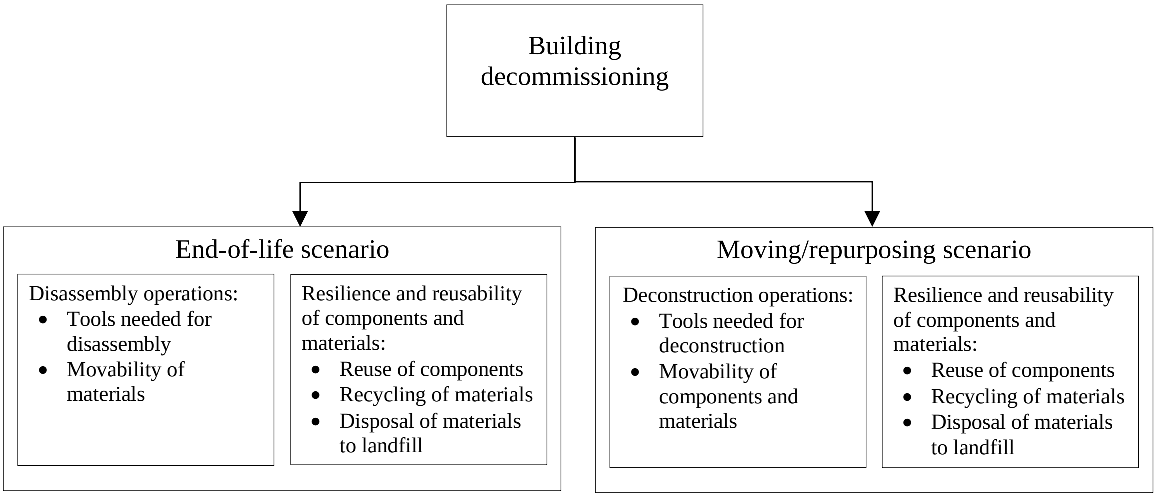

Figure 3.5 – Moving/repurposing and end-of-life scenarios in the circular economy context (Publication VI).

The literature review (O'Grady, Minunno et al. 2021) uncovered two main scenarios at the end of life for a building (Figure 3.5). The first, and unfortunately, most popular scenario is to disassemble the building and investigates the tools and equipment needed to disassemble the building and move and sort the materials on-site. The second scenario is to deconstruct the building into smaller parts and move the parts and materials to be transported from site. Both scenarios require lifting equipment and tools to disassemble the parts for either demolition and disposal or disassembly and reuse, however the degree of difficulty is higher if the project has not been designed to consider its end of life opportunities.

The 3DR method is based on the formulation and resolution of one equation where the quantification of the 3DR method is a normalised index as the sum of the degree of disassembly (DI), deconstruction (DE) and resiliency (R) with a, b *and* c to be used as influencers (equation 1):

1.

$$3DR = DI \times a + DE \times b + R \times c$$

The two limits of the 3DR index are 0 and 1. A higher value indicates a higher level of circular economy achievable due to increased disassembly and deconstructability whilst being built from more resilient building materials.

3DR (equation 1) is the circular economy index, while the value DI, DE and R are the disassembly, deconstruction and resiliency (reusability) indices, respectively. The influencers a, b and c can be modified to suit a relevant scenario, for example, disassembly where DI influencer a would be set to 1 and deconstruction DE influencer b set to 0. The sum of the variables a and c in the disassembly scenario, or b and c must equal 1. Although we suggest assigning a value of 0.5 to the two non-zero variables, the user can decide to change them to increase the weighting of disassembly/deconstruction over resiliency, thereby emphasizing the importance of one or the other aspect. The three other values in equation **Error! Reference source not found.** are identified in equations 0, 3 and 4:

$$DI = \sum_{i=1}^{n} (DIt_i \times DIm_i \times w_i) \times \frac{1}{w_T} \tag{2}$$

$$DE = \sum_{j=1}^{m} \left(DEt_j \times DEm_j \times w_j\right) \times \frac{1}{w_T} \tag{3}$$

$$R = \sum_{k=1}^{t} (Re_k \times w_k) \times \frac{1}{w_T} \tag{4}$$

Disassembly - equation 2. This equation considers the tools required to disassemble the building materials DIt and the difficulty in moving the materials once they are disconnected from the structure. This equation takes into consideration the on-site transportation to move the materials to their loading bay, as off-site transportation would be too broad, and there exists calculation methods for material transport (O'Grady, Minunno et al. 2021). The parameter w_i represents the weight of the i component, while w_T is the total weight of the building. n is the total number of the building's components. The scales for DIt and DIm are given in Table 3.5.

Table 3.5 – Values of the variables DIt and DIm used in equation 2, that define the degree of disassemblability of a building. Adapted from Manuscript VI.

	Operation & tools required		***Value***
DIt	Parameter that depends on the availability of tools, dimensions, manual, power tool etc.	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic plant	0.2
DIm	Possibility of being disassembled and moved in up to two people, more than two people, need for a fork-lift or a crane.	1 person < 25kg	1
		2 people < 42kg	0.9
		Hand trolley < 50kg	0.7
		Fork-lift < 2000 kg	0.4
		Crane > 2000kg	0.1

Deconstruction – equation 3. The Deconstruction equation investigates the tools required to remove the materials from the building and move them around the site. The equation can be used for the deconstruction of parts of a whole building, for example modules of a prefabricated building, and the equipment that would be required to lift them. The symbol w_j represents the weight of the j component. w_T is the total weight of the building. m represents the last component of the building.

Table 3.6 – Values of the variables DEt and DEm used in equation 3, that define the degree of deconstructability of a building. Adapted from Manuscript VI.

	Description		***Value***
DEt	Parameter that depends on the availability of tools, dimensions, manual, power tool etc.	No tool	1
		Hand tool	0.9
		Power tool	0.8
		Gas/pneumatic tool	0.5
		Hydraulic plant	0.2
DEm	Possibility of being disassembled and moved in up to two people, more than two people, need for a fork-lift or a crane.	1 person < 25kg	1
		2 people < 42kg	0.9
		Hand trolley < 50kg	0.7
		Fork-lift < 2000 kg	0.4
		Crane > 2000kg	0.1

Resiliency – equation 4. Once the parts of a structure are either disassembled or deconstructed, they can either be reused or disposed of. The resiliency of a material considers how many times that material is likely to continue being used if care is taken when removing and transporting that material. The symbol R_k takes this variability into account (Table 3.7). The symbol w_k represents the weight of the k component. w_T is the total weight of the building. t represents the last component of the building.

Table 3.7 – Values of the variable Re used in equation 4 that define the degree of resiliency of a part, component or material. Adapted from Manuscript VI.

Description	***Value of Re***
Reusable infinite times	1
Reusable up to 3 times	0.9
Reusable only once	0.7
Recyclable	0.6
Down-cyclable	0.2
Disposable	0

To validate this method, I applied the equations 1-4 to the L3 case study building, both as a prefabricated modular building designed for circular economy and as a typical modular building not considering circular economy. To further validate the method, and to provide applicable results to the broader construction industry, the method was applied to both double brick and timber framed structures to make the results applicable to the greater proportion of global construction typologies. The results are explained in section 4 and in the peer reviewed Publication VI.

3.6 Virtual Reality Methodology and Workflow

The L3 case study was designed and documented in accordance with the strategies identified in Publication I and listed below in Figure 3.6. Throughout the year of design, I drew upon my experience in the construction industry to solve the most problematic barriers in order to implement the CE of buildings.

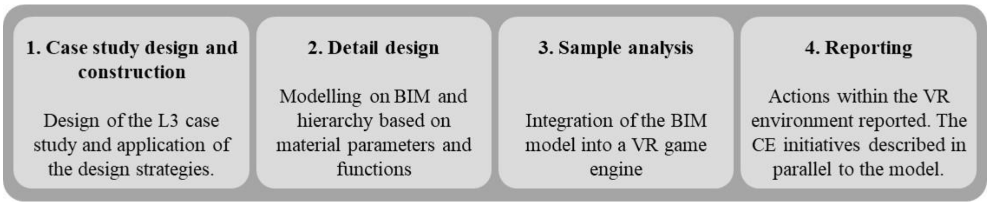

Figure 3.6 – The methodological framework used for Publication VII

The work flow used to visualise the BIM model is similar to that explored by researchers (Bille, Smith et al. 2014, Oerter, Suddarth et al. 2014) and required five steps to enable an immersive experience with the buildings digital twin.

1. *Revit Model preparation.*

The preparation of the BIM model for export was crucial as there are limited modelling capabilities once the software change is made to VR applications. Initially, the BIM model was created as if it were a monolithic structure, that is, each of the buildings modules were joined as two pieces (one per floor), rather than five modules for the ground floor and three modules for the first floor. It was important that the model be changed so that the full extent of the buildings modularity could be conveyed through the VR experience. Once the necessary changes were made, the model was exported to Unity. Unity is a powerful tool for developing real-time interactions with 3D geometry, making it ideal for the task.

2. *Exporting from Revit*

Once the BIM model was finalised in Revit, each module was assigned its own viewport. The FBX file format used to export from Revit into Unity does not optimise lighting and materiality, making the appearance of the BIM model sub-optimal. It was therefore required to use 3DS Max as a stepping stone between the two, in order to manually correct the lighting and material images in the model.

3. *3DS Max*

3DS Max is a professional 3D computer generated graphics program. It was used to fine tune the model to add a more realistic element to the virtual environment. The main change in this step was that the UVM map settings were changed to box mapping, which enables the texture of the elements to be tiled across elements. The result of this change is superior rendering. The Revit FBX exports were replaced with new 3DS Max FBX files.

4. *Importing to Unity*

The Unity project browser can often become cluttered and clear organisation is needed for the program to function correctly. To combat this issue, import data was managed through the creation of individual folders for each of the eight modules. Once imported, the FBX files were given a project hierarchy, then into a scene, in which the VR development begins.

5. *Materials and Lighting.*

To capture a truly immersive experience the material textures were taken on a high resolution DSLR camera of the real live L3 case study and processed in Adobe Photoshop before being uniformly cropped and used as a texture tile in Unity. Once the textures were finalised they were assigned to a correct element within Unity. A helpful feature of Unity is that elements that share the same surface within the BIM model will automatically update which saved significant time for items such as the ‘smart’ power outlets and light switches.

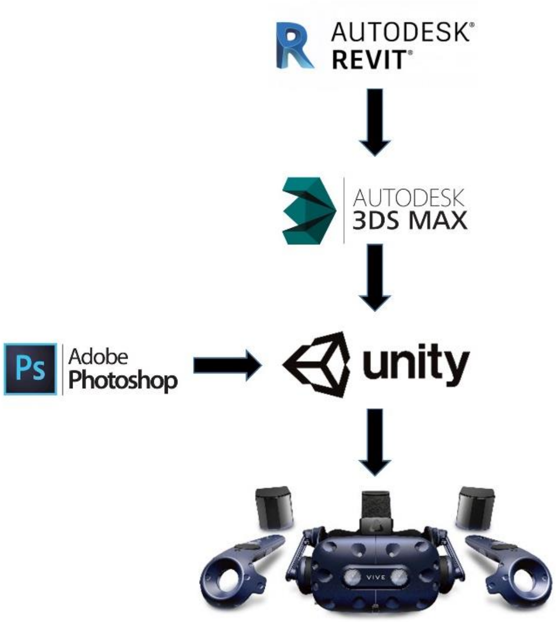

Figure 3.7 – Programs used to create the VR experience and workflow sequence (Publication VII)

The results of this method are detailed in Section 5.6 and in peer reviewed Publication VII.

With an adequate understanding of past literature and a selection of methods which had been employed by researchers to assess the impact of a CE building, it was time to design a case study that would be a CE prototype. The following chapter is a personal, but nonetheless important, narrative that details the case study design from concept to completion, providing an in depth account of the process, challenges and ultimately success of the project.

Chapter 4. Case Study Narrative

This PhD is unique as it involves the design and construction of a full scale building. This chapter has been positioned ahead of the results, as although that is where the unpublished time and effort of this PhD lies, L3 is the demonstration of research and innovation on circular economy at the industry-society-university nexus. This chapter gives a narrative timeline for the development of the Legacy Living Lab.

4.1 Conception

Initially, I was awarded 1 of 2 industry based scholarships to study a volumetric modular hotel project which was planned to be manufactured in Perth and transported to the Pilbara region of Western Australia as mining accommodation. This building was to be constructed by the PhD industry partner. Unfortunately this project never came to fruition, and 4 years later is still under discussion. The absence of a case study presented a significant problem, but an even bigger opportunity.

My research colleague identified that our industry partner had a number of disused frames in the production yard, and learned that these frames belonged to a failed construction project which had lost funding, causing the project to be abandoned. To save these steel frames from being transported to the East coast of Australia for recycling, an idea evolved to create a circular economy building of our own, using the existing steel frames.

Another group of Curtin PhD students at the time were working with DevelopmentWA (DevWA), the state based land developer in Western Australia on innovation through demonstration sites in Fremantle. East Village at Knutsford was the latest offering from DevWA with the estate featuring: a micro-grid power supply fed from a 670kWh battery, recycled concrete walls, in ground water tanks and a completely monitored water and power system. After speaking to the senior development manager, there was interest in the project as a display office on-site. The possibility of the project required additional funding. After presenting the idea to Curtin University, grant funding was annexed triggering a basic design brief and associated preliminary costing.

Figure 4.1 – Image of the frames in the Modular builders' yard (2018). This frame served as the muse for what was to come (picture by author).

Designing a circular economy building to integrate waste means that reverse logistics are necessary (Wilson, Paschen et al. 2022). Typically, a building can start with a blank sheet of paper with designers free to accommodate a client's wishes, however reusing material forces building designers to creatively adapt the available structural elements to fulfil a design vision. For this reason, the design process began with determining the structural layout of the building prior to the internal layout. Figure 4.2 shows the very first space definition concept we drafted and investigated for the building. These four target areas can be considered supplementary research goals, as to design a successful CE case study, it would also have to accommodate the needs of DevWA and our own ideas for a research facility. Hence the case study was divided into 4 zones:

- Commercial space – this area would be used to display information about the estate and could be used by DevWA.
- Visualisation space – this area would display data from DevWA previous precincts allowing visitors to see the energy and water data that was being collected and the associated savings through Curtin University and DevWA joint research projects.
- Technology/ apartment display – this area would use similar kitchen colours to developments on the innovation precinct and tones to act as a mini display suite for potential clients purchasing into the estate. It would also display the dishwasher and cooking appliances that were to be installed.
- Prototyping space – this area would be used by future research students who would need; a case study building, a place to engage with other industry based research programs, or to work on built environment prototypes.

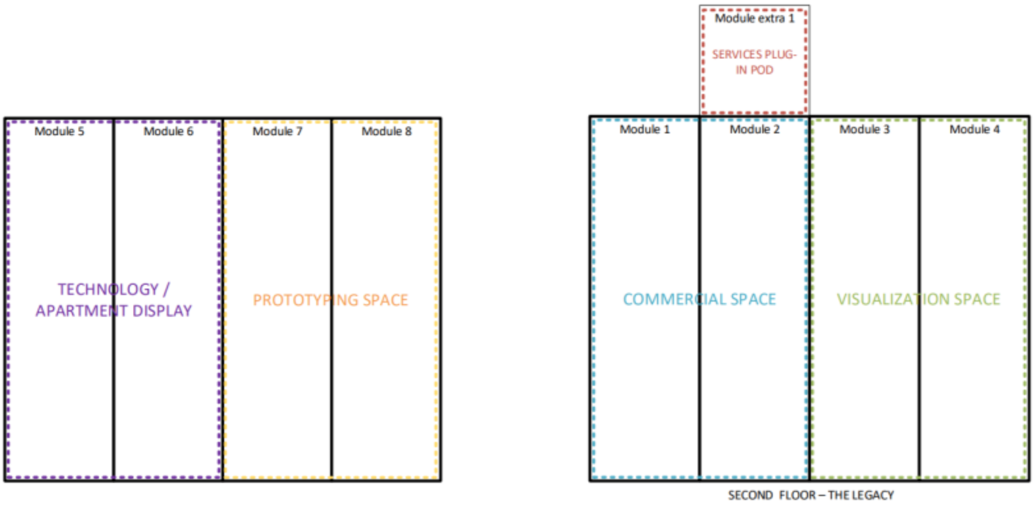

Figure 4.2 – The space definition brief that served as a basic spatial layout, and the functions we had initially wanted the building to fulfil.

*Services pod – It is worth noting that although this pod is drawn on the first plan, it was initially an idea for innovation. The intention was to function as a place for future battery technology research. It is noteworthy that this was outside our research scope.

4.2 Structure

With the basic space definition and floor plan set-out based on using 8 modules of approximately 12x3m in area (Figure 4.2), a cost estimate was given, based on historical data from the modular builder, approximately AUS $800,000. From the working budget, it was clear that the design had to be reworked to reduce the size of the building and incorporate a more feasible design. Although there were 42 frames available of varying dimensions, it was clear the design had to be reduced. The reduction of design was needed not only to reduce construction costs, but also to reduce the amount of modification that was necessary to make the 12x3m frames work. All these larger frames had pitched roofs, as they were originally designed to be on the top story of the town houses. To simplify the design, and minimise re-work, the modules were left in their intended configuration from the failed townhouse project (Figure 4.3). This would allow three townhouse modules to remain in a similar state and two smaller modules could be added to the ground floor to create a more functional space. This change in thinking saved enormous cost and steel work, with the only modification required being increasing the height of the ground floor modules to provide a greater space for an open area office. The internal module height was increased from 2.6m to 3m. Figure 4.4 (a) shows the module layout, with the colour coding showing modules from the same townhouse.

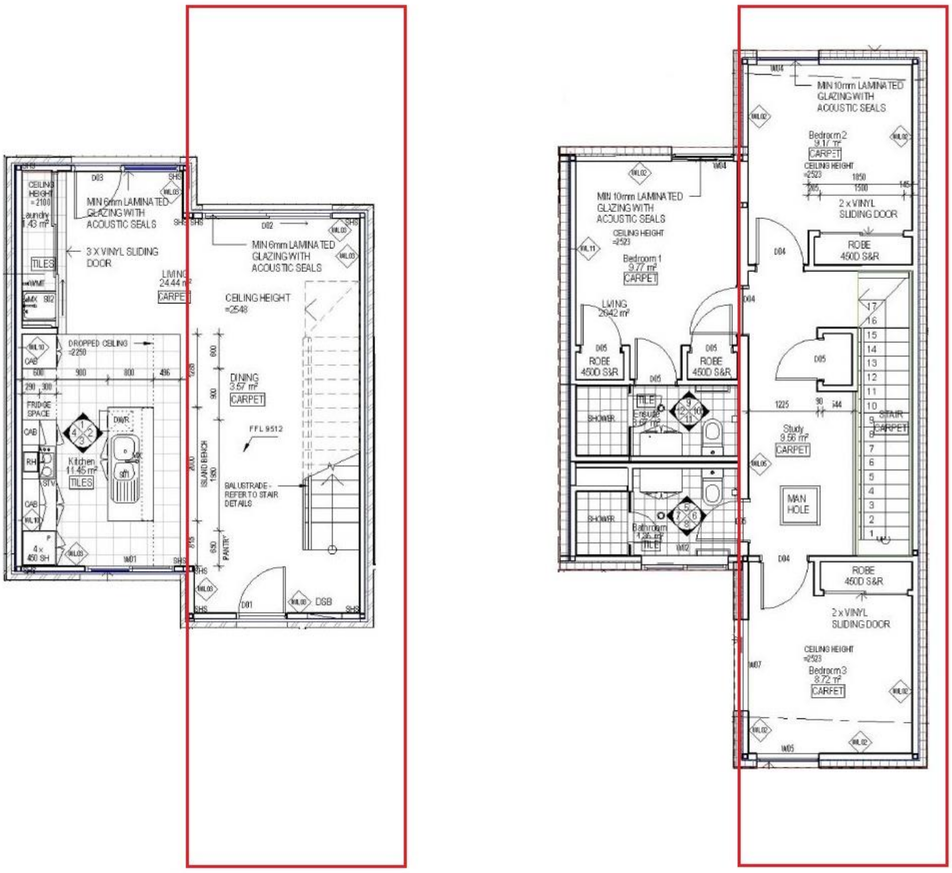

Figure 4.3 – Original floorplan of one of the failed townhouse projects which the structure of the case study was used highlighted in red, and its repurposed position shown in green in figure 20 (a).

Capitalising on the existing structure a wireframe was created in SketchUp to view the building for the first time as a 3D design (Figure 4.4 a). Working with the structural steel designer, the 3D wireframe was transformed from a sketch to a working frame drawing (Figure 4.4 b). In the design process, the post supports were deleted, and the steel design was optimised to bolt through structural members on the first floor so that there would be no posts in the entry way to the building.

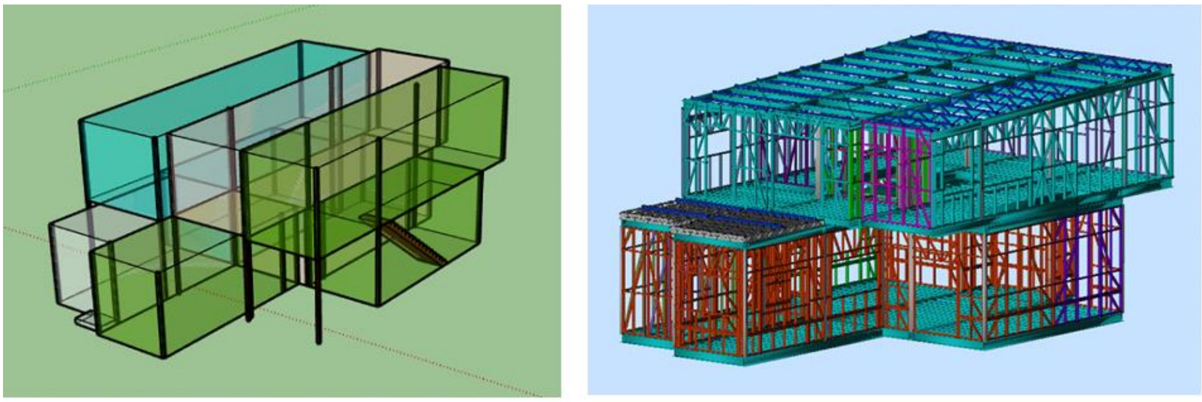

Figure 4.4 – (a) The starting point for the project was the reused structural steel frames. (b) The steel frames reimagined in Framecad software.

The steel frame design was sent to engineering to check that the new design featuring bolted connections would be sufficient. Traditionally, this building would have the structural steel members welded on site to eliminate flex in the structural steel and have supporting posts welded to pick up the overhang on each end. Once confirmed, the structure of the building was engineer stamped, and the internal space definition could commence.

4.3 Internal Space Definition

The internal space definition proved to be one of the most challenging tasks in the design of L3. To assist, interior design PhD candidate, Emma Whettingsteel offered her experience to help coordinate an internal layout that would practically meet the needs of the four design criteria (section 4.1). The iterative design process began as an overlay on the floor plan determined by the structural steel frames. Included below are the sketches of the process with the final sketch being selected (Figure 4.5).

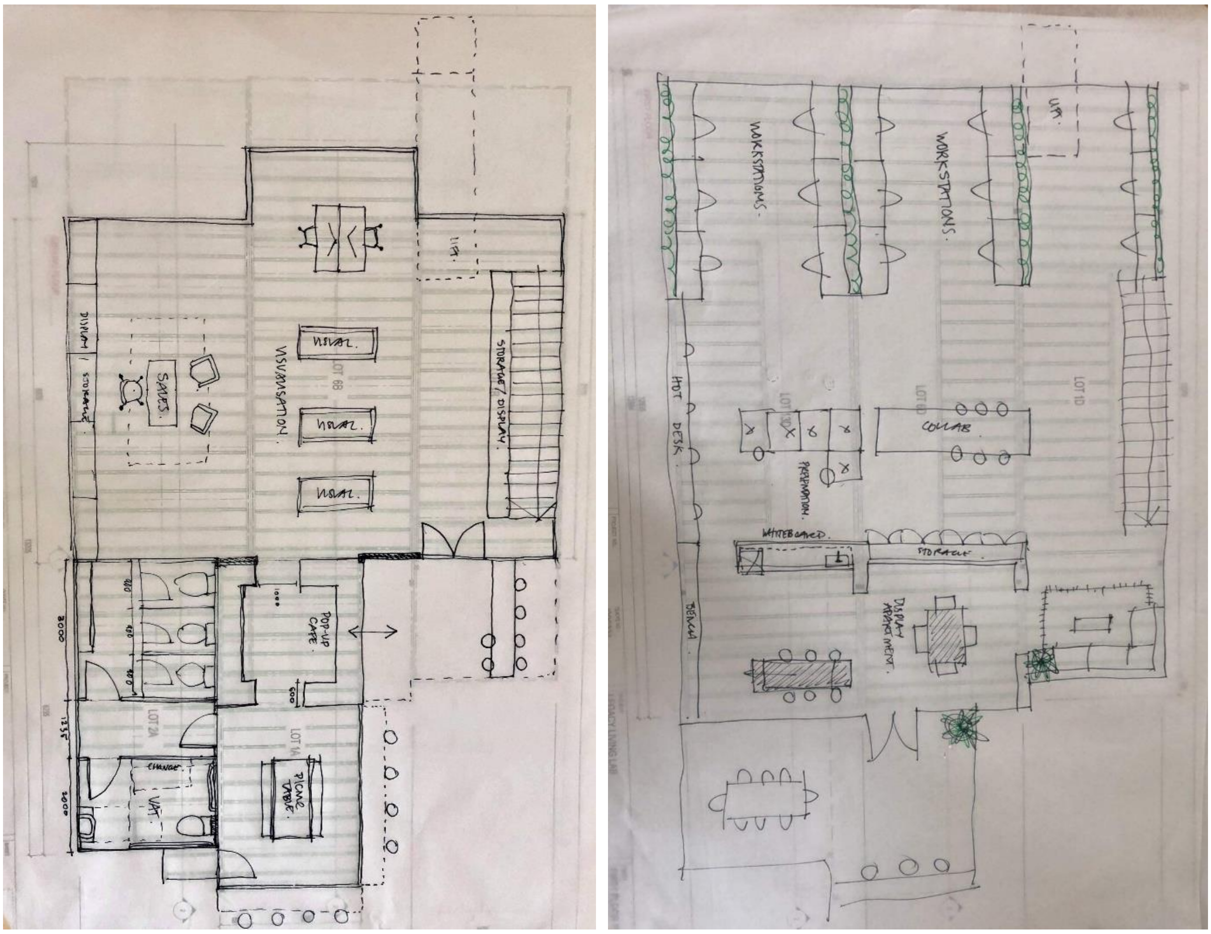

Figure 4.5 – The close to final design sketches by Emma Whettingsteel to determine the internal space definition of L3 (note the sketches over a plan view of the structural steel from Figure 20(b))

4.4 Scope

Once the internal layout was complete, the sketches were given to the architects to complete a floor plan, in order to develop a basic set of plans which would have enough detail to allow the job to be quoted. The estimated cost of the building was now approximately AUS $400,000 installed. This price was for a basic building, which would serve as the control case study (Section 5.4 and Section 5.5.2), as would be built generically by the modular builder. The standard features of this building meant that it would be indistinguishable from a standard transportable classroom or mining office, which did not align with the goals and values we had set for the building and further, did not incorporate any of the CE design at this stage.

Once a full set of plans were developed I began the task of reviewing each aspect of the building to understand the traditional methods the modular builder used and then worked through how each of the seven strategies (publication I) could be applied to the building. This process began as a holistic assessment of the building and its 8 modules, ensuring their disassembly and relocation would be feasible, and ended up examining every element of the building including its foundations to ensure that as much as possible, this building would be a leading example of CE in construction. The results of these connection details are outlined in Publication IV.

The increase in scope was tied directly to an increase in cost. This presented a roadblock as at this point in time we were underfunded by approximately AUS $100,000. This challenge sparked the idea to involve industry partners to join the project to demonstrate their most sustainable technology, innovation, and construction materials and display them in the prototype.

The industry partnership agreement offered the business sponsors future access to the building to show customers and employees the benefits of CE and to demonstrate their involvement. Through this initiative, we were able to team with and link to 26 industry partners and deliver a higher quality product for a significantly reduced cost.

4.5 CE and Project Management

A clear and present gap was identified during the management of this project and that was the lack of detailed information regarding second-life building materials and components. There was no centralised information bank by which materials could be ordered or purchased in the Australian market. The majority of second-life materials incorporated in the building came from calling and visiting salvage yards, contacting suppliers for information on second hand items, or physically removing them from upcoming demolition works. This challenge and practical gap in the market began as the inspiration for Publication VII. The reduction in material cost eventually plateaued as the increase in scope due to material inclusions inevitably met the labour cost involved in filling the space with new technology and CE features.

The Just In Time (JIT) call up was used in this project to secure partnerships at a developing pace during the procurement and documentation stage to reduce the material cost involved. JIT management is the process of ordering and scheduling material delivery at the last minute to avoid storage and damaged goods as a result of the building process (Low 1997). Although the rapid development of the industry partnership enabled the building quality to exceed our initial expectation, it was extremely time consuming and strenuous on the relationship between myself and the modular builder. Each change in the direction of CE triggered a revision of plans, scheduling and subsequently led to a delay. This approach is not suited to modular construction, where ideally designs are set at the start of the project and not altered until completion, and it was also not typical for the modular builder to have a client side project manager contributing to the design of the building, procurement of materials, installation and overseeing work on-site with their nominated supervisors which led to significant issues through the construction of the building.

4.6 Construction

The inclusion of CE design elements developed into friction between the modular builders design team and myself. There was a communal belief within the business that *"we know what we're doing"* and *"that's the way we've always done it"* and these were the two leading statements offered at every point throughout the development. It was as if by suggesting a new method, one was undermining the experience of the individual tradesperson.

Innovation is difficult in a stagnated industry such as construction, made worse by a builder whose market is made up predominantly of constructing mining accommodation, there was never a point where a shared vision of the building could flourish in a closed mindset. In the eyes of the design team, existing clients were happy with what they supplied, so there was no need to do things differently.

The relationship declined further when plans were not drawn as my designs had been intended. On one occasion, the balcony design that exists today was not issued to the construction team as the architect refused to acknowledge the benefit and instead went with his own design. Their reasoning was that the licenced builder had rejected the idea. A stop work meeting was had and the intended flashing design was presented to the builder who had no previous knowledge that he had declined trying the novel method. This was the first of several occasions where direction was not followed, for no reason other than, it was a new idea, again somehow undermining the superiority of an architect.

The reluctance to try new building methods from the design office area eventually spread into the production yard where people were uninterested in fulfilling a vision, which lacked acceptance from their designers. The word had spread, and the lack of acceptance from designers had a particularly negative effect on the construction of the building. Unfortunately, this meant that further site supervision was necessary to ensure that the plans were being followed and traditional practices did not creep back in.

Continued supervision was required into the installation phase of the building as a new footing design, which was engineered to Australian standards was being refused by the architect for no other reason than it hadn't been used before. This challenge sparked a long series of hurdles to ensure the system was safe to use. Increased soil testing, site supervision and meetings to ensure compliance and risk mitigation were exhaustively conducted to ensure new technology was used as specified. This was typical for the design team and once all hurdles had been removed, the technology, design or method would be used. Each time a hurdle was put in place, it caused a significant delay to the project. This was quite challenging, as the deadline was impacting the opening of the sales office function of L3 for the land development. The supervision of this project proved to be close to a 2 year full time commitment from commencement of contract to the final handover.

4.7 Installation

Figure 4.6 – L3 being installed to site 21/11/19 (photo taken by author)

The building was delivered and installed in one day. The first three trucks arriving before a road curfew was in place for morning peak hour traffic and held in near-by streets. Once the first three modules were installed, the road curfew had lifted and they were returned to the production yard for a second load. The cranes first lift was at 8:01am, with the last module was placed at 3:38pm.

4.8 Completion

The building was completed and the following images show the different internal space definitions in their final settings as mention in section 4.1.

Commercial space – This area was designed to be used by Development WA to educate the public and potential clients on the sustainable initiatives which had been implemented on the East Village site. Currently it can be converted into a cinema (shown in Figure 4.7) or act as a sales office with the touch screen PCs displaying house plans and site information.

Figure 4.7 – Commercial space set up as cinema. Presentation of the East Village site being delivered at L3 (photo taken by author)

Visualisation – The visualisation capabilities of L3 are excellent thanks to the incorporation of an ARC-LIEF (Australian Research Council – Linkage Infrastructure Equipment and Facilities) grant. This iHUB grant enabled Curtin University to be nationally linked over the Australian Research Network to 4 other participating universities. The SAGE-2 software enables a greater sharing and collaboration platform for universities to share research strengths to tackle complex projects in remote locations through a system of interlinked 55 inch touch screen PC's and video conferencing through two (one on each floor) 110 inch video walls. This real time integration may enable the progression of design and research into sustainable buildings, precincts and communities (Figure 4.8).

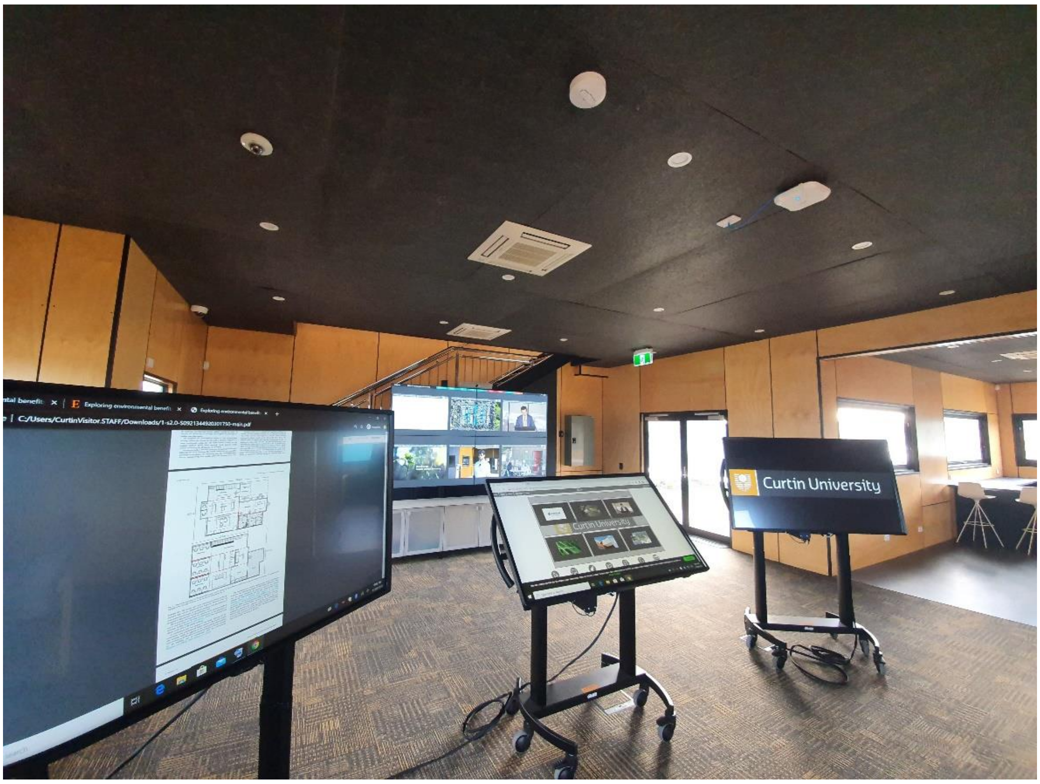

Figure 4.8 – Touch screen Computers on Wheels (CoWs) when L3 is set up for Visualisation purposes (photo taken by author)

Apartment Display area – This space was designed to replicate the upstairs area of the townhouses being built in the development where the Living Lab is located. This breakout space features similar colour tones to the kitchens and displays the appliances that would be installed as part of the house and land packages. The upstairs kitchen leads on to the balcony to provide a similar aspect to that which potential buyers would experience in their new home (Figure 4.9).

Figure 4.9 – Apartment Display space on level 1 of L3 displaying appliances and a similar aspect for potential buyers (photo taken by author)

Prototyping and Research - The upstairs prototyping and research space features 10 spacious workstations and a large boardroom meeting table which can seat 12. There is also video conferencing capability *via* the video wall. This space has already been used to house two low carbon start-up companies, and a host of researchers from Curtin University (Figure 4.10).

Figure 4.10 – The second floor of the Legacy Living Lab is a meeting space and open office for Curtin's researchers (photo taken by author)

Chapter 5. Results

This section summarizes the results from the seven peer reviewed publications produced within this PhD (Table 5.1).

First, the strategies that were uncovered from the review of the circular economy of buildings (Publication I) were used to guide the design and construction of the case study featured in the research, Legacy Living Lab (L3). The detailed design allowed for businesses to join the collaboration to merge insights by and interests of industry and academia successfully.

Second, the systematic literature review (SLR) carried out in Publication II resulted in a proposal for procedural guidelines which can be integrated with the established LCA method (Section 5.1).

Third, the results of the second SLR were integrated into a new framework that highlights the importance of integrative feedback loops. The novel research framework can be used to aid the design of Building Automation Systems (BAS) with a vision to increase uptake and occupant acceptance (Section 5.3).

Fourth, with the learnings from the three reviews the design and construction documentation could commence for L3. The connection details that would help foster the creation of a CE building industry were captured and documented in Publication IV (Section 5.2).

Fifth, using the completed construction documentation, a comparative Life Cycle Assessment was accurately conducted to calculate the impact between a CE building and the same building designed in a traditional fashion (Section 5.4).

Sixth, a circular economy index was created so that the CE of a building could be measured, extending the assessment tools that are available to the industry documented in Publication VI (Section 5.5).

Finally, the seventh Publication extends the physical body of work to prepare a VR model so that the project could be experienced without the need to visit the buildings location; this immersive reality highlights the CE aspects of the building and also provides a novel way to experience Buildings As Material Banks (BAMB) (Publication VII). This research was designed to cover and report on, all aspects of the shift towards CE, in a time where the construction industry (at least in Western Australia) is solidified in a double brick and tile industry, to attempt maximum impact and juxtaposition between the construction methodologies (Section 5.6).

Table 5.1 – Main results obtained in the five publications and manuscripts summarized in this thesis.

Title	*Results*
I. Strategies for Applying the Circular Economy to Prefabricated Buildings. ***Peer-reviewed article published.***	Seven strategies to apply the circular economy to buildings.
II. Investigating buildings' embodied energy and carbon: A systematic literature review and meta-analysis of life cycle assessments. ***Peer-reviewed article published.***	Procedural guidelines to integrate with the LCA method.
III. A Systematic review and meta-analysis of building automation systems. ***Peer-reviewed article published***	Novel research framework which considers both qualitative and quantitative system feedback loops.
IV. Interconnections: An Analysis of Disassemblable Building Connection Systems towards a Circular Economy. ***Peer-reviewed article published.***	Detailed connection analysis of CE prototype building focusing on structural and non-structural connection methods
V. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. ***Peer-reviewed article published.***	Quantification of the environmental impact of a circular economy building and comparison with a linear case study.
VI. Design for disassembly, deconstruction and resilience in construction: A circular economy index. ***Peer-reviewed article published.***	Validation of the design for deconstruction, disassembly and resilience method.
	Calculation of the D^3R index of the Legacy Living Lab and comparison with a linear case study.
VII. Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction. ***Peer-reviewed article published.***	BIM model linked with game engine to allow designers to visualise CE initiatives increasing awareness and uptake, second the buildings materials can be viewed prior to demolition or relocation: Buildings As Material Banks (BAMB)

5.1 Life Cycle Assessment – Procedural Guidelines

The results from Publication II concluded with a procedural guideline which, if integrated into the existing LCA steps for construction materials and buildings, would allow LCA practitioners to rank their results in a proposed benchmark, and reduce the environmental impact of their studied buildings. Traditionally, LCAs are an iterative process with the method unfolding in four steps: goal and scope definition, life cycle inventory, life cycle impact assessment and results interpretation. The procedural guideline proposes two additional steps to this process: result ranking and project improvement (Figure 5.1).

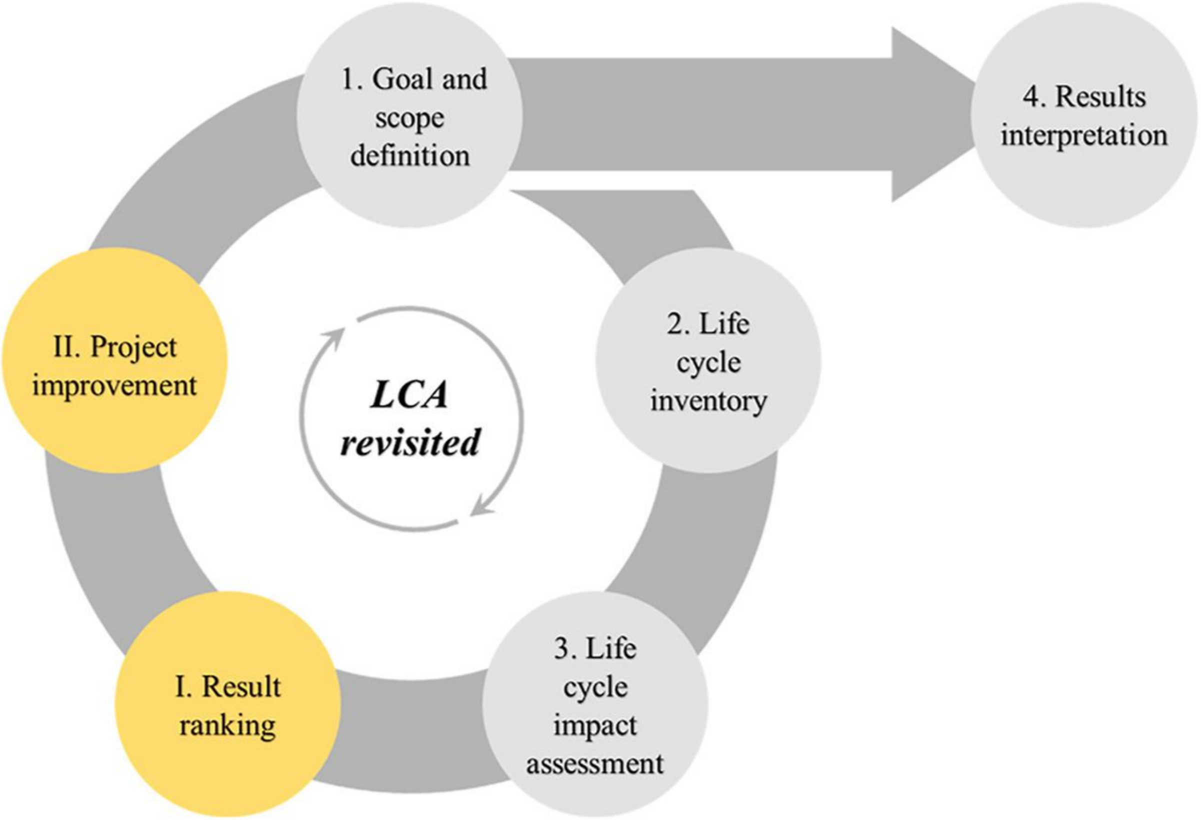

Figure 5.1 – LCA revisited with the integration of the two-step procedural guideline: result ranking step and project improvement step. Extracted from Publication III.

5.1.1 *Result Ranking*

Historical LCAs were divided into two distinct assessments investigating either building materials, or the buildings as a whole. The results were categorised according to the functional units, being either embodied energy or embodied carbon. The results were arranged according to the materials used in the construction of the building i.e. concrete, timber or steel and the results summarised in box-whisker plots. These plots can be used to rank the results of the LCA of any building, as long as the functional unit is normalized to 1 m^2 of floor area, and the environmental indicators used are embodied energy (expressed in GJ/m^2) or embodied carbon (expressed in kg CO$_2$ eq/m^2). The LCA practitioner can use the charts presented in Figure 5.2.

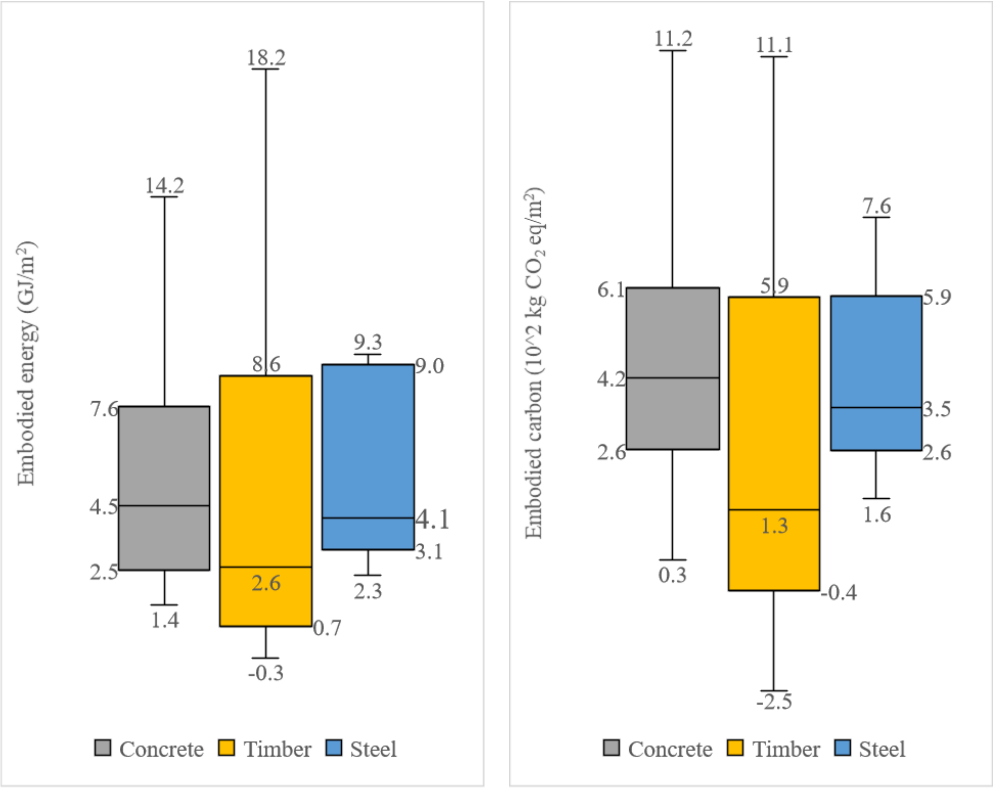

Figure 5.2 – Box-whisker plots of embodied energy (a) and embodied carbon (b) of the LCA results collected and categorized depending on three structural materials: concrete, timber and steel. Plots extracted form Publication II.

The results of LCAs can fall into one of the categories (a through f) outlined in Fig 5.3 below.

a) The results in section a represent the top outliers which are substantially higher than the median values. This could be due to incorrect data collection, mistakes in the LCA process or, an extremely high impacting building being assessed. It is strongly recommended that buildings that fall in this section follow steps of the guidelines for project improvement to reduce their impact, and improve the results of the LCA before progressing.

b) Buildings which fall within this category are amongst the top 24% buildings which adversely impact the environment. It is recommended that buildings this high up the plot have their data collection reviewed to ensure results are true, and if so, take steps towards project improvement, and reduction of environmental impact.

c) And d) this section contains the most common range for environmental impact, however with c being slightly higher than average, there is still room for reduction and efforts should be made to improve the building.

e) The lowest 25% of LCA results are found in this section meaning building practitioners may have already taken steps to reduce the impact of the building being studied. Regardless of the positive results, project improvement is always possible to further reduce environmental impact.

f) This section contains the lowest possible impacting outliers. This section may contain buildings that have an exceptional design and material selection, however there is always a risk that LCA assessments this low may have encountered mistakes in the process. Buildings in this category are of a high standard and there would be very little room for project improvement.

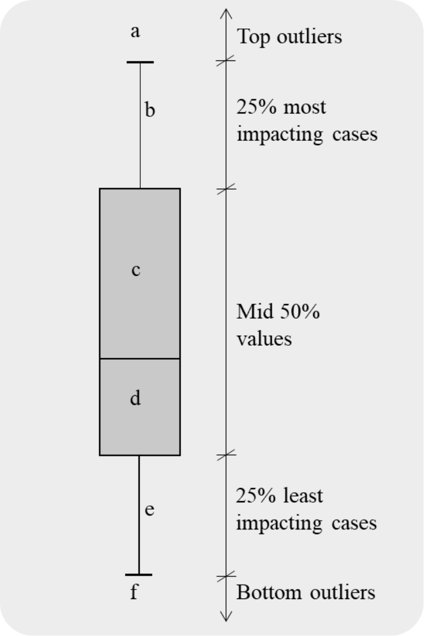

Figure 5.3 – Box-whisker plot guide: six different scenarios of building impact ranking Publication II.

5.1.2 Project Improvement

Five strategies have been put forward to help guide practitioners into making more informed design and material selections. Table 5.2 summarizes the strategies, the range of savings to be expected in terms of embodied energy and embodied carbon and the relevant sources which verify the results. A detailed explanation of all strategies is presented in Publication II.

Table 5.2 – Strategies to decrease the embodied energy and carbon of the studied buildings, and their percentage savings. Extracted from Publication II

Strategy	***Saving of EE (%)***	***Saving of EC (%)***	***Notes***	***Sources***
1. Material substitution				
Timber in place of concrete	43	68	Results calculated for a mix of CLT and timber studs, joists and trusses structures. Timber structure usually involve substantial amount of concrete. End of life and next product stages not included.	Ajayi, Oyedele et al. (2016) Ajayi, Oyedele et al. (2019) Å vajlenka, Kozlovská et al. (2017) Azzouz, Borchers et al. (2017) Cornaro, Zanella et al. (2020) Guo, Huang et al. (2017) Svajlenka and Kozlovska (2017) Takano, Hughes et al. (2014) Tavares, Lacerda et al. (2019)
Steel in place of concrete	9	15	Steel structure usually involves a substantial amount of concrete. End of life and next product stages not included.	
2. Recycle				
Concrete	-5÷29	6÷18	Recycling concrete is related to a negative saving, meaning that this operation has an adverse environmental impact. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates.	Blengini (2009) Chang, Shi et al. (2019) Chau, Hui et al. (2012) Gan, Cheng et al. (2017) Gao, Ariyama et al. (2001) Li and Altan (2012) Liu, Guo et al. (2016) Yan, Shen et al. (2010) Thormark (2002)
Timber	7÷22	15÷200	Recyclability of timber products varies substantially between countries and regulations. Some studies considered energy and carbon recovery using timber as fuel as a recycling strategy.	
Steel	40÷45	22÷60	Up to 80% of steel is typically recycled into new material, which maintain the structural characteristics of virgin steel.	
3. By-product integration and cement substitution	16÷33	21÷63	Results related to the substitution of different amounts of by-products (i.e. Bayer liquor[b], fly ash, volcanic ash, ground granulated blast-furnace slag) instead of cement into concrete. Cement's EC is 248 higher than graphene nanoplatelets' EC, which is a safe substitution in concrete.	Jamieson, McLellan et al. (2015) Gan, Cheng et al. (2017) Kupwade-Patil, De Wolf et al. (2018) Papanikolaou, Arena et al. (2019) Teh, Wiedmann et al. (2017)
4. Design for disassembly and reuse	81	18÷70	Although the literature suggests that concrete structures can be reused multiple times, specific regulations could depend on counties.	Aye, Ngo et al. (2012) Cruz Rios, Chong et al. (2019) Dara, Hachem-Vermette et al. (2019) Eberhardt, Birgisdottir et al. (2019)

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[a] ***Recycling concrete yields a negative saving, meaning that this operation has an adverse environmental impact in terms of EC. Further, although the literature refers to recycling of concrete, concrete is usually down-cycled into aggregates.***
[b] ***Bayer liquor is by-product derived from processing of bauxite to alumina.***

The results of Publications I and II allowed a synthesis of design information which were then implemented in the Legacy Living Lab case study. First, the strategies for CE were known, and secondly, the strategies for environmental impact reduction were categorised, allowing an informed design and documentation process. Armed with this information, the L3 case study was designed to implement as many CE initiatives as possible, Section 5.2 discusses these designs in detail, with Section 5.3 quantifying the savings through the improved LCA method.

5.2 Legacy Living Lab – Interconnections and Design Analysis

Through the design of L3 every effort was explored to ensure the intersection between each of the eight modules was a concealed connection. The goal was to conceal the buildings modularity, and to use as many typical connection methods available so that the prefabricated construction typology was hidden as much as was physically possible. Hence, this study developed into an exploration of the intersection between environmental strategies to decrease construction and demolition waste to create an aesthetically pleasing building. Figure 5.4 presents the study's theoretical and empirical framework. A total mass of 36.3 tonnes of material was used in the creation of the L3 case study. This included steel (61%) and timber (26%). Of the materials used, 58% is disassemblable and reusable infinite times. The results section has been organised to the follow five subsections based on material categorisation of Steel, Timber, Cladding, Insulation, as well as Windows and Doors (Figure 5.5).

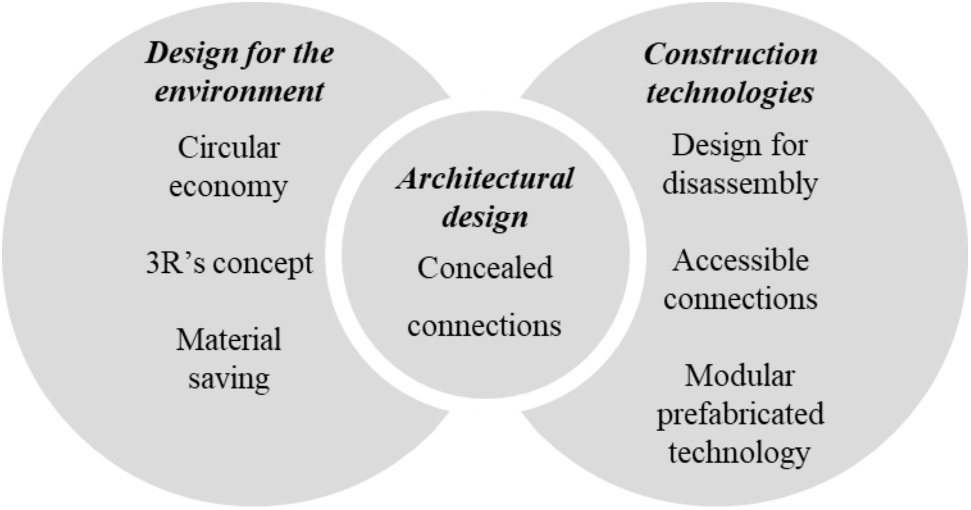

Figure 5.4 – The theoretical framework of interconnection design adapted from publication IV

The following section discusses each effort to conceal each of the disassemblable joints. The joints are critical to enabling this building in achieving a high circularity index. The design *modus operandi* was simple and the following design criteria needed to be met to reframe the public perception of prefabricated construction in Australia (Navaratnam, Ngo et al. 2019):

- It should be possible to dismantle the building into eight modules so that it can be moved,
- Waste created from removal or renovation must be eliminated or reduced;
- Connection details had to be engineered and practical to implement for a full-scale building.

In accordance with this design criteria the following sections will discuss in detail the interconnections necessary to facilitate circular economy building design. L3 is a full size building, a constructed building that meets the Building Code of Australia for commercial construction (Australian Building Codes and Global 2001). The following section discusses the internal and external finishes, as well as structural and service connections which facilitate the circular economy of the L3 case study.

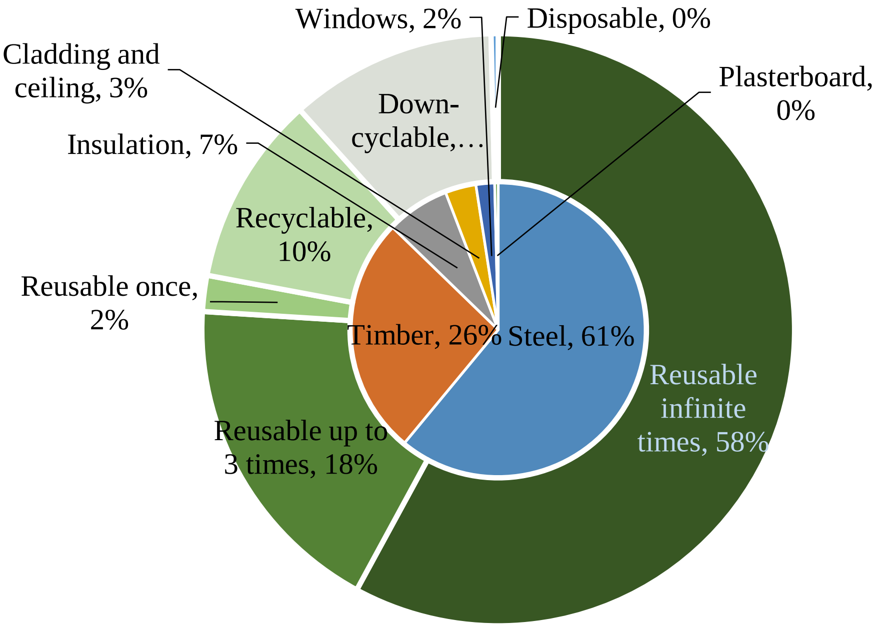

Figure 5.5 – Pie and doughnut chart of material and next product use of materials used in the Legacy Living Lab adapted from publication IV

5.2.1 Steel

The structural steel frames used in this case study were recovered from the recycling stream after they were manufactured for a project which lost funding through bankruptcy. This project alone left 42 frames constructed with no end-of-life use or commercial value. Although steel is a highly recoverable resource, recycling steel is a carbon intensive process (Minunno, O'Grady et al. 2021). To save the energy required for transport and recycling, the buildings were re-engineered to be used as there were with only minor adjustments required to create the steel frame for the building. This allowed 18 tonnes of steel to be reused, with the new structures now engineered for the large overhang spans and sandblasted to remove surface rust which had accumulated while the frames were stored.

Table 5.3 – Steel components used in the L3 case study by mass (kg) and their resilience metric. In=reusable infinite times, 3t=reusable up to three times, 1t=reusable once, Rc=recyclable, Dc=down-cyclable, D=disposable (adapted from publication IV)

Component description	***Material resilience***	***Mass [kg]***
Steel chassis and load bearing structure.	(In)	16,138.9
Stairway steel structure.	(Rc)	422.8
Lightweight steel structure, internal walls.	(In)	3,590.3
Steel sheets used at the first floor for external cladding.	(In)	652.1
Steel sheets used for roof covering.	(In)	531.3
Bolts and nuts	(Rc)	97.7
Screw pile lightweight steel foundations.	(Rc)	735
Total weight		***22,168.10***

Wall frames

The building components were connected using screws, enabling wall frames to be disassembled back to their initial parts at the end of life. The wall frames were designed to be discontinuous (Figure 5.7) so that a section could be removed without the whole wall having to be cut out (Figure 5.6). This will also increase the ability to disassemble the structure without mechanically operated lifting equipment, increasing the likelihood the building will have correct waste separation at its end of life.

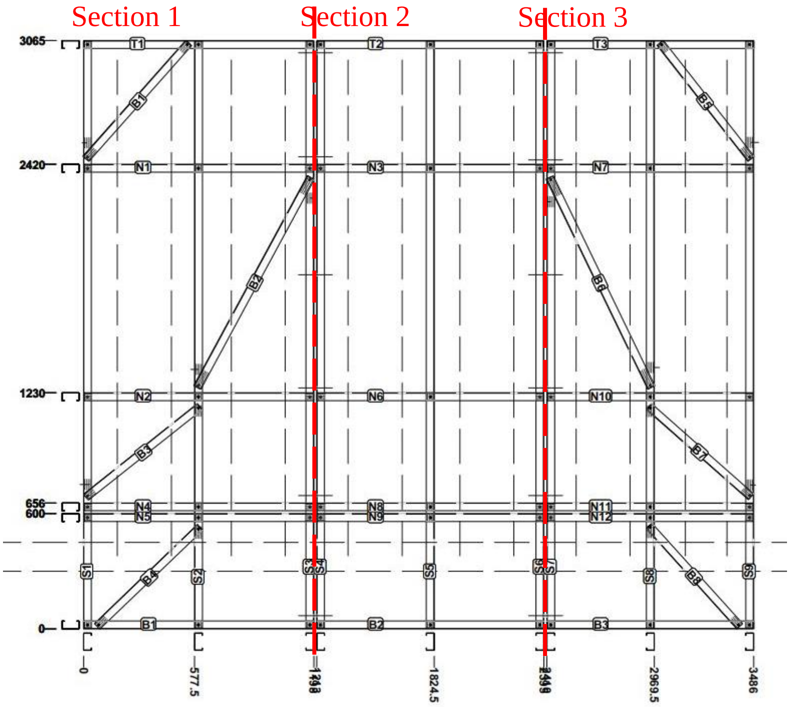

Figure 5.6 – FRAMECAD wall sections, typically built in a single piece, were split into three sections to decrease the weight of each section from 60.6 kg to 20.2 kg. The red dashed lines define the three sections. Publication VI

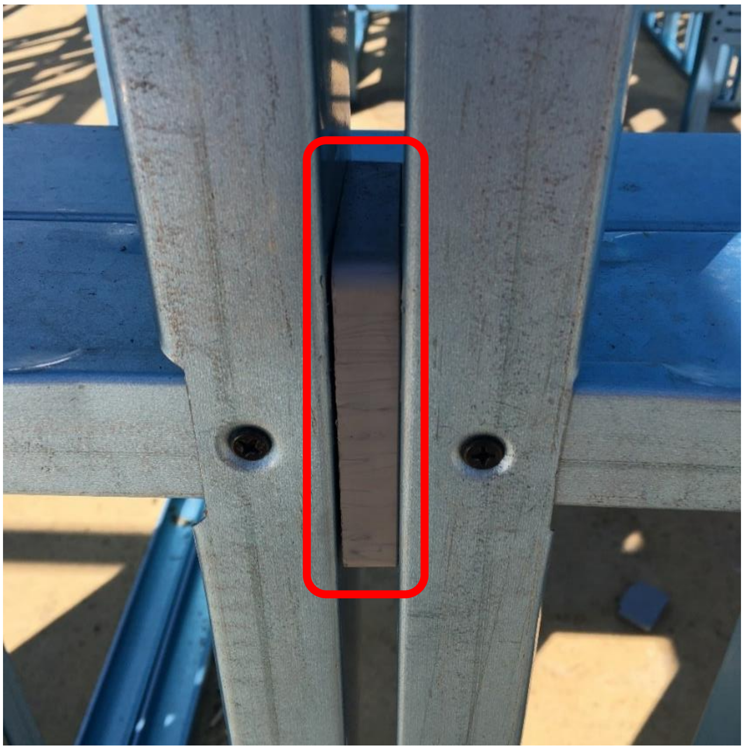

Figure 5.7 – Plastic packers seperated the individual frames, screwed from each side to enable easy disassembly

The structural steel frames were designed so that structural connections were bolted, and concealed behind internal finishes. The bolted connections consisted of 68xNo 16mm bolts. This method was selected as a typical prefabricated building of this size would typically be welded in-situ once delivered to site. Bolting the buildings structure eliminated the need for a chemical join or weld, as would be the case in concrete or traditional steel framed structures.

Internal Balustrading

The internal staircase of L3 spanned two stories and therefore careful consideration had to be paid to the balcony balustrade in order for it to be disassemblable during the relocation of L3. To maximise the level of work completed off-site, and to allow instant fall protection during assembly, the balustrade was manufactured in two sections, each contained in separate modules. Figure 5.8 shows the dot-matrix scan and overlay of the balustrade in position and no connection can be seen between the top and bottom module. The handrail on the opposite side was fixed to the wall with screws so that the rail is the only component that is removed prior to transportation. By selecting this installation method, screws are used *in lieu* of welded connections.

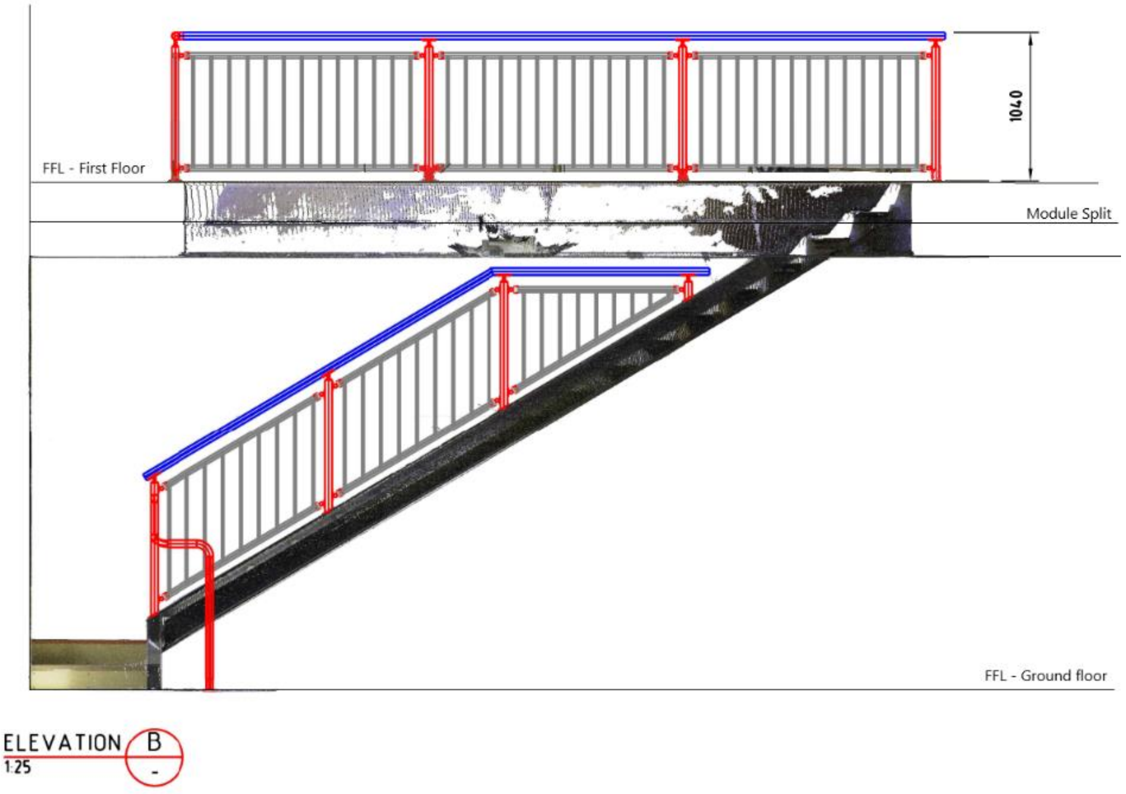

Figure 5.8 – Balustrade Design scan. The balustrade design fosters disassembly, running under the ceiling on the ground module and being self-contained within the first floor module.

Roof and Wall cladding – First Floor

Two different external cladding materials were selected for L3. The use of two different materials enabled the join between the ground floor modules and the first floor modules to be disguised. All building typologies require a flashing to be used to join different cladding materials, thus, people would not be able to see the join in the modules. The wall cladding was also designed so that sheets overlapped on module joins, as not to draw attention to the modularity of the building. If this had been a typical modular building, a joining strip would have ran the entire length of the building, causing the negative perception of a cheaper building to perpetuate. Corrugated steel was selected as the wall cladding due to its high resiliency and ability to be recycled at the end of life.

Footing System

The footing system as designed and specified by the modular builder consisted of a concrete pad footing and a concrete ring footing to maintain an adequate air gap under the building (Figure 5.9 (a)). The engineer's drawings show two different sized concrete footings to be used depending on the load transfer (0.38 and 0.64m^3). The specified amount of concrete to be used was 19.85 tonnes. Concrete footing systems have limited reusability and concrete can only be downcycled, rather than recycled (Zhang, Hu et al. 2020). There are limited second life opportunities for concrete footings, however transport, cranage and relocation costs make this unfeasable.

To reduce the impact of using concrete, a new footing technology was implemented which uses a series of micropile foundations to support the structure. The micropiles are skewered in at predetermined angles through a top-plate which the building is bolted to (Figure 5.9 (b)). This system allows for easy disassembly at the end of life and allows for recycling of the steel, as opposed to downcycling of concrete.

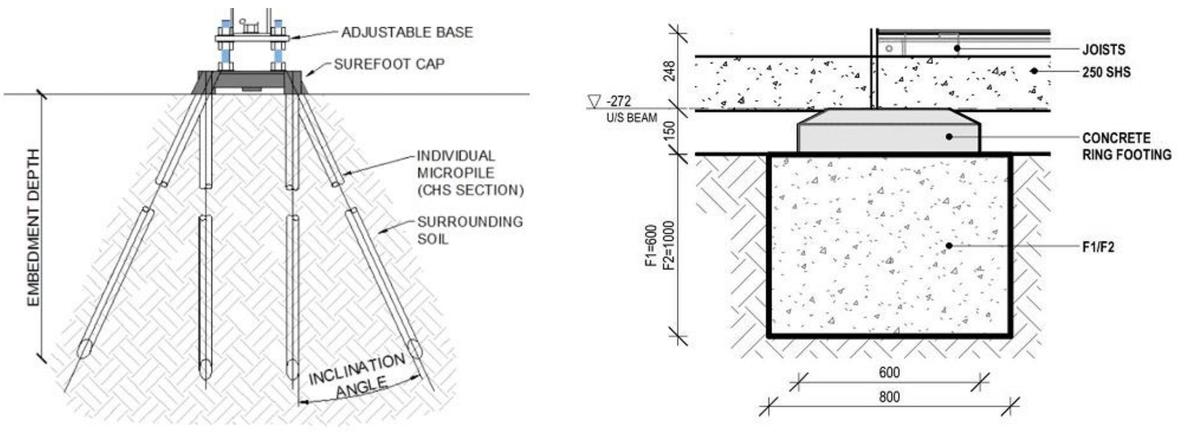

Figure 5.9 – (a) Concrete free micro pile system used as the foundation of L3 (Mehdizadeh, Disfani et al. 2017) (b) Traditional footing design, mass concrete footing with a concrete ring.

5.2.2 Timber

The mass of timber components used within L3 and the associated material resilience metric is detailed in Table 5.4.

Table 5.4 – Timber components used in the L3 case study and their resilience metric. In=reusable infinite times, 3t=reusable up to three times, 1t=reusable once, Rc=recyclable, Dc=down-cyclable, D=disposable

Component description	***Material resilience***	***Mass [kg]***
Pressed fibre particle board used as floor structure.	(Dc)	4,102.6
Plywood covering internal walls and the first floor ceiling.	(3t)	3328
Pressed timber used as ground floor external cladding.	(3t)	1,811.7
Reused timber stair treads.	(3t)	164
Internal timber doors.	(In)	138
Total weight		***9,544.30***

Timber benchtops and stair treads

The internal timber stair treads and bench tops were created using an existing set of red gum stairs which were salvaged from a historic flour mill located close to the case study location (Figure 5.10 (a)). The timber was reworked (pieces laminated to suit the rise and run of the steel stair structure) and sanded to be reinstalled into the L3 building.

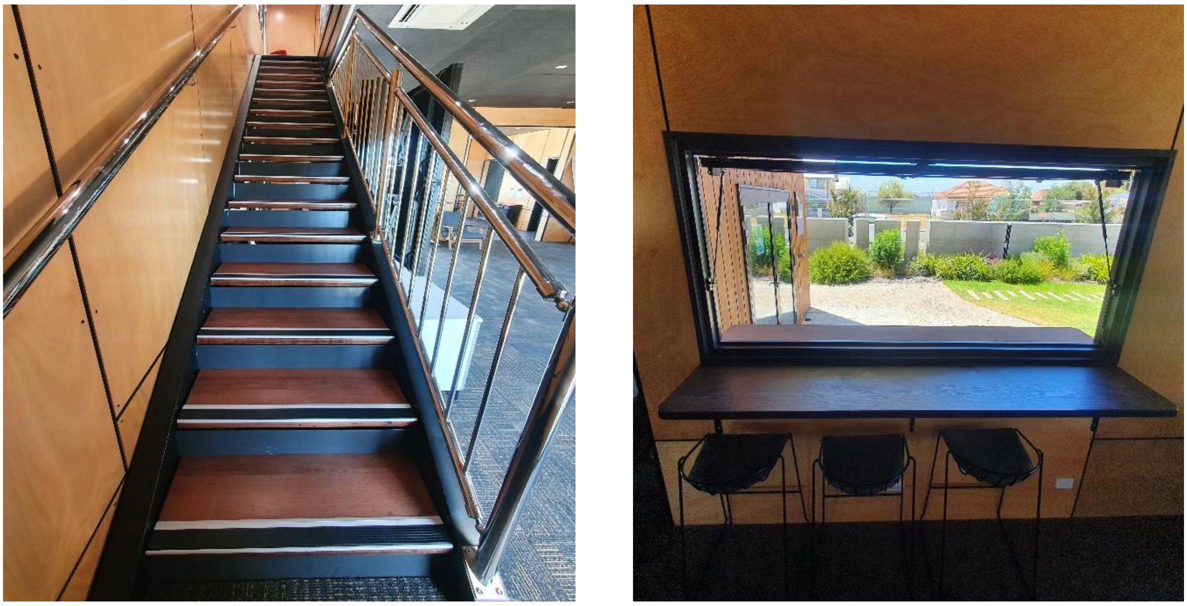

Figure 5.10 – (a) Reused Red Gum stair treads salvaged from a historic Fremantle building (b) Cyprus factory trusses repurposed into indoor-outdoor bench space (pictures by author)

The internal/external dining space benches (Figure 5.10 (b)) are also made from resources recovered from existing structures. The Cyprus timber was originally installed as factory roof trusses and recovered by a timber recycler to be laminated to make the timber slabs which are now the benchtops.

Internal wall lining

Traditionally, buildings are finished internally with a plaster wall, either drywall gypsum sheets (for steel or timber framed building) or a float finished wet set plaster (used in brick and concrete structures). Designing a circular economy building forces reconsideration of the wall lining as there needs to be access maintained for refurbishment and maintenance, as well as the removal and relocation of the building itself. To circumvent this issue presented by common construction techniques I designed a plywood wall lining system which enabled each wall panel to be removed and reinstalled without creating any waste. This system allows access to plumbing, electrical, insulation and duct spaces for easy modification and disassembly throughout the buildings lifecycles as well as the installation and development of new materials; the plywood design ensures a majority of sheets are in standard material sizing of 2400 x 1200mm. The plywood has a natural grain finish and is protected by a clear urethane coating on both sides to protect against moisture penetration from the wall cavities. The plywood sheets are located by an aluminium negative detail, allowing installers to have a working edge during the removal and reinstallation process.

Creating an architectural negative detail has a second value to the project, as it draws occupant attention away from the module joints. Traditionally, modules would have a plastic strip to join the two pieces of plaster on the internal wall lining. Installing the plywood panelling means that the joins are shifted from obvious places and minimal sheets can be removed prior to the building being moved. Figure 5.11 shows the ceiling design with sheets facing lengthways over module joins to reduce the amount needed to be removed for transport. The system is fixed into place with screws and if care is taken can be removed and re-installed many times. To account for possible poor workmanship a total of three times is allocated for the reusability of the wall systems.

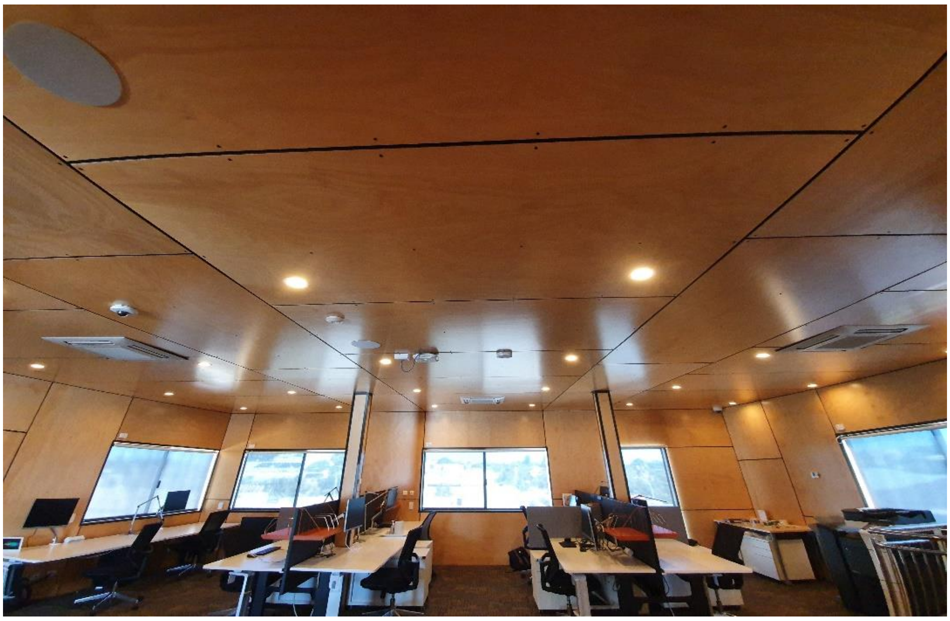

Figure 5.11 – Plywood ceiling design photo by author

External wall cladding

Typically cement sheeting is used for wall cladding in modular construction for its durability and resistance properties. Due to the high embodied energy, and limited end of life opportunities, the cement sheet needed to be replaced. The material selected was a manufactured timber product made from pulped timber and wax which is heated and pressed into a solid board. The material is stronger than a natural timber, but still looks and performs in a similar way (rough sawn look and discolouration) to a natural timber.

To ensure that the buildings aesthetic remained, external module joins were designed to meet at external angles, so that standard aluminium mouldings could be used, and again, the modularity of the buildings would go unnoticed. Typically the wall cladding is fixed using a nail, however, as the building would have to endure transport on trucks, and to promote the removal and reuse of the material, screws were used. Aluminium joining strips were colour coded to allow the material to look as close to natural as possible while enjoying the reduced maintenance of an engineered product.

5.2.3 Cladding and floor covering

Table 5.5 – Cladding and floor covering materials used in the L3 case study by mass (kg) and their resilience metric. In=reusable infinite times, 3t=reusable up to three times, 1t=reusable once, Rc=recyclable, Dc=down-cyclable, D=disposable

Component description	***Material resilience***	***Mass [kg]***
Vinyl covering floors in wet areas.	(1t)	714
Magnetic felt ceiling.	(3t)	333.7
Carpet covering 193m2 of internal floors.	(3t)	183.4
Plasterboard cladding, used in kitchen/bathroom areas and ground floor ceiling.	(D)	140.2
Total weight		***1,371.30***

Noise cancelling acoustic felt was used for the ceiling space in the ground floor areas and upstairs apartment breakout space. This was selected due to the increased likelihood of conversation and to counter the ambient noise downstairs due to the high ceiling height of 3m. The acoustic felt also provides a quality soundscape for the visualisation centre. To increase the ease of disassembly, a new method of fixing the noise cancelling panels was trialled. The sheets followed the same design layout as the first floor plywood discussed in Section 5.2.2, i.e. to promote ease of access to structural connections, reduce the materials to be removed for transportation and to limit focus of module joins. The fixing method, however, was completely new. The 2400 x 1200mm panels each had 3xNo. Steel tracks attached to their internal face. Each of these steel tracks corresponded with 4xNo. 15kN rare earth magnets. The combined magnetic force over a panel was 180kg with a panel weight of just 4.9kg. The ease of assembly and disassembly enables reuse and the acoustic felt panels themselves already contained a high proportion of recycled PET bottles which promotes the CE material flow by avoiding products containing virgin materials.

Carpet Tiles

Carpet tiles have been widely used in office environments since the late 1950's. The modular design of the carpet tile promotes CE as an entire carpet is not ruined by a single stain of tear (life extension), however paints and floor covering products have been identified as major contributors to Volatile Organic Compound (VOC) emissions, with carpet adhesives providing the second largest emission rate of VOCs behind wall and floor construction adhesives (Crump, Squire et al. 1997, Yu and Crump 1998). To counter the release of VOCs, a double sided tactile pad was used to join the corners of each tile together, instead of a solvent to fix the tiles to the substrate.

The carpet tiles used in this project were recovered from an office building in Perth CBD. The building had yet to be rented as a reduction in CBD office space was needed, the building sat vacant for 2 years. This was a significant inclusion in the project as the production of carpet tiles in the EU alone represents 100 million kg per annum of a largely non-renewable resource (S.Shuttleworth 2007), so having a product that was re-used, and fixed in a way made the choice easy for this project. Using the tactile pads for installation also meant that the carpet tiles could be moved from their second life to a potential third with very little effort required for disassembly.

5.2.4 Insulation and Glazing

Table 5.6 – Insulation and glazing materials used in the L3 case study by mass (kg) and their resilience metric. In=reusable infinite times, 3t=reusable up to three times, 1t=reusable once, Rc=recyclable, Dc=down-cyclable, D=disposable

Component description	***Material resilience***	***Mass [kg]***
Aluminum, stainless and glazing.	(3t)	744
Insulation	(Rc)	2516
Total weight		***36,343.70***

In most construction typologies windows can be easily disassembled and reused (Krikke, Blanc et al. 2004, Schultmann and Sunke 2007, Eberhardt, Birgisdottir et al. 2019). This is not always the case for double brick construction (the dominant residential building approach in Western Australia). To have a greater impact on the construction industry where L3 was built, we used standardised sizing, again with dimensions 2400 x 1200mm to enable the development of new products to be retrofitted into the project.

L3 also acted as a test site for a new type of window, which was the result of a cost engineering effort to try and maintain the functional scope of the building (see Section 4.4). To install operable bi-fold serving windows in the building was going to cost approximately AUS $16,000. After several meetings with the chosen industry partner on possible ways to reduce the cost and maintain the function of the serving window, the idea was raised to use a commercial glazed door, turned on its side with gas struts installed to hold the weight of the glazed panel in the air. This innovation was a great success and is currently installed in the building and the prototype has led to these windows being added to the list of products sold by the supplier. The window has a few distinct advantages being that it offers a level of inclement weather protection, it has a larger viewing area than a bi-fold window and the three were installed for only AUS $6,800, a saving of AUS $9,800. The final glazing design element added to promote the CE of L3 was the window reveal located on the West facing elevation of the building which is located in the same position on the ground and first floor. The reason for a full height window in this location was in preparation for an elevator reveal if needed in the next stage of the buildings lifecycle (Figure 5.12).

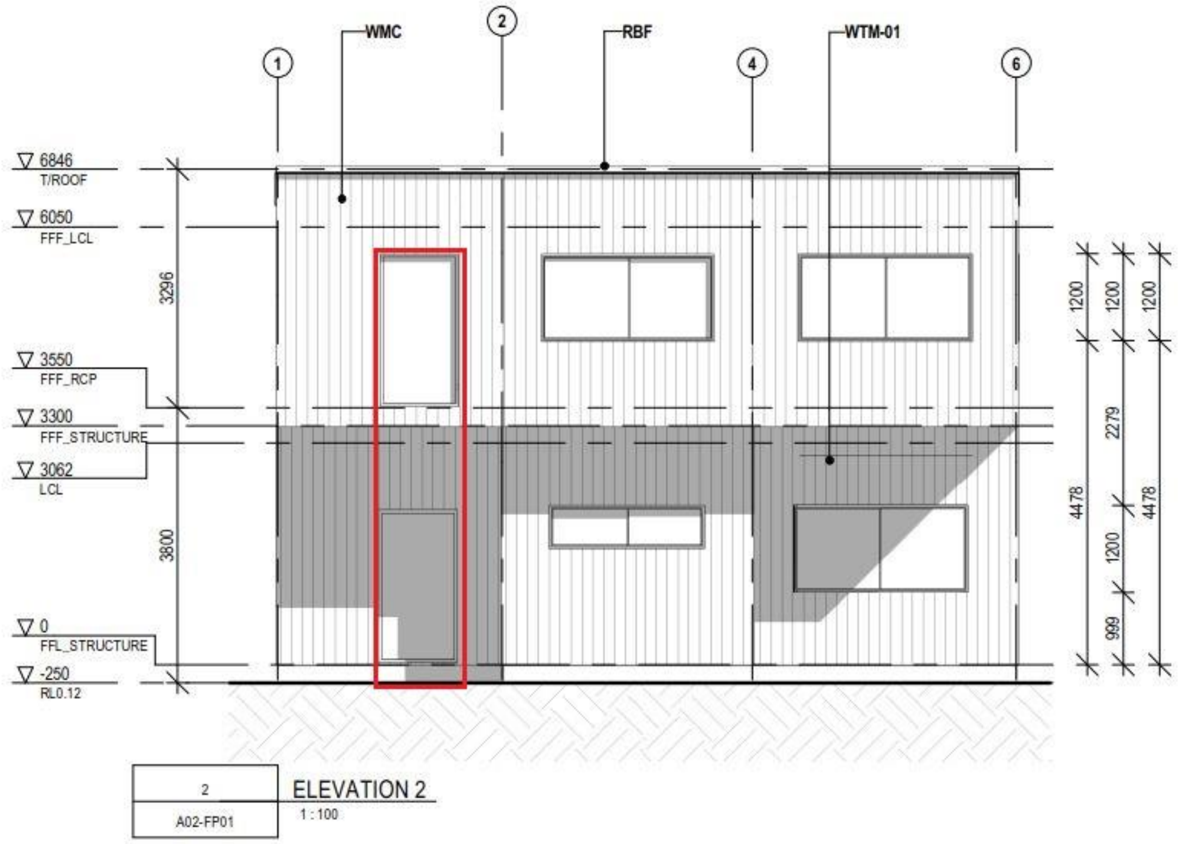

Figure 5.12 – Windows to serve as future elevator reveals (outlined in red)

External balustrade

The external balustrade has been designed in a way where it is easily removed during the transportation of the building. Transport dimensions, especially height, are a major consideration when designing modular prefabricated buildings (Motte 2019). For this reason, the balustrade system needed to be disassemblable as it is fixed to the roof of the ground floor modules and would be over the maximum 4.3m height restrictions for transport on major road corridors. To facilitate the easy removal of the balcony's balustrade system studs were drilled and tapped to the structural steel frames, ensuring the posts would be solidly supported. The glass between the posts was held in place with a grub screw, which meant the panels could be easily removed and relocated into one of the modules. The handrail would need to be removed due to its size, so it was not welded onto position. Alternatively a thread was drilled and tapped from below the handrail into the 90 degree bends to ensure a sound connection. These measures negated the need for Tungsten Inert Gas (TIG) welding, and cutting in order to modify the balcony balustrading, and have not impacted the functional strength or the aesthetic appeal of the system.

5.2.4 Water proofing and plumbing details.

Balcony waterproofing design

Designing a disassemblable, waterproof balcony system proved one of the more difficult challenges of the project. The design issue arose once it was realised that the balcony would span two modules. Having a corrugated iron roof with a timber balcony above was my initial idea to solve the issue, however, with the restrictions in floor height from the first floor this idea proved unfeasible. The solution to this problem was to have the balcony fall away from the first floor to a guttering system. This idea would provide a balcony which would not require a change in height to traverse internally to externally. The issue still remained as to waterproofing the balcony in a way in which it would be disassemblable. A flashing design was configured which draws inspiration from a traditional silo tank design. In locking together the two waterproofed edges, the gap between the two modules would be covered by an over flashing in order to form the waterproof barrier (Figure 5.13 (a)). The returning (high side) would employ a traditional over flashing design to achieve an adequate seal from the elements (Figure 5.13 (b)). The balcony was constructed at a 1:90 degree fall away from the first floor

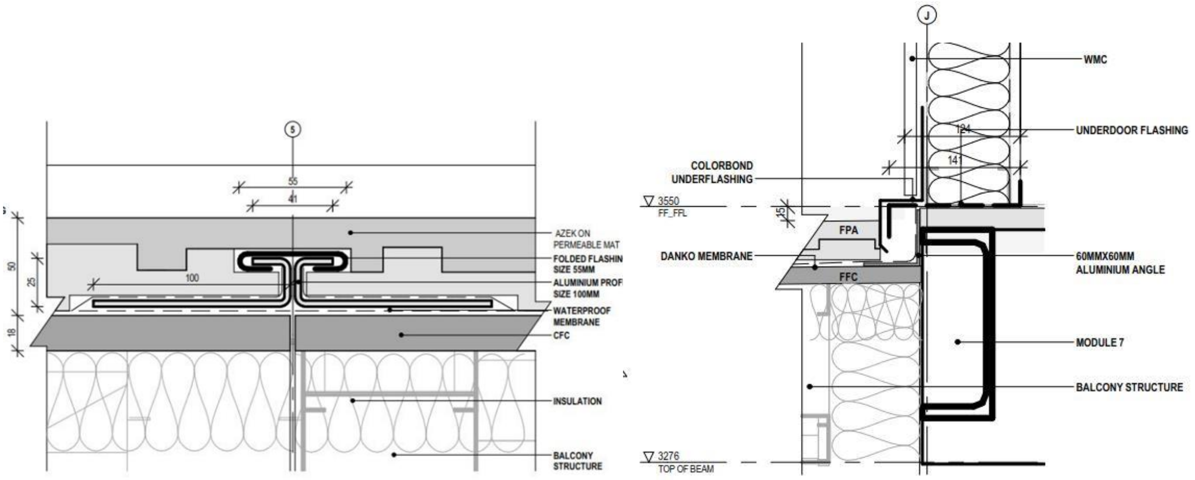

Figure 5.13 – (a) silo flashing as it appears in section view facing up the balcony (b) Return flashing at the top of the balcony where the intersection waterproofs the first floor modules with the ground floor modules

of the building, allowing rainwater to travel through the paving system, onto a waterproof trafficable membrane, to be collected by a gutter and captured as stormwater (Figure 5.14).

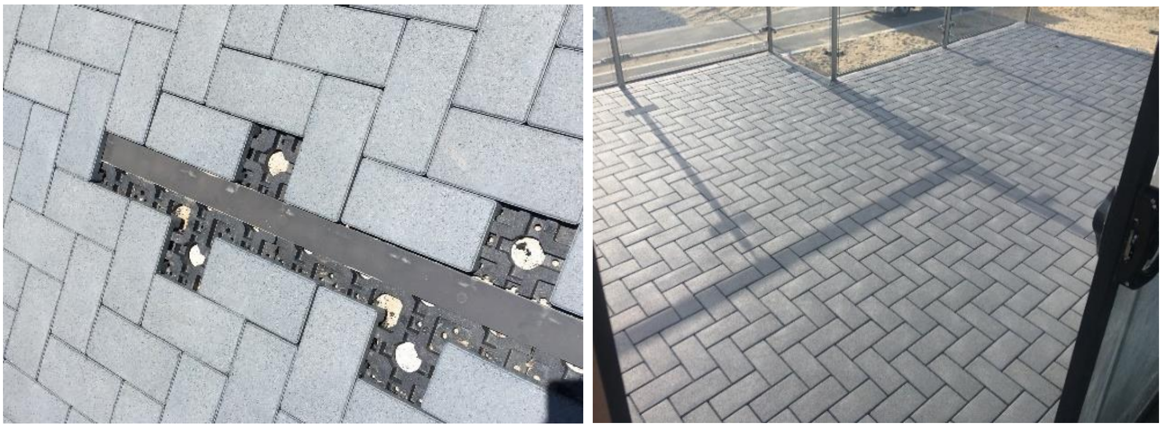

Figure 5.14 – (a) a plan view of the finished silo flashing (b) the finished balcony with the flashing design hidden by the recycled interlocking paving system

Plumbing

The plumbing pipework selected for L3 was a disassemblable brass and PEX piping system. The brass fittings have specially designed teeth which bite into the piping securing the pipework in position, however these fittings can be disengaged by the use of a specific tool which will enable the pipe to be removed and re-fitted. This system was designed so that modules could be individually isolated when it was time for disassembly. This was achieved through access hatches in the bathroom modules roof space cavity which allowed the disconnection of the hot, cold and wastewater drainage systems.

5.3 Building Automation Systems

The Legacy Living Lab was designed to foster research on building automation, by incorporating a design which meant the upgrade and installation of components could be easily facilitated without creating waste, and also by installing a variety of automation and monitoring equipment. The SLR (Publication III) uncovered that a mixed research method (qualitative and quantitative methods in case studies) was needed to capture the human experience if the energy savings were going to be maximised through human acceptance (Figure 5.15). To prepare for this much needed research and in an effort to design a CE building to the furthest extent a range of BAS technologies were installed in the L3 prototype. The installed technology was designed to monitor the energy consumption and improve the indoor environment quality of the building. To enable future research, a range of agnostic technology was used, so that data collection would be through a third party aggregator, enabling easy transfer of data.

To replicate the technology hierarchy stack from Publication III the following technology was implemented in L3:

1. Component – PIR Sensors, LUX sensors, thermostats
2. Device – Blinds, lights, power points switches
3. Process and communication – PLC to control light levels, energy tags on each of the electrical circuits to monitor consumption.
4. Macro – The building sits within an estate which has its own battery and energy grid.

The three phases of building automation are discussed in sections 5.3.1- section 5.3.3 below in accordance with the research framework (Publication III) which influenced the design for L3.

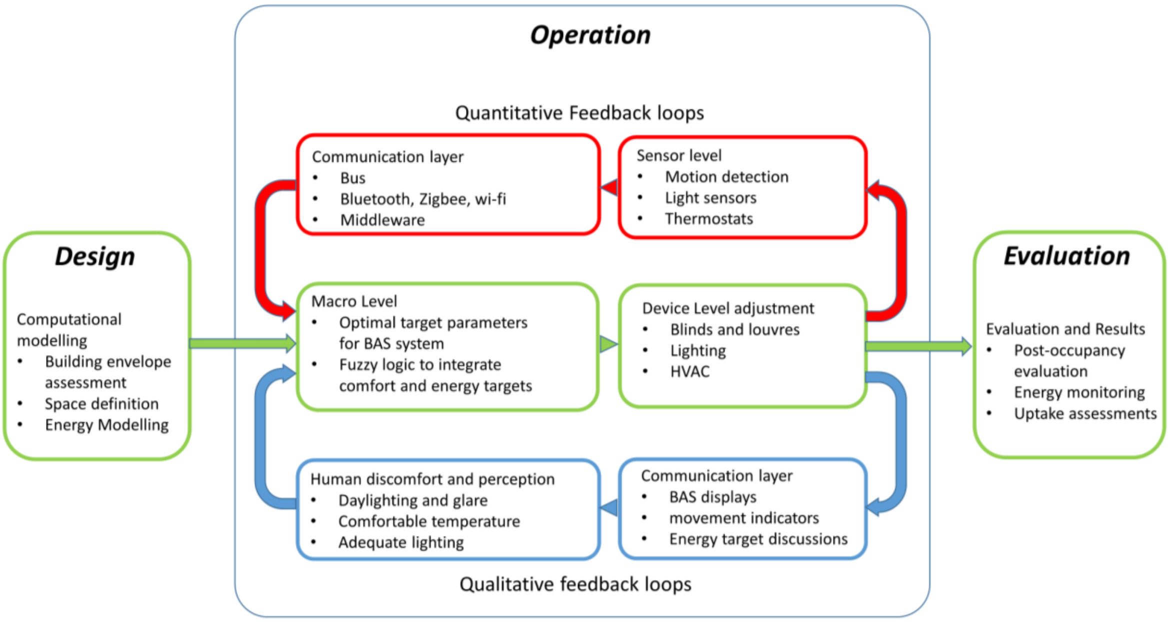

Figure 5.15 – Research framework for BAS with qualitative (blue) and quantitative (red) feedback loops to advance BAS development and research. The section in which each area is reviewed in the text is indicated adapted from Publication III

5.3.1 Design

The aim of the building design was to incorporate the CE as much as possible. The design focused on incorporating a lightweight, well insulated building as a complete contrast to the local building delivery. To continue research into building improvement, there were elements of the building where the most efficient materials were not selected. The windows in L3 are the minimum specification allowable under the Australian building design codes. The reason for this is that the minimum standard windows are installed in the majority of buildings throughout Western Australia. Working with a leading window supplier, we were able to trial a new design which allowed for simple retrofit to change their minimum specification window panes to high performance double glazed units, with minimum re-work necessary to the existing frames. This is a crucial detail, as the double-brick construction in Western Australia means that window frames are often cemented into position, involving major works to switch to double-glazing.

This research partnership also allowed us to gather the data from the single-glazed L3 to monitor the improvements of energy consumption and temperature data across the building before and after the change. The highly insulating thin double glazing was recently installed to replace the original single glaze. The energy and temperature data, once peer reviewed, could be given to the WA building industry to raise awareness, and reduce the overall energy consumption of buildings. In addition to this, future students could use the facility for research into energy saving technology and improvements into indoor environment quality.

The first floor of L3 is the designated BAS research area, therefore, windows also have no eaves, which is a simple way to reduce heat transfer into buildings. These basic measures have not been ignored in this design phase, rather, the windows act as a test case to provide data to our industry partner, including data on energy savings available by installing automated blinds. As the windows will be tested from single to double glazing (phase 1), they will also be tested with and without automated energy saving blinds (phase 2), providing a holistic reference point for the WA building industry at the completion of the project.

5.3.2 Operation

To collect the quantitative data necessary to compare internal environment quality for future research the following sensors have been installed.

Temperature, light and relative humidity sensors – UBIBOT Wi-Fi sensors are located on the first floor of L3 where comparative research into windows is taking place. The WS1-Pro (Figure 5.17) unit is located on the North facing wall of L3 and has been installed with internal and external temperature probes, allowing the outdoor temperature to be collected as a reference for internal heat gain across the window. The monitored window is also equipped with automated block out blinds for phase two of the future research into windows. Heat gain through windows is dependent on the layout of the building and air and occupant movement throughout the day. To monitor the heat drift and temperature across the monitored area, UBIBOT WS1 sensors have been positioned across the floor level (Figure 5.17). These sensors also monitor light levels throughout the day as the installed blinds self-adjust according to sun movement to achieve acceptable light readings for building occupants.

Figure 5.16 – Different monitoring equipment used in the research area of L3 as detailed in Figure 40

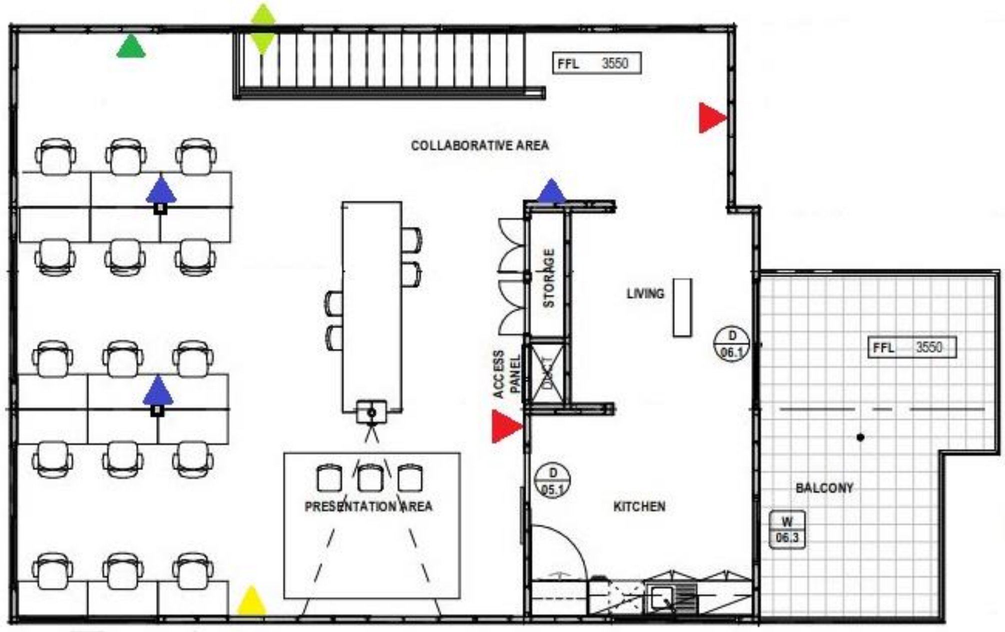

Figure 5.17 – BAS research floorplan - level 1. Green - UBIBOT PRO, Lime Green - internal and external sensors on test window, Blue - UBIBOT LS monitors, Red - Delos Circadian rythym LCD screens, Yellow - Delos internal air quality monitoring equipment

CO_2, TVOC and particulate matter (less than 2.5 and 10 μm) – In addition to the UBIBOT temperature, light and RH sensors, Delos air quality sensors have also been installed to monitor the internal health of the building. This system monitors the effect of a HEPA filtration unit which cycles air within the building during operation (Figure 5.16).

Automated blinds – Automated blinds have been installed in the building to reduce glare and heat gain through windows, resulting in improved energy efficiency and comfortable working environment. The block out roller blinds have individual motors and are adjusted by two external Somfy LUX sensors, one for each of the walls exposed to direct sunlight. The North facing wall of the building is exposed to a longer duration of sunlight throughout the day, allowing natural light to enter through the West facing windows and as the sun sets, the windows are gradually opened to allow natural daylighting from the North whilst reducing solar irradiation from the West.

LED lights – To compliment the blinds a new circadian rhythm lighting system was installed. The DARWIN system is aimed to follow the natural light colours during the day to improve the light of the work environment through the course of the day. The suns light path is displayed on two LCD screens so that occupants aren't exposed to harsh light levels throughout the day.

Smart switches – Smart light switches and general power outlets (GPOs) were installed in L3 to display technology which would be offered to prospective buyers. The new technology from Zimi features a changeable interface and technology card which allows the configuration and upgrade of the switch to be enabled over the Wi-Fi network. This adds to the CE values of the building and facilitates an easy switch from 2.7 GHz to 5 GHz (5G) Wi-Fi in the near future, with the need of only a technology card update. The Zimi GPOs also have the ability to track power consumption and instantly turn the power supply off if occupants are using appliances which are over a pre-set threshold.

5.3.3 Evaluation

The evaluation of results relies on the quantitative data and qualitative data which will be collected over two years and published across phase 1 and phase 2 of the window installation. Occupants who use the building will fill out surveys on the internal comfort of the building as the CE windows are installed to be cross referenced with energy saving data.

Energy Monitoring – L3 has 20 monitored energy circuits, covering all HVAC, lighting and Power loads as well as the total solar export from the buildings 8kW inverter. Tracking the energy consumption will allow the validation of results from the installed monitoring system and enable the value of saving to be quantified.

Although the results of this research are ongoing, and it is to be included in the future research (section 7.1), it is worth noting that there is a significant amount of design work which has been included based on the SLR into the creation of the building, not only to future-proof the design, but also to foster ongoing research.

5.4 Results for the Life Cycle Assessment

With the design and construction of the L3 case study as detailed in sections 5.2 and 5.3 a comparative life cycle assessment was undertaken (Publication V) to compare the benefits of designing towards circular economy building, L3 is categorised in this section as subscript C, and building in a linear fashion with the exact dimension categorised as subscript L. (Note the BoQ and plans used for building L were introduced in section 4.4). The life cycle stages of the Circular L3 are characterised by:

- A_C: reused materials, addition of some raw materials, and assembly of the building.
- B_C: refurbishment and renewal of internal and external finishes. This LCA stage has minimal impact in the circular L3, as all glued and welded connections were replaced by bolted (nut and bolt) or screw connections, making walls and ceilings accessible without having to destroy or cut wall finishes.
- C_C: disposal of the materials that are not reusable or recyclable.
- D_C: discount of CO_2 equivalent emissions attributed to reuse and recycling of components (e.g. steel components, aluminium, and plasterboard).

Similarly, the life cycle stages of the linear version (L) are characterized by:

- A_L: entirely new components, and assembly of the building.
- B_L: refurbishment and renewal of internal and external finishes.
- C_L: disposal of the materials that are not recyclable.
- D_L: discount of CO_2 equivalent emissions due to recycling of materials (e.g. steel, aluminium, plasterboard).

The results of the LCA reported in Publication V were expressed through six environmental indicators: embodied carbon (expressed in global warming potential; GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), abiotic depletion (AP) and embodied energy (expressed in abiotic depletion of fossil fuels; ADFF). In carrying out the comparative LCA of the L3 for Publication V, the decision was made to adopt the entire building as the functional unit.

The results of the LCA show that the circular L3 outperforms the linear version over its lifecycles in all environmental indicators included in this study. In terms of embodied carbon, the circular version of L3 emits 5.4 t CO_2 eq, while the linear L3 emits 44.5 t CO_2 eq, representing a saving of 88% of embodied carbon (Figure 5.18). A more detailed explanation of the LCA results are presented in Publication V.

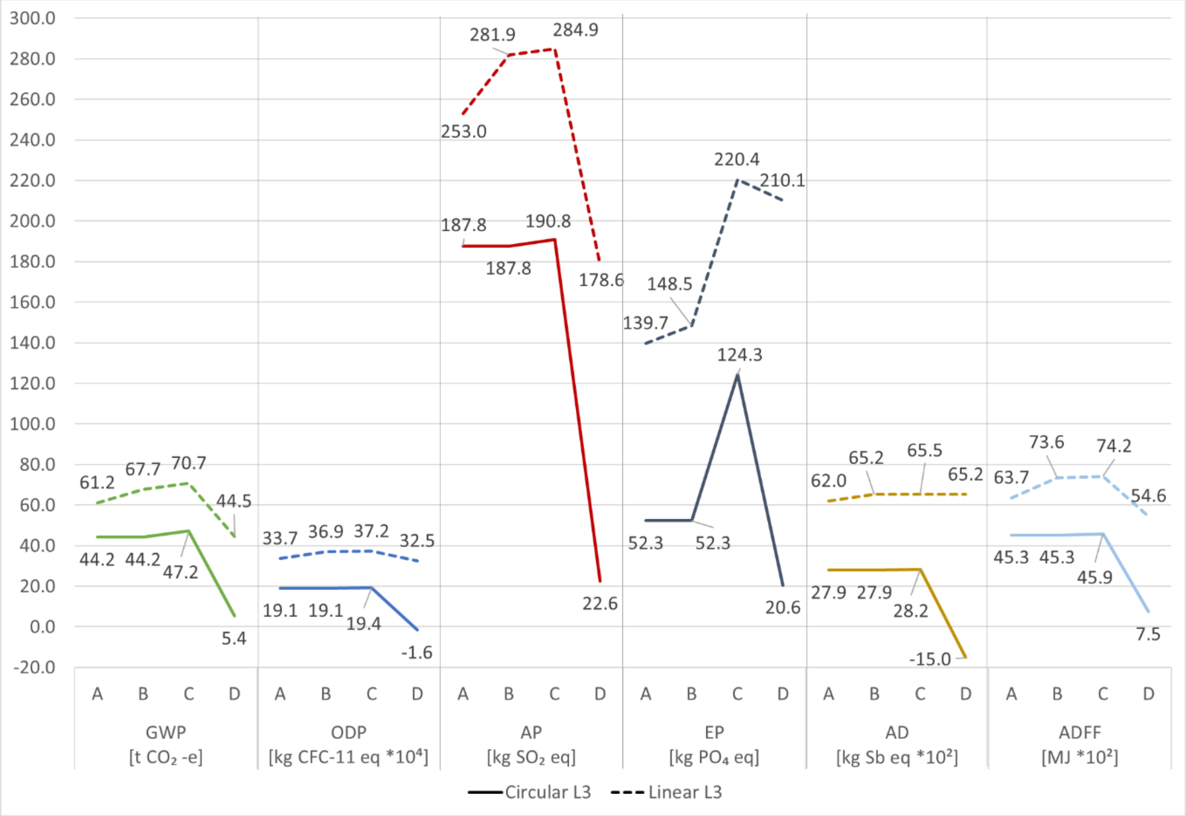

Figure 5.18 – Comparison of the LCA of the circular and the linear versions of the L3. Continuous lines represent the circular L3, dashed lines represent the linear L3. Extracted from Publication V.

The results of the LCA concluded that the circular version of the L3 had significant benefits over the linear version in the environmental impact assessment. As this point in the analysis it was evident that adopting the CE strategies (publication I) with the consideration of improved LCA guidelines and assessment (Publication II and V) would reduce the environmental impact of buildings. With this new addition to the body of knowledge, a gap emerged as there was no indexing system to calculate the level of circularity (circular economy) of the building industry. The following section details the development of a circular economy indexing system, along with the expansion of scope from two comparisons of building typology from two to four.

Table 5.7 – Life cycle impact assessment of the circular, design for disassembly and reuse L3 (C) and its linear version (L), divided in the four LCA stages: A, production; B, operation (refurbishment); C, end of life; D next product system.

	EE (GJ/m^2)	***GWP (10^2 kg CO_2 eq/m^2)***	***ODP (10 kg CFC-11 eq/m^2)***	***AP (10^{-1}kg SO_2 eq/m^2)***	***EP (10^{-2}kg PO_4 eq/m^2)***	***AD (kg Sb eq/m^2)***
A_C	44.2	19.1	187.8	52.3	27.9	45.3
B_C	~0.0	~0.0	~0.0	~0.0	~0.0	~0.0
C_C	3.0	0.3	3.0	72.0	0.2	0.6
D_C	-41.9	-21.0	-168.2	-103.7	-43.1	-38.4
TOTAL	***5.4***	***-1.6***	***22.6***	***20.6***	***-15.0***	***7.5***
A_L	61.2	33.7	253.0	139.7	62.0	63.7
B_L	6.6	3.2	28.9	8.7	3.2	10.0
C_L	3.0	0.3	3.0	72.0	0.2	0.6
D_L	-26.2	-4.8	-106.3	-10.4	-0.3	-19.6
TOTAL	***44.5***	***32.5***	***178.6***	***210.1***	***65.2***	***54.6***

5.5 Results 3DR Index and comparison

The 3DR index was first explained in section 3.4 and is based on the principles of building design, disassembly, deconstruction and resilience. The reusability of buildings is based on a limited number of parameters, such as the tools needed to disassemble and move buildings, and if the components could be reused (if so, the number of times), recycled, down cycled or discarded to landfill.

To validate the L3 case study, a 3DR comparison was applied to four different building types: a circular prefabricated structure; a linear prefabricated structure; a double-brick structure and a timber structure. Hence, the method can be applied worldwide to all types of materials and for many building typologies.

5.5.1 3DR of the circular L3

In calculating the 3DR index of the circular L3, it was important to consider that the building is a disassemblable structure. Thus, parameter b in Equation (1) was set to 0. The remaining parameters a and c were arbitrarily set to 0.5, meaning that the disassemblability of L3 and the reusability of its components were considered of equal relevance. Thus, Equation (1) became:

$$3DR = 0.5 \times DI + 0 \times DE + 0.5 \times R \quad (5)$$

To calculate the values for *DI* and *R*, we used the parameters shown in Table 5.8 (the mass of components and tools needed to disassemble and transport them), enabling the calculation of DI_C (0.51) and R_C (0.84). The $3DR_c$ of the circular L3 was then calculated using Equation (6):

$$3DR_C = 0.5 \times 0.50 + 0.5 \times 0.84 = 0.67 \qquad (6)$$

Equation (6) shows that when the connections between building components, the reusability and recyclability of components and the tools and machinery necessary to disassemble and transport components are taken into account, 67% of the circular L3 was considered circular.

Table 5.8 – Circular L3: DIt, DIm and Ri values.

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Structural materials							
Steel chassis and load-bearing structure	16,138.9	Gas/pneumatic tool	0.5	Forklift	0.4	Infinitely reusable	1
Stairway steel structure	422.8	Gas/pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls	3,590.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Bolts and nuts	97.7	Power tool	0.8	One person	1	Recyclable	0.6
Pressed fibre particle board used as floor structure	4,102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool used in all external walls and ceiling	2,325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Screw pile lightweight steel foundations	735	Hydraulic plant	0.2	One person	1	Recyclable	0.6
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	No tool	1	One person	1	Reusable 3 times	0.9
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Reusable once	0.7
Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Reusable 3 times	0.9
Magnetic felt ceiling	333.7	No tool	1	One person	1	Reusable 3 times	0.9
Plasterboard cladding used in kitchen/bathroom and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber for ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Reusable 3 times	0.9
Steel sheets for first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Infinitely reusable	1

Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Infinitely reusable	1
Aluminium windows and glazed doors	744.0	Hand tool	0.9	Two people	0.9	Reusable 3 times	0.9
Internal timber doors	138.0	Power tool	0.8	One person	1	Infinitely reusable	1

5.5.2 3DR of the linear structure

The same procedure was adopted to calculate the 3DR index of the linear version of the building (designed without consideration of the circular economy framework). To compare the 3DR indices of the linear and circular buildings, we assumed that the linear building was also a steel-framed prefabricated building but with welded connections, glued wall panels and a concrete foundation. Table 5.9 summarises the *DIt*, *DIm* and *Ri* values for the linear version of L3. These parameters enabled the calculation of the values of DI_L (0.31) and R_L (0.36) for the linear version of the L3. Thus, $3DR_L$ was calculated as follows:

$$3DR_L = 0.5 \times 0.31 + 0.5 \times 0.35 = 0.33 \qquad (7)$$

Given the welded building connections, most components were recyclable rather than reusable and the tools and machinery needed to disassemble and transport components, 33% of the mass of the linear version of L3 was considered circular.

Table 5.9 – Linear L3: DIt, DIm and Ri values.

Description	Mass (kg)	Tools needed	*DIt*	Transport tool	*DIm*	Resilience	*Ri*
Structural materials							
Steel chassis and load-bearing components (including nuts and bolts)	16,236.6	Gas/pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Stairway steel structure	422.8	Gas/pneumatic tool	0.5	Forklift	0.4	Recyclable	0.6
Lightweight steel structure, internal walls	3,590.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Pressed fibre particle board used as floor structure	4,102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool used in all external walls and ceiling	2,325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Concrete foundations	19,848.0	Hydraulic plant	0.2	Forklift	0.4	Downcyclable	0.2
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	Hand tool	0.9	One person	1	Downcyclable	0.2
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Downcyclable	0.2

Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glued felt ceiling	333.7	Hand tool	0.9	One person	1	Recyclable	0.6
Plasterboard cladding used in kitchen/bathroom areas and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber used as ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Downcyclable	0.2
Steel sheets used as first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Recyclable	0.6
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Aluminium windows and glazed doors	744.0	Power tool	0.8	Two people	0.9	Disposable	0
Internal timber doors	138.0	Power tool	0.8	One person	1	Disposable	0

5.5.3 3DR of the double-brick structure

In addition to the linear and circular case studies, we calculated the 3DR of a double-brick version of L3, which comprised 122.0 tonnes of bricks, 81.0 tonnes of concrete and 3.1 tonnes of timber roof structure.

Table 5.10 summarises the *DIt*, *DIm* and *Ri* values for the components of the double-brick version of L3. These parameters enabled the calculation of DI_{DB} (0.06) and R_{DB} (0.21) for the double-brick version. Therefore, the $3DR_{DB}$ of the double-brick L3 was:

$$3DR_{DB} = 0.5 \times 0.06 + 0.5 \times 0.21 = 0.13 \tag{8}$$

Given that the bricks and concrete were downcyclable, most components were not reusable and only some were recyclable, the double-brick structure had a very low 3DR index. The tools and machinery necessary to disassemble and transport components resulted in only 13% of the mass of the double-brick version of L3 was considered circular.

Table 5.10 – Double-brick L3: DIt, DIm and Ri values.

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Structural materials							
Brick walls	122,058.0	Hydraulic plant	0.2	Crane/excavator	0.1	Downcyclable	0.2
Timber load-bearing roof structure	3,143.9	Power tool	0.8	Forklift	0.4	Reusable once	0.7
Concrete floor structure, ground and first floors	81,005.07	Hydraulic plant	0.2	Excavator	0.1	Downcyclable	0.2

Steel reinforcement bars	875	Hydraulic plant	0.2	Excavator	0.1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	Hand tool	0.9	One person	1	Downcyclable	0.2
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Downcyclable	0.2
Salvaged timber composing the stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glued felt ceiling	333.7	Hand tool	0.9	One person	1	Recyclable	0.6
Plasterboard cladding used in kitchen/bathroom areas and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber used as ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Downcyclable	0.2
Steel sheets used as first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Recyclable	0.6
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Aluminium windows and glazed doors	744.0	Power tool	0.8	Two people	0.9	Disposable	0
Internal timber doors	138.0	Power tool	0.8	One person	1	Disposable	0

5.5.4 3DR of the timber structure

The fourth example in this research was the calculation of the 3DR of a typical building built with a timber frame. Similar to the linear and double-brick structures, we assumed that the finishes were the same as those used in the circular L3. A timber two-story building typically requires concrete foundations and brick footings.

Table 5.11 summarises the *DIt*, *DIm* and *Ri* values of the components of the timber version of L3. These parameters, obtained using Equations (2) and (4), enabled the calculation of DI_T (0.49) and R_T (0.42). Therefore, the $3DR_T$ of the timber structure was:

$$3DR_T = 0.5 \times 0.50 + 0.5 \times 0.40 = 0.45 \qquad (9)$$

Given the connections used in the timber building and that timber is often down cycled instead of recycled or reused, 46% of the mass of the timber version of L3 was considered circular.

Table 5.11 – Timber L3: DIt, DIm and Ri values.

Description	Mass (kg)	Tools needed	*DIt*	Transport tools	*DIm*	Resilience	*Ri*
Structural materials							
Timber load-bearing wall structure	3,237.4	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Timber load-bearing floor structure	14,553.8	Power tool	0.8	Two people	0.9	Reusable once	0.7
Timber load-bearing roof structure	3,143.9	Power tool	0.8	Crane	0.4	Reusable once	0.7
Pressed fibre particle board used as floor structure	4,102.6	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glass wool used in all external walls and ceiling	2,325.6	No tool	1	One person	1	Recyclable	0.6
Glass wool used in the roof	190.4	No tool	1	One person	1	Recyclable	0.6
Bricks supporting the timber structure	793.6	Power tool	0.8	Hand trolley	0.7	Downcyclable	0.2
Concrete foundations	15,735.6	Hydraulic plant	0.2	Excavator	0.1	Downcyclable	0.2
Finishes							
Carpet covering 193 m^2 of internal floors	183.4	Hand tool	0.9	One person	1	Downcyclable	0.2
Vinyl covering floors in wet areas	714	Hand tool	0.9	One person	1	Downcyclable	0.2
Salvaged timber composing stairway steps	164	Power tool	0.8	Forklift	0.4	Reusable 3 times	0.9
Plywood covering internal walls and first-floor ceiling	3,328.0	Power tool	0.8	Two people	0.9	Downcyclable	0.2
Glued felt ceiling	333.7	Hand tool	0.9	One person	1	Recyclable	0.6
Plasterboard cladding used in kitchen/bathroom areas and ground-floor ceiling	140.2	Power tool	0.8	One person	1	Disposable	0
Pressed timber used as ground-floor external cladding	1,811.7	Power tool	0.8	One person	1	Downcyclable	0.2
Steel sheets used as first-floor external cladding	652.1	Power tool	0.8	Two people	0.9	Recyclable	0.6
Steel sheets used for roof covering	531.3	Power tool	0.8	Two people	0.9	Recyclable	0.6
Aluminium windows and glazed doors	744.0	Power tool	0.8	Two people	0.9	Disposable	0
Internal timber doors	138.0	Power tool	0.8	One person	1	Disposable	0

5.5.5 Comparison of results

Calculation of the 3DR index enables an assessment to the degree to which the circular economy framework has been applied to a building design. The 3DR method is decoupled from the environmental impact assessment of the building, therefore enabling a separate calculation. The use of Tables 5.8-5.11 should allow designers to clearly identify materials which have a higher 3DR index, allowing them to make changes to their traditional practices to incorporate the CE.

Table 5.12 – 3DR indices of four different building types for the same L3 building.

L3 building technology	*DI*	*R*	3DR index
Circular L3	0.50	0.84	0.67
Linear L3	0.31	0.35	0.33
Double-brick L3	0.06	0.21	0.13
Timber L3	0.51	0.41	0.45

Note: 3DR: design, disassemblability, deconstructability, resilience index; L3: Legacy Living Lab; *DI*: disassemblability index; *R:* resilience index.

It was evident in Tables 5.8-5.11 that the 3DR indices of the three variants (linear, double brick and timber framed) of construction were low due to the limited potential reuse of the components. The main difference in these three construction methods is that they all incorporate the use of a concrete footing system (in varying dimensions) which requires large mechanical equipment to be broken up and removed prior to being down cycled. When comparing this to the steel micro pile foundation system used in the circular version of L3, the result is greatly improved as the entire footing system can be recycled (Table 5.8). With each of the building methods results summarised in Table 5.12, it is important to note improvements are possible for each method.

5.6 Distribution of results - Virtual Reality

Having constructed the case study and answered the research questions from publications IV-VI the remaining questions to achieve the goal of circular economy in the L3 construction were:

- Can the building be disassembled easily thereby maintaining commercial value?
- Can the materials and components be viewed and advertised digitally?
- Can the materials and components be safely disassembled at the end of life?

The results of these questions were answered in publication VII, where the seven strategies (Publication I) applied to the building and their corresponding materials were examined. Chapter 5.6 examines how the materials correspond to each of the seven strategies, whereas Chapter 5.2 examines the design detail of the building and its disconnection detail as grouped by material type. A total mass of 36.3 tonnes was used in L3, including steel (61%) and timber (26%). Of the materials used, 58% were disassemblable and reusable multiple times. The results section is organised according to the seven strategies defined in Table 2.2 and summarised below in Table 5.13.

Table 5.13 – Summation of the seven strategies to applying the circular economy to buildings adapted from Publication VII

	Strategy
1.	Reduction of construction waste and the lean production chain
2.	Integration of scrap material, waste, and by-products into new components
3.	Reuse of replacement parts of entire components
4.	Design towards adaptability (reduction through life extension) during operational stages
5.	Design towards disassembly of goods into components to be re-used
6.	Design for recycling of construction materials
7.	Systems to track material and components within their supply chain

5.6.1 Reduction of Waste and Lean Supply Chain

The Virtual reality (VR) environment begins with an image in front of the building (Figure 5.19 a). Once the game begins, the eight prefabricated modules fall into place in the sequence in which the building was erected (Figure 5.19 b). Prefabrication has the added advantage of lean supply chain management and the ability to appropriately store and manage waste products in the manufacturing facility, reducing the amount of mixed waste going to landfill (Fercoq, Lamouri et al. 2016). This visual also shows that the building can be removed as eight modules, making it easy to deconstruct and relocate in the future (Aye, Ngo et al. 2012).

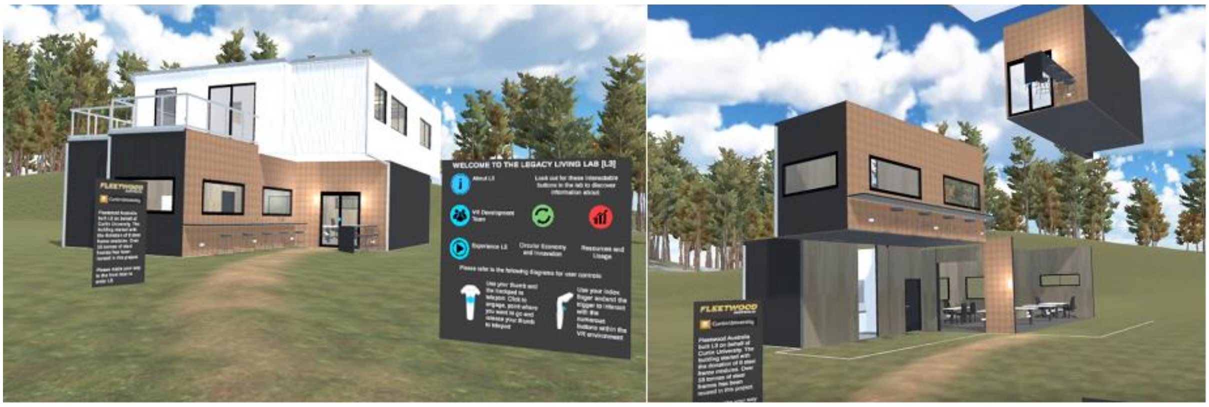

Figure 5.19 – (a) Hero image is the starting sequence for the VR environment. (b) Modules falling into position show how the building was installed on site in the construction sequence.

5.6.2.1 Integration of scrap material, waste and by-products into new components

The total weight of reused material in the L3 prototype is just under 17 tonnes, and is limited to materials that were 100% reused as they were found, thus not considered partially integrated feedstock of (recycled) new materials (Table 5.14). Further to the structural materials used in the construction of the building, all internal furniture is also in its second lifecycle.

Table 5.14 – Weight of materials that were reintroduced into the L3 prototype.

Component description	**Material resilience**	**Mass [kg]**
Steel chassis and load bearing structure	(In)	16,138.9
Reused timber stair treads	(3t)	164.0
Carpet covering 193 m^2 of internal floors	(3t)	183.4
Stairway steel structure	(Rc)	422.8
Total weight		16,909.1

This was possible due to the facilities management at Curtin storing good quality second-hand furniture during renovations and space repurposing. Further, the entire carpet floor tiles for the project were reused. This was due do an industry partner having a strong CE company policy where all second hand carpet tiles are recovered to become feedstock into new tiles. This demonstrated that there was a need for VR digital advertisement of materials as, had the tiles not been recovered, they would have been recycled over direct re-use, adversely affecting the embodied energy of the products (O'Grady, Brajkovich et al. 2021).

5.6.2.2 Integration of by-products

In situations where reused materials were readily available, new materials with a high content of recycled materials were selected. Examples of this are the kitchen cupboards which contain approximately 25% of recycled feedstock (from end of life timber such as chipped pallets) in their production. Similarly, the acoustic felt panels contain a mix of PET plastic bottles which accounts for 70% of their mass (O'Grady, Brajkovich et al. 2021). The balcony tiles are made from a mixture of recycled rubber and plastic waste. The mixture of these materials creates a hard wearing interlocking paving solution which is also made in a trafficable version which can be used in driveway applications (Figure 5.20).

Figure 5.20 – Balcony tiles made where from recycled rubber and plastic waste.

5.6.3 Reuse of parts or entire components

To demonstrate the reuse of parts of components, the game play leads users into the kitchen to reveal components that are in their second lifecycle. A good example is the water chiller units which were salvaged from a demolition project (Figure 5.21). These two chiller units had the lines and filters replaced for hygienic reasons and were then re-installed into the L3 project. Similarly, as the products shown are in their second lifecycle it also acts as a platform to see the components into a third lifecycle.

Figure 5.21 – (a) the recycling logo prompts participants to learn about the provenance of the water chiller and filtration used within L3. (b) On the right, the figure shows the salvaged component within the VR model.

5.6.4 Design towards adaptability (reduction through life extension) during operational stages.

Gypsum is typically used globally as a wall lining solution, and although it is a recyclable material, it is often mixed with other materials during the renovation of refurbishment process and ends up in landfill (Koller, Sandholzer et al. 2013). The plywood wall panelling designed throughout the building allows access to 82% of the buildings internal walls. This helps for general upgrades, such as electrical wiring, however wall access alone is not enough to install new emerging technologies, such as solar heat exchange. A redundant service duct was installed, linking the roof, first and ground floors together. This allocation was made for the future installation of and experimentation for optimised HVAC systems. The service duct is an example of a redundant design feature aimed at promoting the CE which would otherwise go unnoticed (Figure 5.22). However, because such redundant features are typically hidden, they risk oversight in future uses of the building and may not be employed at the right time. To avoid this issue, a VR model of the building empowers the designers and users, who will then be able to make the existing building adaptable to further use before working on the envelope itself.

Figure 5.22 – (a) Wall panelling hides the service duct connecting the roof space to the first floor and ground floor ceiling. (b) VR model exposes the lower access panel, revealing the service duct.

5.6.5 Design towards disassembly of goods into components to be reused

The ceiling panels used in L3 are an acoustic felt product which are magnetically fixed into position, thus enabling strategies 2, 4 and 5 (Table 5.13) to be achieved. The VR environment demonstrates how the panels can be removed and reveals the insulation and structural steel connection behind the panel (Figure 5.23). The design of the buildings ceiling maintains standard industry sizing (1200x2400mm) so that new products may be installed in their place, or replacement panels can be ordered if damaged. This also allows for designers to account for the standard sizing so the materials can be used in their next lifecycle.

The same design strategy has been used for the carpet tiles, to ensure they had the opportunity of being used for a third lifecycle, no chemically setting adhesive was used in the installation of the tiles. Instead, a double sided tactile pad was used to secure the corners of the 4 intersecting tiles and hold the carpet together as a floating floor. The double sided pad allows enough grip on the substrate so that the tiles will not shift, whilst also allowing them to be easily lifted and repositioned when necessary.

Figure 5.23 – Acoustic felt ceiling panels reveal insulation and allow access to mechanical and electrical plant services throughout the multiple lifecycles of the building.

5.6.6 Design for recycling of construction materials

Figure 5.24 shows the revealing of the external wall behind the stairs to demonstrate the modularity of the frame design. The lightweight steel wall-frame has been designed in a discontinuous manner with each section 1200mm wide, hence, they may be easily removed for renovation or expansion of the project. Having discontinuous wall frames will lead to a greater chance of disassembly over demolition as the weight of the wall frame can be easily reduced (see more detail in Section 5.2.1). If the object does not require as much mechanical assistance but still necessitates a two-man lift, the labour rate of the removal will be doubled. These factors all play a part in the adoption of CE in the building industry.

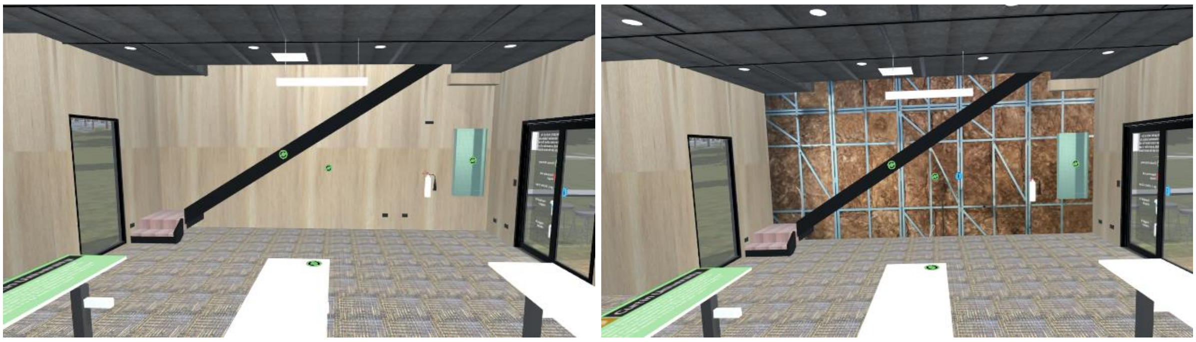

Figure 5.24 – The VR model allows visualisation of the modular construction elements.

5.6.7 Systems to track material and components within their supply chain

The first system used to track consumption is located in the power board. The power board does not show CE strategies used within the VR model, however it is designed in the model for future use (Figure 5.24). It is hoped that in the near future, the VR model will display the energy consumption of the building whilst immersed in the VR in the model. The second system used to track material components is the VR model itself as it demonstrates to users the available materials which can be disconnected in a scaled 3D space, allowing users to visualize available furniture, wall paneling and kitchen components. This is a first step in the space of VR linking Buildings As Material Banks (BAMB) where a buildings components are considered highly valuable resources to promote reuse at end of life, however the model is designed to be an ongoing development so that improvements can be made in future research in the BAMB field.

Chapter 6. Discussion.

This chapter brings together the conclusions of results from the publications discussed in the previous chapters in relation to the overarching research question:

> *Can a building be designed and constructed in-line with the circular economy framework, if so, what would be the environmental benefits?*

Scholars have thoroughly researched the environmental impact of buildings, discovering that they are one of the most impactful on the natural environment. This has led to the development of tools to quantify the impact of a building based on the amount of materials which have been used in the project by way of life cycle assessment. With the realisation of the embodied energy contained in construction materials, a push was made to endeavour to recycle as much material as possible, so that it could be circulated from one project to the next.

Recycling building material has been a major focus for scholars who have investigated many various methods to separate different building elements at the end of life. Recycling building products is difficult due to the size and weight of a building structure when installed as a monolithic entity. With traditional buildings constructed as monoliths, the chemically bonded joints are difficult to reverse. A good example of this is concrete structures. Issues arose from demolition as separation of materials after demolition was difficult, for example, steel reinforcement embedded in concrete structures. This caused the process to demand increased labour, transport and energy requirements for the recycling process to be completed.

Therefore, this PhD proposes an alternative to recycling, by merging CE theory with construction design. This approach contributes to the expansion of knowledge of environmental sustainability, design and project management to answer the research question. In this PhD I designed and implemented CE initiatives to incorporate the reuse of construction materials in order to create a full scale CE building. The environmental benefit of the implementation of CE was assessed by a comparative LCA of a building of the same dimension. A circularity indexing tool was then created and an assessment was performed for three different building types. The results were then published in seven peer reviewed journal papers, and will be discussed in this section.

Many barriers were faced in this process, the most significant was designing a building which went completely against traditional methods, in the sense that chemical connections were minimised. This design process meant a complete rethink of installation and monitoring of trades people to ensure the building was built as per the designs, which led to conflict within different industry partners. The unfamiliar design processes required constant change management and documentation which was frustrating, however these barriers were overcome and a successful case study is a lasting legacy to the hurdles overcome by this research.

6.1 Contextualization of Findings

To implement CE into the construction industry a review of CE applications was necessary to identify strategies which were either being applied to the construction industry already, or were being applied to other industry sectors and had the potential to be adapted to the construction industry (Ghisellini, Cialani et al. 2016). The seven identified strategies published in Publication I acted as guiding principles for the implementation of CE in the built environment (Minunno, O’Grady et al. 2018).

The established method to quantify the environmental impact of products and services is the LCA, Life Cycle Assessment (Sharma, Saxena et al. 2011). LCAs allow the quantification of several environmental indicators (e.g. embodied energy, embodied carbon, ozone depletion potential; (Khasreen, Banfill et al. 2009, Sharma, Saxena et al. 2011, Yellishetty, Mudd et al. 2011, Stocker, Qin et al. 2013, GBCA 2014)). The impact of recent studies were reviewed in Publication II and the LCA method was optimised with a two-step procedural guideline which can assist practitioners in ranking their LCA results. The first step, result ranking, consists of a method to benchmark the embodied energy or carbon in a building. The second step, project improvement, helps designers improve the building through a series of suggestions taken from the literature which consider less impactful alternative solutions for construction (Minunno, O'Grady et al. 2021).

The issue of CE in construction is very much a practical issue, as much as it is theoretical (Tingley, Cooper et al. 2017, Kirchherr and van Santen 2019). Many articles propose theories which call for further research through case studies (Saghafi and Teshnizi 2011, Rios, Chong et al. 2015, Akanbi, Oyedele et al. 2019). To overcome the common research barrier, a CE building was designed (O’Grady, Minunno et al. 2021). The building design should consider each aspect of the building as a whole, enabling it to be deconstructed and relocated if needed with minimal waste to fulfil its current functions in a different location, and further to be completely disassembled into individual components for complete material separation with a host of other maintenance, refurbishment and renovation opportunities to reduce waste creation between these two extremes. The BoQ from the CE building and a standard modular design of the same dimensions were comparatively assessed to measure the environmental impact of and savings in embodied energy and carbon of both buildings. It was shown in Publication V that the CE method saved 88% of GHG emission, whilst also benefiting all other environmental indicators. Thus, confirming the hypothesis posited by Allwood (2014), Kirchherr, Reike et al. (2017) and Stahel (2016) that reuse yields better environmental savings when compared to recycling.

People spend more than 90% of their life in buildings, which makes occupant behaviour one of the leading influencers of energy consumption in buildings (O'Grady, Chong et al. 2021). Thus, occupant behaviour and practice is highly relevant to the reduction of energy consumption in buildings, and a lack of understanding of BAS can result in increased consumption (Oldewurtel, Sturzenegger et al.

2013, Pellegrino, Lo Verso et al. 2016, Karjalainen 2019). Having already considered the embodied energy it was believed that the case study could be used to further improve the built environment beyond the initial research question. For this reason, the case has been equipped with a host of monitoring equipment so that research can continue to further all aspects of the built environment including BAS and the relationship with occupant behaviour (Song, Zhen et al. 2013).

For the reason that improvements in embodied and operational energy were now being tracked through the documented case study, a ranking tool was necessary to enable a simple method of translating the learnings from the case study to other practitioners. The lack of CE assessment tools was clear from Publication I as there only existed the MCI from the Ellen McArthur Foundation (MCI; Lonca, Muggéo et al. (2018), Haas, Krausmann et al. (2015)), which is not specifically designed for buildings, and the Disassembly and Deconstruction Analytics System (D-DAS) for disassembly, which importantly focuses on the BIM model, however it neglects existing built structures (Akanbi, Oyedele et al. 2019). To fill the knowledge gap, the 3DR method was proposed in Publication VI. The 3DR method considers the BoQ of a building and the method of connection that joins the components of a structure together. A determination of the weight of components and the use in a future life will produce a 3DR circularity index for the structure. A high 3DR index, on a scale of 0 to 1, means that a building has a greater chance of achieving circularity (if care is taken at the end of life). A low 3DR index means that the building is far from circular and has little opportunity to progress at the end of life. Publication VI advances from the BoQ used for the comparative lifecycle assessment to consider the four major construction types commonly used for a two story structure so that a global perspective may be presented, beyond the prefabricated examples discussed in publication V.

The high 3DR index of the case study was dependant on a range of design considerations which made disassembly and deconstruction a feasible choice over demolition. A detailed account of these design considerations was reported in Publication IV.

By publishing the construction design details of the L3 case study we identified that a clear and defined theoretical gap exists in the current literature such as cost of disassembly and reuse (Densley Tingley, Cooper et al. 2017), reuse of building components (Ghaffar, Burman et al. 2020), design for disassembly (Akinade, Oyedele et al. 2015) and investigating circular economy in practice (Kirchherr and van Santen 2019).

To further advance the availability of the research findings and to explore novel methods of material advertisement and promotion of second life products a VR model was produced so that the need was removed to visit the building to see the features which had been designed and constructed. This research has successfully demonstrated the implementation of seven identified CE design initiatives applicable to the built environment, and their integration with VR environments, thus filling a noticeable gap in the literature (Rocca, Rosa et al. 2020).

The BIM model also holds within itself the BoQ for the projects, allowing a second benefit of research as it visualises current material stock available for purchase at the end of life, coupled with the assembly and disassembly processes of the building bridging a considerable research gap, as discussed by (Akbarieh, Jayasinghe et al. 2020).

6.2 Theoretical and Practical Implications

The theoretical framework of this PhD is CE. The CE framework aims to replace the end-of-life practice of disposing construction materials with reduction of waste or material use, reintegration and reuse of components into the material loop, or alternatively by recycling the materials (Govindan, Soleimani et al. 2015). The results collected from the seven publications confirm that, applying the CE to the construction industry can greatly reduce the environmental impact of the industry as a whole.

There have been significant findings throughout this PhD, although the stand out is that our CE modular prefabricated design would save 88% of GHG emission. The result of this detailed case study enabled an examination of each of the structural and non-structural interconnection systems so that they may be used widely across the industry (Publication IV). The ease of disassembly was balanced with design features that would not have occupants suspecting they were in a CE building, to increase public perception and lead to faster adoption. To calculate a level of circularity a simple indexing system (3DR) was developed and assessed in Publication VI. This publication found that the CE prefabricated building had a 3DR index of 0.67 as compared to a Timber structure of 0.45 and a double brick structure of 0.13. Finally, Publication VII enables researchers and practitioners to have access to the L3 case study, its CE initiative and the embedded materials globally as a VR model.

Throughout this PhD I have found no evidence that there would be a negative environmental impact caused by applying the CE to the construction industry. I do acknowledge however that the environmental savings linked to the CE theory are only valid if the belief in CE is maintained. It is the case that I have designed a building with adequate documentation to assist in the disassembly, deconstruction, and removal for relocation of the building, however, I cannot guarantee that the building will not be demolished at the end of its life even if it is economically viable and has been made feasible. It is the responsibility of asset owners to make use and take advantage of the CE features of this case study.

The theoretical contribution of this PhD is significant, as it has addressed many important research gaps, however the greatest achievement in this PhD has been the involvement and contribution of many industry partners in a common goal to achieve this CE building. The practical implications of this PhD equal the theoretical contribution as the L3 case study building is a fully operational building which is being used daily to foster relationships with industry, academia and society. What started as a utopian vision three and a half years ago, has come to fruition. The four initial space definitions of; Technology/Apartment, Prototyping, Commercial and Visualisation spaces are all currently being used for their appropriate functions. The case study shows a practical, close to market solution which would enable the immediate implementation of CE initiatives with the collaboration of 26 industry partners.

Chapter 7. Conclusions and Future Research

The circular economy theory sets forth a system to replace end of life disposal with reduction, reuse or recycling of products or services to reduce environmental impact, in a manner which benefits society and the economy.

The circular economy has been applied to many industries to date. For example, the health industry has careful consideration of tools and machines that can be shared, reused or recycled owing to the need for high hygiene standards to ensure no toxicity or bio-hazards are associated with the process. The success of this operation is stakeholder cooperation through the procurement teams, contractors, users and the disposal team to ensure the resources are managed accordingly (Viani, Vaccari et al. 2016). Similar examples can be found in manufacturing (Busch, Steinberger et al. 2014), furniture design (Rieckhof and Guenther 2018) and the electronics industry (Unger, Beigl et al. 2017). These examples employ the circular economy by designing for disassembly, use of standardised sizing and industry wide material takeback schemes.

However, many barriers hinder the application of a circular economy for construction (Kirchherr, Piscicelli et al. 2018), which include cultural, market, political and technological barriers. The case study analysed in this research aimed to address cultural, market and technological barriers of CE in the construction industry.

Of these three barriers, the largest to overcome is the technological aspects related to the construction industry, whereby buildings are typically designed as monolithic structures. With no design consideration to relocate a building (or its parts) it is often extremely difficult or impossible to do so efficiently. This barrier is furthered by building designs being bespoke with many dissimilar parts used across varying projects. The lack of standardised sizing used throughout the design process means that if a building could be removed or deconstructed, its parts might not be interchangeable with a wide range of potential projects, leading to the intense material consumption of the construction industry.

The second barrier relates to the cultural understanding of designing for disassembly and the impact of the construction industry on the natural environment. In the case study location (Western Australia), there is a deep rooted belief in society that buildings should be constructed from bricks, concrete and tile. Anything less than this would mean an inferior product, which should be avoided at all costs. This mentality is associated with very successful marketing campaigns which began in the 1970’s by the brick makers association. Scholars believe a shift in architectural design and understanding of the benefits of different building typologies, for example modular prefabricated design is needed to drive change in the construction industry.

Third, the market for second-life building products is under developed in Australia, limited to individual resource recovery businesses. Without an adequate market for second-life materials, the design integration is impeded as specific product information is missing from the market. For example the spatial dimensions of a window or door, or compressive strength of re-used bricks. A system to track the materials from first to second life is needed to solve these issues and to improve the trust in second life products.

In this PhD I first conducted three published reviews in order to guide this research piece, and specifically the case study building L3. A narrative literature review identified the strategies used by various industries to apply the CE to their sectors. This review distilled seven strategies that was then used to guide the design of the case study. A systematic literature review and meta-analysis method was used to investigate the environmental impact of building materials and buildings. This resulted in an empirically informed procedural guideline to assist practitioners with result ranking and future project improvements. The third review systematically investigated building automation systems (BAS). The SLR into BAS would inform the case study design to reduce operational energy, improve internal comfort of the building and aid in the design understanding to improve the adaptability of the space in an effort to reduce waste over the lifecycle of the building through upgrades and refurbishment in the future.

The results of the reviewed literature was used to design a case study for the PhD. The application of CE to the construction industry is hindered by the lack of empirical case studies (Akanbi, Oyedele et al. 2019). As this was a research gap in itself, I sought to design and build a full size building using the knowledge distilled from the related literature. The technical design features of the building were documented throughout the construction and published in a peer-reviewed article so that practitioners could have future access to the novel design features used to integrate the CE strategies from the various published reviews. The design of the building whilst addressing the technical barriers also considered the market challenges of designing a building using the modular prefabricated method of construction. Prefabrication has a negative stereotype in some cultures, linked to government housing and mining accommodation. To tackle this stereotype, every effort was made to disguise joins in the modules and to hide the modularity of the structure itself by using high quality finishes and products throughout.

The practical application was the next required step to move from theory to practice and see how well designs would work in the real-life application. The environmental benefits from the application of the CE to the building design were significant. A comparative LCA demonstrated that the L3 case study saved 88% of greenhouse gas equivalent emissions, as well as several other tested indicators. Thus, the results obtained in this research confirmed the tested theory and validated the CE application to the construction industry (Publication V).

Although LCA is a well-used tool for assessing the environmental impact of products there was no specific tool available to calculate the circularity of building with the exception of material circularity indicators, such as (MacArthur 2013, Haas, Krausmann et al. 2015), which did not specifically focus on the construction industry. This noticeable research gap was addressed with the creation of the 3DR index. The 3DR method assesses the Design for Disassembly, Deconstruction and Resilience (3DR) which guides practitioners in obtaining a circularity index for their projects. The 3DR index is decoupled from environmental impact metrics and can be applied to any building to gain perspective on circularity as opposed to environmental savings (Linder, Boyer et al. 2020).

The 3DR index is a variable between 0 and 1. Index values which are higher (but less than 1) indicate a more circular project and lower values (close to 0) indicate that the project is largely linear and less suited to the circular economy. To test the 3DR method I applied it to four different building typologies based on the same dimensions and floor plan of the case study building, L3. The four building types included the CE L3, a traditional modular building, a timber-framed version and a double brick example to cover a majority of the construction methods generally used globally. The results show that the application of circular economy principles and the integration of building disassembly, deconstruction and resilience when factored into the design enhance the reusability of building components. This was shown by the CE L3 case study which achieved a 3DR index of 0.67, while the double brick version had a 3DR index of only 0.13 indicating that a majority of that building typology would eventually result in landfill. The timber version achieved the second highest index at 0.41, with a modular prefabricated example achieving an index of only 0.33 (Publication VI).

To further the market constraints of second-life materials a VR environment was created based on the L3 case study. The VR environment demonstrates how materials have been assembled and how their disconnection and disassembly can be carried out. This interactive environment takes the first steps in demonstrating materials and parts of the building that are available for reuse, adding to the concept of buildings as material banks, BAMB). The VR model documented in Publication VII also collates the materials used in the case study against the seven strategies from Publication I. The VR model links all findings to provide a holistic account of how to design, build, assess, educate and advertise a CE building across its various lifecycles, which can then be accessed virtually without the need to visit the building site. The aim of the VR model is to rapidly increase the availability of information transfer.

Beyond the environmental savings and theoretical contribution of this PhD, this project developed a significant following within the construction industry with the involvement of 26 industry partners. The industry partners who participated in the project also helped to improve it, whilst re-developing their products at the same time. One example of this is the *win-door* example from Section 5.2.4 where the developed and tested product is now being sold to market as a direct result of this research.

The participation of academia, industry and society positions this building as a living lab (on an innovation through demonstration precinct) and its future potential for building research is limitless owing to its flexible design and monitoring features.

The research reported in this PhD has resulted in a deep understanding of the practical and theoretical implications of applying the CE to the construction industry. Moreover, it opens up future research opportunities.

7.1 Future research

There are four future research opportunities that arise from this research

First, improvements to the 3DR method could be possible by incorporating a time variable equation into the index method. As the industry gradually begins to adopt the CE, for its environmental endeavour, the practices must start to incorporate a time function for accurate pricing. Once a time component is added to the tools, and lifting requirements, prospective building disassemblers will be able to better quote for the reuse of building components, removing the uncertainty surrounding disassembly over demolition, and stabilising the second-life material markets.

Second, this PhD made some preliminary investigations into building automation systems for the case study, however there is ongoing research needed to investigate the link of human interaction with the overall BAS system. Publication III sets forth the proposed methodology (Figure 5.15). The L3 case study is completely equipped for this research to continue into human occupancy comfort levels with varying levels of BAS technology which has been implemented in the building. Future research should evaluate the occupant's relationship with the building system to address the research gap identified within the SLR.

Third, the VR model has redundant features built in to display live energy data from the building. The model at its inception has fulfilled its role as intended, however improvements can be made and the features have been built in to enable an upgrade in the next iteration of the VR environment. The VR model has the provision to link the LCA data in the same screen panel so once a link is developed to add live energy data, the reduction of CO_2 and operational energy may both be visible from within the VR environment. The power tags which are used to track the energy consumption of the building are already gathering the data, however there needs to be an easy way to transfer data in real time which proved to be too time demanding to solve for the initial research purposes.

Fourth, the operational energy of L3 can be tracked and improvements in building technology can be assessed through the reduction of operational energy consumption. L3 was designed to be disassembled for a reason and that was to replace and test as many new ideas as possible. This will hopefully increase the research of insulation, novel shading/daylighting methods and materials resilience testing.

Finally, research should investigate the next lifecycle of the building. The L3 case study has already been erected and disassembled once, however the next lifecycle of this building should be investigated to provide the longitudinal impact case study of CE for this built structure.

7.2 Final remarks

This PhD addresses the gap between CE theory and practice. It does so by linking 26 industry partners, with the rigour of academic process and distributing results to the public through a built example of theoretically proven concepts.

The CE has been considered by academics as the solution to the mounting demand on global resources and the reduction of waste, however challenges for the application of CE in construction are still present. This PhD delivers a circular economy prototype building, and it is hoped that with this building, the barriers of circular economy will be stripped away. This PhD set forth to investigate how the circular economy could be applied to the construction industry and then confirmed through delivery of an empirical case study. The environmental saving has been significant and it is hoped that this case study will evolve through many research iterations to benefit sustainable construction practices into the future.

Å vajlenka, J., et al. (2017). "The benefits of modern method of construction based on wood in the context of sustainability." International journal of environmental science and technology **14**(8): 1591-1602.

Abdallah, M., et al. (2016). "Economic and GHG Emission Analysis of Implementing Sustainable Measures in Existing Public Buildings." Journal of Performance of Constructed Facilities **30**(6).

Adhikari, R., et al. (2018). "An algorithm for optimal management of aggregated HVAC power demand using smart thermostats." Applied Energy **217**: 166-177.

Aghemo, C., et al. (2014). "Building automation and control systems: A case study to evaluate the energy and environmental performances of a lighting control system in offices." Automation in Construction **43**: 10-22.

Ahmadi-Karvigh, S., et al. (2017). "One size does not fit all: Understanding user preferences for building automation systems." Energy and Buildings **145**: 163-173.

Ahmadian F.F, A., et al. (2017). "BIM-enabled sustainability assessment of material supply decisions." Engineering, Construction and Architectural Management **24**(4): 668-695.

Ahmed, I. M. and K. D. Tsavdaridis (2018). "Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems." Journal of Building Engineering **20**: 624-633.

Ahuja, K. and A. Khosla (2018). "Importance of smart metering in diverse fields of smart cities." International Journal of Grid and Distributed Computing **11**(3): 33-50.

Ajayi, S. O., et al. (2015). "Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements." Resources Conservation and Recycling **102**: 101-112.

Ajayi, S. O., et al. (2019). "Changing significance of embodied energy: A comparative study of material specifications and building energy sources." Journal of Building Engineering **23**: 324-333.

Ajayi, S. O., et al. (2016). "Are sustainable buildings healthy? An investigation of lifecycle relationship between building sustainability and its environmental health impacts." World Journal of Science Technology and Sustainable Development **13**(3): 190-204.

Akanbi, L., et al. (2019). "Reusability analytics tool for end-of-life assessment of building materials in a circular economy." World Journal of Science Technology and Sustainable Development **16**(1): 40-55.

Akanbi, L. A., et al. (2018). "Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator." Resources, Conservation and Recycling **129**: 175-186.

Akanbi, L. A., et al. (2019). "Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy." Journal of Cleaner Production **223**: 386-396.

Akbarieh, A., et al. (2020). "BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review." Sustainability **12**(7): 2670.

Akinade, O. O., et al. (2015). "Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS)." Resources, Conservation and Recycling **105**: 167-176.

Aksamija, A. (2016). "Regenerative design and adaptive reuse of existing commercial buildings for net-zero energy use." Sustainable Cities and Society **27**: 185-195.

Alembagheri, M., et al. (2020). "Anti-collapse resistance mechanisms in corner-supported modular steel buildings." Journal of Constructional Steel Research **170**: 106083.

Allwood, J. M. (2014). Chapter 30 - Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies. Handbook of Recycling. E. Worrell and M. A. Reuter. Boston, Elsevier**:** 445-477.

Allwood, J. M. (2014). Squaring the circular economy: the role of recycling within a hierarchy of material management strategies. Handbook of recycling, Elsevier**:** 445-477.

Allwood, J. M., et al. (2011). "Material efficiency: A white paper." Resources, Conservation and Recycling **55**(3): 362-381.

Allwood, J. M., et al. (2012). Sustainable materials: with both eyes open, UIT Cambridge Limited Cambridge, UK.

Arge, K. (2005). "Adaptable office buildings: theory and practice." Facilities.

Arora, M., et al. (2019). "Residential building material stocks and component-level circularity: The case of Singapore." Journal of Cleaner Production **216**: 239-248.

Ashcraft, H. W. (2008). "Building information modeling: A framework for collaboration." Constr. Law. **28**: 5.

Australian Building Codes, B. and S. A. I. Global (2001). Building code of Australia plus standards online. BCA + standards on-line. Sydney], [Sydney] : SAI Global.

Aye, L., et al. (2012). "Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules." Energy and buildings **47**: 159-168.

Azzouz, A., et al. (2017). "Life cycle assessment of energy conservation measures during early stage office building design: A case study in London, UK." Energy and Buildings **139**: 547-568.

Babu, S., et al. (2019). "Investigation of an integrated automated blinds and dimmable lighting system for tropical climate in a rotatable testbed facility." Energy and Buildings **183**: 356-376.

Bakhtiari, H., et al. (2019). "Evaluation of thermal comfort in a historic building refurbished to an office building with modernized HVAC systems." Advances in Building Energy Research.

Bellia, L., et al. (2018). "University building: Energy diagnosis and refurbishment design with cost-optimal approach. Discussion about the effect of numerical modelling assumptions." Journal of Building Engineering **18**: 1-18.

Bellido-Outeirino, F. J., et al. (2012). "Building lighting automation through the integration of DALI with wireless sensor networks." IEEE Transactions on Consumer Electronics **58**(1): 47-52.

Benachio, G. L. F., et al. (2020). "Circular economy in the construction industry: A systematic literature review." Journal of Cleaner Production **260**: 121046.

Bille, R., et al. (2014). Extending building information models into game engines. Proceedings of the 2014 conference on interactive entertainment.

Bisadi, M., et al. (2018). "IoT-Enabled Humans in the Loop for Energy Management Systems: Promoting Building Occupants' Participation in Optimizing Energy Consumption." IEEE Electrification Magazine **6**(2): 64-72.

Blengini, G. A. (2009). "Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy." Building and Environment **44**(2): 319-330.

Blengini, G. A. and E. Garbarino (2010). "Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix." Journal of Cleaner Production **18**(10): 1021-1030.

Blismas, N. and R. Wakefield (2009). "Drivers, constraints and the future of offsite manufacture in Australia." Construction Innovation **9**(1): 72-83.

Bocken, N. M., et al. (2017). Taking the circularity to the next level: a special issue on the circular economy, Wiley Online Library. **21:** 476-482.

Bonnema, E., et al. (2010). "Advanced energy design guide for small hospitals and healthcare facilities." Journal of Healthcare Engineering **1**(2): 277-296.

Brambilla, G., et al. (2019). "Environmental benefits arising from demountable steel-concrete composite floor systems in buildings." Resources, Conservation and Recycling **141**: 133-142.

Braungart, M., et al. (2012). Cradle-to-cradle design: Creating healthy emissions—A strategy for eco-effective product and system design, Birkhäuser.

Brown, M. and V. Buranakarn (2003). "Emergy indices and ratios for sustainable material cycles and recycle options." Resources, Conservation and Recycling **38**(1): 1-22.

Browning, T. R. and R. D. Heath (2009). "Reconceptualizing the effects of lean on production costs with evidence from the F-22 program." Journal of operations management **27**(1): 23-44.

Busch, J., et al. (2014). "Managing critical materials with a technology-specific stocks and flows model." Environmental Science & Technology **48**(2): 1298-1305.

Catalli, V. W., M. (2001). "Designing for disassembly [An innovative strategy for attaining environmental

goals and building adaptability] [Mountain Equipment Co-op Ottawa store case study]. ." Can. Arch. **46**: 27-29.

Chaiwiwatworakul, P., et al. (2009). "Application of automated blind for daylighting in tropical region." Energy Conversion and Management **50**(12): 2927-2943.

Chan, E. K. F., et al. (2017). "IoT based smart classroom system." Journal of Telecommunication, Electronic and Computer Engineering **9**(3-9): 95-101.

Chan, J., et al. (2020). "Potential economic and energy impacts of substituting adaptive reuse for new building construction: A case study of Ontario." Journal of Cleaner Production **259**: 120939.

Chang, C. C., et al. (2019). "Life cycle energy assessment of university buildings in tropical climate." Journal of Cleaner Production **239**.

Chau, C. K., et al. (2012). "Assessment of CO 2 emissions reduction in high-rise concrete office buildings using different material use options." Resources, Conservation and Recycling **61**: 22-34.

Chaudhary, G., et al. (2016). "Evaluation of “Autotune” calibration against manual calibration of building energy models." Applied Energy **182**: 115-134.

Chen, X., et al. (2019). "Energy optimization of high-rise commercial buildings integrated with photovoltaic facades in urban context." Energy **172**: 1-17.

Chen, Y., et al. (2017). "Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis." Applied Energy **205**: 323-335.

Chomkhamsri, K., et al. (2011). "International reference life cycle data system (ILCD) handbook: Review schemes for life cycle assessment." Towards life cycle sustainability management: 107-117.

Cleophas, T. J. and A. H. Zwinderman (2017). "Modern meta-analysis." Modern Meta-Analysis. https://doi. org/10.1007/978-3-319-55895-0.

Cohen, J. (1960). "A coefficient of agreement for nominal scales." Educational and psychological measurement **20**(1): 37-46.

Cook, C. (2009). Julia H. Littell Jacqueline Corcoran Vijayan Pillai Systematic reviews and meta-analysis 2008 Oxford University Press New York 202 ISBN: 978-0-19-532654-3, Elsevier Ltd. **31:** 495-496.

Cooper, D. R. and T. G. Gutowski (2017). "The environmental impacts of reuse: a review." Journal of Industrial Ecology **21**(1): 38-56.

Cornaro, C., et al. (2020). "An innovative straw bale wall package for sustainable buildings: experimental characterization, energy and environmental performance assessment." Energy and Buildings **208**: 1.

Costa, H. R. N. and A. La Neve (2015). "Study on application of a neuro-fuzzy models in air conditioning systems." Soft Computing **19**(4): 929-937.

Crowther, P. (2000). Developing guidelines for designing for deconstruction. Deconstruction-Closing the Loop Conference Proceedings, Building Research Council.

Crowther, P. (2018). Re-Valuing Construction Materials and Components Through Design for Disassembly. Unmaking Waste in Production and Consumption: Towards the Circular Economy. R. Crocker, C. Saint, G. Chen and Y. Tong, Emerald Publishing Limited**:** 309-321.

Crump, D. R., et al. (1997). "Sources and Concentrations of Formaldehyde and Other Volatile Organic Compounds in the Indoor Air of Four Newly Built Unoccupied Test Houses." Indoor and Built Environment **6**(1): 45-55.

Cruz Rios, F., et al. (2019). "Reusing exterior wall framing systems: A cradle-to-cradle comparative life cycle assessment." Waste Management **94**: 120-135.

Cullen, J. (2017). "Circular economy: theoretical benchmark or perpetual motion machine?".

Cullham, W. (1975). "Construction and demolition debris need special care." Solid Wastes Manag **18**: 50-52.

Dajiang, W. (2009). "Intelligent in-house service: Hotel guests can now enjoy increased comfort with fewer energy requirements thanks to abb's i-bus® knx building control system." ABB Review(2): 55-57.

Dara, C., et al. (2019). "Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study." Building and Environment **163**: 106332.

Dave, M., et al. (2017). "Performance and Perception in Prefab Housing: An Exploratory Industry Survey on Sustainability and Affordability." Procedia Engineering **180**: 676-686.

Dean, B., et al. (2016). "Towards zero-emission efficient and resilient buildings.: Global Status Report."

Demir, I. and M. Orhan (2003). "Reuse of waste bricks in the production line." Building and Environment **38**(12): 1451-1455.

Densley Tingley, D., et al. (2017). "Understanding and overcoming the barriers to structural steel reuse, a UK perspective." Journal of Cleaner Production **148**: 642-652.

Desai, A. and A. Mital (2005). "Incorporating work factors in design for disassembly in product design." Journal of Manufacturing Technology Management.

Dhalluin, A. and K. Limam (2014). "Comparison of natural and hybrid ventilation strategies used in classrooms in terms of indoor environmental quality, comfort and energy savings." Indoor and Built Environment **23**(4): 527-542.

Dorizas, P. V., et al. (2015). "A holistic approach for the assessment of the indoor environmental quality, student productivity, and energy consumption in primary schools." Environmental Monitoring and Assessment **187**(5): 1-18.

Eberhardt, L., et al. (2019). Comparing life cycle assessment modelling of linear vs. circular building components. Iop Conference Series: Earth and Environmental Science, IOP Publishing.

Eberhardt, L. C. M., et al. (2019). "Life cycle assessment of a Danish office building designed for disassembly." Building Research and Information **47**(6): 666-680.

Eberhardt, L. C. M., et al. (2019). "Life cycle assessment of a Danish office building designed for disassembly." Building Research and Information **47**(6): 666-680.

Eltaweel, A. and S. Yuehong (2017). "Using integrated parametric control to achieve better daylighting uniformity in an office room: A multi-Step comparison study." Energy and Buildings **152**: 137-148.

Fazel, A., et al. (2016). "Low-cost solar thermal based adaptive window: Combination of energy-saving and self-adjustment in buildings." Solar Energy **133**: 274-282.

Fercoq, A., et al. (2016). "Lean/Green integration focused on waste reduction techniques." Journal of Cleaner Production **137**: 567-578.

Finkbeiner, M., et al. (2006). "The new international standards for life cycle assessment: ISO 14040 and ISO 14044." The International Journal of Life Cycle Assessment **11**(2): 80-85.

Formoso, C. T., et al. (2002). "Material waste in building industry: main causes and prevention." Journal of construction engineering and management **128**(4): 316-325.

Galle, W., et al. (2017). "Integrating scenarios into life cycle assessment: Understanding the value and financial feasibility of a demountable building." Buildings **7**(3): 64.

Gan, V. J. L., et al. (2017). "Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings." Journal of Cleaner Production **141**: 825-836.

Gao, W., et al. (2001). "Energy impacts of recycling disassembly material in residential buildings." Energy and Buildings **33**(6): 553-562.

García-Sanz-Calcedo, J. and F. López-Rodríguez (2017). "Analysis on the performance of a high efficiency administrative building in Spain." International Journal of Green Energy **14**(1): 55-62.

GBCA (2014). "Materials Life cycle Impacts."

Ghaffar, S. H., et al. (2020). "Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery." Journal of Cleaner Production **244**: 118710.

Ghisellini, P., et al. (2016). "A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems." Journal of Cleaner Production **114**: 11-32.

Ginga, C. P., et al. (2020). "Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production." Materials (Basel, Switzerland) **13**(13).

Glass, B., et al. (2010). "Expanding Horizons with Chameleon: Team Missouri's Innovative Home Automation System." Energies **3**(6): 1142-1153.

Go, T., et al. (2011). "Disassemblability of end-of-life vehicle: a critical review of evaluation methods." Journal of Cleaner Production **19**(13): 1536-1546.

Gomes, L., et al. (2019). "IoH: A platform for the intelligence of home with a context awareness and ambient intelligence approach." Future Internet **11**(3).

Gontia, P., et al. (2020). "Spatiotemporal characteristics of residential material stocks and flows in urban, commuter, and rural settlements." Journal of Cleaner Production **251**: 119435.

Gorgolewski, M. (2008). "Designing with reused building components: some challenges." Building Research & Information **36**(2): 175-188.

Government, A. (2013). Heating, Ventilation & Air-Conditioning High Efficiency Systems Strategy.

Govindan, K., et al. (2015). "Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future." European Journal of Operational Research **240**(3): 603-626.

Gunay, H. B., et al. (2014). "On adaptive occupant-learning window blind and lighting controls." Building Research and Information **42**(6): 739-756.

Guo, H., et al. (2017). "A Comparison of the Energy Saving and Carbon Reduction Performance between Reinforced Concrete and Cross-Laminated Timber Structures in Residential Buildings in the Severe Cold Region of China." Sustainability **9**(8).

Guy, B. and S. McLendon (2000). "Building deconstruction: reuse and recycling of building materials." Gainesville, FL: Center for Construction and Environment, Report to the Florida Department of Environmental Protection, September1999.

Guy, B., et al. (2006). "Design for deconstruction and materials reuse." Proceedings of the CIB Task Group **39**(4): 189-209.

Haas, W., et al. (2015). "How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the world in 2005." Journal of industrial ecology **19**(5): 765-777.

Haeusler, M. H., et al. (2021). "(Computationally) designing out waste: Developing a computational design workflow for minimising construction and demolition waste in early-stage architectural design." International Journal of Architectural Computing **19**(4): 594-611.

Hardie, M., et al. (2007). "The efficacy of waste management plans in Australian commercial construction refurbishment projects." Construction Economics and Building **7**(2): 26-36.

Harun, F. K. C., et al. (2011). "Voice recognition home automation system (VRHAS)." Jurnal Teknologi (Sciences and Engineering) **54**: 361-369.

He, Q., et al. (2021). "A cost-effective building retrofit decision-making model – Example of China’s temperate and mixed climate zones." Journal of Cleaner Production **280**: 124370.

Heim, D. and M. Pawłowski (2019). "The methodology of thermal energy management for nearly zero energy buildings." Periodica Polytechnica Civil Engineering **63**(2): 499-517.

Hernandez, A. V., et al. (2020). "Meta-Analysis." Chest **158**(1, Supplement): S97-S102.

Hirschl, B., et al. (2003). "New concepts in product use for sustainable consumption." Journal of Cleaner Production **11**(8): 873-881.

Hölzle, I. (2019). "Contaminant patterns in soils from landfill mining." Waste Management **83**: 151-160.

Homod, R. Z. (2018). "Analysis and optimization of HVAC control systems based on energy and performance considerations for smart buildings

" Renewable Energy **126**: 49-64.

Höök, M. and L. Stehn (2008). "Applicability of lean principles and practices in industrialized housing production." Construction management and Economics **26**(10): 1091-1100.

Hopkinson, P. C., H-M.; Zhou, K.; Wang, Y.; Lam, D. (2018). "Recovery and reuse of structural products from end-of-life buildings." Proceedings of the Institution of Civil Engineers **172**(3): 119-128.

Hossain, M. U. and C. S. Poon (2018). "Global warming potential and energy consumption of temporary works in building construction: A case study in Hong Kong." Building and Environment **142**: 171-179.

Hossain, M. U., et al. (2016). "Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA." Resources, Conservation and Recycling **109**: 67-77.

Hoxha, E., et al. (2017). "Influence of construction material uncertainties on residential building LCA reliability." Journal of Cleaner Production **144**: 33-47.

Hoyo-Montaño, J. A., et al. (2019). "Environmental impacts of energy saving actions in an academic building." Sustainability (Switzerland) **11**(4).

Hu, J. and S. Olbina (2011). "Illuminance-based slat angle selection model for automated control of split blinds." Building and Environment **46**(3): 786-796.

Hu, M. (2019). "Building impact assessment—A combined life cycle assessment and multi-criteria decision analysis framework." Resources, Conservation and Recycling **150**: 104410.

Hwang, B.-G., et al. (2018). "Key constraints and mitigation strategies for prefabricated prefinished volumetric construction." Journal of Cleaner Production **183**: 183-193.

Hyemi, K., et al. (2018). "Study on Variation of Internal Heat Gain in Office Buildings by Chronology." Energies **11**(4): 1013.

Iacovidou, E. and P. Purnell (2016). "Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse." Science of the Total Environment **557**: 791-807.

Iwata, T., et al. (2017). "Automated blind control based on glare prevention with dimmable light in open-plan offices." Building and Environment **113**: 232-246.

Jamieson, E., et al. (2015). "Comparison of embodied energies of Ordinary Portland Cement with Bayer-derived geopolymer products." Journal of Cleaner Production **99**: 112-118.

Jimenez-Rivero, A. and J. Garcia-Navarro (2017). "Best practices for the management of end-of-life gypsum in a circular economy." Journal of Cleaner Production **167**: 1335-1344.

Jin, R., et al. (2018). "A holistic review of off-site construction literature published between 2008 and 2018." Journal of Cleaner Production **202**: 1202-1219.

Junak, J. and A. Sicakova (2018). "Effect of surface modifications of recycled concrete aggregate on concrete properties." Buildings **8**(1): 2.

Kamel, E. and A. M. Memari (2018). "Automated Building Energy Modeling and Assessment Tool (ABEMAT)." Energy **147**: 15-24.

Kandasamy, N. K., et al. (2018). "Smart lighting system using ANN-IMC for personalized lighting control and daylight harvesting." Building and Environment **139**: 170-180.

Karjalainen, S. (2019). "Be active and consume less—the effect of venetian blind use patterns on energy consumption in single-family houses." Energy Efficiency **12**(3): 787-801.

Khasreen, M. M., et al. (2009). "Life-Cycle Assessment and the Environmental Impact of Buildings: A Review." Sustainability **1**(3): 674-701.

Kibert, C. J., et al. (2000). Deconstruction as an essential component of sustainable construction. Proceedings of the second Southern African conference on sustainable development in the built environment, Pretoria.

Kim, N., et al. (2016). "Normalized step size approach to signal processing based on lagged cross-correlation of probability." Journal of Theoretical and Applied Information Technology **89**(2): 397-403.

Kim, S., et al. (2019). "Development of a consecutive occupancy estimation framework for improving the energy demand prediction performance of building energy modeling tools." Energies **12**(3).

Kirchherr, J., et al. (2018). "Barriers to the circular economy: evidence from the European Union (EU)." Ecological Economics **150**: 264-272.

Kirchherr, J., et al. (2017). "Conceptualizing the circular economy: An analysis of 114 definitions." Resources, Conservation and Recycling **127**: 221-232.

Kirchherr, J. and R. van Santen (2019). "Research on the circular economy: A critique of the field." Resources, Conservation and Recycling **151**.

Kirchherr, J. and R. van Santen (2019). "Research on the circular economy: A critique of the field." Resources, Conservation and Recycling **151**: 104480.

Knoeri, C., et al. (2013). "Comparative LCA of recycled and conventional concrete for structural applications." The International Journal of Life Cycle Assessment **18**(5): 909-918.

Kolarik, J., et al. (2009). "Occupant responses and office work performance in environments with moderately drifting operative temperatures (RP-1269)." HVAC and R Research **15**(5): 931-960.

Koller, M., et al. (2013). "Biopolymer from industrial residues: Life cycle assessment of poly (hydroxyalkanoates) from whey." Resources, Conservation and Recycling **73**: 64-71.

Krikke, H., et al. (2004). "Product modularity and the design of closed-loop supply chains." California management review **46**(2): 23-39.

Kupwade-Patil, K., et al. (2018). "Impact of Embodied Energy on materials/buildings with partial replacement of ordinary Portland Cement (OPC) by natural Pozzolanic Volcanic Ash." Journal of Cleaner Production **177**: 547-554.

Kwon, H. J., et al. (2018). "Evaluation of Building Energy Saving Through the Development of Venetian Blinds’ Optimal Control Algorithm According to the Orientation and Window-to-Wall Ratio." International Journal of Thermophysics **39**(2).

Lan, C.-H. (2007). "The design of multiple production lines under deadline constraint." International Journal of Production Economics **106**(1): 191-203.

Lawrence, T. M., et al. (2016). "Ten questions concerning integrating smart buildings into the smart grid." Building and Environment **108**: 273-283.

Lazim, J., et al. (2015). "Energy Management Strategies at Emergency Department Block C Hospital Sungai Buloh, Malaysia." Applied Mechanics and Materials **735**: 243-246.

Leal, S., et al. (2014). "A software architecture for simulation support in building automation." Buildings **4**(3): 320-335.

Lee, E. S., et al. (2012). "End user impacts of automated electrochromic windows in a pilot retrofit application." Energy and Buildings **47**: 267-284.

Lehmann, B., et al. (2013). "Intermediate complexity model for Model Predictive Control of Integrated Room Automation." Energy and Buildings **58**: 250-262.

Li, S. and H. Altan (2012). "Environmental Impact Balance of Building Structures and Substitution Effect of Wood Structure in Taiwan." International Journal of Environmental Protection **2**(1): 1.

Lin, G., et al. (2019). "An optimal energy-saving strategy for home energy management systems with bounded customer rationality." Future Internet **11**(4).

Lin, Q., et al. (2019). "A Coupling Control Model of Color Temperature and Illumination in Naturally Lighted Room Based on Evolutionary Algorithm." Sensors and Materials **31**(6): 2061-2072.

Lin, Y.-K., et al. (2012). "Reliability evaluation for a waste-reduction parallel-line manufacturing system." Journal of Cleaner Production **35**: 93-101.

Linder, M., et al. (2020). "Product-level inherent circularity and its relationship to environmental impact." Journal of Cleaner Production **260**: 121096.

Liu, Y., et al. (2016). "Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach." Sustainability **8**(10).

Lonca, G., et al. (2018). "Does material circularity rhyme with environmental efficiency? Case studies on used tires." Journal of Cleaner Production **183**: 424-435.

London, B. (1932). "Ending the depression through planned obsolescence." Retrieved March **25**: 2016.

López, J. M. G., et al. (2019). "Smart Residential Load Simulator for Energy Management in Smart Grids." IEEE Transactions on Industrial Electronics **66**(2): 1443-1452.

Low, S. P. (1997). Managing Productivity in Construction : JIT Operations and Measurements, Milton : Routledge.

MacArthur, E. (2013). "Towards the circular economy, economic and business rationale for an accelerated transition." Ellen MacArthur Foundation: Cowes, UK.

Marinakis, V., et al. (2013). "An integrated system for buildings’ energy-efficient automation: Application in the tertiary sector." Applied Energy **101**: 6-14.

Martirano, L., et al. (2016). "A Fuzzy-Based Building Automation Control System: Optimizing the Level of Energy Performance and Comfort in an Office Space by Taking Advantage of Building Automation Systems and Solar Energy." IEEE Industry Applications Magazine **22**(2): 10-17.

Mataloto, B., et al. (2019). "Lobems—IoT for building and energy management systems." Electronics (Switzerland) **8**(7).

Meerbeek, B. W., et al. (2016). "Automated blinds with light feedback to increase occupant satisfaction and energy saving." Building and Environment **103**: 70-85.

Merrild, H., et al. (2016). Building a circular future, GXN.

Mesa, J., et al. (2020). "Developing an indicator for material selection based on durability and environmental footprint: A Circular Economy perspective." Resources, Conservation and Recycling **160**: 104887.

Meyer, C. (2009). "The greening of the concrete industry." Cement and concrete composites **31**(8): 601-605.

Miciu, I. and C. Ogescu (2015). "Management system for improving energy consumption in public buildings *." Revista Romana de Inginerie Civila **6**(2): 164-173.

Minunno, R., et al. (2020). "Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building." Resources, Conservation and Recycling **160**: 104855.

Minunno, R., et al. (2021). "Investigating the embodied energy and carbon of buildings: A systematic literature review and meta-analysis of life cycle assessments." Renewable and Sustainable Energy Reviews **143**: 110935.

Minunno, R., et al. (2018). "Strategies for applying the circular economy to prefabricated buildings." Buildings **8**(9): 125.

Minunno, R., et al. (2018). "Strategies for applying the circular economy to prefabricated buildings." Buildings **8**(9): 125.

Morseletto, P. (2020). "Targets for a circular economy." Resources, Conservation and Recycling **153**: 104553.

Motte, N. D. L. (2019). "Main Roads Guide to design of oversize and over-mass vehicle corridors." **5**.

Munaro, M. R., et al. (2020). "Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment." Journal of Cleaner Production **260**: 121134.

Navaratnam, S., et al. (2019). "Performance Review of Prefabricated Building Systems and Future Research in Australia." Buildings **9**(2): 38.

Nezamdoost, A., et al. (2018). "Assessing the energy and daylighting impacts of human behavior with window shades, a life-cycle comparison of manual and automated blinds." Automation in Construction **92**: 133-150.

Nwodo, M. N. and C. J. Anumba (2019). "A review of life cycle assessment of buildings using a systematic approach." Building and Environment **162**: 106290.

O'Grady, T., et al. (2021). "A systematic review and meta-analysis of building automation systems." Building and Environment: 107770.

O'Grady, T., et al. (2021). "A systematic review and meta-analysis of building automation systems." Building and Environment **195**: 107770.

O'Grady, T., et al. (2021). "Design for disassembly, deconstruction and resilience: A circular economy index for the built environment." Resources, Conservation and Recycling **175**: 105847.

O'Grady, T. M., et al. (2021). "Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction." Energies **14**(13): 4065.

O'Grady, T. M., et al. (2021). "Interconnections: An Analysis of Disassemblable Building Connection Systems towards a Circular Economy." Buildings **11**(11): 535.

Oerter, J., et al. (2014). "A system architecture and simulation environment for building information modeling in virtual worlds." The Journal of Defense Modeling and Simulation **11**(3): 205-210.

Olbina, S. and J. Hu (2012). "Daylighting and thermal performance of automated split-controlled blinds." Building and Environment **56**: 127-138.

Oldewurtel, F., et al. (2012). "Use of model predictive control and weather forecasts for energy efficient building climate control." Energy and Buildings **45**: 15-27.

Oldewurtel, F., et al. (2013). "Importance of occupancy information for building climate control." Applied Energy **101**: 521-532.

Osello, A., et al. (2013). "Energy saving in existing buildings by an intelligent use of interoperable ICTs." Energy Efficiency **6**(4): 707-723.

Pan, F., et al. (2018). Design and Simulation of the Autonomous Decentralized Dispatching System of Generalized Demand Side Resources. 2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia).

Papanikolaou, I., et al. (2019). "Graphene nanoplatelet reinforced concrete for self-sensing structures – A lifecycle assessment perspective." Journal of Cleaner Production **240**.

Pellegrino, A., et al. (2016). "Lighting Control and Monitoring for Energy Efficiency: A Case Study Focused on the Interoperability of Building Management Systems." IEEE Transactions on Industry Applications **52**(3): 2627-2637.

Penteado, C. S. G., et al. (2016). "Reusing ceramic tile polishing waste in paving block manufacturing." Journal of Cleaner Production **112**: 514-520.

Perepelitza, M., et al. (2015). "Performance validation case study: Federal office building with an integrated facade." Journal of Building Physics **39**(6): 542-569.

Poon, C. S., et al. (2004). "Reducing building waste at construction sites in Hong Kong." Construction management and Economics **22**(5): 461-470.

Power, D. and R. L. Gruner (2017). "Variable use of standards-based IOS enabling technologies in Australian SMEs: an examination of deliberate and emergent decision making processes." European Journal of Information Systems **26**(2): 164-184.

Ravindrarajah, R. S. and C. Tam (1987). "Recycling concrete as fine aggregate in concrete." International Journal of Cement Composites and Lightweight Concrete **9**(4): 235-241.

Rieckhof, R. and E. Guenther (2018). "Integrating life cycle assessment and material flow cost accounting to account for resource productivity and economic-environmental performance." The International Journal of Life Cycle Assessment **23**(7): 1491-1506.

Rios, F. C., et al. (2015). "Design for Disassembly and Deconstruction - Challenges and Opportunities." Procedia Engineering **118**: 1296-1304.

Ritter, E. (2012). "Findings of an ASHRAE level II energy audit of a senior living facility." Energy Engineering: Journal of the Association of Energy Engineering **109**(3): 31-40.

Rocca, R., et al. (2020). "Integrating Virtual Reality and Digital Twin in Circular Economy Practices: A Laboratory Application Case." Sustainability **12**(6): 2286.

Romero, D., et al. (2013). "The DigiHome Service-Oriented Platform." Software: Practice and Experience **43**(10): 1205-1218.

S.Shuttleworth, P. (2007). "Ph.D. Thesi." University of York.

Sacks, R., et al. (2010). "Requirements for building information modeling based lean production management systems for construction." Automation in construction **19**(5): 641-655.

Saghafi, M. D. and Z. A. H. Teshnizi (2011). "Building Deconstruction and Material Recovery in Iran: An Analysis of Major Determinants." Procedia Engineering **21**: 853-863.

Salama, W. (2017). "Design of concrete buildings for disassembly: An explorative review." International Journal of Sustainable Built Environment **6**(2): 617-635.

Salamone, F., et al. (2017). "Design and development of a nearablewireless system to control indoor air quality and indoor lighting quality." Sensors (Switzerland) **17**(5).

Sanchez, B. and C. Haas (2018). "A novel selective disassembly sequence planning method for adaptive reuse of buildings." Journal of Cleaner Production **183**: 998-1010.

Sarc, R., et al. (2019). "Digitalisation and intelligent robotics in value chain of circular economy oriented waste management – A review." Waste Management **95**: 476-492.

Schultmann, F. and N. Sunke (2007). "Organisation of reverse logistics tasks in the construction industry." Portugal SB07: Sustainable Construction, Materials and Practices: 577-584.

Sedláková, A., et al. (2020). "Environmental impacts assessment for conversion of an old mill building into a modern apartment building through reconstruction." Building and Environment **172**: 106734.

Sehar, F., et al. (2016). "An energy management model to study energy and peak power savings from PV and storage in demand responsive buildings." Applied Energy **173**: 406-417.

Sehar, F., et al. (2017). "Integrated automation for optimal demand management in commercial buildings considering occupant comfort." Sustainable Cities and Society **28**: 16-29.

Sharma, A., et al. (2011). "Life cycle assessment of buildings: A review." Renewable and sustainable energy reviews **15**(1): 871-875.

Shu, F., et al. (2009). "Building automation systems using wireless sensor networks: Radio characteristics and energy efficient communication protocols." Electronic Journal of Structural Engineering **9**: 66-73.

Sicignano, E., et al. (2019). "Mitigation Strategies for Reduction of Embodied Energy and Carbon, in the Construction Systems of Contemporary Quality Architecture." Sustainability **11**(14).

Siddaway, A. P., et al. (2019). "How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses." Annu Rev Psychol **70**(1): 747-770.

Solís-Guzmán, J., et al. (2009). "A Spanish model for quantification and management of construction waste." Waste Management **29**(9): 2542-2548.

Soltanaghaei, E. and K. Whitehouse (2018). "Practical occupancy detection for programmable and smart thermostats." Applied Energy **220**: 842-855.

Song, Z. P., et al. (2013). "Collaborative Building Control to Optimize Energy Saving and Improve Occupants' Experience." ASHRAE Transactions **119**: AA1-AA8.

Sotehi, O., et al. (2016). "Hybrid PV/T water solar collector for net zero energy building and fresh water production: A theoretical approach." Desalination **385**: 1-11.

Sovacool, B. K., et al. (2018). "Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design." Energy Research & Social Science **45**: 12-42.

Stahel, W. (2016). The circular economy. Nat. News 531, 435.

Stahel, W. R. (1997). "Some Thoughts on Sustainability, Insurability and Insurance." The Geneva Papers on Risk and Insurance - Issues and Practice **22**(4): 477-495.

Stahel, W. R. (1997). "Some thoughts on sustainability, insurability and insurance." The Geneva Papers on Risk and Insurance-Issues and Practice **22**(4): 477-495.

Stahel, W. R. (2016). "The circular economy." Nature News **531**(7595): 435.

Stocker, T. F., et al. (2013). Climate change 2013: The physical science basis, Cambridge University Press Cambridge.

Svajlenka, J. and M. Kozlovska (2017). "Modern method of construction based on wood in the context of sustainability." Civil Engineering and Environmental Systems **34**(2): 127-143.

Tabsh, S. W. and A. S. Abdelfatah (2009). "Influence of recycled concrete aggregates on strength properties of concrete." Construction and building materials **23**(2): 1163-1167.

Takano, A., et al. (2014). "A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context." Building and Environment **82**: 526-535.

Tavares, V., et al. (2019). "Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study." Journal of Cleaner Production **212**: 1044-1053.

Teh, S. H., et al. (2017). "Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia." Journal of Cleaner Production **152**: 312-320.

Tellis, W. (1997). "Application of a case study methodology." The qualitative report **3**(3): 1-19.

Tesiero, R. C., et al. (2014). "LOW-COST STRATEGIES TO SAVE ENERGY IN K-12 SCHOOLS." American Journal of Engineering and Applied Sciences **7**(1): 41.

Tesiero, R. C., et al. (2014). ""Low-Tech/No-Cost" Control Strategies to Save Energy in K-12 Schools." ASHRAE Transactions **120**: R1-R10.

Thormark, C. (2002). "A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential." Building and Environment **37**(4): 429-435.

Thyer, S., et al. (2018). "Optimising energy use in an existing commercial building: a case study of Australia’s Reef HQ Aquarium." Energy Efficiency **11**(1): 147-168.

Tingley, D. D., et al. (2017). "Understanding and overcoming the barriers to structural steel reuse, a UK perspective." Journal of Cleaner Production **148**: 642-652.

Tingley, D. D. and B. Davison (2011). "Design for deconstruction and material reuse." Proceedings of the institution of civil engineers-energy **164**(4): 195-204.

Toniolo, S., et al. (2017). "Allocation strategies in comparative life cycle assessment for recycling: Considerations from case studies." Resources, Conservation and Recycling **117**: 249-261.

Unger, N., et al. (2017). "The greenhouse gas benefit of recycling waste electrical and electronic equipment above the legal minimum requirement: An Austrian LCA case study." Journal of Cleaner Production **164**: 1635-1644.

Van Den Wymelenberg, K. G. (2014). "Visual comfort, discomfort glare, and occupant fenestration control: Developing a research agenda." LEUKOS - Journal of Illuminating Engineering Society of North America **10**(4): 207-221.

Vefago, L. H. M. and J. Avellaneda (2013). "Recycling concepts and the index of recyclability for building materials." Resources, Conservation and Recycling **72**: 127-135.

Viani, C., et al. (2016). "Recovering value from used medical instruments: A case study of laryngoscopes in England and Italy." Resources, Conservation and Recycling **111**: 1-9.

Wan Mohd Nazi, W. I., et al. (2017). "Office building cooling load reduction using thermal analysis method – A case study." Applied Energy **185**: 1574-1584.

Wang, H., et al. (2018). "Low carbon transition of global building sector under 2-and 1.5-degree targets." Applied Energy **222**: 148-157.

Wang, S., et al. (2021). "Sustainable product development and service approach for application in industrial lighting products." Sustainable Production and Consumption **27**: 1808-1821.

Wei, W., et al. (2015). "How to Conduct a Proper Sensitivity Analysis in Life Cycle Assessment: Taking into Account Correlations within LCI Data and Interactions within the LCA Calculation Model." Environmental Science & Technology **49**(1): 377-385.

Wen, T. J., et al. (2015). "Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia." Energy and buildings **93**: 295-302.

Wheaton, W. G. (2017). "Designing for Disassembly in the Built Environment.".

Wilson, M., et al. (2022).

Wu, Y., et al. (2019). "Automated 'Eye-sight' Venetian blinds based on an embedded photometric device with real-time daylighting computing." Applied Energy **252**.

Xiong, A. M., et al. (2013). "Intelligent Shading Control System Based on the Lonworks Bus." Applied Mechanics and Materials **273**: 665.

Yan, H., et al. (2010). "Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong." Building and Environment **45**(4): 949-955.

Yang, T., et al. (2016). "An automated optimization method for calibrating building energy simulation models with measured data: Orientation and a case study." Applied Energy **179**: 1220-1231.

Yang, Z., et al. (2014). "A systematic approach to occupancy modeling in ambient sensor-rich buildings." SIMULATION **90**(8): 960-977.

Yellishetty, M., et al. (2011). "The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue?" Journal of Cleaner Production **19**(1): 78-90.

Yeon, S., et al. (2019). "ANN based automatic slat angle control of venetian blind for minimized total load in an office building." Solar Energy **180**: 133-145.

Yin, R., et al. (2016). "Linking measurements and models in commercial buildings: A case study for model calibration and demand response strategy evaluation." Energy and Buildings **124**: 222-235.

Yin, R. K. (1992). "The case study method as a tool for doing evaluation." Current sociology **40**(1): 121-137.

Yin, R. K. (1994). "Discovering the future of the case study. Method in evaluation research." Evaluation practice **15**(3): 283-290.

Yin, R. K. (2012). "Case study methods."

Yu, C. and D. Crump (1998). "A review of the emission of VOCs from polymeric materials used in buildings." Building and Environment **33**(6): 357-374.

Yu, H., et al. (2009). "Development of lean model for house construction using value stream mapping." Journal of construction engineering and management **135**(8): 782-790.

Zabalza Bribián, I., et al. (2011). "Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential." Building and Environment **46**(5): 1133-1140.

Zhang, C., et al. (2020). "Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands." Journal of Cleaner Production **266**: 121718.

Zhang, Y., et al. (2018). "The optimization of visual comfort and energy consumption induced by natural light based on PSO." Sustainability (Switzerland) **11**(1).

Zhong, R. Y., et al. (2017). "Prefabricated construction enabled by the Internet-of-Things." Automation in construction **76**: 59-70.