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Sustainable non-residential development model – A shift in material decision-making towards mass timber

by Le Hong Thuy Nguyen

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Dr Rijun Shrestha,
Associate Professor Grace Ding and
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University of Technology Sydney
Faculty of Engineering and Information Technology

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Certificate of Original Authorship

I, Le Hong Thuy Nguyen, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Ding, G., & **Nguyen, T.** (2020). Carbon management: Forest conservation and management. *Advances in carbon management technologies*.

Conference paper

Nguyen, T. L. H., Ding, G., Shrestha, R., & Crews, K. (2019, July). Australian construction practitioners' perception of mass timber construction – The emerging challenges and strategies for further development. In *5th Pacific Timber Engineering Conference (PTEC 2019).*

Nguyen, T. L. H., Shrestha, R., & Crews, K. (2018, January). How the choice of building materials affects the environmental burdens in non-residential and multistorey residential building construction. In *WCTE 2018 – World Conference on Timber Engineering.*

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Abbreviations

^{0}C	Degrees Celsius
ACT	Australian Capital Territory
AusLCI	The Australian National Life Cycle Inventory Database
BCA	Building Code of Australia
BEES	Building for Environmental and Economic Sustainability
BREEAM	Building Research Establishment Environmental Assessment Method
CLT	Cross-laminated timber
CO$_2$	Carbon dioxide
CO$_2$ eq	Carbon dioxide equivalent
DfMA	Design for Manufacture and Assembly
DTS	Deem-to-satisfy
EoL	End-of-life
EPD	Environmental product declaration
EWPs	Engineered wood products
FAO	Food and Agriculture Organization
FSC	Forest Stewardship Council
FWPA	Forest and Wood Products Australia
GFA	Gross floor area
GHG	Greenhouse gas
GJ	Gigajoules
Glulam	Glue-laminated timber
HPL	High-pressure laminate
Hr	Hour
ISO	International Organisation for Standardisation
kg	Kilogram
KPIs	Key performance indicators
kWh	Kilowatt-hour
LCA	Life cycle assessment

LCC	Life cycle cost
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LEED	Leadership in Energy and Environmental Design
LVL	Laminated veneer lumber
m^2	Square metres
m^3	Cubic metres
MDF	Medium-density fibreboard
MJ	Megajoules
Mt	Million tonne
NABERS	National Australian Built Environmental Rating System
NCC	National Construction Code
NLA	Net lettable area
PEFC	Pan-European Forest Certification
t	Tonne
tkm	Tonne.Kilometre
UNEP-SBI	UN Environment Programme – Sustainable Building and Climate Initiative
W	Watt

Abstract

The construction industry accounts for 30 – 50% of raw material consumption and is responsible for a large portion of global greenhouse gas emissions. While steel and concrete dominate non-residential construction, there is a growing interest in the use of environmentally friendly building materials in Australia and worldwide.

Sawn timber has been used in construction, both in structural and non-structural applications, for many centuries, especially for low-rise and residential buildings. Advances in engineered wood products (EWPs), also known as mass timber, and the environmental benefits of using timber in construction have been driving the adoption of mass timber construction (MTC) in Australia and worldwide. Mass timber offers considerable environmental advantages, including lower energy consumption and greenhouse gas emissions during production compared to concrete and steel. Additionally, timber waste such as offcuts and sawdust can be repurposed for bioenergy, and end-of-life mass timber elements require less energy for demolition. Despite successful demonstration projects, wides-cale adoption of mass timber faces obstacles. This study explores the perceptions of Australian construction practitioners towards mass timber, with a particular focus on non-residential development. Using semi-structured interviews with construction practitioners experienced in mass timber construction in Australia, this study identifies benefits, obstacles, and strategies for broader adoption of mass timber in non-residential development.

Findings of the interviews are categorised into key performance indicators: cost, time, quality and environmental performance. In conjunction with insights identified from the literature review, the three most important indicators, quality, cost and environmental performance, were selected to develop a sustainable non-residential development model. This model aims to guide material selection in non-residential development towards sustainability. To validate the model, an actual concrete office design was compared with an alternative mass timber redesign. The results demonstrate that mass timber can deliver comparable quality, costs, and energy efficiency, while considerably reducing greenhouse gas emissions and fossil fuel depletion. Furthermore, demolition of mass timber structure requires less energy, equipment and labour, and results in less waste than concrete, which highlights mass timber's potential for sustainable non-residential construction in Australia.

Chapter 1 Introduction

1.1 Introduction

Sustainable development is getting more attention in the construction industry. Efforts to use renewable resources to mitigate environmental impacts have motivated the use of engineered wood products or mass timber in building construction. Historically, 90% of residential housing in Australia uses timber wall and timber roof frames (Forest and Wood Products Australia, 2005). On the contrary, steel and concrete are more commonly used in mid-rise and high-rise multi-residential and commercial building construction (Bayne & Page, 2009). There has been increasing interest in using timber for non-residential and multi-residential buildings in the last few years since there are many benefits of using timber in construction compared to other competing materials. This study aims to develop a strategic model for sustainable non-residential development using mass timber as the key structural material. This model considered how mass timber performs against traditional heavy materials in terms of embodied energy and embodied carbon in conjunction with other aspects such as quality and cost performance.

1.2 Background

The construction industry is a foundation of social growth and economic development. Globally, it provides employment to over 111 workforces and accounts for 13% of the global gross domestic product (João Ribeirinho et al., 2020). Construction is one of the most vital industries in the Australian economy. It is the third-largest industry in Australia for its share of gross domestic product (Australian Bureau of Statistics, 2020). Furthermore, construction activities support large upstream and downstream supply chains, including building material products such as tiles, wood, steel, cement, bricks and glass (Australian Industry Group, 2015). However, the construction industry is also responsible for environmental impacts of high energy usage, and overconsumption of water and natural resources. The construction industry is responsible for two-fifths of global energy consumption, one-fourth of waste generation and water use, and one-third of the world's greenhouse gas (GHG) emissions (Hong et al., 2019). Therefore, using building materials that consume a low amount of energy, water and natural resources will release fewer greenhouse gas emissions. Additionally, applying more sustainable construction methods will reduce waste, shorten construction time, and minimise offsite work. These are the major benefits for the sustainable construction industry.

In the building industry, embodied carbon is the total greenhouse gas emissions (measured in carbon dioxide equivalent) released during the extraction, manufacturing, transportation to construction site, installation, maintenance, replacement and disposal of building materials (González & Navarro, 2006). Clean Energy Finance Corporation (2021) stated that embodied carbon in the production of building materials accounts for 28% of emissions from the building and construction sector globally. Embodied carbon is expected to be responsible for half of the total emissions from new constructions between 2019 and 2050. Since the improvements to mitigate operational emissions have already become common practice (e.g., the Australian Capital Territory (ACT) grid's is 100% renewable energy, all electricity utilised in the ACT can be considered renewable), embodied carbon is the next focus to achieve Australian's net zero emissions targets by 2050. Among building materials used in building and infrastructure projects, concrete and steel are identified as difficult to decarbonise (Clean Energy Finance Corporation, 2021). The use of mass timber in building construction potentially reduces embodied carbon while providing similar quality and cost performance compared to competing heavy materials. However, despite demonstration projects having been completed, several obstacles and challenges need to be addressed in the widescale adoption of mass timber in the construction industry. This study aims to investigate perceptions of Australian construction practitioners about mass timber usage, particularly in non-residential development, to provide a sustainable model which facilitates a shift in material selection towards sustainability to contribute to Australia's net zero emissions targets.

1.3 Problem definition

Since the first mass timber residential building in Australia – the Forté building in Docklands, Melbourne, was completed in 2012, there has been growing interest in promoting the use of mass timber in not only the residential sector but also in the non-residential sector. A few mass timber office buildings have been completed in the past few years in Australia. However, limited construction practitioners have sufficient knowledge and experience in mass timber construction, especially in the non-residential sector. Increasing the uptake of mass timber usage in the non-residential sector requires addressing concerns in terms of technical issues, legislation, cost performance and current building procurement processes that might not suit mass timber non-residential development. Thomas (2015) developed a model for sustainable residential development and tested the proposition of the model by comparing how timber performed against brick and concrete in terms of life cycle cost, life cycle energy and thermal performance in residential building construction. The model was beneficial for the homeowners by reducing construction time, life cycle cost and energy while retaining the same quality as traditional concrete and brick houses. However, the building procurement process of non-residential buildings is more complex than that of residential buildings. It requires more stakeholders involved in project development (Morledge & Smith, 2013; Nolan, 2010). Hence, the model for residential development might not be applicable for the non-residential building sector.

Additionally, studies carried out in the past decade have proved that mass timber buildings outperform traditional heavy material buildings consume more embodied energy, especially non-renewable fossil energy and release more CO_2 emissions than timber buildings do (Durlinger et al., 2013; Perez Fernandez, 2008b; Robertson et al., 2012). Australian Government has targeted to achieve net zero emissions by 2050 to tackle climate change while keeping the economy growing. Since embodied carbon is the focus to decarbonise the building and construction sector, it is necessary to outline materials and design strategies that can mitigate carbon emissions in new projects, without a significant increase in cost (Clean Energy Finance Corporation, 2021). At the end of the functional building life cycle, disposal options vary depending on national policies, regulations and standards, such as landfilling, recycling or incineration (Ding, 2019). In Australia, waste disposal levy or landfill levy is a tax imposed for all types of waste for each tonne of waste sent to the licensed landfill. Waste levy varies across states and territories in Australia. For instance, it is applied in New South Wales, Victoria, South Australia, Western Australia and the Australian Capital Territory to encourage recycling and resource recovery (Zhao et al., 2022). However, the comparison of the end-of-life scenario in terms of energy use and associated CO_2 emissions between sustainable buildings and traditional heavy material buildings has received less attention. Therefore, there is a gap in the literature of a strategic model for sustainable non-residential development using the circular concept considering the potential of recycling or reuse of building materials.

This study addresses the following research questions:

- What are the obstacles that hinder the uptake of mass timber usage in Australia?
- How can the advantages of using mass timber in construction be strengthened?
- Can the current building procurement process be used in the sustainable non-residential development sector?
- What are the most important indicators when assessing the success of a building project?
- How can a strategic model for sustainable non-residential development be developed?

- How does mass timber perform against traditional heavy materials in terms of different aspects such as quality, cost, embodied energy and embodied carbon in non-residential development?
- How can mass timber construction contribute to Australia's net zero emissions targets?
- How does mass timber perform against heavy materials at the end of the life cycle?

1.4 Research aims and objectives

Section 1.3 discussed research gaps that have not been addressed and identified research problems and questions addressed in this study. The main aim of this study is to develop a model for sustainable non-residential development and to examine how mass timber performs against traditional heavy materials such as concrete in non-residential applications. To achieve these aims, this study set specific objectives as follows:

- Investigate the benefits and current obstacles of using mass timber as an alternative to traditional heavy materials such as concrete and steel.
- Investigate the perceptions of Australian construction practitioners on mass timber construction, particularly in the non-residential sector.
- Identify key performance criteria to assess the performance of mass timber use in non-residential applications.
- Review current building procurement process using heavy materials.
- Identify a suitable building process for mass timber construction.
- Develop a non-residential development model using sustainable material as a key structural material.
- Test the propositions of the proposed model by using case study buildings to see how mass timber performs against traditional heavy materials such as concrete, in terms of identified key performance criteria. The propositions of the model are described in this study that a mass timber

building has similar thermal performance as a concrete building but performs better in terms of embodied energy and embodied carbon without incurring higher cost.

1.5 Significance of the research

The use of mass timber in non-residential buildings offers many benefits, not only to the environment but also to the human occupants of such buildings. Indeed, the production of mass timber requires less energy and releases less carbon emissions compared to concrete and steel (Durlinger et al., 2013; Perez Fernandez, 2008b). Timber brings a natural aesthetic, and a recent study has revealed that using timber in buildings can contribute to healthier homes and productive workplaces (Planet Ark, 2017). Timber is considered a natural insulator that, with proper design, can reduce heating and cooling costs. In that sense, mass timber construction potentially contributes to Australia's net zero emissions targets by 2050. However, there are still many obstacles that hinder the uptake of mass timber in construction, particularly in the non-residential sector in Australia. This research investigates the perceptions of construction practitioners in Australia on mass timber construction. They are the pioneers in mass timber construction in Australia, and thus their perceptions reveal lessons that have been learnt, as well as actual challenges they are facing. These perceptions, along with the principles of sustainability and the concept of circular economy in sustainable development, are the foundation of the model developed for the sustainable non-residential sector. More importantly, the findings from the case study model verification show how mass timber performs against concrete in terms of selected key performance criteria. The design professionals, especially architects and structural engineers, will directly benefit from the proposed model when working with a new construction method in building construction. Consequently, the clients or the owners of the building potentially have an environmentally friendly building with the same quality and cost performance as a traditional heavy material building.

1.6 Research scope

This study mainly focuses on the use of mass timber as an alternative structural material to traditional heavy materials in the non-residential sector in the Australian market. While mass timber has been used in Australia in the multi-storey building sector during the past decade, there are still only a limited number of construction practitioners who have experience with using mass timber. Therefore, a comprehensive literature review and in-depth interviews are used to investigate the perceptions of different stakeholders to identify the current key barriers in mass timber construction. The scope for the literature review and initial data collection includes the stages of design, regulation approval, material manufacturing, construction, operation, and end-of-life.

To test the proposition of the proposed model, the case study buildings are selected based on a number of factors such as type and scale of the case study buildings as well as intellectual confidentiality. Since limited construction firms have experience with mass timber construction, their experience is considered valuable intellectual property. Hence, it is not possible to obtain full details of an actual mass timber design. Therefore, this study uses a traditional concrete office design provided by a client and redesigns structural elements into an alternative mass timber design. The redesign is reviewed by experts who have experience in mass timber construction in Australia to ensure the efficiency of the alternative mass timber design. The case study testing comprises the stage of raw material acquisition to material manufacturing, construction, operation, end-of-life, and benefits and loads beyond building lifetime.

1.7 Research methodology

Three main types of research methods including qualitative, quantitative and mixed methods are reviewed. While the qualitative approach is used to handle textual data, a quantitative approach is used in numerical measurement data, and mixed-methods research is employed for research with both textual and numerical data. Therefore, this study uses mixed-methods research, in which a qualitative approach is used for the data collection and analysis process to:

- undertake a comprehensive literature review to understand current strengths and challenges of mass timber construction and identify key performance indicators
- conduct semi-structured interviews with construction practitioners to understand their perceptions of mass timber construction in Australia
- develop a sustainable non-residential development model.

A quantitative approach is employed for the case study verification. Depending on which key performance indicators are selected to test the model, a suitable approach is used to examine the selected performance indicators.

1.8 Structure of the thesis

The thesis is structured as follows.

Chapter 1 Introduction

This chapter provides the background, research problems and current gaps in the literature. Research aims and objectives are also identified. The significance of the research and the research structure are also included.

Chapter 2 Literature review: Sustainability and sustainable building materials

This chapter reviews the concept of sustainability and the concept of a circular economy for sustainable development. This chapter also examines traditional material usage, its impacts on the environment and the need for a shift in material selection towards sustainable building materials. The introduction of engineered wood products in building construction, particularly in the non-residential sector, is also discussed. To develop a model for sustainable non-residential development, it is essential to understand the strengths and weaknesses of sustainable materials as well as the current adoption of them in building construction in Australia and worldwide.

Chapter 3 Selection of key performance indicators in building construction

This chapter uses comprehensive literature to identify key performance indicators of construction projects. The identified indicators include time, cost, quality and environmental performance. This chapter also provides a review of different methods to examine these indicators.

Chapter 4 Research methodology

This chapter discusses the research design and methodology to explain how this research is conducted. Both qualitative and quantitative methods are adopted in this research. A comprehensive literature review and semi-structured interviews with practitioners are used for data collection and analysis, and case study is used for model verification.

Chapter 5 Data collection and interview results analysis

This chapter represents the purpose, data collection methods and results of the semi-structured interviews with construction practitioners who have experience in delivering mass timber projects in Australia. In conjunction with the literature, the results of the interviews identify current key challenges and strategies to increase the uptake of mass timber usage in commercial developments in Australia. This chapter comprises two parts: data collection explanation, and analysis of the semi-structured interviews. The conclusion summarises the results and introduces their purpose in developing a strategy for the uptake of mass timber usage in commercial development in the Australian context.

Chapter 6 Proposing a model for sustainable non-residential development

Based on the results of a comprehensive literature review and interviews, selected key performance indicators are identified for the development of the sustainable non-residential model. Through the results of interviews with construction practitioners, a suitable building procurement process for mass timber construction is suggested. This building procurement process is also fundamental to the sustainable non-residential model.

Chapter 7 Case studies and model verification

This chapter reveals the results of testing the proposition of the sustainable non-residential model using case study buildings. In this chapter, the details of the selected case study buildings are provided. The results provide a comparative view between mass timber and traditional heavy material performance.

Chapter 8 Conclusions and Recommendations

This chapter summarises the findings of the research and presents conclusions within the research scope to evaluate the aims and objectives that have been set for the research. After the model verification, the final results are presented in this chapter. It reveals the outcomes and contributions of this research. It also suggests directions for further studies.

Chapter 2 Literature review: Sustainability and sustainable building materials

This chapter reviews the concept of sustainability and the concept of the circular economy for sustainable development. This chapter also examines traditional material usage, impacts on the environment and the need for a shift in material selection towards sustainable building materials. The introduction of engineered wood products in building construction, particularly in the non-residential sector, is also discussed. To develop a model for sustainable non-residential development, it is essential to understand the strengths and weaknesses of sustainable materials as well as the current adoption of them in building construction in Australia and worldwide.

2.1 Sustainability and circular economy for sustainable development

Young (1997) defined sustainability "as a measure of how humans are living in harmony with the environment". Sustainability can be described as a three-legged stool of which each leg represents one of the three major parts – ecosystem, economy, and society. In a sustainable society, there is no systematic over-extraction of fossil carbon and metals from the Earth's crust, and sustainable use of natural resources from forests, soil and the ocean. Consequently, humans will be affected in terms of physical and mental health, personal development, happiness and well-being (Broman & Robèrt, 2017). A study by Gutés (1996) revealed that strong sustainability is labelled as non-decreasing natural capital stock and leaving future generations a natural capital stock not smaller than the stock being used by the present generation. Hence, an economy is considered sustainable when its saving rate is greater than the combined decreasing rate of natural and human-made capital. The goal of sustainable development can only be gained when all the three components of sustainability including ecosystem, economy and society are linked together (Azapagic et al., 2003; Young, 1997). According to Brundtland (1987) and Ortiz et al. (2009), sustainable development means that people meet the needs of living in a healthy environment with improved social, economic and environmental conditions without compromising the ability of future generations. Despite technological and infrastructure advancement, human beings depend on natural systems (Diesendorf, 2000). Hence, both developed and developing countries are facing the challenge to improve their economy and quality of human life without harming the ecosystem and human health. Furthermore, it is of great importance to change the thinking that the economy should be improved in quality rather than quantity (Brundtland, 1987). The importance of balancing industrial and economic development with environmental and human health is the main motivation for resource use and low-carbon development strategies. These strategies are included in the application of the circular economy (CE) concept which is currently being adopted in many countries around the world such as Canada, China, Europe, Finland, France, Japan, The Netherlands, Sweden and the United Kingdom (Korhonen et al., 2018; Winans et al., 2017). The concept of the circular economy for sustainable development is described in Figure 2.1.

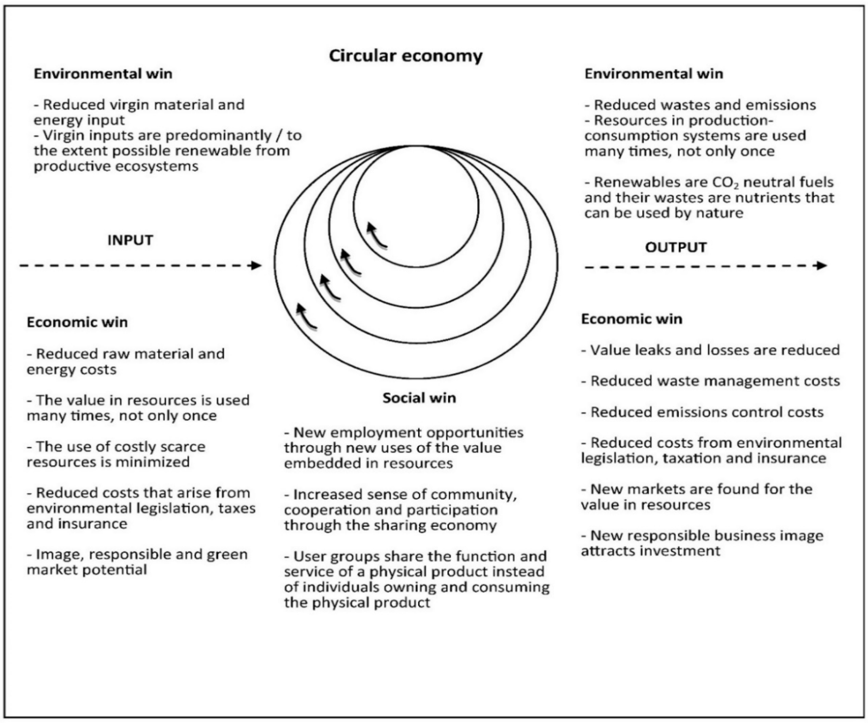


Figure 2.1 Circular economy for sustainable development (Korhonen et al., 2018)

The basis of the circular economy for sustainable development is the valuation of cyclical material flows to gain the win–win–win potential of a successful circular economy that balances all three pillars of sustainable development – economic, environmental, and social. The circular economy for sustainable development encourages the use of renewable resources and recycling and reusing materials (Korhonen et al., 2018). Bioenergy, pulp, paper, timber and biomaterials are part of the cyclical material flows since their wastes can be recycled or reused as biomass to substitute for non-renewable fossil fuels in production and consumption systems (Korhonen et al., 2018).

Anthropogenic GHG emissions, which are the emissions associated with human activities include fossil fuel combustion and industrial processes, deforestation, agricultural activities, livestock, etc. have continued to increase during the last decade from 2010 to 2019. Global net anthropogenic GHG emissions were 59±6.6 GtCO_2-equivalent (CO_2-eq) in 2019, which were approximately 12% higher than in 2010 and 54% higher than in 1990 (Shukla et al., 2022). Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and synthetic gases are the main GHGs generated by human activities. CO_2 is the most important anthropogenic GHG emissions which contributes to global warming potential. CO_2 alone was responsible for 65% of total annual anthropogenic GHG emissions by gases 1970 – 2010 (IPCC, 2014; Pachauri & Reisinger, 2008). The GHG emissions warm the Earth by absorbing and re-radiating much of the outgoing heat energy. Different GHG emissions have different global warming potential, depending on the ability to absorb the heat energy in the atmosphere over a specific time. Therefore, CO_2 equivalent (CO_2-eq) is common metric used to measure how much GHG emissions contribute to Global Warming Potential over a time horizon (usually 100 years). UNEP-SBI's report estimated that building construction emits up to 30% of annual global GHG emissions and consumes up to 40% of all energy as a result of manufacturing, transport from factory to construction site of building materials, and the construction, operational activities, and demolition of buildings. Such observation is common both in developed and developing countries and if not a single effort is made, GHG emissions from buildings will more than double in the next 20 years (UNEP-SBCI, 2009). In building construction, sustainable development can be achieved when the sector satisfies economic growth with the responsibility of protecting the environment and improving social factors (Burgan & Sansom, 2006). Therefore, it is vital to adopt the circular economy concept for sustainable development in the construction industry to gain industrial growth without harming the ecosystem and human health and well-being.

2.2 Traditional material usage in non-residential development and the need for a shift in material selection towards sustainable materials

Traditionally, reinforced concrete and steel are the first choice of structural building materials for non-residential building construction (Bruneau & MacRae, 2017). A report published by Australia's Department of Climate Change and Energy Efficiency estimated that the stock of commercial buildings comprising stand-alone offices, hotels, retail (shopping centres), hospitals, schools, universities, VET buildings, public buildings and law courts is over 134 million m^2 in Australia in 2009 and it is expected to increase by 23% in 2020 (Commonwealth of Australia, 2012). According to McGraw Hill Construction (2013), the commercial building sector is the major focus for the world's green building campaign.

During the lifetime from cradle to grave, buildings consume a huge quantity of energy. This energy can be classified as embodied energy (energy consumed during building construction) and operational energy (energy consumed during building operation). Greenhouse gas generation is therefore governed by both construction and operational activities. There are various green building rating tools around the world, such as LEED (Leadership in Energy and Environmental Design) in North America, and BREEAM (Building Research Establishment Environmental Assessment Method) in the United Kingdom. Green Building Council of Australia launched Green Star voluntary rating system for buildings, fitouts and communities in 2003 to encourage green building practice (Green Building Council Australia, 2020). Green Star rating tools, including Green Star Buildings and Green Star – Design and As Built, Green Star – Communities, Green Star – Interiors, and Green Star – Performance use a rating scale of 1 – 6 Star Green Star to assess and reward new or existing building projects that achieve best practice, Australian excellence or world leadership (Green Building Council Australia, 2020; Xia et al., 2013). In addition, NABERS, which stands for the National Australian Built Environment Rating System, is a performance rating tool to measure building's energy and water efficiency for hotels, offices, shopping centres and apartments. NABERS has cooperated with Climate Active organisation which is a partnership with Australian Government and Australian Businesses, to provide carbon neutral certification for buildings (Residovic, 2017). Operational energy is mainly affected by the design of buildings while embodied energy is the energy needed in the process of building material manufacturing, transport to site, building construction, refurbishment and maintenance, and hence it is influenced by the choice of building materials and construction method (Spence & Mulligan, 1995). Research and efforts have been applied to maximise energy efficiency throughout a building life cycle such as using well-managed energy strategies (non-technical management), adopting technical energy management systems or replacing fossil fuel resources in electricity generation with non-fossil and renewable energy including solar and wind energy (Beyond Zero Emissions, 2013). The major goal of the Zero Carbon Australia Buildings Plan is to find how to cut down the energy consumption of buildings and achieve a future neutral emissions economy. Although the Zero Carbon Australia Buildings Plan concentrates only on operating energy and emissions, energy and emissions from building construction are also endorsed to have an important responsibility for environmental impact (Beyond Zero Emissions, 2013). On the other hand, embodied energy of most residential, commercial, institutional, and educational buildings in Australia is between 20 to 50 times the annual operational energy. The annual embodied energy consumption in Australian construction sector is roughly identical to the annual operational energy of the built stock.

Embodied and operational energy is responsible for 30 – 40% of the national energy consumption and GHG emissions (Graham Treloar et al., 2001). Each building is a combination of multiple building materials and each of them plays a significant role in the embodied energy consumption (Graham Treloar et al., 2001). Embodied carbon emissions of building materials used in Australia is approximately 30 – 50 million tonnes CO_2 equivalent per year, which is roughly five to ten percent of national greenhouse gas emissions (Clean Energy Finance Corporation, 2021). Therefore, the challenges to mitigate embodied energy and energy carbon in the construction industry are the drivers of a shift in building material selection.

Global and Australian green building trends are to make buildings more energy-efficient, yet it requires more embodied energy. As mentioned above, heating and cooling are affected by the choice of building materials. To reduce operational energy, insulation and other specified designs are needed that increase the material usage, and consequently, increase embodied energy (McGraw Hill Construction, 2013; Graham Treloar et al., 2001). Statistics about the embodied energy and associated greenhouse gas emissions for commercial buildings in Australia are limited, however research on the differences between the embodied energy requirements of alternative structural systems such as concrete, steel and timber structures have been taken into consideration both in Australia and worldwide. For instance, early in 1995, Cole and Kernan analysed the differences in life cycle energy use of timber, concrete and steel office structures in the USA (Cole & Kernan, 1995). The results showed that the embodied energy of a steel building is 1.61 times higher than that of a concrete structure, and the embodied energy of a timber structure is 1.27 times lower than that of a concrete structure (Cole & Kernan, 1996). Recently, Felton, Fuller and Crawford (2014) used the design of the 15-storey Royal Domaine Centre (RDC) located at 380 St Kilda Road, Melbourne, Australia, to analyse the difference of replacing reinforced concrete and steel structural and non-structural elements with wooden products, using the input-output LCA based methodology. They concluded that, in total, the replacement reduced roughly 78.7 GJ embodied energy and 4.75 kt CO_2-e emissions. Hence, construction technology with the use of engineered wood products, which is known as mass timber construction, potentially offers an enormous opportunity for the use of renewable materials to decrease embodied energy and associated greenhouse gas emissions (Felton et al., 2014). The development of engineered wood products will be reviewed to explore why they are sustainable materials in the next section.

2.3 The development of engineered wood products

Engineered wood products (EWPs), also called mass timber, are emergent timber technologies that enable more widespread use of timber and timber products in buildings. Popular EWPs include laminated veneer lumber (LVL), glue-laminated timber (glulam) and cross-laminated timber (CLT). They have been developed over the years to enable the construction of prefabricated timber structures to compete with steel and concrete in mid-rise and high-rise buildings. Mass timber construction is an innovative construction method, which mainly uses EWPs as key structural materials. The adoption of digital design and prefabrication in mass timber construction allows building elements such as beams, columns, floors and walls to be pre-cut, prefabricated and transported to the construction site for immediate installation.

The use of EWPs in construction has developed since World War II mainly for non-structural elements, but it has now been developed for structural applications (Manninen, 2014). In North America, the number of mass timber buildings per year has increased from under 20 projects in 2014 to more than 200 projects in 2018 (The Beck Group, 2018). Most EWPs are typically made of softwood such as spruce, pine or fir. The density of softwood is approximately 500 kg/m^3 whereas the density of steel is 7800 kg/m^3 and concrete is 2400 kg/m^3. Therefore, the use of EWPs in construction can significantly reduce the overall weight of the structure. This reduction in weight can simplify foundation design and lead to lower embodied energy and associated CO_2 emissions. However, it is important to note that the structural capacity per unit mass may vary between materials.

Light weightness and flexibility characteristics of EWPs also mean that building components are simple and safe to construct and the prefabrication method can be applied relatively quickly. Incorporating prefabrication in construction, in turn, can considerably reduce building time as well as labour costs, delays due to adverse weather conditions, and environmental impacts. CLT, LVL and glulam are the three most common EWPs used for prefabricated structural applications (Yadav & Kumar, 2021)

2.3.1 Cross-laminated timber (CLT)

CLT is the leading innovation among EWPs used in mass timber construction. It is made of at least three cross-bonded layers (usually three, five or seven) of solid sawn timber. CLT was first developed in Switzerland in the early 1970s and widely used in the 2000s when some countries in Europe such as Austria, Germany, Norway, Sweden, Switzerland and the United Kingdom changed building code to permit multi-storey timber buildings. Approximately 90% of worldwide CLT production volume (around 800,000 m^3) is in Central Europe, particularly in the alpine area (Fink et al., 2018). Outside Europe and North America, the CLT market is relatively young and it is estimated that North America consumes 45,000 m^3 CLT for buildings each year (Schwarzmann et al., 2018). In New Zealand, the first commercial manufacturer of CLT, the company XLam, started production in 2012. Since the market for CLT has increased with both the local and the global demand, Australian CLT production has reached the capacity of 60,000 m^3 per year.

CLT is mainly made from softwood such as radiata pine (Pinus radiata) or spruce (Picea abies). However, hardwood is also a potential for CLT production. It is also possible to replace single layers of CLT with other engineered timber products such as LVL, oriented strand board (OSB), plywood or multi-layer solid wood panels (Brandner et al., 2016). CLT manufacturing offers the possibility of utilising lower-grade dimensional lumber. Hence, low-grade lumber and forest mortality caused by insect, disease and fire could be effectively used (Karacabeyli & Douglas, 2013). According to the United States net annual growth between the harvest removals and mortality from 1952 to 2012, even though the rate of forest mortality slightly goes up, the rate of growing stock is still more than the total amount of timber harvested and forest mortality. This means that the mass timber development demand does not overwhelm the raw material supply (The North American Mass Timber State of the Industry 2019).

Phenol resorcinol-formaldehyde (PRF), emulsion polymer isocyanate (EPI) and one-component polyurethane (PUR) are the three types of adhesives mainly used for CLT production. PUR, which is a formaldehyde-free and light-coloured adhesive, is mostly used in CLT manufacturing (Mohammed & Munoz, 2011). It is important to ensure that adhesives have to meet specific requirements such as strength, durability, moisture resistance and heat performance. The overall yield rate of CLT production is around 43%, which means every 1 m^3 of the log can produce 0.43 m^3 of CLT. However, the production of CLT is a circular process where waste such as wood chips, sawdust and offcuts is efficiently reused, mainly to generate energy for factory equipment, kiln drying and local communities (Waugh Thistleton Architects, 2018).

CLT has been used in the construction of housing, and multi-storey residential and non-residential buildings. Using CLT in construction offers several benefits including short construction time, light weight (20% the weight of concrete), minimal waste and noise during construction, competitive cost, good lateral and seismic load resistance, adequate fire performance, stiffness, and high aesthetic value. CLT can be used for large panel prefabrication to provide floor slabs, roofs, beams, columns, load-bearing walls or shear walls. The typical dimension of CLT is 20 m in length, 50–300 mm thick and up to 4800 mm width. Non-residential and commercial and office buildings need long spans of up to 7 m, mainly for parking spaces in the basement and desired open office layouts. CLT has a high strength-to-weight ratio, which allows expanding the floor span without increasing weight, and CLT is, therefore, a competitive alternative to concrete and steel.

2.3.2 Laminated veneer lumber (LVL)

The manufacturing of LVL occurs by bonding multiple rotary-peeled veneers with their grain parallel to the longitudinal axis of the section under heat and pressure. LVL provides a wide range of structural applications such as beam, column, truss, portal frame post and beam structure, structural decking, I-joist flanges and stressed skin panels. The length can be up to 20 m, the width is from 19 to 200 mm, and the depth can vary from 90 up to 2500 mm.

The log is cut to length, debarked and soaked or sprayed with hot water before peeling in a rotary lathe to ensure the quality of veneers. Since LVL is a veneer-based wood product, the quality of veneer is, therefore, one of the driving factors for its overall quality. In the last few decades, technological improvements in wood processing minimise waste and can process smaller diameter logs from young and fast-grown plantation forests (Leggate et al., 2017). Good quality veneers are used for the production of LVL, and offcuts with defects such as knots, wane, voids or end of log veneer sheets can be used as strands for laminated strand lumber (LSL), oriented strand lumber (OSL) or parallel strand lumber (PSL) manufacturing. This helps to optimise material usage.

However, to optimise material usage and increase mechanical properties of LVL, more research on the potential of using secondary quality wood must be undertaken. Purba et al. (2019) have recently shown that the knot proportions on the veneer surface do have a negative influence on mechanical properties of LVL produced from secondary quality hardwood. Although thick veneers consume less adhesive and production time, they may reduce the modulus of elasticity and modulus of rupture of LVL. On the other hand, a thinner veneer increases LVL strength by better distributing defects. Using thin veneers leads to consumption that uses much more adhesive, effort and time in LVL production. The 3 mm thick veneer optimises the mechanical properties of LVL (Purba et al., 2019).

2.3.3 Glued laminated timber (glulam)

Glulam is an EWP manufactured by glueing several graded timber laminations with their grain parallel to the longitudinal axis of the section. Members can be straight or curved, horizontally or vertically laminated and can be used to create different structural forms. Solid 20 to 50 mm thick laminates are typically finger-jointed into lengths and clamped together by adhesive under pressure. Glulam can be used for large structural elements, beams, columns, trusses, bridges, portal frames, and post and beam structures. The common size of glulam ranges from 60 to 250 mm wide and 180 to 1000 mm deep. There are no limits for length or shape. The dimension is, therefore, determined by transport capacity (Glued Laminated Timber Association of UK).

In conclusion, the key properties of CLT, LVL and Glulam are summariesd in Table 2.1 below

Table 2.1 Key property differences between CLT, LVL and Glulam

Key property differences		
CLT	**LVL**	**Glulam**
CLT is made of at least three cross-bonded layers (usually three, five or seven) of solid sawn timber	LVL is manufactured by bonding multiple rotary-peeled veneers with their grain parallel to the longitudinal axis of the section under heat and pressure	Glulam is manufactured by gluing several graded timber laminations with their grain parallel to the longitudinal axis of the section
Low-grade lumber can be used to produce CLT	Good quality veneers are used for the production of LVL	Low-grade lumber can be used to produce CLT

Key property differences		
CLT	**LVL**	**Glulam**
The typical dimension of CLT is 20 m in length, 50–300 mm thick and up to 4800 mm width	The length can be up to 20 m, the width is from 19 to 200 mm, and the depth can vary from 90 up to 2500 mm.	The common size of glulam ranges from 60 to 250 mm wide and 180 to 1000 mm deep. There are no limits for length or shape
CLT can be used for large panel prefabrication to provide floor slabs, roofs, beams, columns, load-bearing walls or shear walls	Structural applications such as beam, column, truss, portal frame post and beam structure, structural decking, I-joist flanges and stressed skin panels	Glulam can be used for large structural elements, beams, columns, trusses, bridges, portal frames, and post and beam structures

EWPs should be manufactured using timber from sustainably managed forests and plantations. Third-party certification and labelling systems have also been developed internationally in order to set standards and to promote responsible forest management for local implementation in individual countries. Indeed, Green Building Council Australia rewards the use of products that meet the criteria outlined in the Responsible Products Framework. This initiative aims to encourage the adoption of transparent, healthy, low-impact, and net-zero carbon products within a circular economy. The framework also includes specific requirements for product certification schemes concerning timber and engineered wood products. For these products, it is mandatory to have a valid FSC, Responsible Wood, or PEFC chain of custody certification (Green Building Council Australia, 2020), The Forest Stewardship Council (FSC) was first established in 1993 as a not-for-profit organisation which certifies timber and timber products from responsible sources (FSC, 2019; Guan et al., 2018). The FSC certified approximately 1/3 of the world’s forests. The Programme for the Endorsement of Forest Certification (PEFC) was developed in 1999 and was also known as the Pan-European Forest Certification in 2004 (PEFC, 2010). The PEFC is the world’s most extensive forest certification and labelling system of forest and forest-related products that certified approximately 2/3 of the world’s forests (Guan et al., 2018; PEFC, 2010; Stupak et al., 2011). FSC and PEFC together account for almost 100% of certified forests in the world. Timber sourced from certificated forests is well recognised and accepted in the environmental assessment of buildings in BREEAM, LEED and GreenStar. The national and international collaborations play a significant role in the conservation and management of forests. The collaborative efforts help in broadening and engaging different stakeholders to support sustainable land-use and forest management. In addition, the collaborative actions help raise awareness for the importance of forest protection and promote the use of timber and timber products in the design and construction of low impact building. As part of the climatic change mitigation approach, research and development of prefabricated EWPs has gained momentum as they are increasingly used as alternative structural materials to replace traditional steel and concrete and reduce the energy consumption and greenhouse gas emissions related to the manufacturing process (Ding & Thuy, 2020).

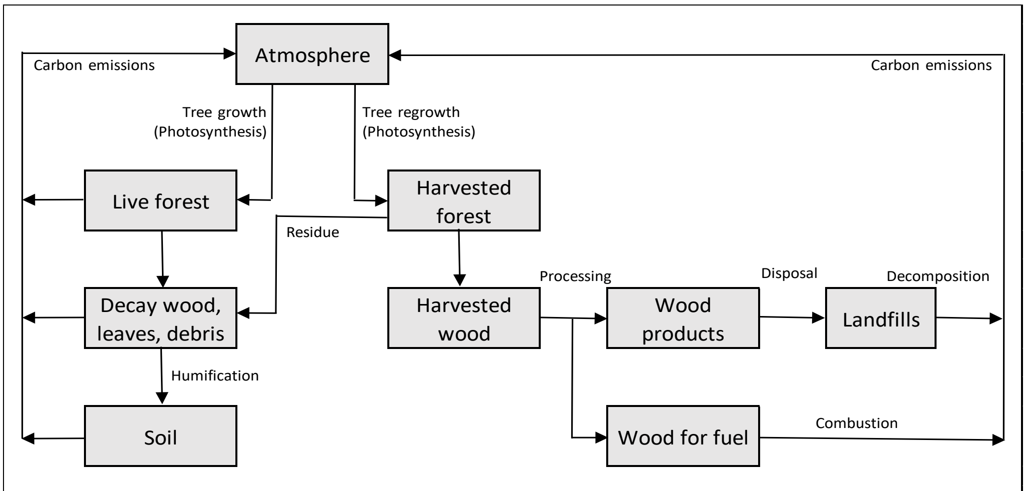
2.4 The advantages and challenges of using mass timber in building construction

2.4.1 The advantages of using mass timber in building construction

Engineered wood products or mass timber are one of the most renewable building materials. There are many benefits of using mass timber in building construction.

(i) The ability to store and sequester carbon from the atmosphere

Carbon sequestration of forests is one of the essential ecosystem services and is defined as the net rate of carbon uptake by an ecosystem per annum (Yan, 2018). Carbon sequestration is the natural process of CO_2 being extracted from the atmosphere and stored in plants and soil for an extended period of time. Carbon sequestration in renewable products, including wood, bamboo or agricultural products, can be either at the product level or global level. The product level is related to the carbon stored in wood during the growth of a tree (Van der Lugt et al., 2012). At the global system scale, CO_2 is captured in the forests, ocean, and the soil. It is estimated that the amount of CO_2 emissions each year that are a result of burning fossil fuels and deforestation in tropical and sub-tropical forests is about 6.4 Gt and 1.93 Gt, respectively, whereas carbon sequestration each year due to reforestation on the Northern Hemisphere is about 0.85 Gt (Vogtländer et al., 2014). The forest carbon cycle (Figure 2.2) is where live forests sequestrate carbon from the atmosphere through the natural process of photosynthesis, the harvested forest, however, will need reforestation in order to continue with the process of carbon sequestration. Above ground, carbon is absorbed for growth and stored, while below ground, carbon is absorbed and stored in tree roots and soil. The harvested forest will turn into harvested wood and bioenergy. Managing young forests can maximise carbon uptake while conserving old forests and prolonging rotations lead to greater carbon storage in the below-ground soil pool (Carroll et al., 2012). Yan (2018) conducts research to assess carbon sequestration between living and harvested forest.



Source: Adapted from NAFI 2007; Carroll 2012; Paulick et al. 2017, Yan 2018

Figure 2.2 Forest carbon cycle

Research results reveal that the impact of harvested forest on carbon sequestration can be improved by increasing growth rate, extending harvest period, and reducing harvest intensity. Carbon can also be sequestered in wood products as long as they continue to be in use and will only be released when they are burned or decomposed at the end of the useful life. Approximately two million tonnes of timber and timber products are disposed of in landfills each year at the end of the useful life of wood products (Ximenes et al., 2013). Several studies have investigated the fate of carbon stored in wood products in landfills. In an early study by Micales and Skog (1997), the amount of methane and CO_2 generated from timber products in landfills was approximately 3% into the atmosphere. Ximenes et al. (2008) examined the decomposition of wood products in landfills in Australia. Research results reveal that after 46 years in the landfills, the loss of carbon was 8.7% for hardwood and 9.1% for softwood. Ximenes et al. (2013) calculated the amount of captured carbon in wood products in landfills based on the results of the bioreactor experiments. They concluded that particleboard and medium-density fibreboard (MDF) reactors stopped producing gas after two months, but no gas was produced in high-pressure laminate (HPL). In anaerobic reactors, in the laboratory under optimal decay conditions, the proportions of carbon loss were 1.65%, 0.65% and 0%, respectively, for particleboard, MDF and HPL, and carbon can be retained in storage indefinitely. The use of traditional heavy materials in buildings is well recognised as environmentally and timber is proposed to be a suitable substituting material for the construction of buildings. From a life cycle assessment perspective, sequestration is only a net positive if EoL pathways minimise carbon release through reuse, recycling, or stable long-term storage (Grossi et al., 2023). Combustion, whether for waste removal or energy recovery, eliminates the sequestration benefit. Therefore, integrating EoL planning into timber construction via design-for-deconstruction, product recovery, and recycling ensures that the carbon captured during forest growth remains locked away for as long as possible (Lin et al., 2025). Finally, the type and origin of timber are critical. Unsustainable harvesting of tropical hardwoods, which exceeds plantation supply (only 35–40% of FSC-certified wood comes from plantations), risks accelerating deforestation and disrupting the carbon cycle. In contrast, responsibly sourced plantation timber can encourage afforestation and reforestation, expanding global carbon storage capacity (Vogtländer et al., 2014). In this way, combining sustainable forest management with thoughtful EoL strategies maximises the long-term carbon sequestration potential of timber in construction.

(ii) Embodied energy and carbon of timber products

In the context of a building, embodied energy is defined as the energy embedded in the process of raw materials extraction, manufacturing of building materials, transportation to construction site, building construction, maintenance and refurbishment, and demolition (Thomas & Ding, 2018; GJ Treloar et al., 2001). Embodied energy can be categorised into three primary elements, namely (1) initial energy, (2) recurring embodied energy, and (3) demolition energy. These components align with the three key phases of a building's service life: initial construction stage, use stage, and end-of-life stage (Dixit, 2019; Rauf & Crawford, 2015). Initial embodied energy is the energy embedded in the acquisition of raw materials, the manufacturing process, transportation, and construction. It is influenced by the choice of materials and construction methods (Holtzhausen, 2007). Recurrent embodied energy is the energy required for the maintenance and refurbishment of the building during its lifetime. It depends on the durability and maintenance of materials, systems and components installed in the building, and the life cycle of the building (Holtzhausen, 2007; Perez Fernandez, 2008b). Recurrent embodied energy represents approximately 15–20% of total embodied energy and 2–3% of total life cycle energy (Perez Fernandez, 2008). In addition, the study of Perez Fernandez (2008) revealed that the recurrent embodied energy of timber building is 24.5% less than that of concrete building. Similarly, embodied carbon, which is associated with the same process and often referred to as global warming potential, represents the quantity of carbon emissions produced throughout the manufacturing of building materials, the construction process, ongoing maintenance and refurbishment, as well as the final demolition (Minunno et al., 2021). The manufacturing of timber products requires less energy consumption and releases less CO_2 emissions than traditional building materials such as concrete and steel (John et al., 2011; Knauf et al., 2015). They also provide a carbon sink as a construction material in reducing the CO_2 concentration in the atmosphere (Schmidt & Griffin, 2013).

Traditional reinforced concrete structure is a high embodied energy design. Concrete is predominantly one of the primary materials used for buildings and within which cement is a critical element. The production of cement is a major energy consumption process in producing the clinker (Holtzhausen, 2007; Hossain et al., 2017). Cement production is high in energy intensity and GHG emissions from extracting raw material, producing clinker, grinding and mixing with other components to produce cement. The production of cement is a complicated process that requires the input of many elements. According to Huntzinger and Eatmon (2009), the production of 1 tonne of cement will require the input of 1.6 tonnes of raw materials that include lime, silica, iron, alumina, additives and fuels. Approximately 70% of energy consumption and emissions are related to cement production, with the rest being from the consumption and combustion of fossil fuels (IEA, 2018; Possan et al., 2017). Research indicates that producing one tonne of cement results in the release of approximately 0.9 tonnes of CO_2 into the atmosphere (Law et al., 2012; Lee et al., 2021; Roy et al., 2000; Song & Saraswathy, 2006). In 2019, the global cement production was 4,081 million tonnes (Mt), increasing 3% over 2018 (Armstrong, 2019). Australian cement production was 10.4 Mt with an increase of 9% over the last year and emitted approximately 5.1 Mt CO_2-e in 2019 (Armstrong, 2019). Steel production is also high in both embodied energy and emissions. The embodied energy required for the manufacturing of steel includes the extraction of iron ore and melting it in a furnace with oxygen to remove impurities and reduce carbon content. According to Quader et al. (2016), the production of 1 tonne of steel generates approximately 1.8 tonnes of CO_2.

Recent LCAs have further clarified the environmental benefits of using mass timber in multi-storey construction. In a comparative study, Kumar et al. (2024) analysed mid- to high-rise residential buildings constructed with mass timber (MT), steel (SS), and reinforced concrete (RC), all designed according to the 2021 and 2024 editions of the International Building Code. Using whole building life cycle assessment with cradle-to-grave system boundaries, they found that MT buildings had significantly lower global warming potential, reducing emissions by

39 – 51% compared to RC, and 28 – 34% compared to SS. When end-of-life considerations and biogenic carbon storage (module D) were included, the emissions savings increased to 81 – 94% and 76 – 91% respectively. Although MT and SS had similar total embodied energy values, MT derived a greater proportion of this energy from renewable sources (approximately 24%), while RC and SS relied almost entirely on non-renewable inputs. Structural components such as walls and floors were identified as the largest contributors to MT's embodied emissions, indicating opportunities for further refinement. A related study by Skullestad et al. (2016) examined the climate impact of replacing reinforced concrete (RC) structures with timber alternatives across a range of buildings between three and 21 storeys high. Their analysis applied both attributional and consequential LCA methods, considering factors such as biogenic CO_2 storage and concrete carbonation. Results showed that timber structures consistently produced lower emissions than RC, with reductions ranging from 34% to 84%, depending on the calculation method. When evaluated from a consequential perspective, the timber designs even achieved net-negative climate impacts, meaning that the emissions avoided by substituting RC with timber exceeded those generated during construction and use. The largest benefits were observed in taller buildings (12 – 21 storeys), partly due to greater floor area gains enabled by longer timber spans. The findings strongly support the substitution of RC with timber as a highly effective strategy for reducing embodied carbon.

Timber is increasingly favoured in construction due to its lower embodied energy compared to traditional building materials (Fraisse et al., 2006). Furthermore, the potential CO_2 displacement from using timber instead of alternative materials is estimated to be around 3.9 tonnes per tonne of timber (Sathre & O'Connor, 2010). Additionally, estimates suggest that timber can sequester approximately 1 tonne of carbon per cubic meter (Crocker & Lehmann, 2013). Together, these studies illustrate that the strategic adoption of timber-based structural systems offers a highly effective approach to reducing embodied carbon and supporting broader climate change mitigation goals.

(iii) Economic benefits

The forest ecosystem provides economic benefits to humanity. Forests sustain approximately 80% of terrestrial biodiversity which provides immense benefits and well-being for rural populations in the world, particularly in developing countries (Mitchard, 2018; UN Climate Summit, 2014). Forests are also an important source of income to inhabitants near the forest. The 2018 edition of the State of the World's Forests, conducted by the Food and Agriculture Organization (FAO), examined the vital role that forests play in supporting the livelihoods of impoverished individuals globally. In order to analyse this, the FAO used scientific resources to investigate the direction and rate of changes in forest areas across different regions worldwide. The results indicate that Australia and New Zealand experienced positive changes in terms of alterations in forest area, above-ground biomass stock in forests, the proportion of forested areas protected by legally established conservation zones, the proportion of forests managed according to long-term plans, and the forest area under independently verified certification schemes for forest management (Muller et al., 2018). The study also indicates that forests and trees may contribute approximately 20% of the income for rural households in developing countries, encompassing both cash income and the satisfaction of subsistence needs. Moreover, forests provide consumer products and ensure food security for rural individuals living on less than US$1.25 per day in proximity to the forests (Muller et al., 2018). Therefore, the loss of forest and biodiversity not only impacts the loss of the richness and variety of species but also the performance of the entire ecosystem (Levashova, 2011).

Forests are also important sources of food supply and provide nutritional varieties for the survival of rural people. According to UN Climate Summit (2017), more than 1.6 billion people in the world depend on forests for food, water, fuel, nutrition and medicines. Forests are sources of renewable energy and materials that can help to reduce the demand for fossil fuels. Forest is a major global bioenergy supply, contributing to approximately 6% of the world’s total primary energy (Knauf et al., 2015). According to Muller et al. (2018), approximately 33% (2.4

billion) people rely on wood for fuel and charcoal for cooking, sterilising drinking water and heating homes. The use of wood for energy is considered CO_2 neutral through offsetting the CO_2 emissions from simplifying activities at the earlier stages in the value chain such as forest management, transport, manufacturing, and tree regrowth. This is particularly the case if forests are sustainably managed, produced and harvested as biofuel to replace fossil fuels and the regrowth in the subsequent rotation can contribute to reducing atmospheric emissions as carbon is absorbed again in new growth (Stupak et al., 2011).

(iv) Material substitution in buildings

Compared to heavy building materials like concrete and steel that are non-renewable, timber is a renewable resource that is abundant and can be regenerated through sustainable forest management practices. Substituting 1 tonne of steel with timber in building structures results in approximately 1 tonne less carbon being released into the atmosphere (Buchanan & Levine, 1999). In addition, there is significant scope for higher carbon storage in houses by increasing the use of timber and timber products for the construction of sub-floor and wall cladding systems. As an example, doubling the wood used in houses to 0.14 m^3 per m^2 of floor area would result in additional annual carbon storage in houses in Australia from 1.6 Mt CO_2-e in 2008 to 4 Mt CO_2-e in 2050 (Kapambwe et al., 2008).

(v) The technology of wood products to improve forest carbon management

The lifetime of wood products may affect carbon sequestration stocks. Profft et al. (2009) investigated the fate of timber harvested in well-managed state forests in central Germany to quantify carbon stocks and the lifetime of primary wood products made from this source of timber. Harvested timber could be sold to produce a range of wood products from high quality sawn timber to cheap pulp, chips or fuelwood. Mean residence time (MRT), which is defined as the time that carbon stores in initial wood products until they are decomposed or burned, is, therefore, dependent on the value of timber sale assortment. Advancement in wood product technology allows small diameter and medium quality logs to be used to produce long-lived wood products such as timber floors or engineered timber. At the same time, MRT is also governed by consumer attitudes, socio-economic constraints and new trends in furniture and construction styles. For instance, wood products like furniture may be disposed of before the end of physical life because of consumer (lack of) interest. Annually, about 47% of raw timber was sold for short-lived wood product production with MRT of below 25 years; 31% went into wood product production with MRT of 25 to 44 years and only 22% went to longest-lived wood products used for construction with MRT of 50 years. Hence, the longer life of wood products, the greater the amount of carbon sequestered. The main concern is if short-rotation production causes more CO_2 emissions emitted into the atmosphere. Perez-Garcia et al. (2007) demonstrated that a shorter harvest cycle still resulted in lower CO_2 emissions due to the reduced use of fossil-intensive building materials in housing construction.

2.4.2 The challenges of using mass timber in building construction

While there are many advantages of using timber in construction as discussed in section 2.4.1, there are also many challenges. Major challenges are the fire performance of timber buildings, lack of emerging technologies in timber construction, and lack of information and evidence relating to constructability and technical guidelines such as prefabrication and standardised connection details, particularly for mid to high-rise non-residential buildings. In addition, the supply chain in timber is not as well organised as other building materials such as concrete and steel.

In term of fire safety, some countries in Europe restricted the use of timber for load-bearing structures of more than two storeys due to fire regulations until 1994 (Falk, 2005). However, several countries now have no specific regulations or do not limit the number of storeys in timber buildings (Östman & Källsner, 2011). In the United States, the development of new technologies and innovation in wood framing designs has permitted the construction of timber buildings up to four storeys depending on the occupancy classification and the presence of an automatic sprinkler system (American Wood Council & International Code Council, 2015). Before 1992, a timber structure was limited to three storeys in New Zealand but changes in the Building Code since then have increased both the number and size of multi-storey timber buildings erected in New Zealand. For instance, the 5-storey Gulf View Towers Apartment building, constructed in 1995, utilised a timber moment-resisting frame, plywood sheathed shear walls, and plywood floor diaphragms. Similarly, the 4-storey Strand Apartment & Office complex, built in early 1999, employed steel frames, and plywood clad shear walls with plywood floor diaphragms (Banks, 1999).

In Australia, the National Construction Code (NCC) had previously limited the height of combustible structures due to fire regulations. Compared to other countries, the Building Code of Australia restricted the height of timber structures to up to 2 storeys if no sprinkler system is provided. However, based on a recent proposal for change submitted by Forest and Wood Products Australia (FWPA), the NCC now permits the use of timber framing for buildings in Class 2 (apartments) and Class 3 (hotels) up to 25 metres height (approximately 8 storeys) as of 1 May 2016 under deem-to-satisfy (DTS) provisions. This code change created a significant opportunity for a commercial timber building industry to be developed in Australia in the future. Unfortunately, the Australian construction industry has been slow in adopting innovations compared to some other developed countries (Forsythe, 2012b). Paevere and McKenzie (2006) assessed 114 international emerging technologies (ETs) relevant to timber construction and concluded that there are 88 ETs potentially suitable for the Australian construction context. Furthermore, Forsythe (2012b) reviewed, identified and evaluated 88 ETs selected from Paevere and McKenzie’s (2006) research and other new international ETs collected from Europe, Japan, New Zealand, North America and the UK. Finally, 21 ETs from Paevere and McKenzie's research and 25 new ETs which support structural systems, materials technology and design and supply chain management were selected for further evaluation. However, most of them are concentrated on residential construction, therefore, non-residential construction systems' technical supporting documents need more attention.

Moreover, one of the major reasons why timber is not commonly used in the non-residential building sector, especially in the mid-rise scale, is the lack of prefabrication and standardised connection details. In the timber residential building sector, designers and builders already have sufficient knowledge of assembling and connecting the various components. However, in the multi-storey non-residential building sector, due to the complexity of a large-scale building, the fabrication is not a simple procedure, particularly relating to connection details, and the storage and onsite assembly aspects remain a concern. Hence, offsite prefabrication could help improve attitudes to the use of timber in non-residential buildings (Bayne & Taylor, 2006).

2.4.3 Mass timber case studies

(i) New Zealand

The NMIT Arts and Media Building in Nelson completed in 2011 demonstrated that timber could be successfully used in multi-storey commercial buildings. The building used LVL for structural components including columns, beams, floor systems and shear walls. The shear walls were designed to resist lateral load, especially seismic load. The system relies on coupled pairs of LVL shear walls incorporating high strength post-tensioned steel tendons. The shear walls are centrally fixed to allow them to rock during a seismic event; a series of U-shaped steel plates placed between the walls form a coupling mechanism and act as dissipaters to absorb seismic energy. This allows the primary structure to remain essentially undamaged while these replaceable connections act as plastic fuses. LVL has strength properties that allow fabrication of beams, columns and walls at dimensions similar to concrete and steel design. Spanning 9.6 m, the primary LVL floor beams provide a large open floor plate, comparable to traditional commercial structures (John et al., 2011).

(ii) Australia

The Forté building in Docklands, Melbourne, completed in 2012, is a 10-storey CLT apartment block and was the world's tallest timber residential building until 2016. The timber structure weighed 485 tonnes, and was connected with 5,500 angle brackets using 34,550 screws. The ground and first-floor slab were constructed from geopolymer concrete due to the larger spans required in the retail space and for moisture and termite resistance purposes. Prefabricated CLT panels were shipped from Europe and transported to the construction site and then craned into positions and screwed together. By using the platform-frame system, each floor was set on the walls below and then another storey of walls was raised and on up the building (Durlinger et al., 2013)

The commercial and office building sector in Australia has illustrated the possibility of a long-span mass timber floor and exposed mass timber system. International House Sydney at Barangaroo completed in 2017 is the first 6-storey exposed engineered timber office building in Australia. Six levels above the concrete retail ground floor are all engineered timber. Daramu House, which is currently under construction, will be a sister of International House Sydney. Daramu House is being constructed with structural CLT and glulam system. The building has 7 storeys with more than 10,000 m^2 of commercial floor space and 680 m^2 of retail space.

In Brisbane CBD at 25 King Street, the world tallest and largest mass timber office building was completed in late 2018. The 52 metre tall building has ten exposed engineered timber floors and has a six by eight-metre grid of glulam columns with CLT cladding and CLT flooring system.

(iii) Canada

The UBC Brock Common building, completed in 2016, is currently the tallest mass timber building for student accommodation at the University of British Columbia in Vancouver. It is an 18-storey building in which 17 storeys are mass timber structures. It took only ten weeks to complete the mass-timber levels. The building has a flooring system with no less than 2 hours of fire-resistance rating and sprinkler system throughout. The structural system of the building is a hybrid configuration of concrete podium and cores, CLT/LVL columns and floors, and steel roof system. Results of life cycle analysis from cradle to gate showed that the use of mass timber instead of concrete has a positive impact on the environment. For instance, compared to the original concrete building, mass timber design has negative global warming potential due to the possibility of carbon sequestration in mass timber, even beyond the building lifetime (Connolly et al., 2018).

All of these case studies have demonstrated the possibility of using engineered wood products in mid and potentially high-rise scale building construction. However, at the same time, that there are only a few mid-rise timber commercial buildings around the world indicates the lack of confidence and understanding amongst design and construction professionals about how timber can be used in commercial applications.

2.5 Conclusion

This chapter provided background on sustainability and sustainable development in construction. The concept of the circular economy for sustainable development was introduced with the aim to highlight the importance of adopting the circular economy concept for sustainable development in the construction industry to balance industrial growth and environmental and human health.

The environmental impacts of the construction industry and traditional heavy materials were reviewed. The construction industry is responsible for a huge percentage of environmental impacts such as high energy, water and natural resources consumption and carbon emissions released into the atmosphere. This chapter reviewed the use of engineered wood products or mass timber in building construction to mitigate embodied energy consumption, especially non-renewable fossil energy and associated CO_2 emissions. Mass timber's ability for carbon storage until the end-of-life was highlighted since it plays an important role in reducing CO_2 emissions.

In conclusion, the benefits of mass timber and constructed mass timber projects have proved the possibility of using mass timber in sustainable mid and potentially high-rise building construction. However, it is important to recognise and address the current challenges that mass timber construction faces. This chapter provided an overview of mass timber construction in Australia, and this can be used as a foundation for the interview questions to investigate the perception of construction practitioners to strengthen the benefits and overcome the obstacles to mass timber construction.

Chapter 3 Selection of key performance indicators in building construction

This chapter reveals the selection of key performance indicators in building construction through a comprehensive literature review. These indicators, which include quality, time, cost and environmental performance, are normally used to assess the success of a building project. The literature review of assessment tools such as life cycle assessment, life cycle cost, time and thermal performance is also included in this chapter. The results of this chapter are the foundation to create the interview questions and analyse the interview results. Together with the indicators identified from the interview results, the indicators from this chapter are used for the selection of final indicators to develop the sustainable non-residential development model.

3.1 Incorporating key performance indicators from a comprehensive literature review

Cox et al. (2003) defined that key performance indicators (KPIs) are a set of data measures used to assess the performance of a construction project. This section reviews KPIs from related studies during the last decade from 2010 to 2019 to identify the most important KPIs. The technique uses keywords such as selection criteria, multi-criteria, and key performance indicators in construction to search related journal articles in Scopus. The term “construction management” is used to limit the search results to the building construction research area from the beginning. By reviewing the abstracts of 466 articles, the 10 most relevant studies were selected (Table 3.1).

A total of 130 KPIs were identified in the 10 selected studies. Table 3.2 shows the key performance indicators of each study from the 10 selected relevant studies. They were then grouped into 33 due to similar meanings. A KPI which is cited only once was discarded (Table 3.3). Finally, a total of 17 KPIs were selected.

Table 3.1 Most relevant selected studies

Researchers and published year	**Journal**	**Study title**
Reddy et al. (2019)	International Journal of Sustainable Engineering	Preference-based multi-criteria framework for developing a Sustainable Material Performance Index (SMPI)
Mahmoudkelaye et al. (2018)	Case Studies in Construction Materials	Sustainable material selection for building enclosure through ANP method
Szafranko (2017)	IOP Conference Series: Materials Science and Engineering	Chosen aspects of multi-criteria analysis applied to support the choice of materials for building structures
Govindan et al. (2016)	Renewable and Sustainable Energy Reviews	Sustainable material selection for the construction industry – A hybrid multi-criteria decision-making approach
(Thomas & Ding, 2018)	Energy and Buildings	Comparing the performance of brick and timber in residential buildings–The case of Australia
Arroyo (2014)	PhD Dissertation, University of California, Berkeley	Exploring decision-making methods for sustainable design in commercial buildings
Takano et al. (2014)	Building and Environment	A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context
Akadiri et al. (2013)	Automation in Construction	Multi-criteria evaluation model for the selection of sustainable materials for building projects
Yeung et al. (2013)	Journal of Construction Engineering and Management	Developing a benchmarking model for construction projects in Hong Kong
Bakhoum and Brown (2012)	Journal of Construction Engineering and Management	Developed sustainable scoring system for structural materials evaluation

Table 3.2 Key performance indicators from relevant studies

Key Performance Indicators	**Yeung et al. 2012**	**Thomas & Ding 2018**	**Akadiri, Olomolaiye & Chinyio 2013**	**Arroyo 2014**	**Bakhoum & Brown 2011**	**Reddy, Kumar & Raj 2019**	**Govinda, Shankar & Kannan 2016**	**Takano, Hughes & Winter 2014**	**Mahmoudkelaye et al. 2018**	**Szafranko 2017**	**Frequency**
Life cycle cost	X	X	X	X	X	X	X	X	X	X	10
Safety performance and human health	X		X		X	X	X		X	X	7
Time/schedule	X	X		X							3
Environmental performance	X	X	X	X	X	X	X	X	X		9
Aesthetics	X		X		X	X	X		X		6
Quality performance (e.g., technical specification, resistance to decay)	X	X	X				X		X	X	6
Reusability and recyclability			X		X	X	X			X	5
Client satisfaction	X										1
Effectiveness communication	X										1
Effectiveness of planning	X										1
Functionality	X									X	2
Labour availability			X				X		X		3
Fire safety			X				X		X		3
Constructability/ buildability			X	X			X			X	4
Use of local material			X				X				2
Maintainability & durability			X	X			X		X		4

Key Performance Indicators	**Yeung et al. 2012**	**Thomas & Ding 2018**	**Akadiri, Olomolaiye & Chinyio 2013**	**Arroyo 2014**	**Bakhoum & Brown 2011**	**Reddy, Kumar & Raj 2019**	**Govinda, Shankar & Kannan 2016**	**Takano, Hughes & Winter 2014**	**Mahmoudkelaye et al. 2018**	**Szafranko 2017**	**Frequency**
Thermal insulation, thermal mass, thermal comfort			X	X							2
Earthquake losses				X							1
Research value				X							1
Deconstructability				X							1
Local economic development					X	X					2
Practicability & flexibility				X	X	X					3
Productivity							X				1
Revenue (Profit)							X				1
Tax contribution							X				1
Market value									X		1
Social, religious, and cultural identity									X		1
Designer’s knowledge									X		1
Availability of materials										X	1
Availability of machines and equipment needed for the assembly of the structure										X	1
Production and transportation							X			X	2

Table 3.3 17 key performance indicators selected from the literature review

KPIs	Reddy, Kumar & Raj 2019	Mahmoudkelaye et al. 2018	Szafranko 2017	Govinda, Shankar & Kannan 2016	Thomas & Ding 2018	Arroyo 2014	Takano, Hughes & Winter 2014	Akadiri, Olomolaiye & Chinyio 2013	Yeung et al. 2012	Bakhoum & Brown 2011	Frequency
Life cycle cost	X	X	X	X	X	X	X	X	X	X	10
Environmental performance	X	X		X	X	X	X	X	X	X	9
Safety performance and human health	X	X	X	X				X	X	X	7
Quality performance (e.g., technical specification)		X	X	X	X	X		X	X		7
Reusability and recyclability	X		X	X				X		X	5
End user satisfaction	X			X					X	X	4
Constructability/ buildability			X	X		X		X			4
Maintainability & durability		X		X		X		X			4
Time/schedule					X	X			X		3
Aesthetics		X		X				X			3
Labour availability		X		X				X			3
Fire safety		X		X				X			3
Practicability & flexibility	X					X				X	3
Functionality			X						X		2
Use of local material				X				X			2
Local economic development	X									X	2
Production and transportation			X	X							2

3.2 The selection of key performance indicators

Seventeen KPIs collected from the literature review are divided into subjective and objective indicators in Table 3.4. Objective indicators can be quantified such as construction time, life cycle cost, quality (e.g., technical specification), safety, and environmental performance (e.g., life cycle energy consumption and associated life cycle CO_2 emissions). On the other hand, subjective indicators are based on personal perception such as the level of satisfaction of stakeholders, aesthetics, labour availability, and the use of local material.

Table 3.4 Subjective indicators and objective indicators

Subjective Indicators	Objective Indicators
End user satisfaction	Life cycle cost
Aesthetic	Environmental performance
Labour availability	Quality (e.g., technical specification)
Functionality	Constructability/Buildability
	Practicability & flexibility
	Time/Schedule
	Safety and human health
	Production and Transportation
	Reusability and Recyclability
	Local econimic development
	Use of local material
	Maintainability and Durability
	Fire safety

This thesis mainly focuses on measurable objective indicators. Some research defined quality criteria of a project as achieving technical performance including thermal comfort, constructability, maintainability and durability (Chan & Chan, 2004; Serrador & Turner, 2015; Thomas, 2015). Most of the objective indicators, including life cycle cost, time, quality and environmental performance, are selected for further assessment in this thesis. This result matches with the requirements of a successful construction project found in the literature that a construction project reaches expected quality with the reduction in time, cost and environmental impacts simultaneously (Panwar & Jha, 2019; Thomas, 2015).

3.2.1 The indicator of life cycle cost (LCC)

Life cycle cost analysis (LCCA) is the process of evaluation of all relevant costs during the physical, technical, economic or functional life of a construction project, over a defined period of study, including future predicted factors, such as occupancy levels, legislative and regulatory changes (ISO, 2017). The whole life cycle cost takes into consideration the following categories (Figure 3.1):

- non-construction costs such as finance, business costs, administration costs, taxes
- income
- costs associated with whole life cycle building stages, including construction, operation, maintenance and end-of-life costs (ISO, 2017).

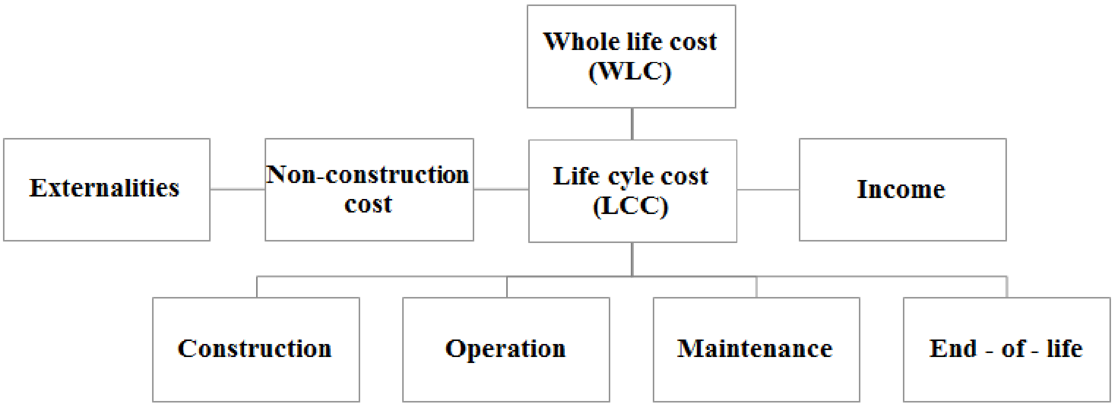


Figure 3.1 Definition of whole life cycle cost (ISO, 2017)

LCCA is especially applicable for the evaluation of building design alternatives. The developers have the opportunity to look at the whole picture of different design options with different expected service life and cost performance of different life cycle building stages in the early design stage.

In LCCA, the time value of money, which indicates future inflation and discount rates, needs to be considered. Hence, future costs will be discounted to present value (PV) using an appropriate discount rate. In LCCA, some studies account for both inflation and discount rate. The applied discount rate ranges from 2% to 8%, depending on nominated life cycle time, assumptions and system boundaries (Islam et al., 2015). The whole life cycle cost may consider the cost of environmental impacts associated with a building's life cycle stages including initial construction, operation, maintenance and end-of-life (ISO, 2017; Robati et al., 2018). Indeed, some studies have integrated LCC as well as environmental cost early in the design stage as a decision-making strategy to identify the most suitable structural materials and construction methods. Robati, McCarthy and Kokogiannakis (2018) took into account both life cycle building cost and environmental cost to determine which construction method of flat slab or waffle slab and which structural building material of normal concrete or ultra-lightweight concrete is more efficient. The analysis was based on a case study of a typical high-rise office building in Australia. They pointed out that the LCC over a 50-year lifetime of the design of a lightweight waffle slab using normal concrete as a main structural material was lower than other alternative designs. The results showcased that proper decision-making of structural building material and construction technique leads to 7% of material cost saving; and a 5% cut in life cycle energy consumption and CO_2 emissions, respectively. The results were applied to all five major cities across Australia (Robati et al., 2018).

Stakeholders can use LCCA in the design stage to evaluate the long-term cost saving benefit of a design. An LCCA in 2011 was conducted to examine the LCC performance of sustainable designs over 60 and 100-year lifetimes (John et al., 2011). The analysis was based on four alternative designs including concrete, steel, timber, and low energy timber design (TimberLow) of the Arts and Media building of Marlborough Institute of Technology in Nelson, New Zealand. A discount rate of 5% was applied (John et al., 2011). Overall, the concrete design had the lowest life cycle cost, followed by steel design, timber and TimberLow designs. The results indicated that all four designs had an initial cost lead over energy cost and other costs including maintenance, replacement, and operational cost, in either 60 or 100-year lifetimes. Moreover, the initial cost of timber-based designs was higher than that of heavy material designs. For instance, the initial cost of the TimberLow design was 6.8% higher than that of the concrete design, due to higher initial expenditure for ongoing energy savings of the TimberLow building. However, the TimberLow building saved only 0.39% more of ongoing costs than the concrete building in 60 years. Consequently, LCCA plays an important role in the design stage to predict the cost-effectiveness of a design option during its future lifetime.

In terms of sustainable development decision-making, Thomas (2015) compared the LCC performance of 10 brick residential projects and alternative timber re-designs in a 50-year lifetime with a discount rate of 5%. Costs associated with land purchase, design consultant, legal services, fit-out and operation were discarded in the analysis, as they were roughly the same for both construction methods. The analysis included costs for initial construction, recurring (maintenance) and disposal stages. The results showed that the construction stage cost the most, followed by the maintenance and end-of-life stages. On average, compared to brick projects, costs for construction and end-of-life stages of timber projects were 3.3% and 0.3% lower, respectively. The maintenance cost for timber projects was 3.5% more expensive than brick projects, due to the replacement and painting of timber cladding during a 50-year lifetime. Overall, timber residential re-designs were more cost-effective than brick projects when considering a whole life cycle of 50 years.

Mass timber construction in Australia, especially the non-residential sector, is still limited compared to traditional heavy material building construction. Therefore, there is a lack of research on LCC performance as well as life cycle cost guidelines for mass timber building construction. WoodSolutions Australia has recently developed a guideline of cost engineering, particularly for mid-rise timber buildings, which are over 3 storeys and under or equal to 25 metres high from the ground floor to the top walking surface. This guide provides LCC methodology for both indirect and direct activities in the design and construction of timber buildings in Australia, particularly for the mid-rise sector. The guideline reveals that the advantages of using mass timber in construction, which are listed in Table 3.5, potentially achieve cost saving (Forest and Wood Products Australia, 2019a).

Table 3.5 Advantages of mass timber and the potential cost saving achievement

Advantages of mass timber	Potential cost-effectiveness achievement
High strength to weight ratio	Potentially cost saving thanks to the lightweight structure
Reduce substructure size thanks to the lightweight superstructure	Potential construction cost-saving achievement
Defect mitigation due to tighter dimensional tolerances	Cost-saving achievement thanks to material waste minimisation
Fast delivery due to: - No curing time - Scaffolding is unnecessary - Easier and faster to lift with a small crane - Fast installation thanks to reducing onsite works - Fewer crews and trades on site	Cost-saving thanks to time and labour reduction and probable productivity improvement

One of the greatest advantages of mass timber construction over heavy material construction is the speed of construction. Hence, the construction cost of mass timber buildings may be lower than that of other construction systems. When the first floor is installed, the rest of the timber building can be quickly completed with a high install rate and construction productivity is therefore increased. However, the install rate depends on the complexity of the design, size of building elements, the builder’s experience, and climate conditions. In Australia, completed mass timber projects, both residential and non-residential such as the Forté building and the Library at the Dock, have proved that there are fewer maintenance requirements than other typical buildings in the same class (Forest and Wood Products Australia, 2019a).

A number of studies have presented the positive arguments of LCC performance for timber buildings (John et al., 2011; Thomas, 2015). The results of John et al.'s study showed the cost ineffectiveness of the TimberLow design when it increased the initial cost by 6.8% to save only 0.39% ongoing costs in a 50-year lifetime. The lack of LCC reports on actual commercial and office timber buildings, especially in Australia, also makes it more difficult for the developers in terms of building material and construction method selection. Hence, it is necessary to develop LCC performance criteria, particularly for timber commercial and office buildings.

3.2.2 The indicator of time performance

Time is defined as the duration for completing a project and typically measured by schedules (Chan & Chan, 2004; Gonzalez et al., 2014). Gonzalez et al. (2014) revealed that the actual time of a project was usually more than the planned time, and this is called a delay or overrun. Delays can increase schedules and cost and potentially affect the quality and safety of a construction project. Consequently, delays cause a negative impact on the interests of all stakeholders, including clients, designers, contractors, subcontractors and occupants (Gonzalez et al., 2014). Gonzalez et al. (2014) investigated the most important delay causes among design changes and delays, field interference, poor planning, defective drawings, lack of labour, lack of materials, lack of supervision, subcontractor delays and poor execution. The results showed that planning and subcontractors were two major contributors that affect time performance negatively. Delays related to planning are caused by poor planning, control and scheduling of the project by mistakes or oversights in the planning process whereas delays due to subcontractors are caused by low productivity or deadlines missed by subcontractors.

Durdyev and Hosseini (2019) reviewed studies published from 1985 to 2018 on delay causes of construction projects to find the most common factors that affect the time performance of construction projects. Among 149 causes selected from 97 studies, the authors revealed that there were ten most important delay causes: weather/climate conditions; poor communication; lack of coordination and conflicts between stakeholders; ineffective or improper planning; material shortages; financial problems, payment delays; equipment/plant shortage; lack of experience/qualification among projects stakeholders; labour shortages; and poor site management. On the other hand, Chan and Chan (2004) argued that delay causes related to the construction stage, which was calculated from the commencement date onsite to practical completion of a project, had a larger impact on the time performance of a project than the pre-project planning. Liao et al. (2011) revealed that site preparation and speed of construction had a major effect on the schedule of a project.

Construction method plays an important role in the time performance of a construction project. Using appropriate construction methods potentially increases constructability, shortens construction speed and reduces rejection and rework, therefore greatly decreases the construction time and cost (Kerridge, 1993). Prefabrication is the method of construction that includes assembling components of a structure in a manufacturing or production site, and transporting complete assemblies or partial assemblies (Tam et al., 2007). Jaillon and Poon (2008), when applying the prefabrication method, found construction time reduces by 15% compared to the traditional in-situ method. Over a third (35%) of builders who have applied prefabrication techniques experience a decrease in the project schedule of four weeks or more by conducting offsite work and reducing onsite work (Figure 3.2). By reducing construction time, prefabrication potentially saves labour costs and consequently has been shown to reduce over 6% of a typical building project budget (McGraw Hill Construction, 2011).

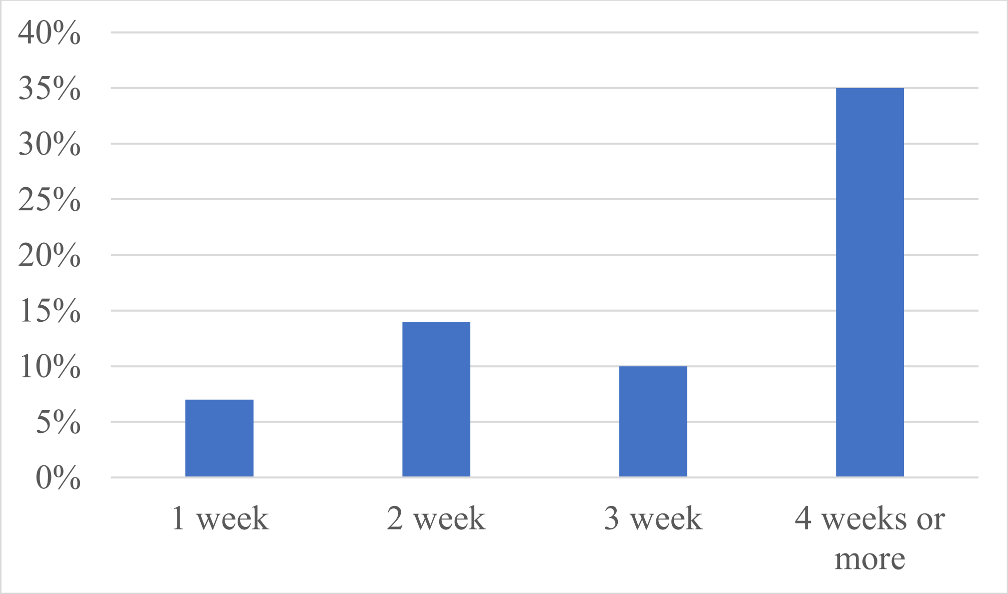


Figure 3.2 Level of decrease in project schedule due to prefabrication (McGraw Hill Construction, 2011)

Mass timber construction using prefabricated panelised engineered wood products has been identified as having the potential to be a key driver in adopting timber construction in multi-storey buildings (Forsythe, 2012a). When prefabricated mass timber is used in the construction, mass timber components are craned and assembled using lightweight tools; hence it is generally safer and more rapid than using conventional methods. The publication, which reviewed 100 CLT projects in the UK, concluded that the overall construction of a prefabricated mass timber system is normally 20% faster than an equivalent system using reinforced concrete (Waugh Thistleton Architects, 2018b).

Overall, time is one of the important factors used to assess the success of a construction project. There are many causes of delays in the completion of construction projects identified from the literature review. Mass timber construction using prefabricated mass timber elements is a construction system that enhances productivity and safety and reduces erection time.

3.2.3 The indicator of quality performance

Quality performance is one of the most important indicators of any construction project. It refers to the extent to which a completed building meets its intended functional, technical, and regulatory specifications, while also satisfying occupant expectations for comfort, safety, and usability. It encompasses measurable outcomes that reflect how effectively these requirements are achieved throughout the building's life cycle. It can be defined as "compliance with customer's satisfaction or specification" or "performance to standards" (Abas et al., 2015; Jha & Iyer, 2006). Poor quality performance can lead to cost overruns, project delays, and excessive rework, undermining both efficiency and stakeholder satisfaction (Abas et al., 2015). Quality performance criteria in building projects span multiple dimensions: thermal performance, lighting performance, acoustic performance, indoor air quality, structural performance, maintainability, and durability (Chan & Chan, 2004; Serrador & Turner, 2015; Thomas, 2015). Of these, thermal performance, lighting, acoustics, and indoor air quality are directly linked to occupant comfort, health, and productivity, as well as the building's operational efficiency and sustainability credentials (Mewomo et al., 2023; Wu et al., 2020).

In Australia, the Building Code of Australia (BCA) requires that Class 2 to 9 buildings meet minimum energy efficiency requirements under the Section J Energy Efficiency provisions. To comply, building certifiers and certifying authorities require energy efficiency performance assessment reports to be prepared, assessing the building against the Deemed-to-Satisfy Provisions, or using energy modelling at the construction certificate stage (BCA, 2019). Thermal performance refers to a building's ability to maintain indoor thermal comfort with minimal heating and cooling energy input. This performance is governed by a range of factors, including the thermal properties of construction materials, insulation levels, glazing, air tightness, thermal mass, building orientation, and climatic conditions. (John et al., 2011). In non-residential buildings, heating, ventilation, and air-conditioning (HVAC) systems are essential to meeting comfort requirements alongside fire and acoustic compliance. Among the key thermal properties that influence envelope performance are U-value and R-value. U-value quantifies thermal transmittance, or the rate of heat flow through a material, whereas R-value represents thermal resistance, or a material's capacity to resist heat flow. These values are inversely related and are combined to calculate the total thermal resistance of a building element, as shown below (Gaspar et al., 2016).

$$R_T = \frac{1}{U} = \mathrm{R_{si}} + \mathrm{R_1} + \mathrm{R_2} + \ldots + \mathrm{R_n} + \mathrm{R_{se}} \quad (3.1)$$

Where:

R_T ($\mathrm{m^2.K/W}$) is thermal resistance of a construction element

U ($\mathrm{W.K.m^2}$) is the thermal transmittance of a construction element

$\mathrm{R_1}$, $\mathrm{R_2}$, … $\mathrm{R_n}$ are the thermal resistances of each layer, including bridged layers

R_{si} and $\mathrm{R_{se}}$ are the internal and external surface resistance.

A material that has higher R-value and lower U-value can reduce thermal bridges in buildings (Williamson & Beauchamp, 2005). Williamson and Beauchamp (2005) listed thermal conductivity of building materials including concrete, brick, plywood, softwood, and hardwood to compare the value among these materials. Table 3.6 shows that the higher the density of a material is, the lower the thermal conductivity of a material.

Table 3.6 Thermal conductivity of materials

Material	**Density ($\mathrm{kg/m^3}$)**	**U-value ($\mathrm{W/K.m^2}$)**
Brickwork – generic extruded 110 mm	1580	0.611
Concrete block solid, 90 mm	1800	0.750
Solid concrete	2440	1.44
Plywood	530	0.14
Timber – hardwood	688	0.16
Timber – softwood	506	0.1

Another important factor that affects the thermal performance of a building is thermal mass. Thermal mass of a building is the ability to absorb heat energy, and thus it affects indoor temperatures, power requirements and occupant comfort (Reilly & Kinnane, 2017). Thermal mass is also determined by the density of materials. This means heavy materials such as concrete and brick are higher thermal mass materials, whereas timber has lower thermal mass. Reilly and Kinnane (2017) found that while buildings with high thermal mass can reduce cooling energy in hot climates, they may require additional heating energy in colder climates.

Building energy simulation tools allow designers to model and predict operational energy consumption before construction (John et al., 2011). Programs such as DesignBuilder, which uses the EnergyPlus simulation engine, are commonly used for non-residential building performance assessments. For instance, Perez Fernandez (2008) employed DesignBuilder to compare operational energy demand of a concrete building at the University of Canterbury in Christchurch, New Zealand and alternative steel, timber, and timber-plus redesigns. The purpose of this section was to investigate the effect of material selection on the thermal performance of a building. The timber-plus building not only had a timber structure but also had timber components such as linings, window frames, louvres and cladding. The results show that the energy needed for heating and cooling of the four buildings was slightly different (Figure 3.3). However, the consumption of other operational energy such as room electricity, lighting, miscellaneous systems, and domestic hot water was identical for all four buildings. Therefore, these operational energy uses were possibly not determined by the selection of building materials but by the architectural design and the operation of the systems. Lighting consumed the largest amount of energy and accounted for 39% of total annual operational energy consumption.

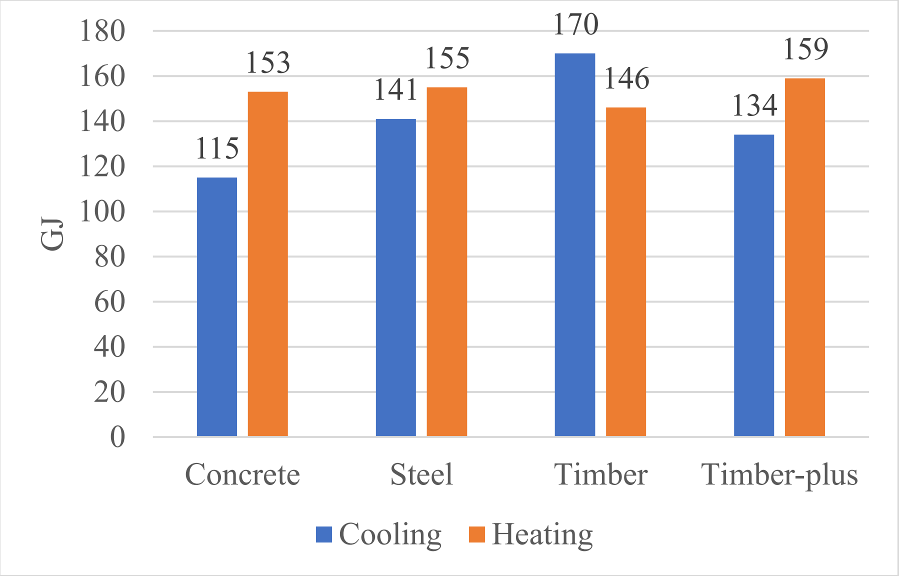


Figure 3.3 Annual energy uses for heating and cooling of four case study buildings (Perez Fernandez, 2008)

There were two major causes of these variations in cooling and heating between the four buildings. First, because of the difference in the applications of structural components in the envelope walls that played an important role as thermal bridges, heat losses through the walls of each building would vary. The main structural system of the steel building was put inside the offices and therefore there was no significant loss of heat through the structure system. In the case of the concrete building, an extra layer of polyurethane was used in the core structure. However, there were no such insulations attached to the shear walls of timber and timber-plus buildings. The thermal mass of the building also plays a major role in heat losses. Concrete is recognised as the building material with the highest thermal mass building material compared to steel and timber. The most notable characteristic of thermal mass is the ability to absorb heat generated within a building. Therefore, building materials with high thermal mass, such as concrete, can reduce the cooling energy needed for a building, particularly during the summer. This explains why timber buildings, which have lower thermal mass, require a greater amount of cooling energy but less heating energy. The difference between cooling and heating consumption of the timber and timber-plus buildings, in which the timber-plus building consumed less operational energy was due to the extra timber added in the timber-plus building's components performing as a thermal mass. The study was consistent with the arguments found in the literature review and proved that the thermal performance of a building is influenced by material selection and design.

Building on the concept of occupant comfort, lighting performance plays a crucial role in supporting visual comfort, health, and productivity. Research shows that well-designed lighting systems – balancing daylight and artificial illumination – can improve occupant well-being and reduce energy consumption through techniques such as daylight harvesting (Wong, 2017). Daylight availability depends on factors such as window size, orientation, glazing type, and shading devices, while artificial lighting performance relies on system design, glare control, and uniformity. Although structural materials may indirectly influence daylight penetration (for example, through floorplate depth or beam spacing), architectural design and lighting specifications remain the primary determinants of lighting quality (Gentile et al., 2022). In turn, good lighting conditions often go hand-in-hand with effective acoustic performance, which is equally critical for occupant comfort, productivity, and privacy. In non-residential buildings, prolonged exposure to noise, particularly in open-plan offices can impair concentration, increase stress, and lower performance (Standands Australia, 2016). Australian Standard AS/NZS 2107:2016 sets recommended design sound levels and reverberation times for different building uses. Key measures include airborne and impact sound insulation, as well as reverberation time control. Because mass timber generally has a lower density than concrete, it offers less inherent sound insulation; however, layered assemblies, resilient junctions, and the use of sound-absorbing materials can achieve performance levels equivalent to heavier construction systems (Loshin & Blount, 2023). Similarly, indoor air quality is also a key factor in occupant health, comfort, and productivity. It is influenced by ventilation design, HVAC system performance, pollutant sources, and material emissions. The National Construction Code and AS 1668.2 set minimum ventilation rates and control strategies to maintain acceptable indoor air quality in Australian buildings (Reed & Shepherd, 2020). Timber can contribute positively to indoor air quality by regulating indoor humidity through moisture buffering (Alapieti et al., 2020). However, emissions from timber products, particularly volatile organic compounds (VOCs) from adhesives in engineered wood must comply with limits set by standards such as E0 or E1 formaldehyde emission classes (Ayrilmis et al., 2016). The effect of structural material choice on indoor air quality is therefore context-dependent and often secondary to ventilation and building services design.

Beyond their thermal performance benefits, mass timber elements also exhibit substantial structural strength, supporting their integration into structural roles that have traditionally relied on steel and concrete. CLT, manufactured by laminating solid timber boards in alternating directions, enables effective load transfer along both major axes. This makes CLT a reliable material for use in structural components such as floors, walls, and roof panels. Research has shown that CLT performs well under compressive, flexural, and shear stresses, with its behaviour influenced by panel thickness, layering patterns, and joint detailing (Yihune & Nega, 2023). Furthermore, comparative studies indicate that its structural stiffness and load-bearing capacity are similar to those of reinforced concrete floor systems, particularly in low- to mid-rise construction (Bahrami et al., 2021). Glulam, composed of longitudinally bonded timber layers, has also proven its effectiveness in load-bearing applications. When prestressing techniques are applied, the flexural strength of glulam beams can increase by as much as 45%, enhancing both stiffness and ultimate capacity over conventional glulam configurations (Mei et al., 2021). Similarly, LVL, produced from stacked timber veneers, demonstrates exceptional structural properties. Experimental testing of LVL has recorded a high modulus of elasticity (22,015 MPa) and a bending strength of 85.6 MPa, surpassing that of conventional sawn timber and placing LVL in direct competition with lower-grade steel sections in terms of strength-to-weight performance (Martins & Dias, 2025). Taken together, these engineered timber products offer a compelling combination of structural reliability, lightweight efficiency, and sustainability, making them well-suited to meet the demands of contemporary building design and construction.

3.2.4 The indicator of environmental performance

Environmental performance indicator is an essential tool for assessing the impact of human activities, specifically construction activities, on the environment. This indicator provides measurable data to understand the state of various environmental components, such as air, water, soil, and ecosystems. By tracking the environmental impact of construction activities, policymakers, researchers, and the public to make informed decisions aimed at reducing negative impacts and promoting sustainability in construction industry. Life cycle assessment is utilised to track environmental performance comprehensively.

(i) The overview of life cycle assessment

According to the ISO 14040:2006 and ISO 14044:2006, the environmental performance of a product system during its lifetime is compiled and evaluated by life cycle assessment (LCA) (VanDuinen & Deisl, 2009b) (Figure 3.4). The lifetime of a product is defined as the process from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal (ISO, 2006).

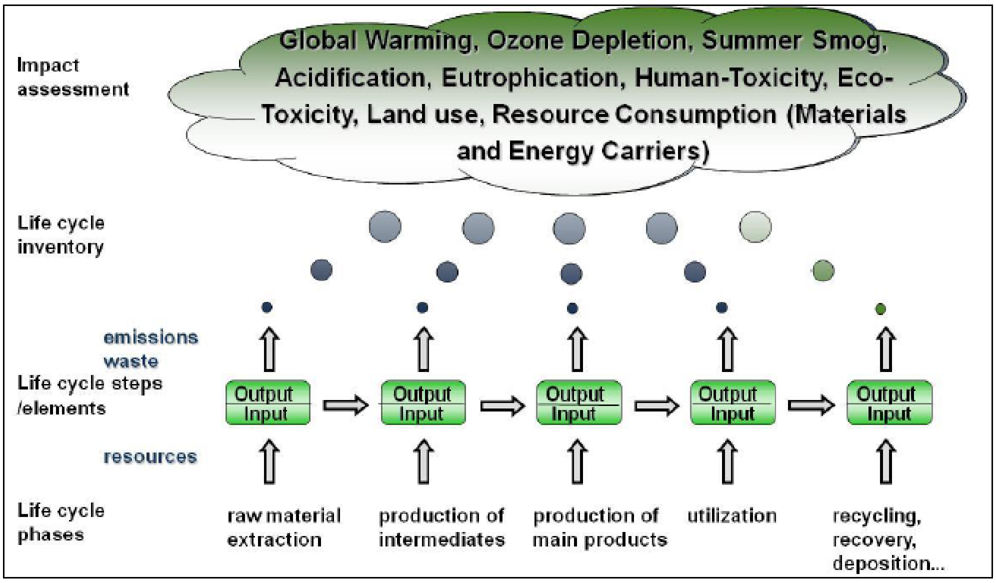


Figure 3.4 Overview of life cycle assessment (VanDuinen & Deisl, 2009a)

LCA can be used by government, industry or research organisations for various purposes such as identifying the opportunities to improve the environmental aspects of a product at different points in its life cycle, strategy planning, public policymaking, and marketing including environmental claims, eco-labelling schemes or environmental product declarations. There are four main steps to perform an LCA (Figure 3.5): goal and scope definition, inventory analysis, impact assessment and results interpretation.

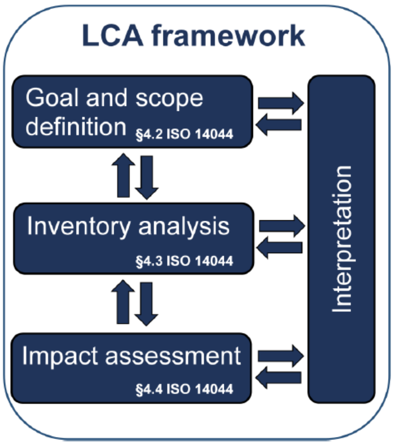


Figure 3.5 Life cycle assessment framework (VanDuinen & Deisl, 2009a)

Step 1: Goal and scope definition

Goal and scope definition is the first step that defines the main purpose of the assessment. In this step, it is necessary to describe in detail the function of the system. This is to make sure that the function of each product is exactly defined in case different products are compared.

Then the functional unit, which is the quantified definition of the function of a product, needs to be identified. For example, to compare two products, the functional units must be equivalent. Hence, it is not correct to compare a building in Australia to another one in Europe since the building materials, transport and fuel costs are different. Similarly, LCA of a residential and a non-residential building cannot be compared, as the usage of the two buildings is different.

In this step, reference flow is defined to measure product components and materials. All data used in the LCA must be calculated or scaled under the reference flow.

Furthermore, the description of system boundary is to identify which processes will be included in or excluded from the system. System boundary can be defined as the options below (Figure 3.6):

- Cradle-to-Grave includes all the processes from raw material acquisition, production, transport, use phase to the end-of-life of the product.
- Cradle-to-Gate includes all the processes in the production of a product including raw material acquisition and production phase (gate of the factory).
- Gate-to-Grave assesses the environmental impacts of a product when it is in use, hence, this option includes the processes from the use and end-of-life phases (postproduction).
- Gate-to-Gate includes the process of the production phase only which is used to assess the environmental impacts of the production phase.

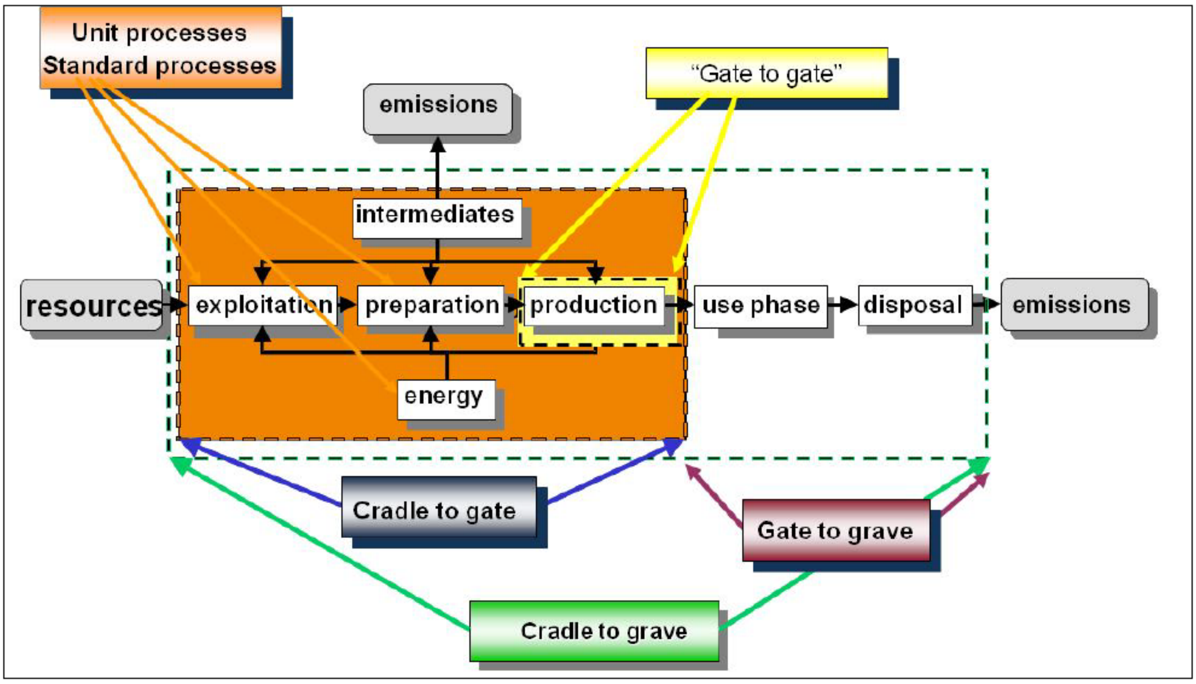


Figure 3.6 System boundary (VanDuinen & Deisl, 2009a)

Step 2: Inventory analysis

This step includes the collection and definition of inputs and outputs of a system throughout its life cycle. This is the procedure of data collection and data calculation. Inputs comprise raw materials, energy, products or semi-finished products which are outputs from other processes. Outputs are emissions, products, semi-finished products and energy, which are emitted to the environment or used in another process. The life cycle inventory (LCI), which is a list of all the material and energy input and output, will be created. There are two basic methods for compiling an LCI: process analysis and input–output analysis. Each method has its strengths and weaknesses. Hybrid analysis, which is the combination of process and input–output analyses, is therefore developed to combine the strengths and reduce the weaknesses. Details of each method of LCI are listed in Table 3.7.

Table 3.7 Life cycle inventory approaches (Crawford et al., 2018; Onat et al., 2014; Suh & Huppes, 2005; Suh et al., 2004)

LCI approaches	**Process Analysis**		**Input–Output Analysis**		**Hybrid Analyses (a combination of process and input–output analyses)**	
	Process flow diagram approach	Matrix notation		Tiered hybrid analysis	Input–Output based hybrid analysis	Integrated hybrid analysis
Function	Use materials and energy data for each process in the manufacturing of a product	Describe the relations between processes and computing LCIs	A top-down technique so it's viable to collect process-specific data for the whole economy	Integrates input–output and process coefficients to include system boundary and information missed in-process and input–output analyses	Important input–output industry sectors are further separated	Integrates process-based and input–output data with a single matrix framework
Strengths	Detailed analysis of accurate results	Represent infinite orders of upstream process relations. Accurate results	Data is regularly compiled as part of national statistics. The entire supply chain is included. Error eliminated.	Easy to use, accurate and adequate results	Double counting errors solved	Avoid double counting errors Consistent mathematical framework throughout a product whole life cycle
Weaknesses	Broader system boundary and scopes consume labour and time. Systematic truncation error due to cost and time constraints	The number of processes is limited. Inclusion or exclusion of processes based on subjective choices. Systematic truncation error due to cost and time constraints.	Provide information only for typical processes that are well represented by I-O categories. Uncertainties due to level of aggregation in analysed industry or commodity classifications	Double counting errors Not suitable for countries that rely on the import of important materials	Use and end-of-life phases should be added	Complex to use High data and time requirements

Step 3: Life cycle Impact assessment

The impact assessment step aims to study the potential effects concerning human health, the availability of resources, and the natural environment. This step makes the results of an LCA easier to interpret. The energy use and emissions generated are classified and characterised into impact categories and impact potentials including global warming potential, acidification potential and eutrophication potential (ISO, 2006; UNEP, 2003).

Step 4: Interpretation

In the interpretation phase, LCA users aim to identify the most important aspects of the inventory analysis and the impact assessment; evaluate the study's outcomes, completeness check, sensitivity analysis, uncertainty analysis and consistency check; and make conclusions, recommendations, reporting, and critical review (UNEP, 2003; VanDuinen & Deisl, 2009b).

(i) Tools and databases for life cycle assessment

Life cycle assessment tools are used to assess the environmental impact of building products and buildings which can be existing buildings, new buildings or refurbished buildings (Haapio & Viitaniemi, 2008). Environmental assessment tools are broadly divided into assessment and rating tools. Assessment tools indicate the quantitative performance of a building such as energy consumption, water usage, and greenhouse gas emissions, whereas rating tools rate the performance level of a building in stars (Ding, 2008). Some LCA tools analyse all phases of the life cycle of a building including production, construction, use/operation, maintenance, demolition, and disposal. However, some others do not analyse the full life cycle of a building (Haapio & Viitaniemi, 2008).

The study of Haapio and Viitaniemi (2008) provided a critical review of some European and North American environmental assessment tools that can be used at the national or global level. The Building Research Establishment Environmental Assessment Method (BREEAM), which was developed in 1990 in the UK, was the first commercial environmental assessment method for the building sector. Since then, many different tools have been established (Ding, 2008; Haapio & Viitaniemi, 2008). BREEAM evaluates the procurement, design, construction, and operation of a building based on performance benchmarks. Building performances are rated and certified on a scale of fair, good, very good or excellent. BREEAM has been used in many countries such as Australia, Canada and Hong Kong. Many countries used BREEAM methodology to develop their own environmental assessment tools such as HKBEAM, BEPAC and GreenStar, BASIX, Accurate, etc. (Ding, 2008). BREEAM does not assess the phase of demolition, but it covers disposal.

Building for Environmental and Economic Sustainability (BEES) software was developed by the National Institute of Standards and Technology (NIST) and it is available to download online for free. BEES measures the environmental performance of building products based on standards of the ISO 14040 series from the stage of raw material acquisition, manufacturing, transport, installation and using, to the end-of-life including recycling and waste management.

ATHENA Environmental Impact Estimator (EIE) was developed by Athena Sustainable Materials Institute, Canada. ATHENA™ is mainly used in North America. In North America, it is the only free software that can be used to evaluate whole buildings and assemblies based on life cycle assessment methodology. It allows users to assess and compare the environmental impact of residential or non-residential new buildings, existing buildings, or refurbishment buildings. The estimator takes into account the phases of material acquisition and manufacturing, transport to the construction site, onsite construction, maintenance, demolition and disposal. Unfortunately, it does not directly calculate the phase of use or operation of a building.

SimaPro was developed by PRé Sustainability, Netherlands. It is the world's leading LCA software used by industry, research institutes and consultants in more than 80 countries. The software is widely used in Australia and New Zealand and users have access to an Australian LCA database which also includes data relevant to New Zealand. SimaPro allows users to model products and systems from a life cycle perspective with a variety of applications such as:

- monitoring corporate and product sustainability performance
- carbon and water footprint calculation
- product design and eco-design
- environmental product declarations (EPD)
- environmental reporting (GRI)
- determination of key performance indicators (KPIs).

SimaPro has many databases available, including Ecoinvent, which is one of the most comprehensive databases.

The second widely used professional LCA software is GaBi created by Thinkstep, formerly known as PE International, Germany, with conformation to ISO 14040 and 14044 (VanDuinen & Deisl, 2009b). GaBi LCA software with high-quality databases supports every single life cycle phase from “cradle to grave” including material extraction and manufacturing, transport to the construction site, onsite construction, maintenance, demolition and disposal. To date, the latest GaBi databases 2017 have been enriched with nearly 600 new datasets adding to the over 10,000 datasets. Therefore, it allows users to get more energy data globally, more association and industry data, regionalised water and land used, expended Indian database content, and PEF/OEF (Product Environmental footprint/Organisation Environmental Footprint) support.

SimaPro and GaBi are two leading life cycle assessment tools that are used worldwide. From 2010 to 2013, 116 articles submitted to International Journal of Life cycle Assessment and Journal of Industrial Ecology used SimaPro for life cycle impact assessment, 38 articles used GaBi and 7 articles used other LCA tools. Therefore, SimaPro and GaBi have been the preferred choices for LCA researchers who submitted their articles for these journals (Speck et al., 2015). Herrmann and

Moltesen (2015) investigated the difference in the results of using the two databases of SimaPro and GaBi for life cycle assessment. The comparison was carried out on the newest versions available at that time, which were GaBi 4.4.139.1 (Compilation) and SimaPro 7.3.3 (Faculty). While many cases yielded identical results in SimaPro and GaBi, there were some instances where the results differed significantly, which could impact decision-making. From randomly selected 100 processes, there were six flows identified differently in SimaPro and GaBi with a ratio of SimaPro/GaBi higher than 1.01. These differences came from the differences and errors in the different databases of SimaPro and GaBi. However, as newer updated versions of SimaPro and GaBi are now available, these results may change.

(ii) Implementation of life cycle analysis in the building construction industry

In the Australian context, construction is the second largest industry by gross domestic product share (Yu et al., 2019), yet it is responsible a significant environmental damage contribution, particularly greenhouse gas emissions and natural resources depletion. The global building construction industry contributes 30–40% of annual greenhouse gas emissions and consumes 25% of the wood harvest; 40% of stone, sand and gravel; 16% of water usage and 40% of all primary energy across each life cycle stage (Figure 3.7) (Joseph & Tretsiakova-McNally, 2010).

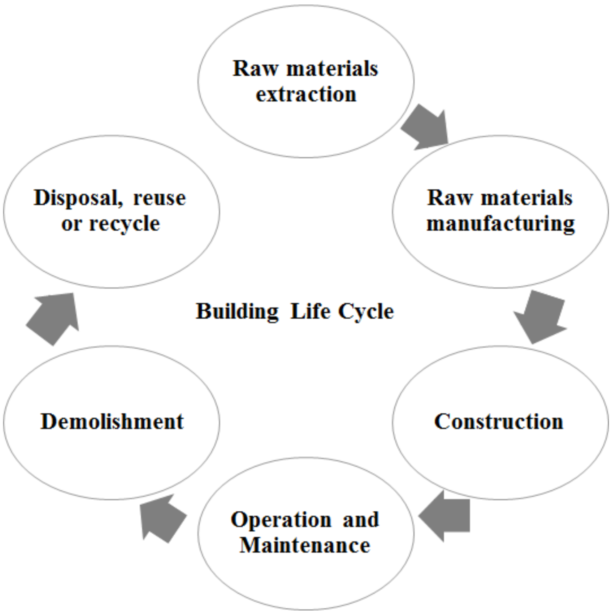


Figure 3.7 Building life cycle stages

Life cycle analysis is therefore used to assess the environmental impacts including energy consumption and associated greenhouse gas emissions as a result of building construction activities in every stage of a building life cycle:

- raw materials extraction
- raw materials manufacturing
- construction
- operation and maintenance
- demolition
- disposal and end-of-life.

Numerous Australian and international studies have conducted a life cycle analysis to investigate the difference in environmental performance between conventional and sustainable building construction. In the study of Perez Fernandez (2008), the author also compared life cycle embodied energy and CO_2 emissions of a mid-rise commercial building in different designs including concrete, steel, timber, and timber plus. By using LCA, the author revealed that embodied energy played the main role in the difference in life cycle energy use among the four designs. The Timber Plus design consumed 15% less life cycle energy compared to the highestconsuming design, which was the Steel design. Additionally, the Timber Plus design released approximately 27% less CO_2 emissions over its life cycle than the highest-emitting design when carbon sequestration was considered.

In Canada, Robertson et al. (2012) used life cycle analysis to compare the environmental performance between two different design scenarios of a mid-rise office building: a cast-in-place reinforced concrete frame and a mass timber design which has CLT and glulam as main structural materials. The mass timber redesign was based on an actual 14,233 m^2 office building, constructed in 2009 in Burnaby, British Columbia, Canada. The study assessed 11 impact categories, based on the US Environmental Protection Agency's TRACI, including global warming potential, ozone depletion, human health effects, criteria air pollutants, water intake, eutrophication, ecological toxicity, smog, acidification, fossil fuel depletion and embodied energy. The results showed that 10 impact categories of mass timber design were lower than those of the reinforced concrete building. In particular, the mass timber design contributed 71% lower global warming potential than the reinforced concrete building when carbon storage is taken into account. Only one impact category of the mass timber design, which is embodied energy, was higher than that of the concrete building. Most relevant LCA studies demonstrated that timber-based buildings resulted in lower embodied energy than other alternative designs (Cole & Kernan, 1996; Dodoo et al., 2014b; Perez Fernandez, 2008a). However, Robertson, Lam and Cole's study anticipated that the cumulative embodied energy of timber redesign was higher than that of the original concrete design by 3.6 GJ/m^2. This is because the study accounted for feedstock energy in LCA (Table 3.8). They defined that embodied energy included process energy which is related to the combustion of fuels used during all processes of the production of a building and feedstock energy which is then easily accessible potential energy contained in fuel resources extracted from the Earth such as bio-based EWPs and fossil fuel-based wood adhesives. Therefore, higher embodied energy did not display worse environmental performance. The timber-based design contained a large amount of potential energy which is useful after its service life.

Table 3.8 Cumulative energy demand for concrete and redesign timber

	Original concrete design (GJ/m^2)	Redesign timber design (GJ/m^2)
Feedstock energy	0.82	4.43
Process energy	3.51	3.49
Unallocated	0.27	0.27

Later in 2013, Durlinger, Crossin and Wong conducted an LCA for the Forté building, which is Australia's first mass timber multi-storey apartment, located in Melbourne. The Forté building was constructed with 758 CLT panels imported from Austria. The ground and first-floor slab were constructed from reinforced concrete due to the larger spans required in the retail space and for moisture and termite resistance purposes. The environmental impact assessment indicator in Durlinger, Crossin, and Wong's LCA study is global warming potential, including considerations of carbon sequestration. The results indicated that the Forté building had a lower environmental impact compared to the alternative design, regardless of whether carbon sequestration was included or excluded (Figure 3.8) (Durlinger et al., 2013).

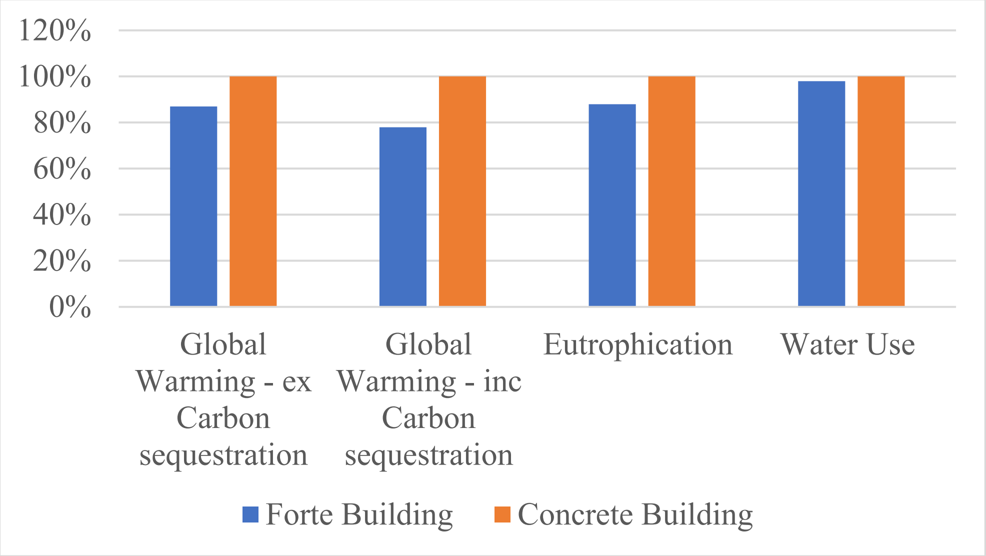


Figure 3.8 Comparative results on environmental impacts of Forté building and alternative building (Durlinger et al., 2013)

3.3 Conclusion

This chapter sought to identify key performance indicators used to assess the success of a sustainable development project. Through the analysis of the literature review, the four most common indicators were identified: cost, time, quality and environmental performance. The literature review showed that prefabricated mass timber structures perform better in time, cost and environmental aspects. Mass timber structures need to be properly designed, based on the National Building Code, to obtain equivalent thermal performance as other heavy material structures such as concrete. These four key performance indicators are the foundation to develop the interview questions and the analysis of the interviews with construction practitioners in Chapter 5. The next chapter reviews the research methodology and identifies the most suitable approaches used for this study.

Chapter 4 Research methodology

This thesis aims to develop sustainable non-residential development to increase sustainability in the construction industry in Australia by the use of engineered wood products or mass timber as key structural materials. Through a number of interviews conducted with construction practitioners who have experience in mass timber construction in Australia, the emerging benefits, barriers and strategies to increase the uptake of mass timber usage in Australia are investigated. Based on identified benefits and barriers from the literature review and interviews the sustainable non-residential development model is developed to overcome current obstacles and exploit the benefits of using mass timber in construction. The proposition of the model is tested by actual case study buildings to compare nominated key performance indicators. The purpose of the comparison is to assess how mass timber performs against heavy material, such as concrete, in the model.

This chapter discusses how the research design and methodology are selected. Data collection, including interviews and the selection of the case study for model verification, are also discussed.

4.1 Research methodology

The selection of an appropriate research methodology plays an important role in the success of a research project. Kothari (2004) stated that research methodology is a way to systematically figure out the research problem and thus varies depending on the research problem defined. Research methodology can be distinguished into five basic types (Kothari, 2004).

(i) Descriptive vs. Analytical research

Descriptive research is used to describe the characteristics of the population or phenomenon. This research methodology mainly focuses on answering the research questions of what, rather than why. On the other hand, analytical research relates to the critical evaluation of facts or information relevant to the research.

(ii) Applied vs. Fundamental research

The goal of applied research is to find a solution for a practical problem in society or an organisation, whereas fundamental (basic) research focuses on fundamental understanding or formulation of a theory.

(iii) Quantitative vs. Qualitative research

Quantitative research indicates the results of measurement which can be expressed in numbers. In quantitative research, a hypothesis can be tested by systematically collecting and analysing data. Alternatively, qualitative research emphasises non-numerical data such as phenomenon, thoughts and experience. Qualitative research enables the researcher to support the theory for potential quantitative research at a later stage.

(iv) Conceptual vs. Empirical research

The conceptual research methodology is used to analyse or explain existing information in a given topic. No experimental work is needed in conceptual research. Philosophers tend to use conceptual research to develop new theory or interpret existing theories. In contrast, empirical research depends on empirical evidence gained from observation or experience. Empirical research can be obtained by using qualitative or quantitative approaches.

(v) Other types of research

Other types of research vary based on the purpose of research, the time required to complete the research or the environment in which the research is accomplished, such as longitudinal research, laboratory research or historical research. In order to conduct the above research types, there are two main approaches: the quantitative approach and the qualitative approach (Kothari, 2004). The quantitative approach relies on numerical data and can be categorised into inferential, experimental and simulation approaches. The qualitative approach focuses on subjective assessment such as behaviour, attitudes or opinions. In addition to these basic approaches, a mixed method is the combination of quantitative and qualitative approaches (Kothari, 2004; Liu, 2014).

4.1.1 Qualitative method

The qualitative method is the approach to conduct qualitative research. It is used to identify opinions, meanings and attitudes about a phenomenon by gathering non-numerical data. The qualitative method allows researchers to understand perceptions of either individuals or groups about a phenomenon. The methods to gather data may be unstructured or semi-structured (Fellows & Liu, 2015; Thomas, 2003a). Accordingly, the analysis of data is different from the quantitative approach and requires suitable analytic techniques such as sorting, filtering of transcribed interviews and analysing the contents of conversations (Fellows & Liu, 2015). Hence, the results of the qualitative method are descriptive rather than predictive. Thomas (2003a) showed common types of methods used in a qualitative method include case study, ethnographic, and experience narrative approaches. It is necessary to understand both the strengths and weaknesses of each qualitative method to choose an appropriate method.

(i) Case study method

The case study method is widely used in qualitative research. It is used to explore an individual, group or phenomenon through unstructured interviews or observations to investigate the experience or behaviour of an individual. The researcher can use descriptive, exploratory or explanatory methods to explore the phenomenon. However, this method consists of a small number of cases, and is poor in scientific generalisation, especially for the single-case study (Thomas, 2003a).

(ii) Experience narrative method

The experience narrative method allows the narrator to narrate a story or event that takes place over a period of time. Narrative can be obtained through different approaches of data collection and analysis, including transcripts from in-depth interviews, conversations, focus groups, biography or life history. Narrative analysis therefore seeks to investigate the experience or perceptions of respondents about the given subject (Thomas, 2003a).

(iii) Ethnographic method

Researchers employ the ethnographic method to acquire rich data in terms of cultural anthropology from a group of people or society through their behaviour, language and opinions. Since the data collection takes place in public, the ethnographic method may take a long time to complete and the cooperation of research participants can be a challenge (Thomas, 2003a).

4.1.2 Quantitative method

In contrast to the qualitative method, the quantitative method is the process of collecting and analysing numerical data. The quantitative method is widely used in different disciplines such as construction, science, economics and health. Bryman (2016) revealed that findings in quantitative research can be generalised to a wider population. Research is also replicable, which means other researchers can repeat the study, based on the numerical measurement data. There are two main types of quantitative research methods: exploratory research and conclusive research.

(i) Exploratory research

Exploratory research is used to research an unclear problem. Therefore, it only helps to better understand the existing problem, not provide any conclusive results. The results of exploratory research can be used for further research. Two main approaches can be used for exploratory research: the primary research approach and secondary research approach (Bryman, 2016). Figure 4.1 below summarises different approaches to primary and secondary research that researchers can apply in exploratory research.

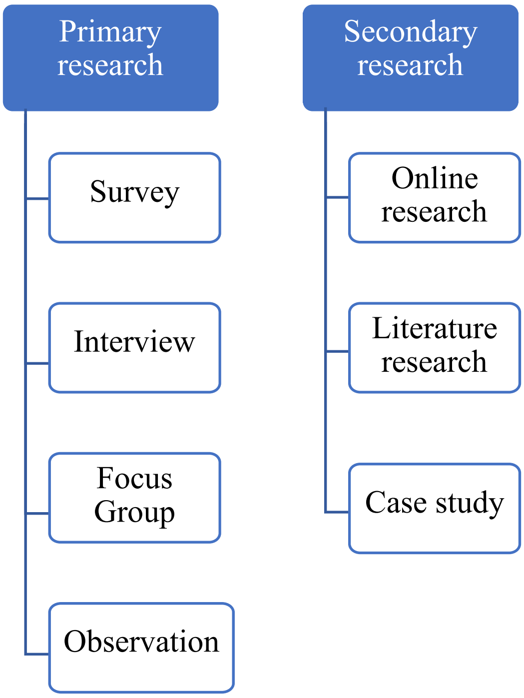


Figure 4.1 Types of exploratory research (Bryman, 2016)

(ii) Conclusive research

Conclusive research is applied to obtain conclusions or decision-making through complete and accurate information of the study. It is usually used to verify or quantify the results of exploratory research. Conclusive research can be categorised into two different approaches: descriptive research and causal research (Bam, 1992). The descriptive method describes the functions or characteristics of a phenomenon, condition or event by using accurate data. On the other hand, the causal method is applied to investigate cause-and-effect relationships. Each method can be divided into different groups, as in Figure 4.2.

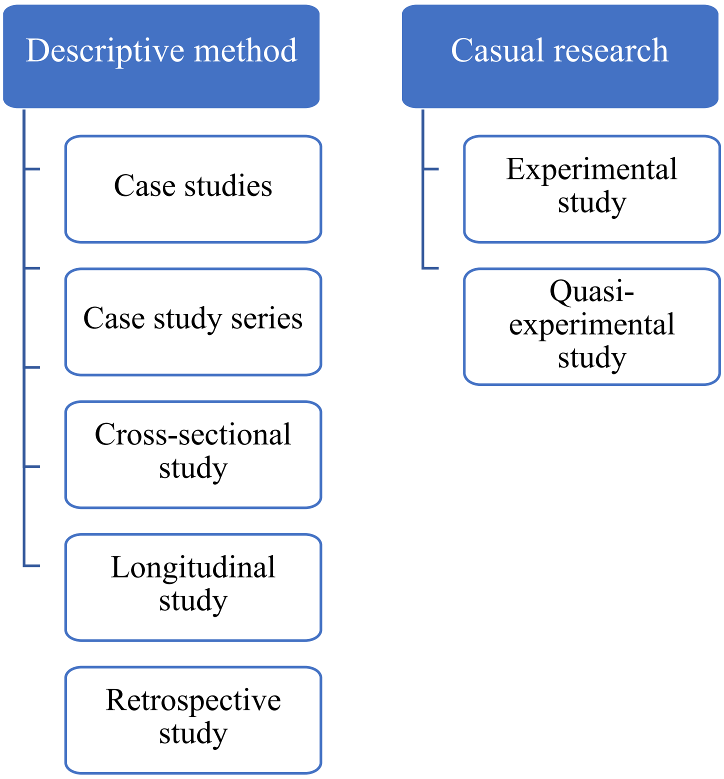


Figure 4.2 Types of causal research (Bam, 1992)

Qualitative and quantitative research methods are designed to explore different types of research questions. A quantitative method allows researchers to deal with numerical data, whereas a qualitative method provides a better understanding of the complexity of a phenomenon or event. Each method has pros and cons and is suitable for certain research questions. A combination of qualitative and quantitative methods to maximise the strengths and minimise limitations is called a mixed-methods approach.

4.1.3 Mixed-methods research

The mixed-methods approach enables the researcher to have a better understanding of research problems and answer certain research questions that using only one type of method cannot answer (Creswell & Creswell, 2017). Researchers can combine methods of collecting, analysing and interpreting qualitative and quantitative data in a study or multiple studies of the same research problems. Therefore, data from mixed-methods research tends to be more complex to interpret and analyse (Creswell & Creswell, 2017). Consequently, mixed-methods research requires researchers to have knowledge of different research methods, an in-depth understanding of the assumptions of each method, and ability to use tools to analyse and interpret results of both qualitative and quantitative data (Terrell, 2012). More importantly, Terrell (2012) identified there are several ethical concerns that must be addressed, as summarised in Table 4.1.

Table 4.1 Ethical concerns of mixed-methods research (Terrell, 2012)

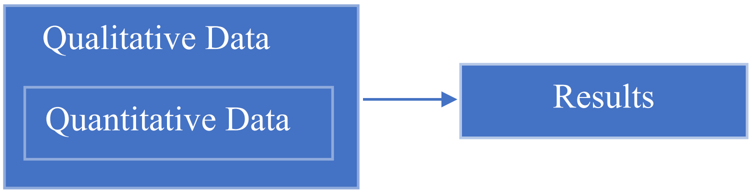
Participants	Researchers
Be willing to participate	Maintain the research places undisturbed until the end of the study
Perceive the aims, benefits and procedures of the study	Respect privacy of participants
Perceive that they have the right to get the results of the study	Must keep the data responsibly for a period of time
Perceive that they have the right to terminate their participation	Maintain anonymity during data analysis process
	Explain the study well to enable readers to assess the quality of the study

Creswell and Creswell (2017) showed three different methods to mix qualitative and quantitative approaches within one study, as presented in diagrams below:

(i) Merge the data:

(ii) Connect the data:

(iii) Embed the data:



Mixed-methods research strengthens the advantages of both qualitative and quantitative research. Quantitative research cannot provide an understanding of the research problem related to people's perceptions, perspectives and conversation whereas the findings from qualitative research are difficult to generalise and are not replicable when readers repeat the study. By merging qualitative and quantitative methods, the mixed-methods approach enables researchers to handle with multiple types of data, including numerical measurement, observation or interview data.

Mixed-methods research has been widely applied in the construction industry. Akadiri et al. (2013) used mixed-methods research to develop a multi-criteria evaluation model for material selection for building projects. The authors first applied the qualitative research method to analyse data from a questionnaire survey to identify key performance criteria to form the model. Then the quantitative research method was used through a numerical technique called a fuzzy extended analytical hierarchy process (FEAHP) to weight the importance of identified criteria. The model provided a benchmark for construction practitioners in building material selection. This is an application of the method of connecting data, as listed in diagram (ii) above, where the results from qualitative and quantitative methods are used to solve the research problems.

Similarly, Yeung et al. (2013) employed mixed-methods research to create a benchmark model for the assessment of project success in Hong Kong. The authors integrated both leading and lagging key performance indicators, which are represented as indicators to predict the future trend and to demonstrate the current outcomes, obtained from the literature review. A questionnaire survey was developed, based on the identified key performance criteria, to choose the most important indicators. The results revealed the ten most important indicators which were used for the final stage of the study, including safety performance, cost performance, time performance, quality performance, client satisfaction, effectiveness of communication, end user satisfaction, effectiveness of planning, functionality and environmental performance. Finally, a quantitative approach was used through the reliability interval method to develop the assessment model.

In addition, Thomas (2015) used both qualitative and quantitative research methods in his PhD dissertation to develop a model for sustainable residential development, focusing on the use of timber as an alternative to heavy materials such as concrete and brick. The author first used a qualitative approach to conduct a questionnaire survey to identify the perception of the residential development market. The results from the survey were then used for the semi-structured interview questions. The main purpose of the interviews with construction practitioners was to investigate current barriers to the use of timber in the residential market. The results from the interviews were fundamental to develop a sustainable residential model. A quantitative approach was then implemented in the form of using a simulation program to test timber performance in a residential application.

In the past decade, mixed-methods research has been extensively used in the construction industry. The adoption of mixed-methods research in the construction industry provides a better understanding of the perception of different stakeholders through interviews, observation or literature review. More importantly, numerical measurement reduces the impact of a researcher’s bias and generalises the results.

Overall, the combination of qualitative and quantitative approaches in one study strengthens advantages and reduces weaknesses, compared to using one method alone.

4.2 Data collection and instrumentation

Data collection plays a vital role since it affects the results of the research. According to Thomas (2003b), there are three important data collection processes: content analyses, observations and interviews. The three most important instruments are factual questionnaires, inventories and tests.

4.2.1 Data collection processes

(i) Content analyses

Content analyses are the process of finding the answers to research problems through the information including audio records, video records, transcripts and photographs, which enable researchers to quickly find the keyword and the number of times that keyword appears in the content. Content analyses are often used in research of a person's life, history of a country or, in comparing the legal systems across different nations. It can be conducted from either a qualitative or quantitative perspective (Thomas, 2003b). However, content analyses have some limitations: it can be time-consuming, and the results may lack accuracy and comprehensive detail. The quality of the results largely depends on the documents analysed. The closer the documents' field is to the researcher's study, the more relevant and valuable they are (Thomas, 2003b).

(ii) Observations

The observation process enables researchers to obtain information through either watching or listening directly or indirectly to a phenomenon or event and then recording it. Direct observation can occur in unplanned, unexpected events, without any special tools such as a video or audio recorder. However, it is difficult for the researcher to take notes and achieve an accurate record. On the other hand, indirect observation can be accomplished by the use of an auditory or visual record of a phenomenon or event. Other researchers who observe the same event might have a different point of view. Hence, accurate results may not be achieved from the observation process (Thomas, 2003b).

(iii) Interviews

Research interview is defined as the method that researchers use to obtain desired information from research participants through specific research questions (Longhurst, 2003). Interviews can occur face to face, one researcher to one participant, or group interviews or via telephone or the internet. Interviews can also be conducted in written form where the researcher sends a list of questions to participants to answer. Interviews help researchers gain more information about personal experience, opinions and perspective compared to observations. Interviews also give researchers greater flexibility and personal control than a questionnaire survey. However, this type of data collection process can take a lot of time since researchers may meet respondents individually. To conduct interviews, researchers are required to have experience, especially to deal with sensitive issues (Thomas, 2003b).

4.2.2 Data collection instruments

(i) Factual questionnaires

The questionnaire is a research instrument that contains a list of questions to gather information from respondents. There are two common types of questions and responses, checking the choice or writing down the answer. This research instrument allows researchers to gain a large amount of information in a short time. Questionnaires can be sent via email or mail, and thus researchers are not required to be present when respondents answer. However, respondents might not complete and return their answers due to the absence of researchers at the time of the survey (Thomas, 2003b).

(ii) Inventories

By using an inventory, researchers provide a printed document in which research participants can record their attitudes or preferences. The inventories can be in a form of a list of questions. The advantages and disadvantages of inventories are the same as factual questionnaires (Thomas, 2003b).

(iii) Tests

A test helps researchers through the use of a list of questions to answer and problems to solve. The respondents can provide their answers on a separate answer form. Types of test instruments include true–false, multiple choice, matching, completion, short answer and essay. Each type has its own advantages and limitations, making it suitable for specific research aims and questions. True–false is simple for both researchers and respondents. However, it might be confusing for respondents to choose the correct answer. Multiple choice allows respondents to select the most appropriate answer from among several alternatives, whereas an essay requires respondents to have writing ability, and thus takes more time to complete than true–false or multiple choice instruments (Thomas, 2003b).

4.3 Research design

Kothari (2004) expressed that it is necessary to prepare for the design of the research when the research problem is defined. Research design is described as the conceptual framework which contains the arrangement of the collection, measurement and analysis of data. The research design is a plan that indicates the source and type of desired information related to the research problem. It is a strategy which indicates which approach will be employed to gather and analyse the data, and a plan shows the time and budget to conduct the research (Kothari, 2004).

Fellows and Liu (2015) reported that questionnaire, interview and case study are the three most common methods used in research on construction. The studies of

Akadiri et al. (2013), Yeung et al. (2013) and Thomas (2015) have proved that literature reviews, questionnaires, interviews and case study are dominant in research on construction. Each of these methods has both strengths and weaknesses. For instance, literature research is the most inexpensive approach with abundant resources such as libraries, online sources (books, articles) and reports. It enables researchers to gain the basic knowledge in a particular research topic and create new ideas and directions for a specific research field. However, the quality of resources used for literature reviews needs to be strictly assessed and evaluated (Snyder, 2019). Questionnaire survey research provides broad but not deep results. The questionnaire can be delivered directly to respondents in-person or online. However, a questionnaire may require a large number of participants to allow for those who do not complete and return the answers or give invalid answers. In contrast, the interview method enables researchers to have greater flexibility and personal control than a questionnaire survey. The case study allows researchers to investigate in-depth a program, a process, an activity, or one or more individuals.

This study aims to develop a model for sustainable non-residential development and thus understanding the current advantages of and barriers to sustainable project development, particularly in the non-residential sector, is essential. Therefore, the literature review approach is first used to explore research gaps and to develop research aims and objectives.

A comprehensive literature review was conducted to investigate sustainable development in the construction industry, the use of traditional building materials, and the advantages and barriers of adopting engineered wood products (mass timber), known as sustainable building materials in non-residential application. Since the use of mass timber in construction in Australia has only become prevalent in the past decade, not many construction practitioners have experience in this field yet. Therefore, it would be a great challenge to recruit research participants to conduct a questionnaire survey. A comprehensive literature review is therefore undertaken to identify the key performance indicators which are usually used to assess the success of building projects. These indicators are fundamental to the interview questions at the later stage of the research.

An in-depth semi-structured interview approach is employed to investigate construction practitioners' perceptions of the advantages of and obstacles to using mass timber as structural materials in construction, particularly in the non-residential application, based on the identified key performance indicators. The analysis results from the interviews are fundamental to the suggested building procurement process and model for sustainable non-residential development. In addition, interviewees are asked to participate in the second stage of the interview to review the redesign of the case study building. After the model is proposed, a case study is used to verify the model.

In conclusion, qualitative research is used to identify the research gaps, and develop research aims and objectives. Qualitative research, through the use of a literature review and interview approach, is used to develop the building procurement process and model for sustainable non-residential development. The proposition of the model is then tested by using a case study. The quantitative method is used to evaluate how mass timber performs compared to traditional heavy materials, such as concrete, in non-residential development. Figure 4.3 indicates the outline of the research methodology for this study.

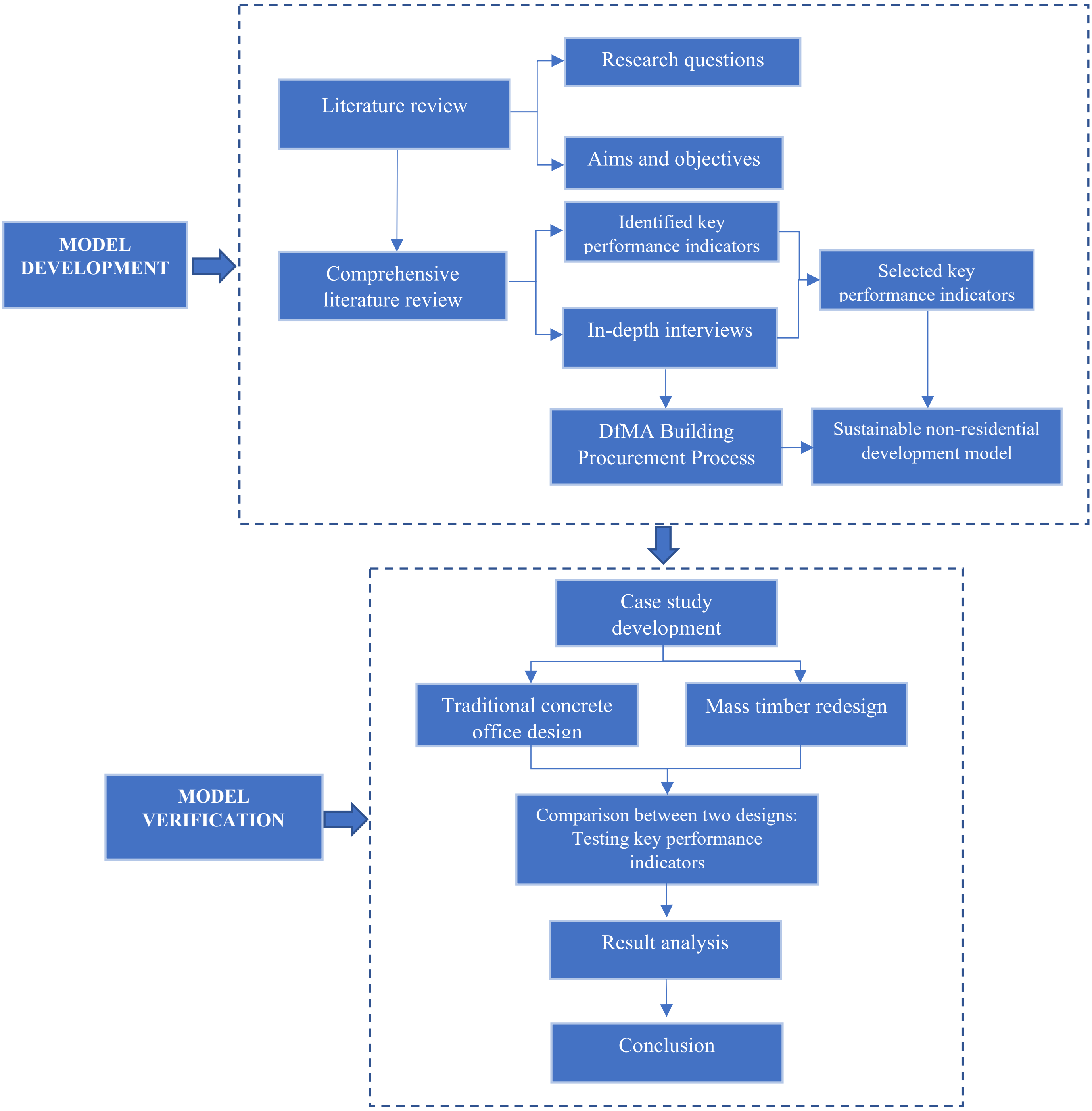


Figure 4.3 Research outline

4.4 Ethics in research

There are ethical issues to consider when conducting research related to human and animal subjects (Bryman, 2016). There are four main areas of ethical concerns:

- Is there harm to participants?
- Is there a lack of informed consent?
- Is there an invasion of privacy?
- Is deception involved?

There are many ways that research can harm participants. The harm could be physical harm or psychological and legal harm. Therefore, researchers need to protect participants in terms of physical and psychological effects, privacy and confidentiality. Since in-depth interviews are used in this research, it is necessary to take ethical considerations into account before recruiting participants. The ethics application for the research was reviewed and approved by the University of Technology Sydney Human Research Ethics Committee (Approval Number: ETH18-2697, see Appendix A). The application provided information on data collection, storage, the use of data, confidentiality and the interview information sheet, samples of interview questions and the consent form for research participants. Information on interview times and locations which suit research participants was also included in the application.

4.5 Conclusion

This chapter reviews different research methodologies and approaches. The advantages and limitations of each research methodology and approach have been analysed. Qualitative research methods, including literature review and in-depth interviews, are employed to develop the main goal of this study – a sustainable non-residential development model. A comprehensive literature review is fundamental to key performance indicators and interview questions. The combination of identified key performance indicators from the literature review and the interviews is used to weigh the most important indicators for model development. This study uses quantitative research to verify the proposed model by comparing selected performance indicators between two designs, traditional concrete office design and alternative mass timber redesign. The literature review was presented in Chapter 2. The next chapter discusses the data collection process and analyses the interview results.

Chapter 5 Data collection and interview results

This chapter presents the purpose, data collection methods and results of the semi-structured interviews with construction practitioners who have experience in delivering mass timber projects in Australia.

Advances in timber engineering, particularly the development of engineered wood products such as LVL, CLT and glulam, have enabled prefabricated mass timber construction. This has been proved not only through a number of studies but also demonstration buildings, both in residential and non-residential sectors such as Forté building in Melbourne and International House Sydney. However, since engineered wood products are not yet as well established as traditional heavy materials, there are opportunities and challenges for the development of sustainable construction and using mass timber as a key structural material. In conjunction with the literature, the results of the interviews identify current key challenges and strategies to increase the uptake of mass timber in commercial developments in Australia. The interview results are used to develop the sustainable non-residential development model in Chapter 6. This chapter has two parts: explanation of the data collection, and analysis of the semi-structured interviews.

The conclusion summarises the results and introduces their purpose in developing a strategy for increasing mass timber in commercial developments in the Australian context, which is then discussed in Chapter 6.

5.1 Data collection

5.1.1 Interview purpose

Despite the recognition of numerous benefits of mass timber construction and successful completion of mass timber projects, there are still barriers and challenges slowing the uptake of mass timber construction in Australia. Under ethics approval of the University of Technology Sydney (UTS HREC Approval Number: ETH18-2697), this study sought to investigate the industry's perception of mass timber construction through semi-structured interviews with construction practitioners. The purpose of the interviews was to explore perceptions of construction practitioners, which related to the issues identified in the literature, to verify key challenges in mass timber construction, as well as exploiting potential development and strategies to increase mass timber usage in commercial development in Australia. Importantly, the interviews aimed to identify key criteria for building material selection, especially in sustainable development. Interview questions mainly focused on the use of mass timber or engineered wood products in commercial and office buildings in Australia. The interview questions are listed in Appendix B.

5.1.2 Semi-structured interviews

A research interview is defined as the way in which one person (the interviewer) extracts desired information from another person (the interviewee) through specific research questions (Longhurst, 2003). There are three categories of the interview: structured, unstructured and semi-structured. In the structured interview, sometimes called the standardised interview, respondents answer the same predetermined list of questions, in the same order. This ensures the responses can be aggregated (Bryman 2016). However, participants in a structured interview tend to have a passive role, and may therefore have an impression that the interviewer has already decided what is important in their mind (Chauncey, 2014). On the other hand, the unstructured interview has no predetermined format. Therefore, either the interviewer or participant governs the direction of the interview. However, the goals of the interview need to be defined clearly to avoid conversations irrelevant to the main topic, which requires a skilled and flexible interviewer (Chauncey, 2014; Thomas, 2015). Hence, this study adopted the semi-structured interview to balance the predetermined questions of the structured approach with the flexibility of the unstructured interview. This allowed the participants to raise their own perspectives.

The semi-structured interviews were mainly conducted face-to-face at a particular location to enable comprehensive understanding and adjustment of the discussion based on participants' responses. Some interviews were carried out via Skype, for the convenience of participants located outside Sydney.

(i) Pilot interviews

A pilot study is defined as a small-scale version of the proposed research conducted before a full-scale research project. This allows the researchers to adjust and revise research methods (Kim, 2011). In this study, three pilot semi-structured interviews were conducted to assess the clarity, relevance, and scope of the interview questions, and to address potential procedural issues before conducting the full set of interviews. The pilot participants were recruited following their attendance at industry events relevant to mass timber construction. Specifically, participants were approached following their engagement in a series of industry events, including a strategic workshop hosted by the Australian Research Council (ARC) Future Timber Hub at UTS Tech Lab in Sydney on 30 – 31 October 2018, the WoodSolutions Young Professional Network event held in Sydney on 21 March 2019, and the Mass Timber Update: Code Changes, Case Studies & New Solutions workshop conducted in Sydney on 10 April 2019. These events were attended by professionals across the construction sector, including engineers, architects, suppliers, and consultants involved in mass timber projects.

WoodSolutions is an Australian industry initiative supported by Forest & Wood Products Australia (FWPA), designed to promote and increase the use of wood and engineered timber in the built environment through technical resources, training, and stakeholder engagement. The Future Timber Hub is a research initiative funded by the ARC, focused on developing and advancing timber innovation for mass timber buildings, with an emphasis on sustainability, performance, and structural systems.

Participants for the pilot interviews were selected using a purposive sampling approach, based on their professional experience and relevance to the research focus. They were identified during networking sessions at the aforementioned events and formally invited via email. Selection criteria for the pilot interviews included:

- A minimum of 10 years of experience in the construction industry;
- Active involvement in mass timber projects (either residential or non-residential);
- Representation of different roles and organisation types in the construction process.

Table 5.1 below presents details of the pilot interview participants.

Table 5.1 Details of the pilot interviews

Participant ID	**Years of experience**	**Position indicated**	**Organisation**	**Interview time**
SE1	20–25	Structural engineer	Builder/Contractor	60 minutes
SE2	10–15	Structural engineer	Subcontractor	50 minutes
SE3	15–20	Structural engineer	Manufacturer/Supplier	70 minutes

These pilot interviews were essential in identifying and resolving two key issues. First, discussions occasionally diverged into topics not directly relevant to the research objectives. Second, some participants expressed concern about the length of the interview. As a result, the interview duration was limited to 45 minutes in the main study, aligning with the ethics approval requirements and to minimise demands on participants’ time. Furthermore, based on participants' responses and expertise during the pilot interviews, several interview questions were refined or added to better reflect practical industry insights. The finalised interview guide is presented in Appendix B.

(ii) Sampling method and response rate

Sampling is the process of recruiting people who will potentially represent the research population (Chauncey, 2014). Sampling strategies can be divided into two categories: probability sampling and non-probability sampling. Probability sampling is a sampling strategy in which the sample from a total population is selected based on the theory of probability. Every participant in probability sampling has an equal chance of being chosen (Bloor & Wood, 2006). Hence, the probability sampling technique is not suitable for this study. In contrast, non-probability sampling does not acquire a random selection method. In non-probability sampling, the research population is selected by the judgement of the researcher to achieve research questions and research objectives. The non-probability sampling approach includes three main different techniques: convenience, quota and snowball sampling (Bryman, 2016).

Convenience is the sampling method where data collection relies on a group of the population that is available to participate in the research. Hence, it might not be possible to generalise the findings. Quota sampling is defined as the process of gathering representative data from a group, which reflects the relative proportions of people from different categories such as gender, ethnicity and socio-economic characteristics. These two sampling approaches do not suit the research aims of this study (Bryman, 2016).

The snowballing approach enables the researcher to make initial contact with a small group of potential participants who are relevant to the research topic and then create contacts with others who might qualify for participation through a referral process (Bryman, 2016; Robinson, 2014). The semi-structured interviews of this study aim to approach construction practitioners who already have experience in mass timber construction. It is not easy to recruit potential participants with different expertise, as mass timber construction is not yet as well established as conventional construction in Australia and not many construction practitioners have experience with mass timber construction. Hence, the chain referral process in the snowballing strategy suited this study best. Initial participants were recruited through a network of work colleagues or seminars and workshops organised by industry initiative groups such as WoodSolutions and the Australian Research Council (ARC) Future Timber Hub. These initial participants recommended their peers who qualified for participation. The participant information sheet was then emailed as a detailed introduction to the project. There were several selection criteria to participate in the semi-structured interviews:

- Experience: This study sought to recruit participants who already had experience in mass timber construction, either in residential or non-residential projects. Participants have a wide range of experience years in the construction industry, from 3 years to over 20 years.
- Position indicated: This study sought to recruit participants with diverse professional expertise in consulting, design and construction including structural engineers, fire engineers and architects.
- Organisation type: A variety of organisation types including client/developer, consultant, architectural firm, EWP supplier, subcontractor and builder was required to ensure that research participants provided diverse perceptions from the projects they are involved in.
- Company size: The recruitment of research participants took place regardless of the company size to ensure the interview results reflect the breadth of the construction industry in Australia.
- Location: Due to a limited number of construction practitioners who have experience in mass timber construction, participants were sourced nationally. Four interviews were conducted through Skype since the participants were located outside Sydney.

Seventeen individuals consented to participate in the interviews from 31 invitations. The response rate was 54.8%. The background of research participants and the analysis of participants' profile are summarised in Table 5.2, Table 5.3, Table 5.4 and Table 5.5.

Table 5.2 Background of research participants

Participant ID	Years of experience	Position indicated	Organisation
SE1	20–25	Structural engineer	Builder/Contractor
SE2	10–15	Structural engineer	Subcontractor
SE3	15–20	Structural engineer	Manufacturer/Supplier
FE4	0–5	Fire engineer	Engineering services
SE5	10–15	Structural engineer	Client/Developer
SE6	10–15	Structural engineer	Subcontractor
AR7	20–25	Architect	Manufacturer/Supplier/Academic
SE8	5–10	Structural engineer	Consultant/Academic
FE9	5–10	Fire engineer	Engineering services
FE10	0–5	Fire engineer	Engineering services
FE11	0–5	Fire engineer	Engineering services
FE12	0–5	Fire engineer	Engineering services
FE13	5–10	Fire engineer	Engineering services
FE14	0–5	Fire engineer	Engineering services
AR15	10–15	Architect	Architectural firm
AR16	5–10	Architect	Client/Developer
QS17	5–10	Quantity surveyor	Consultant

Table 5.3 Position indicated of research participants

Position indicated	Percentage (%)
Fire engineer	41.18
Structural engineer	35.29
Architect	17.65
Quantity surveyor	5.88
Total	**100**

Table 5.4 Organisation type of research participants

Organisation	**Percentage (%)**
Academia	10.53
Architectural firm	5.26
Builder/Contractor	5.26
Consultant	42.11
Client/Developer	10.53
Engineering services	5.26
Manufacturer/Supplier	10.53
Subcontractor	10.53
Total	**100**

Table 5.5 Experience years of research participants

Years of Experience	**Percentage (%)**
0–5	29.41
5–10	29.41
10–15	23.53
15–20	5.88
20–25	11.76
Total	**100**

The participants had a wide range of positions, such as architect, structural engineer, quantity surveyor and fire engineer, in diverse organisations representing involvement in different stages of project development. Most of the organisations are pioneers in mass timber construction in Australia. The experience of participants varied from 3 years to more than 20 years. Importantly, 5 of the 17 participants had multiple professional backgrounds. For instance, some of them were structural engineers and working in the role of the builder's director or manager or in charge of an EWP supplier representative. Some participants were working in the industry and pursuing an academic career. Therefore, these participants gave a broader point of view. Overall, their responses were not only based on personal perspectives but also experience and practice in actual mass timber projects they had been involved in.

Typical stakeholders in building construction are diverse and each of them takes part in different steps in the development procurement such as pre-design, design, building and construction (Bal et al., 2013). This study mainly focused on the involvement of clients, consultant and design teams, material suppliers and builders, as they deeply understand the technical obstacles as well as the benefits of using mass timber as an alternative key building material to heavy materials in mid-rise project developments, especially commercial and office projects. In addition, they can suggest strategies to improve the uptake of sustainable development using mass timber as key building materials based on the lessons they have learnt from mass timber projects in Australia. All of these participants took part in residential and non-residential mass timber projects in Australia.

The interview invitations, interview information sheet and consent form were emailed to potential participants to ensure that all participants understand the purpose of the interviews as well as their right to withdraw from the research. The interview information sheet and consent form are in Appendix A.

5.2 Interview results

The interviews began with a question about recent mass timber projects that participants had been involved in. This was to ensure that the interviewees had experience with mass timber construction. Participants were then asked about the challenges and benefits of using mass timber, particularly in mid-rise commercial and office projects. Subsequent questions were tailored to each participant's expertise to identify opportunities and strategies for increasing the adoption of mass timber in Australia. The study recruited more fire engineers than other stakeholders to explore fire safety considerations in mass timber construction.

The interviews were audio-recorded for further analysis using NVivo 12. NVivo 12 was acquired to transcribe the audio and the results were analysed using thematic analysis. Emerging patterns or themes were raised by creating nodes. The first step of the analysis was to find the key-driven factors (key performance indicators) that govern mass timber usage in building construction, especially commercial and office development. Key performance indicators found in participants' perception, including cost, performance, sustainability, aesthetics and time, are listed in Table 5.6

Table 5.6 Key performance indicators governing mass timber usage in commercial/office development

Key performance indicators	**Frequency**	**Percentage (%)**
Cost	9	23.1%
Quality performance	6	15.4%
Environmental performance	4	10.3%
Aesthetics	4	10.3%
Construction speed/Time	3	7.7%
Others	13	33.2%
Total	**39**	**100%**

Other factors, such as availability, health and wellbeing, site limitation and construction stakeholders' experience, appeared once only. Key performance factors identified in the literature and the semi-structured interviews were consolidated to finalise the most important indicators for use in the later analysis stage. KPIs collected from the literature review and semi-structured interviews are divided into subjective and objective indicators (Table 5.7). Objective indicators can be quantified such as life cycle cost, construction time, quality, safety and environmental performance. On the other hand, subjective indicators are based on personal perception such as level of satisfaction of stakeholders, aesthetics and use of local material.

Table 5.7 Subjective and objective indicators

Subjective Indicators	Objective Indicators
End user satisfaction	Cost
Aesthetics	Environmental performance
Labour availability	Thermal performance
	Constructability/Buildability
	Practicability and Flexibility
	Maintainability and Durability
	Time/Schedule
	Acoustic performance
	Use of local material

This thesis mainly focuses on measurably objective indicators. Some research has defined quality criteria of a project as achieving technical performance including thermal performance, constructability, maintainability, durability and functionality (Serrador & Turner, 2015; Thomas, 2015). Safety and human health criteria in general are related to national building regulations and are normally audited at the completion of a project. Hence, safety and human health are not included in this study. Most of the objective indicators including life cycle cost, time, quality and environmental performance are selected for further discussion in this thesis. This result matches the requirements of a successful construction project found in the literature that a construction project reaches expected quality with the reduction in cost, time and environmental impacts simultaneously (Panwar & Jha, 2019; Thomas, 2015).

Further steps of the interview analysis are to discuss the challenges and obstacles as well as the opportunities for improving the uptake of mass timber in non-residential (mainly in commercial/office) development, particularly focusing on cost, time, quality performance and sustainability.

5.2.1 Time and cost performance

Construction speed is one of the biggest advantages of mass timber construction. Quick assembly of prefabricated elements enables overall construction time reduction. From a supplier's perspective, concrete is a wet trade and needs to be given time to dry out to cure. Mass timber does not need to dry and is ready to be quickly installed as soon as it arrives on the building site. A structural engineer (SE1) stated that "when mass timber elements such as column and floor were fixed in place, they could be load-bearing elements instantly. Hence, mass timber can be faster to build than concrete. Steel could be as fast to build as mass timber, but steel was heavy, and it was harder to work with than mass timber. In addition, there were dangerous activities at the construction site because steel had to be welded, whereas mass timber elements are only mounted and screwed together". Therefore, mass timber performs better than concrete and steel in terms of safety at the construction site. The timber structure allows the use of cordless screw guns, which are light, quick and easy to use. Concrete structures require drilling into concrete, which is slow, noisy and dirty work. Also, the schedule of mass timber construction is not greatly impacted by weather and outside circumstances. Prefabricated mass timber construction is 30% faster than traditional methods. Consequently, potential cost savings can be achieved through the reduction in construction time.

One of the advantages of mass timber construction over traditional construction using heavy materials is potential preliminary cost saving due to lightweight structure, material waste minimisation, time and labour reduction and probable productivity improvement when using timber. From a client (AR16) point of view, a mass timber structure saves foundation cost due to the lighter structure. Mass timber can provide a similar structural capacity as other materials such as concrete or steel. In particular, mass timber can be easily prefabricated and delivered to the construction site, thus reducing crews and cranes onsite.

A quantity surveyor (QS17) confirmed that “based on the previous mass timber projects, labour cost reduced from 50–60% to 20–30% of cost, improved safety, 20% reduced prelims, 20% reduced substructure costs, 10% reduced superstructure costs, and 30% reduced holding costs. However, depending on the timber solutions adopted, additional requirements for fire-rated plasterboard, particleboard and acoustic membrane or additional load-bearing walls in place of columns may result in a cost increase. It is still a challenge for quantity surveyors to ensure that all these additional requirements are captured, additional connection details to connect timber panels and core connections, acoustic/waterproofing/fire requirements for accurate pricing, as they are not familiar with the new system. Additionally, contractors who are not familiar with the product tend to price ‘risk’ into the project. This might look like additional contingencies and allowances within their price due to the unknowns of working with a product they have not worked with before”.

At the same time, as mass timber construction is not yet as well established as conventional construction using steel and concrete, the financing of a mass timber project might become challenging. Indeed, two mass timber projects of Lendlease in Melbourne and 60% of projects listed in the survey of international tall wood buildings were self-funded (Forestry Innovation Investment and Binational Softwood Lumber Council, 2014; Kremer & Symmons, 2018). In addition, a subcontractor (SE2) said that “as mass timber construction was a new technology, insurance premiums would be higher than conventional development”. He emphasised that “it was important to convince developers to select mass timber in their projects by showing the profits that they could get from mass timber project development”. In fact, a quantity surveyor (QS17) confirmed that tier one contractors (large size construction firms and developers) have not yet seen any increase in insurance premiums for mass timber buildings, in comparison to concrete buildings. However, the comparison of insurance premiums between mass timber building and concrete building for tier two builders is currently still unknown. The delay in getting the approval may affect certain regulation costs for the construction and can lead to hesitancy about mass timber project development. According to a fire engineer (FE4), developers often inquire about the timeline for fire brigade approval when considering mass timber building projects. Typically, this approval process takes around 6 weeks if everything goes smoothly. However, if revisions and reassessment are required, it can add an additional two weeks. This is particularly challenging for exposed cross-laminated timber (CLT) structures, which involve performance-based design and require extensive fire testing reports for justification. Therefore, the primary hurdle for mass timber developers lies in securing timely approval from fire authority.

Another challenge of mass timber construction from a supplier (SE3) perspective is the way to be involved in the project. “When thinking about challenges of mass timber construction a few years ago, I probably would have said fire engineering, perception and the lack of solid structural information and design codes. I think probably one of the biggest hurdles that we are facing at the moment is that the construction industry in Australia has a very traditional mindset and it approaches timber in a very conventional way”. He stated that early collaboration between supplier and the design teams could save the overall building cost due to good understanding of technical information and individual manufacturers’ machinery limitation. He thought that understanding the concept of Design for Manufacture and Assembly (DfMA) played an important role in prefabricated mass timber projects. Therefore, manufacturers should be involved in the early design stage.

Currently, the lack of suppliers, skilled builders and skilled labour means the cost of a timber building might not be comparable to other buildings using heavy materials. A consultant (SE8) claimed that “lack of supply chain may increase the material costs”. If the number of timber buildings increases, there are not enough suppliers and skilled builders and carpenters. Consequently, the cost might be more than a comparable concrete solution. Mass timber is also more expensive in material costs. Therefore, it is necessary to take advantage of saving cost from the construction program to compensate for costs associated with material costs.

During the construction stage, a timber structure goes up quickly and the core strategy is getting everything organised and ready. An experienced builder (SE1) believed that "taking the advantage of fast construction time would potentially save the cost. However, if the construction teams do not manage the project properly, the advantage of fast construction speed of mass timber construction cannot be taken". Simultaneously, two important elements that may impose more cost on the construction are logistics and fixing the design. SE1 stated that "getting the right panel quickly could save time. Mass timber elements need to be well-organised to move easily". At the same time, fixing the design takes the time and effort of crews onsite. Hence, the builder and contractor must be involved in the design stage earlier to minimise the uncertainties of the installation stage.

5.2.2 Quality performance

This section reveals the perception of Australian construction practitioners in terms of the performance of mass timber, including structural capacity and fire, thermal and acoustic performance, particularly in commercial and office buildings. Through the first few commercial and office mass timber projects in Australia, in which most of these projects using exposed and unprotected mass timber, construction stakeholders have learnt lessons and raised challenges and barriers which may hinder the uptake of mass timber in commercial development.

According to an interview with a client (SE5), Australia is a world-leading country in mass timber construction, especially commercial and office buildings. For instance, International House Sydney was the first commercial mass timber building in Australia. In particular, the building proved that recycled hardwood timber could be used in structural applications. SE5 stated that the mass timber commercial market has potential to develop since there were not too many commercial mass timber buildings in Australia and other countries, such as Europe. In terms of structural perspective, each mass timber system, including CLT, glulam and LVL, has different strengths. One of the emerging advantages of these three systems is their light weight and high strength to weight ratio, which allow longer span floor solutions with the same structural capacity as heavy materials such as concrete and steel. However, one of the biggest concerns from the client side, in general, is that timber is combustible. Hence, mass timber should prove that it can achieve similar or even better fire resistance, especially with the exposed elements.

Indeed, fire engineering has been raised as one of the major barriers in mass timber development even “charring when exposed to a fire could potentially provide good fire resistance level to timber”, a fire engineer (FE10) commented. She stated that “timber was a combustible material, and it was challenging particularly for residential buildings. It was very difficult to justify leaving CLT unprotected for residential buildings because when people were sleeping it could take time to wake up. That is the main challenge of exposed CLT for residential buildings. However, the commercial sector is easier to justify because occupants are usually awake and raise an alert”.

Another fire engineer (FE12) commented that there were challenges for fire engineers to work with mass timber construction because of the lack of understanding of the fundamentals of fire dynamics concerning fire performance of mass timber. It needs to go with performance based as testing has not been done for Deemed to Satisfy (DTS) required Fire Resistance Levels (FRLs) for type A construction. For instance, slabs have not been tested for 2-hour FRL, but most fire engineers do not have sufficient knowledge to properly justify it. Similarly, the structural engineers found that it is a challenge to achieve DTS compliance for fire safety, as there is no Australian Standard available for design, especially for CLT. SE5 stated that they could use the same design rules and methods as given for solid timber or glue-laminated timber. However, these design standards are based on European code and standards. The design of exposed elements also needs to be performance-based and needs to be based on technical fire engineering reports. These fire engineering reports are based on testings. However, it takes time for a registered testing authority to repeat the tests that were done initially by the manufacturer and then write the compliance report. Mass timber is still in the stage of building up the tests for different situations. Hence, it can be difficult to design and provide the correct certification for fire and acoustic performance for particular mass timber elements. Therefore, the main problem is that it takes time to get familiar with the new building materials. According to an interview with a supplier (AR7), there are only two registered testing authorities in Australia, thus it takes time for them to repeat the tests of different types of mass timber.

In terms of thermal and acoustic performance, all participants concluded that among timber, concrete and steel, steel has the worst thermal and acoustic performance. Steel buildings always have additional layers added to the elements to achieve thermal and acoustic requirements. Timber is a good material for thermal insulation, compared to concrete and steel. AR7 stated that "timber was a natural insulator which performed much better in terms of thermal insulation than concrete and steel. If CLT was used as an external wall, it acted as an insulator already which was not normally the case with concrete. Concrete could transfer heat through, and steel was a very good conductor. With this sort of consideration, if you took into account the thermal performance of the external timber wall, you could save money on external insulation (if there was any external insulation required on the external side of the wall)". The literature has indicated that timber is good thermal insulation, and concrete has the highest thermal mass among timber, concrete and steel (Perez Fernandez, 2008b; Reilly & Kinnane, 2017; Williamson & Beauchamp, 2005).

However, timber needs to be taken into consideration with acoustic performance and fire performance to satisfy the minimum requirements of acoustic requirements. It requires good knowledge by the architects. Therefore, it is important to educate architects on achieving specific performance. Acoustically, concrete is very dense and works quite well in the low spectrum but does not work well in the high spectrum, whereas timber performs the opposite. An architect

(AR16) said that “if someone walked on a concrete floor with bare feet, the concrete floor would absorb the sound very well and not much of that sound would travel through to a tenancy below. However, the concrete floor would not perform well with high-frequency sound when someone walked in high heels. The sound would easily travel through the floor below. In contrast, a timber floor worked well with high-frequency sound but not with lower one”. For all floor systems, regardless of the materials, it is necessary to have additional layers added to them to improve better acoustic performance. For instance, a concrete floor will have extra layers to deal with high-frequency sound, whereas a timber floor will have extra layers designed to deal with low-frequency sound.

In a recent mass timber project, for the medical and health faculty of a university, timber elements are all exposed and fire and acoustic engineering are therefore important parts. However, an experienced builder (SE1) found it a challenging project, as it was quite technical, and the consultant teams were inexperienced in mass timber. SE1 commented that “they just noticed a lack of experience from the consultants and the need to be patient and work with them to try to get the right result. If they did not get involved through the design stage, there would be uncertainties and risks during the installation stage which resulted in delays, fixings, etc.”. Although this building has very high acoustic requirements, the builder emphasised that mass timber elements performed acoustically well. This proves the importance of project stakeholders’ engagement in the early design stage to ensure the best performance of mass timber design, in terms of structural, fire, thermal and acoustic performance.

5.2.3 Sustainability

Sustainability means people can meet their living needs in a healthy environment, considering social, economic and environmental conditions without compromising the ability of future generations to do so. Hence, the selection of building materials plays an important role in reducing our footprint through less energy, water and a material intensive lifestyle. A fire engineer (FE9) emphasised that “fewer materials required to support the upper storeys compared to a heavy structural steel or concrete building. Timber building was lighter and may require less material in general”.

Importantly, most participants agreed that sustainability is one of the important key factors of building material selection. The biggest advantage of timber structures is aligning with the sustainability aspect. A client (AR16) stated that mass timber was considered as one of the renewable structural materials that had been selected in their recent projects. Despite some clients not considering sustainability benefits but tending to look more at cost and construction speed, recent big clients such as a major university in Sydney find sustainability is important. “Timber is going to become a material of the future. People will see the full benefits of timber”, SE1 commented.

The manufacturing process of mass timber consumes less embodied energy than heavy materials such as concrete and steel. A supplier (SE3) commented “each of the manufacturing processes of the materials, timber, concrete and steel was different. From an environmental perspective, the raw material to produce mass timber was wood and it grew naturally. In contrast, the raw materials such as limestone and iron ore used to produce concrete and steel were finite materials, which could not grow more and there was only a certain amount that the earth had. In addition, the processing of concrete and steel was energy and water intensive. That gave mass timber a big advantage environmentally”. Moreover, participants agreed that there are many benefits of living in timber buildings. It is a breathable structure; hence it creates a happy and warm environment. It changes the moisture content, changing according to the environment, and creating a pleasant environment.

However, there are still concerns about the risks of adopting new sustainable technology and the underestimation of the environmental benefits of mass timber over cost. A subcontractor (SE6) commented: “There is less waste, and it is good for the environment. But again, the main cause that developers look for is how much money they are going to save or how much money they are going to make”. This is an explanation of why environmental, social, economic and technical aspects should be elaborately linked together. The goal of sustainability in building construction can only be achieved when all of these components are captured all together and any missing component will lead to instability (Zabihi & Habib, 2012). In addition, participants raised concerns about the availability of local CLT in Australia and the impact of long-distance transport on the environment as most completed mass timber projects relied on overseas CLT, mainly from Europe.

5.3 Conclusion

This chapter analysed the results of semi-structured interviews with 17 construction practitioners on selected key performance indicators that may affect the selection of building material as well as the success of a construction project. The results raised the benefits, challenges and barriers of using mass timber as a sustainable building material in building construction, particularly in commercial and office development. Research participants had been involved in mass timber projects, particularly the first commercial and office buildings in Australia. These included construction practitioners from different fields such as architects, structural engineers, quantity surveyors, fire engineers, builders and academics.

In conclusion, there are concerns with the cost performance of mass timber due to the potential delay in legislation and lack of early involvement of manufacturers in the planning and design stage, which can potentially increase cost in the tendering process. In addition, early engagement of structural engineers, builders and offsite manufacturers in the preliminary stage could potentially save materials and help take advantage of DfMA strategies in the construction process. Offsite manufacture, coupled with DfMA, can reduce onsite labour cost, site risk and construction time. Understanding the limits of an individual manufacturer’s machinery can make huge differences in the cost of a project. Builders are currently getting familiar with the installation of mass timber structure and the logistics of importing material from overseas. Hence, there are no difficulties or delays due to logistics and lack of installation experience. However, these participants are pioneers in mass timber construction, and they are getting familiar with the system. It is necessary to educate skilled labour, especially when the demand for mass timber construction increases. Currently, the lack of suppliers may affect cost competitiveness and the availability of material. Most of the completed mass timber projects in Australia used overseas CLT, mainly imported from Europe. Although the results of the interviews show that there is no delay in logistics, relying on imported material has raised a concern of a significant CO_2 contribution due to transport. Participants agreed that most completed mass timber projects have the equivalent thermal and acoustic performance to traditional heavy material structures despite the high requirements. Nevertheless, the technical understanding of construction practitioners is still one of the hurdles in mass timber development in Australia. This is because there are not many Australian construction practitioners who have experience with mass timber construction. Importantly, there is a lack of Australian design and material standards and accepted test methods, particularly related to fire performance, for construction practitioners to apply. The insurance premium is rated based on historical data. Therefore, it potentially hinders the implementation of mass timber in construction as construction practitioners may hesitate to take a risk from new technology. This is understandable because mass timber is not yet as well established as heavy materials such as brick, steel or concrete. Hence, it naturally takes time and effort from different stakeholders in the industry.

According to the results of the interview analysis, sustainability is nominated as one of the most important criteria in non-residential development. While construction speed is recognised as a big advantage of mass timber construction to enhance cost and safety benefits of the construction site, sustainability needs to be attached to cost and quality performance.

Chapter 6 Proposing a model of sustainable non-residential development

This chapter proposes a sustainable development model for non-residential construction and identifies key performance criteria and sub-criteria that can be used for case study and model verification. The proposition of the model is based on analysis of results from the semi-structured interviews and literature review showing the obstacles hindering the uptake of mass timber usage in non-residential development in Australia.

6.1 Mass timber use in the Australian construction industry and barriers to increasing its use in the non-residential sector

Mass timber has been considered a sustainable building material for structural application in recent projects in Australia. Despite demonstration projects having been completed in recent years, there are a number of challenges and barriers that need to be addressed. In a survey conducted by the Centre for Sustainable Architecture with Wood, Nolan (2010) revealed that only 12% of the sales capacity of timber and wood products was in the non-residential construction sector, while residential construction accounted for the bulk of the sales market. This is essential because traditional reinforced concrete, precast concrete panels and steel framing are dominant in Class 2 to 9 building construction in Australia (Bylund, 2017). The ratio of building material selection in 74 buildings among steel, concrete and timber is 10:10:1 (Bruneau & MacRae, 2017). According to the recorded data from the Timber Development Association, from the first mass timber building completed at the end of 2012 until mid of 2019, there have been 52 mass timber projects completed across all states in Australia, except the Northern Territory (Figure 6.1) (Dunn, 2018). In Figure 6.1, the darker the colour the fewer the mass timber projects in that state (other than the Northern Territory). New South Wales is leading with 26 projects, followed by Victoria with 18 projects. Queensland, South Australia and Tasmania have two completed projects each, whereas

Australian Capital Territory and Western Australia have only one completed project each. Currently, residential buildings are the predominant market for Australian mass timber (Figure 6.2). Hence, there are crucial opportunities for the increase of mass timber usage in the non-residential sector in Australia.

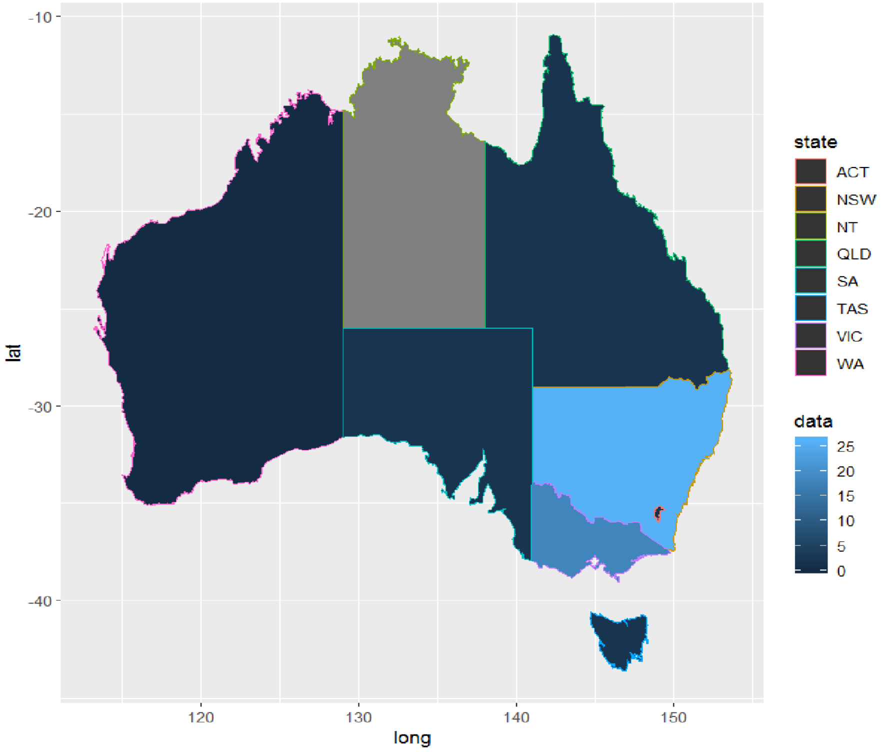


Figure 6.1 Number of mass timber projects by Australian state, from the end of 2012 to mid-2019 (Dunn, 2018)

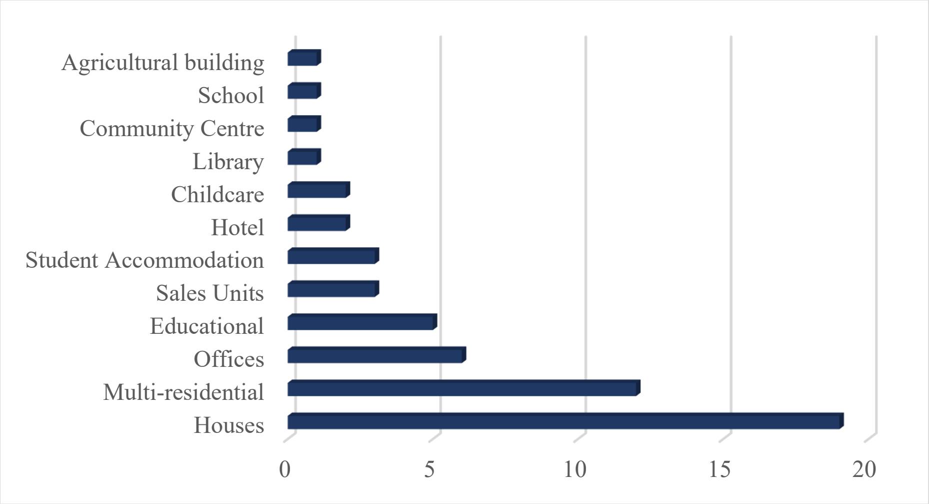


Figure 6.2 Figure 6.2. Number of mass timber buildings by building type in Australia, from the end of 2012 to mid-2019 (Dunn, 2018)

This section integrates construction stakeholders' perceptions of mass timber construction in Australia, based on the literature review and the results of analysis of the semi-structured interviews, to identify the key barriers for use of mass timber in non-residential construction (Table 6.1). Table 6.1 summarises the key strengths and barriers of mass timber construction in Australia. In terms of cost performance, mass timber systems can reduce preliminary cost due to lightweight structure, material waste minimisation, time and labour reduction and probable productivity improvement. However, potential delay in legislation and a lack of early involvement of manufacturers in the planning and design stage can potentially increase cost in the tendering process. In addition, clients are still concerned about risks associated with the new construction system since construction practitioners have lack of experience working with mass timber construction.

Construction speed is one of the greatest advantages of mass timber construction. The prefabricated mass timber systems are quick and easy to install. Also, crane and formwork usage are minimised. According to the interview results, there are no delays in logistics when CLT panels are imported from overseas. However, more time might be required in the design stage due to a lack of experience and early engagement of an offsite manufacturer and builder.

In terms of quality performance which covers technical specifications such as structural, thermal, fire and acoustic performance, mass timber systems can provide the equivalent structural capacity to concrete and steel systems. Fire performance is one of the most important concerns due to the lack of understanding of the fundamentals of fire dynamics concerning the fire performance of mass timber. Well-designed mass timber structures provide equivalent structural, thermal and acoustic performance to concrete and steel structures, as confirmed by the construction practitioners and in the literature.

Environmental benefits of mass timber are mostly underestimated over cost performance since most clients in the industry are concerned about the profit of each project. In addition, it is crucially important to use local mass timber, especially CLT, to mitigate the impacts on the environment and support local economic development.

Table 6.1 Integrating perceptions of mass timber into key performance criteria

KPIs	Barriers	Strengths
Cost	Establishment costs of prefabrication facility The higher level of mechanisation and handling creates higher cost. Proper investment in plant, processes, systems, and training is needed.	Reduce Preliminary cost
	Lack of early engagement of builder and offsite manufacturers in the design stage	Offsite manufacture coupled with Design for manufacture and assembly (DfMA) reduces onsite labour cost
	Concerns about cost performance due to potential delay in legislation	
	Risks associated with innovation	
	Availability – Local supply chain capacity Lack of local prefabricated timber suppliers may affect cost competitiveness	
	Cost competitive with other systems	
	Impacts of Australia's geography and isolated population on transport cost	
Time	More time is required in the design stage due to lack of experience and early engagement of offsite manufacturer and builder	No delay in logistics
	More time is required in the approval stage due to the authority approval process for fire safety	Reduce construction time, including quick and easy installation, minimise crane and formwork usage. It is ready to be quickly installed as soon as it arrives on the building site.
		Minimise delay onsite

KPIs	Barriers	Strengths
Quality	Lack of understanding of the fundamentals of fire dynamic concerning the fire performance of mass timber	Light weight and high strength to weight ratio allows longer span floor solutions with the same structural capacity as heavy materials such as concrete and steel
	Timber is combustible and it burns in fire. Fire engineering has been raised as one of the major barriers in mass timber development	Proper mass timber designs can offer equivalent structural, thermal and acoustic performance to concrete and steel structures
	There are still challenges for fire engineers to work with mass timber construction because of the lack of understanding of the fundamentals of fire dynamic concerning fire performance of mass timber	
	Public and industry's understanding and perception of timber and prefabricated systems regarding quality performance, especially buildings in Class 2 to 9	
	Architects, structural engineers, fire engineers and acoustic engineers need to have enough experience to provide proper design in terms of structural, thermal, acoustic and fire performance as there is no Australian Standard available for design, especially for CLT	
Sustainability	Underestimation of environmental benefits of mass timber over the cost	Less non-renewable fossil energy consumption
	Impact of long-distance transport on the environment as most completed mass timber projects relied on overseas CLT	Carbon sequestration
		Less waste on construction site
		Natural aesthetics; breathable structure; create a happy and warm environment
		Changing the moisture content, changing according to the environment, and creating a pleasant environment.
		Wood grows naturally

Sources: (Bylund, 2017; Kremer & Symmons, 2018) and Interview analysis results

6.2 Building procurement process for mass timber construction

Introduction of any new products and systems or solutions to building construction, especially Class 2 to 9 construction, requires a shift in the procurement process as well as the perception of all stakeholders involved. This section discusses the conventional building procurement process and reveals a suitable procurement process for the prefabricated mass timber system.

Building project procurement is described as a process that includes a set of steps, starting from the client need for a new or altered building project. This is followed by design, approval, tendering, construction, acceptance and occupation, depending on the complexity of the project. Residential buildings in Class 1 require at least a client, a designer, an authority for design approval and a builder, whereas each step for buildings in Class 2 to 9 is more complex and requires teams of stakeholders (Morledge & Smith, 2013; Nolan, 2010). According to Nolan (2010), the building procurement process consists of five primary stages: (i) client need, (ii) design, (iii) approval and tendering, (iv) construction, and (v) acceptance and occupation. The linkage between these stages is influenced not only by contractual relationships but also by a blend of competition and cooperation, with the aim of achieving cost effectiveness. divided the building procurement process into five main stages: (i) client need, (ii) design, (iii) approval and tendering, (iv) construction, and (v) acceptance and occupation (Morledge & Smith, 2013).

Conventionally, a building brief is established based on the client needs and is drawn up by experience regarding a particular function, performance characteristics and budget of a construction project. In short, a building brief is considered as a “client’s wish list”. The type of clients varies depending on the type and complexity of the project. While clients for Class 1 residential buildings are usually private individuals who are also the homeowners, clients for Class 2 to 9 buildings are usually developers or companies. Based on the building brief, the design and specification of the project is established and approved by the clients and the regulatory authority, followed by a tendering process to select a head contractor. The selected contractor will handle the employment of specialists and subcontractors as well as procurement of materials, which includes obtaining materials, manufacturing, engineering, assembly of elements, and finally onsite construction. The completed building is then delivered to the end user (Morledge & Smith, 2013). Nolan (2010) stated that there are key points or decision points in the procurement process. The decision points appear at client need, and design and tendering stages where the selection of materials and equipment is made (Figure 6.3). In addition, these decision points reflect the strengths and weaknesses of the procurement process being used.

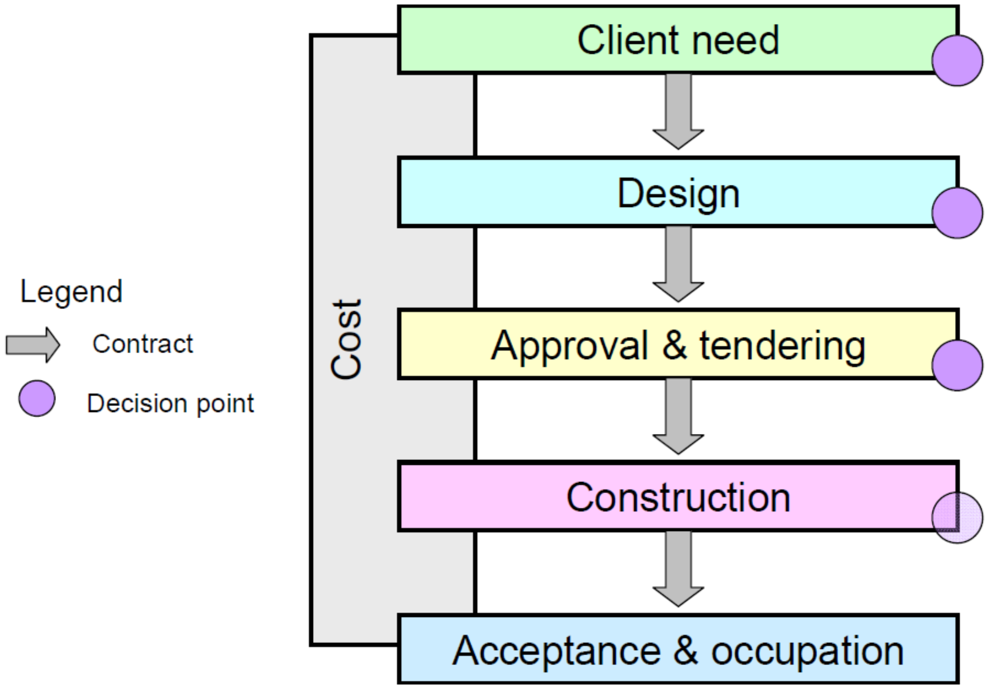


Figure 6.3 Building procurement process with decision points (Nolan, 2010)

DfMA, which stands for Design for Manufacture and Assembly, is a methodology and design philosophy that originally came from the manufacturing industry. It evolved through two stages: design for manufacture (DfM) and design for assembly (DfA), which emerged during the late 1960s and early 1970s. DfMA is a systematic approach that integrates design, manufacturing, and assembly while following DfMA principles. This process enhances the overall value of the entire production process (Langston & Zhang, 2021). In mass timber construction, as part of DfMA technology, the success rate relies highly on the collaboration among design teams, manufacturers and assemblers. These experts should have a mutual level of commitment and willingness to engage with DfMA technology (Gao et al., 2018). According to the semi-interview results, one of the current obstacles in mass timber construction in Australia is that builders and mass timber manufacturers do not have the opportunity to be involved earlier in the planning and design stage. Hence, it is crucial to adjust the conventional building procurement process by integrating the design team, offsite manufacturing and construction contractor. This enables the contractor to be selected at an earlier stage to choose an appropriate offsite manufacturer and builder (Figure 6.4).

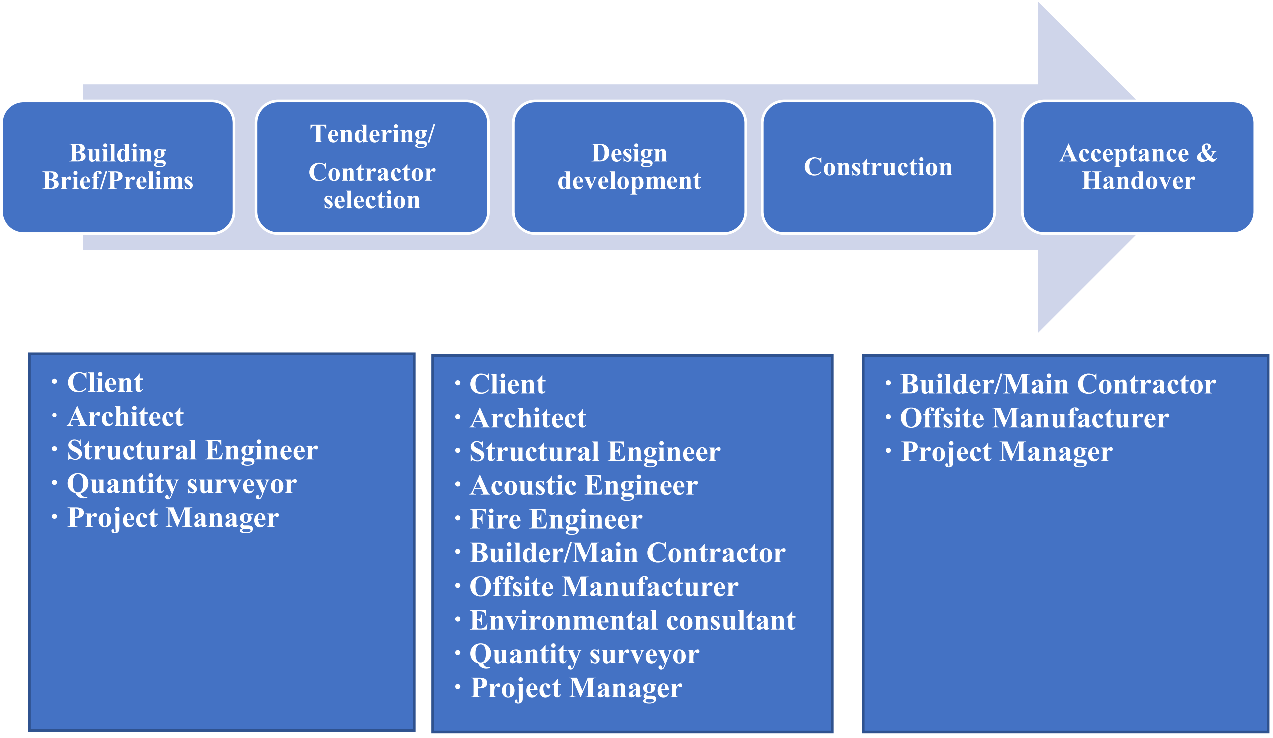


Figure 6.4 Suggested DfMA building procurement process for Class 2 to 9 buildings

6.2.1 Building brief and preliminaries

The DfMA building brief is strongly influenced by cost and other aspects such as aesthetics, maintenance, environmental performance, health and safety of the final occupier. Therefore, together with design teams, a quantity surveyor and project manager with experience in a particular new solution or innovation in a construction project may participate in the development of the building brief for planning and shaping the client's expectations in terms of cost, time and quality performance. Gao et al. (2018) stated that clients play a determining role in the adoption of DfMA technology because of their control over the decision-making process. In addition, they can determine the inclusion or exclusion of materials or solutions in the building brief (Nolan, 2010). Data analysis results from the interviews and literature review show that there are certain risks for developers and clients associated with cost in mass timber construction in Australia. Clients tend to bear "risk" cost due to the adoption of new technology (Table 6.1). In addition, delays in legislation, late engagement among design teams, the builder and offsite manufacturer, and supply chain capacity can potentially increase cost and thus hinder the selection of mass timber in a building project.

6.2.2 Tendering and contractor selection

In the traditional procurement process, tendering, which is used to procure the main construction contractor, occurs after the detailed design is approved by the client and regulatory authority in terms of design, estimated cost and Building Code of Australia compliance. Tenders are invited to propose a price for the construction of the building and then submit it to the client. Hence, tenders will seek subcontractors, such as material suppliers, fabricators and trade companies, to build up the proposed contract sum. The tender with the lowest proposed price is normally accepted. However, it is usually not a fixed price and allows for the uncertainty during the construction program (Morledge & Smith, 2013; Nolan, 2010). In DfMA procurement, the main builder contractor and the offsite manufacturer will be selected at the earlier stage after the building brief is developed. Based on the building brief with specific performance requirements, design teams, the selected builder and main contractor, and the offsite manufacturer will develop a detailed design. The strength of this approach is to allow the offsite manufacturer and builder to participate in the design stage, which can help to optimise design time, reduce risks and understand the offsite manufacturer's machinery capacity and uncertainties in the installation stage. The selection criteria for main contractor are based on the type of building project and track record in terms of expertise and experience of the contractor.

6.2.3 Design development

The design stage of Class 2 to 9 buildings is more complicated than Class 1 buildings because of the size and complexity of the project. It requires the involvement of a range of professionals such as architects, structural engineers, quantity surveyors, fire engineers and acoustic engineers. The design of mass timber buildings may take more time as there is no Australian Standard available and it is a challenge for the structural engineer, fire engineer and acoustic engineer to achieve Deemed-to-Satisfy compliance. However, it is more cost-efficient due to onsite time and delay reduction. Normally, each mass timber supplier has their own design guide.

DfMA is strongly tied to prefabrication, thereby the building is designed in a way that is as easy as possible for offsite manufacture and onsite assembly (Gao et al., 2020). Analysis results from the interviews with pioneers in mass timber construction in Australia reveal that early collaboration among design teams, the builder and offsite manufacturer or mass timber supplier enhances the DfMA method in the design stage. Although Australia is a world-leading country in mass timber construction, especially buildings in Class 2 to 9, insufficient construction professionals in the market have enough experience to use the many advantages of mass timber in terms of cost savings. Builders and offsite manufactures generally get contracted conventionally when the detailed design has already been finalised. In addition, architects and structural engineers have a limited understanding of the manufacturer's machinery and mass timber installation technique. By integrating design teams, main construction contractor and offsite manufacturer or mass timber supplier, the detailed design is developed in a way to save materials and reduce uncertainties and thus save cost.

6.3 Developing a sustainable non-residential development model

Concrete and steel are currently the most widely used materials in non-residential and multi-storey residential buildings. While innovation in the construction industry has introduced a new choice of materials and systems which is more environmentally friendly, this may require a change in building development stages to suit the new technology. The previous section has suggested a procurement process for DfMA, which may enable the optimisation of offsite manufacturing and onsite installation. The main aim of this section is to develop a sustainable non-residential development model and select key performance criteria as well as sub-criteria, in order to verify the proposition of the model by using mass timber as the main structural material in non-residential development in the next chapter.

6.3.1 Sustainable non-residential procurement model using the circular economy concept

The circular economy concept aims to control the use of natural resources and minimise burdens on the environment through waste management and increase the cyclic use as well as proper disposal of waste (Takahashi, 2018). The World Circular Economy Forum (WCEF) in 2018, with representation from 64 countries, discussed the forming of a circular economy. The forum concluded that it was time for the conventional linear economy model to transform into the circular economy model to support long-term repeated resource usage and waste minimisation (Figure 6.5).

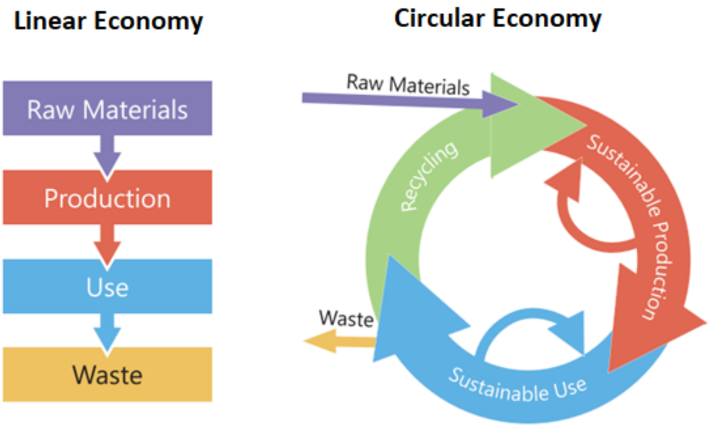


Figure 6.5 Linear economy vs. circular economy (Ministry of the Environment Government of Japan, 2019)

Based on the procurement process in Figure 6.3 and the linear economy model in Figure 6.5, the linear procurement model for traditional concrete buildings, which does not consider the design for easy assembly during the construction stage and demolition at the end of the building's lifetime, is formed (Figure 6.6). In this model, design for disassembly or reuse is typically absent, and demolition at the end of a building's life generates significant construction and demolition waste. Environmental performance is not prioritised in material selection; operational energy receives more focus than embodied energy or end-of-life impacts, and clients often delegate end-of-life considerations to future building owners (Thomas, 2015). In the linear procurement model for traditional concrete buildings, environmental performance is not the key performance criteria of material selection. Additionally, operational energy gets more attention than embodied energy and energy used for the end-of-life stage and clients tend to not consider end-of-life scenarios as this is the responsibility of the building's owner (Thomas, 2015). Hence, this model shows that the conventional concrete building consumes more energy to build and to demolish, and more construction and demolition waste will be sent to landfill rather than being reused or recycled.

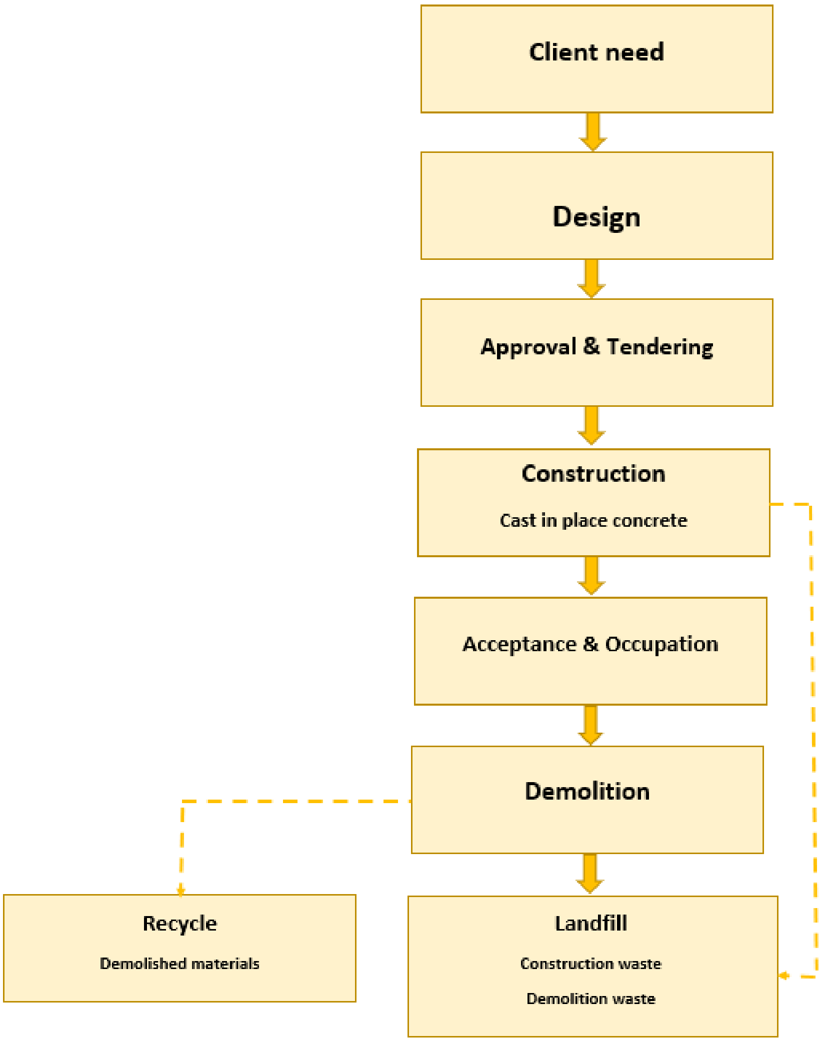


Figure 6.6 Linear procurement model for traditional concrete buildings with material flows (Ministry of the Environment Government of Japan, 2019; Nolan, 2010; Thomas, 2015)

In contrast, this study proposes a sustainable non-residential procurement model with circular material flows (Figure 6.7). The model integrates the principles of Design for Manufacture and Assembly (DfMA) and design for disassembly, enabling components to be easily recovered, reused, or recycled at the end of their service life. This circular flow begins with raw material manufacturing, continues through construction, operation, and maintenance, and concludes with disassembly, sorting, and recovery of materials.

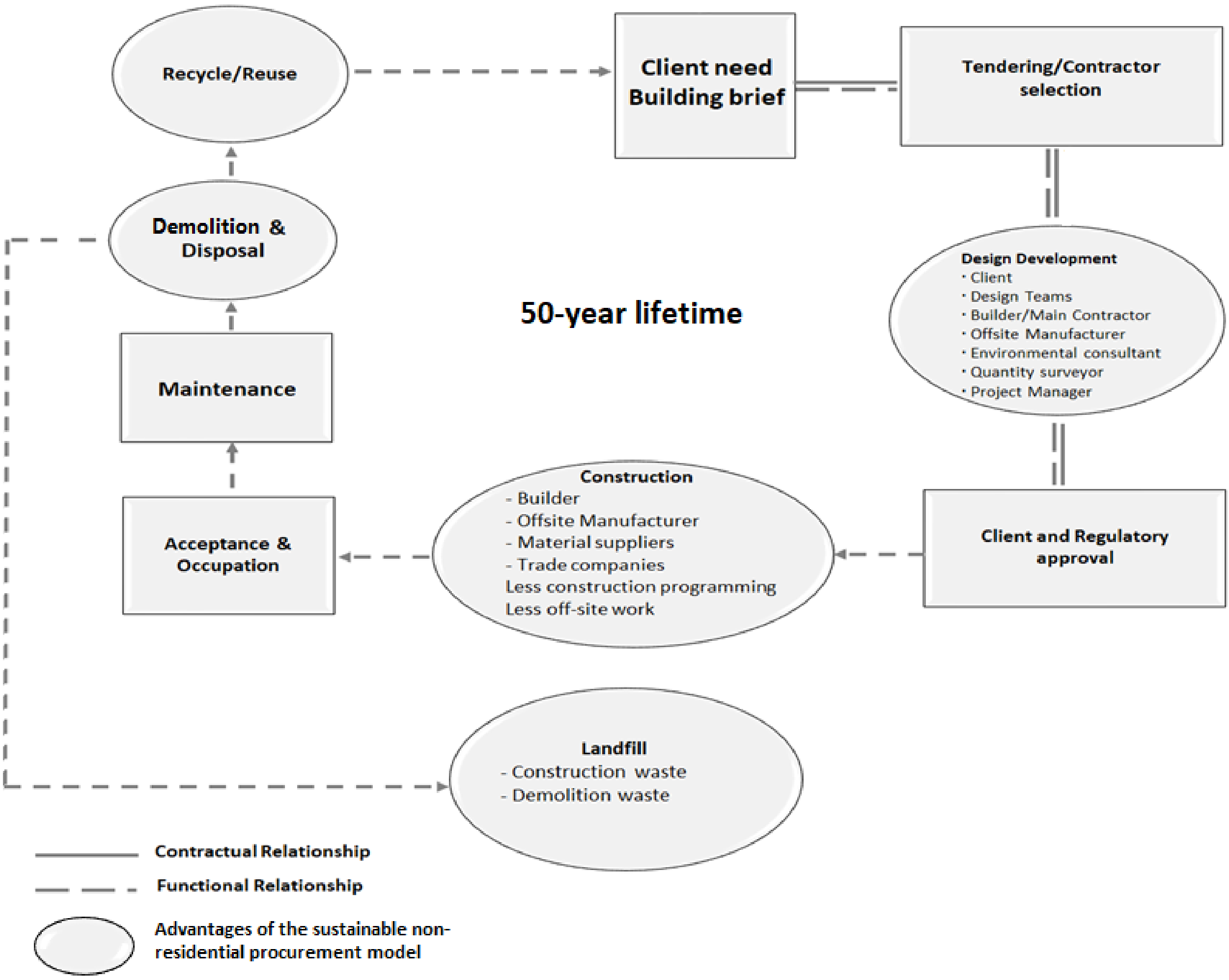


Figure 6.7 Sustainable non-residential procurement model with circular material flows

This approach offers an opportunity for sustainable building material to be selected from the beginning of a building project. As explained in section 6.2, tendering occurs at an early stage to enhance the DfMA process. In addition, since using sustainable material in structural elements is not yet well-understood in the industry, the design teams must cooperate with an experienced offsite manufacturer and builder to shorten design time and reduce risks and uncertainties in the construction stage. Importantly, one of the notable advantages of this approach is reduced construction time, energy consumption and construction waste in the construction stage compared to the traditional approach. Additionally, construction waste from sustainable material can be reused or recycled instead of being sent to the landfill. The early involvement of an offsite manufacturer also optimises the design in terms of material savings, which can potentially reduce construction cost. When the design is planned for easy manufacture and assembly from the beginning of the project, the demolition stage does not require a heavy excavator, as a traditional concrete building does, as the majority of the building components can be disassembled in the same way as they were assembled. Therefore, this approach maximises the potential of reusing demolished material and easy sorting waste for recycling and minimises environmental impacts of the demolition stage.

Overall, material flow in the sustainable non-residential procurement model is a closed loop in which a life cycle of material begins from raw material manufacturing to a complete building and goes through operational time to end-of-life demolition, disposal, reuse and recycle scenarios. The model reveals the proposition of sustainable development in the construction industry by using sustainable building material to save life cycle energy usage and mitigate environmental impacts without increasing cost and decreasing quality. This proposition is tested and discussed further in Chapter 7.

6.3.2 Sustainable non-residential development model

This section discusses how the sustainable non-residential development model is developed and how key performance criteria are selected to verify the model. Table 6.1 shows the strengths and barriers of mass timber construction in Australia and discloses concerns about the use of mass timber as a sustainable building material in non-residential structures. The strengths and barriers were categorised into four groups of cost, time, quality, and environmental performance. These four key performance criteria are reviewed, and the most important criteria are selected to include in the proposed model. Among these, time performance raised the least concern. Evidence from the literature and semi-structured interviews with building practitioners consistently shows that prefabricated mass timber systems offer significantly shorter construction times than conventional in-situ concrete systems. Once the first level is completed, prefabricated mass timber panels can be craned directly into place and connected using hand-held tools, avoiding the extended sequence of tasks required for concrete construction—formwork installation, reinforcing bar placement, concrete pouring, and curing before the next floor can be erected (Forest and Wood Products Australia, 2019a; Waugh Thistleton Architects, 2018a). Studies have quantified time savings of 15–20% or more, with many projects achieving schedule reductions of four weeks or greater. The only time-related barriers identified in the interviews were associated with the design and approval stages, stemming from limited experience and the absence of early engagement with the offsite manufacturer and builder. These are procedural issues that can be mitigated through procurement strategies and do not reflect the inherent performance of the mass timber construction method. Given this strong and consistent evidence base, combined with the minimal variability in on-site construction time across projects, time performance is unlikely to be a decisive factor when comparing the sustainability of alternative structural systems. For these reasons, time performance was excluded from the sustainable non-residential development model, enabling greater focus on performance criteria where significant differences and uncertainties remain, namely cost, quality, and environmental performance. These three criteria are further divided into sub-criteria as illustrated in Figure 6.8.

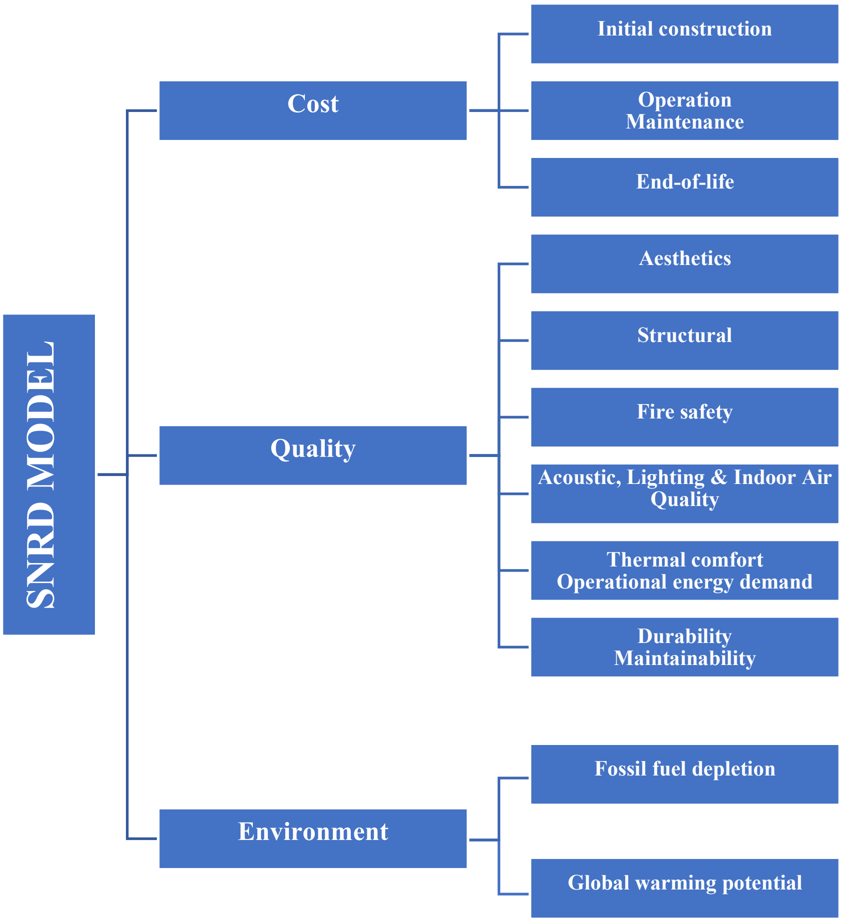


Figure 6.8 Sustainable non-residential development model

The model contains three most important criteria of cost, quality and environment, which were identified through the literature review and semi-structured interviews with pioneers in mass timber construction in Australia. Table 6.2 shows the sub-criteria which are selected to test the SNRD model through the nominated case study in the next chapter.

Table 6.2 Selected sub-criteria for case study and model verification

	Sub-criteria included in SNRD model	**Selected sub-criteria to test the SNRD model in the case study**
Cost	Initial construction	Yes
	Operation	Yes
	Maintenance	No
	End-of-life	Yes
Quality	Aesthetics	No
	Structural	Reviewed by structural engineers
	Fire safety	No

	Sub-criteria included in SNRD model	**Selected sub-criteria to test the SNRD model in the case study**
	Acoustic, Lighting & Indoor Air Quality	No
	Thermal comfort	No
	Life cycle operational energy	Yes
	Durability	No
	Maintainability	No
Environment	Life cycle fossil fuel depletion	Yes
	Life cycle global warming potential	Yes
	Benefits and loads beyond building's life cycle	Yes

The main purpose of using these selected criteria to test the SNRD model through a case study is to investigate how mass timber in the circular material flows performs against traditional concrete used in non-residential development. The details of each criterion including quality, cost and environmental performance are explained as follows.

(i) Cost performance

This study evaluates cost performance from a life cycle perspective, incorporating three main components: (i) capital cost (including materials, transportation, and construction), (ii) operational cost, and (iii) end-of-life (EoL) disposal cost. Non-construction-related expenses such as land acquisition, design consultancy, and legal services are excluded. Additionally, interior fit-out and maintenance costs are not included in the model, as maintainability was excluded from the quality performance criteria to narrow the study's focus to structural systems.

Nevertheless, the exclusion of maintenance cost is recognised as a limitation of the analysis. While mass timber manufacturers typically warrant a service life of 50 years for their structural products which is consistent with the standard building design life assumed in Australia, differences in material ageing, exposure, and maintenance regimes between timber and conventional materials such as concrete or steel may influence long-term costs (Prolam, 2018; XLam Australia & XLam New Zealand, 2021). Future studies should incorporate maintenance profiles under diverse environmental and operational conditions to enable more comprehensive life cycle cost assessments, particularly when comparing mass timber to highly durable materials.

In alignment with circular economy principles, reuse and recyclability are acknowledged as increasingly important in the design and procurement of sustainable buildings. Prefabricated mass timber components are well-suited to modular construction and may offer future reuse opportunities. However, the economic valuation of reuse and recycling was not included in this LCC model due to current market uncertainties and the absence of standardised recovery pathways for engineered wood products in Australia. This represents a further limitation of the current assessment, as material recovery could contribute significantly to cost savings at the end of a building's life cycle. Research into design for disassembly, deconstruction logistics, and reuse marketplaces could enable the integration of reuse and/or recycling benefits into future economic modelling.

Operational energy consumption results evaluated from the quality performance assessment are used to calculate the operation cost. End-of-life demolition expenses are quantified in the SNRD model since expenses might vary between prefabricated mass timber and traditional cast-in-place concrete structures. If the thermal performance of the two structures is equal, the initial construction and end-of-life expenses will determine which system outperforms the other.

The calculation of life cycle cost (LCC) is based on the formula below, which is adapted from Robati et al. (2018).

$$LCC = PV_{CP.C} + PV_{OP.C} + PV_{EoL.C} \quad (6.2)$$

Where:

- LCC: Life cycle cost
- PV_{CP}: Present value of capital cost (or initial cost including material, transport and construction costs)
- $PV_{OP.C}$: Present value of operational cost during 50 years of building lifetime
- $PV_{EoL.C}$: Present value of end-of-life disposal costs.

The details of the assessment of cost performance are explained further in Chapter 7.

(ii) Quality performance

Aesthetics, structural performance, fire performance, acoustic performance, thermal performance (thermal comfort and operational energy demand), maintainability and durability are the main representatives of quality performance when measuring the success of a building project. Among these, aesthetics is considered as a subjective criterion which is not quantifiable, yet indeed a project needs to please the architects, clients and end users. Based on data analysis results from the interviews, mass timber has pleased architects by its natural aesthetics and the end users by creating a breathable and warm environment. Other design-based criteria have to comply with national building codes as well as the client's expectation. The literature review, completed mass timber projects and results from the semi-structured interviews have proved that mass timber elements can provide the equivalent structural capacity as heavy material elements such as concrete and steel (Bylund, 2017; Kremer & Symmons, 2018). The interview results revealed that fire performance is one of the greatest concerns of structural engineers and fire engineers when using mass timber as a key structural material due to lack of experience and designs. They found that it is a challenge to achieve Deemed-to-Satisfy compliance for fire safety since there is no Australian Standard available for design, especially for CLT. Hence, they are currently relying on design guidelines from mass timber manufacturers. Mass timber has been introduced to the multi-storey building construction market later than heavy materials such as concrete and steel and therefore takes time to become well-established. This shows that the early involvement of mass timber manufacturers and builders in the design stage plays an important role in mass timber project development.

As a result of advancements in manufacturing and treatment processes, mass timber products are now engineered to be highly resistant to biological degradation. Treatments and protective detailing are applied to mitigate termite risks and mould growth due to weathering, particularly when products are used in compliance with relevant building codes and standards (Wang et al., 2007). When appropriately designed, installed, and protected from prolonged moisture exposure, structural mass timber elements can achieve durability performance comparable to traditional materials. Interview participants, including those with direct experience in mass timber project delivery, confirmed that with correct detailing and maintenance practices, structural timber can meet or exceed the 50-year design benchmark. Nevertheless, differences in maintenance frequency, inspection requirements, and risk management approaches between materials warrant further research. Future studies should quantify maintenance impacts on both cost and environmental performance to improve the robustness of LCA.

Literature review (John et al., 2011; Gaspar et al., 2016; Reilly & Kinnane, 2017; Perez Fernandez, 2008), along with insights from semi-structured interviews with Australian construction practitioners, suggests that well-designed mass timber structures can achieve thermal performance comparable to that of traditional heavy materials. This highlights the importance of comparing the thermal performance of mass timber and conventional heavy material structures by evaluating their operational energy consumption. Operational energy results are also used to calculate associated costs, ensuring a comprehensive life cycle cost analysis. Moreover, assessing operational energy demand is essential for confirming functional equivalence, which is a critical condition for fair environmental comparisons. Thermal performance was assessed using DesignBuilder version 6 (DesignBuilder-6.1.7.007), powered by the EnergyPlus simulation engine. The detailed methodology and results of this assessment are discussed in the following chapter.

(iii) Environmental performance

The SNRD model comprises a life cycle perspective of the environmental aspect of mass timber usage in building construction. Since embodied carbon is the next focus to achieve Australian's net zero emissions targets by 2050, the SNRD model also accounts for the CO_2 emissions released into the atmosphere to prove that mass timber is a low carbon material and can be used as a substitute for concrete in building construction. The consumption of non-renewable fossil energy, such as oil, coal and natural gas, has put more burdens on the environment especially in OECD countries. Hence, it is necessary to assess the abiotic depletion (fossil fuels) of sustainable non-residential development. The calculation of the benefits of reuse, recovery and/or recycling potentials is also included in the model to raise the importance of recycling and reusing in building construction.

Life cycle global warming potential from the material production, transport, construction, operation, end-of-life and benefits beyond building life cycle are calculated based on the following formula:

$$LCO_2 = ICO_2 + OCO_2 + EoLCO_2 - DCO_2 \qquad (6.3)$$

Where:

- LCO_2 (kg CO_2 eq/m^2): Life cycle global warming potential in 50-year lifetime
- ICO_2 (kg CO_2 eq/m^2): Initial global warming potential
- OCO_2 (kg CO_2 eq/m^2): Operational global warming potential (operational energy and water use)
- $EoLCO_2$ (kg CO_2 eq/m^2): End-of-life (i.e. demolition, transport to waste processing, waste processing for reuse, reuse and/or recovery and/or recycling, and disposal) global warming potential
- DCO_2 (kg CO_2 eq/m^2): Avoided global warming potential as a result of reuse, recovery and/or recycling potentials.

Life cycle abiotic depletion (fossil fuels) in a 50-year lifetime is calculated based on the following formula:

- $LCE_{\text{fossil fuel depletion}} = IE_{\text{fossil fuel depletion}} + OE_{\text{fossil fuel depletion}} + EoL_{\text{fossil fuel depletion}} - D_{\text{fossil fuel depletion}}$ (6.4)
- Where:
- $LCE_{\text{fossil fuel depletion}}$ (GJ/m^2): Life cycle fossil fuel depletion
- $IE_{\text{fossil fuel depletion}}$ (GJ/m^2): Initial embodied fossil fuel depletion (product stage and construction stage)
- $OE_{\text{fossil fuel depletion}}$ (GJ/m^2): Operational fossil fuel depletion (operational energy and water use)
- $EoL_{\text{fossil fuel depletion}}$ (GJ/m^2): End-of-life (i.e. demolition, transport to waste processing, waste processing for reuse, recovery and/or recycling, and disposal) fossil fuel depletion.
- $D_{\text{fossil fuel depletion}}$ (GJ/m^2): Avoided fossil fuel depletion as a result of reuse, recovery and/or recycling potentials.

The calculation of life cycle fossil fuel depletion and life cycle CO_2 emissions are discussed further in Chapter 7.

6.4 Conclusion

This chapter investigated the current circumstances of mass timber usage in the Australian construction industry. According to perceptions of construction practitioners about mass timber acquired from the literature review and semi-structured interviews, this chapter integrated strengths and weaknesses when using mass timber as a sustainable building material in construction, particularly in non-residential development. The greatest barriers that Australian construction practitioners currently face are the lack of experience, design standards and early involvement of offsite manufacturers and builders in the design stage. This may lead to delay in the design stage and risks and default in the construction stage and thus increase the cost. Therefore, this chapter suggested a suitable building procurement process for Class 2 to 9 mass timber buildings, which mainly supports the Design for Manufacture and Assembly (DfMA) concept. Additionally, based on the advantages that mass timber can potentially offer to non-residential development and the suggested procurement process, a circular material flow, which illustrates the potential for recycling and reuse after the building's lifetime, was shaped. Consequently, the most important criteria including quality, cost and environmental aspects were nominated to form the SNRD model. Sub-criteria, which are used to test the proposition of the SNRD model in the next chapter, were also identified. By using a case study non-residential building, the model is evaluated to see if the application of mass timber in non-residential development can outperform traditional heavy materials, such as concrete, in terms of quality, cost and environmental aspects.

Chapter 7 Case studies and model verification

7.1 Introduction

This chapter aims to verify the model of sustainable non-residential development (SNRD) that was developed in Chapter 6. The verification is based on a selected case study building with an alternative redesign to assess how mass timber performs against heavy material in the SNRD model. The performance criteria and sub-criteria of the proposed SNRD model were identified in Chapter 6. The main purpose of the verification is to investigate the potential contribution of mass timber to reduce embodied energy, embodied carbon and demolition waste without a significant increase in operational energy demand and incurring higher cost, to help Australia reach net zero emissions target by 2050. The selected case study building is an actual concrete office building, with an alternative mass timber redesign.

To evaluate the proposed model, structural elements of the original concrete design are redesigned into mass timber. The analysis result of thermal performance of the original case study design becomes the benchmark for the design of the alternative mass timber structure. This is to ensure that the two designs have similar thermal performance for equitable comparisons in terms of life cycle cost and environmental performance. Based on the literature review and semi-structured interviews, proper mass timber design can offer the same thermal performance and outperform traditional concrete in terms of cost and environmental performance. Hence, the main focus of the next sections is to validate mass timber in the sustainable non-residential development model by confirming the following arguments:

- The concrete office design and the alternative mass timber redesign have equivalent thermal performance.
- Life cycle cost of the alternative mass timber redesign is lower than that of the concrete design.

- The alternative mass timber redesign has lower impacts on the environment than the concrete design.

As identified in Chapter 6, the assessment of thermal performance is focused on the calculation of operational energy use in the 50-year life cycle; cost performance includes initial construction cost, operation cost and end-of-life demolition cost; and environmental performance is presented in two categories including life cycle non-renewable fossil energy demand and associated CO_2 emissions with consideration of carbon sequestration.

7.2 Background information of original concrete office case study building

Initially, the original case study was intended to be an actual mass timber office building, then redesigned into an alternative concrete structure. However, it was difficult to acquire the drawings of an under-construction mass timber office building due to intellectual confidentiality. Therefore, an actual cast-in-place concrete office building was selected to be the original case study and the structural elements were then redesigned into mass timber by a structural engineer. The selected case study building is located in New South Wales, Australia. The building includes two basement levels, a ground floor entry, five office levels and a rooftop plant with an approximate gross floor area of 13,037 m^2 (Figure 7.1 and Figure 7.2).

Figure 7.1 Original concrete office design – 3D view

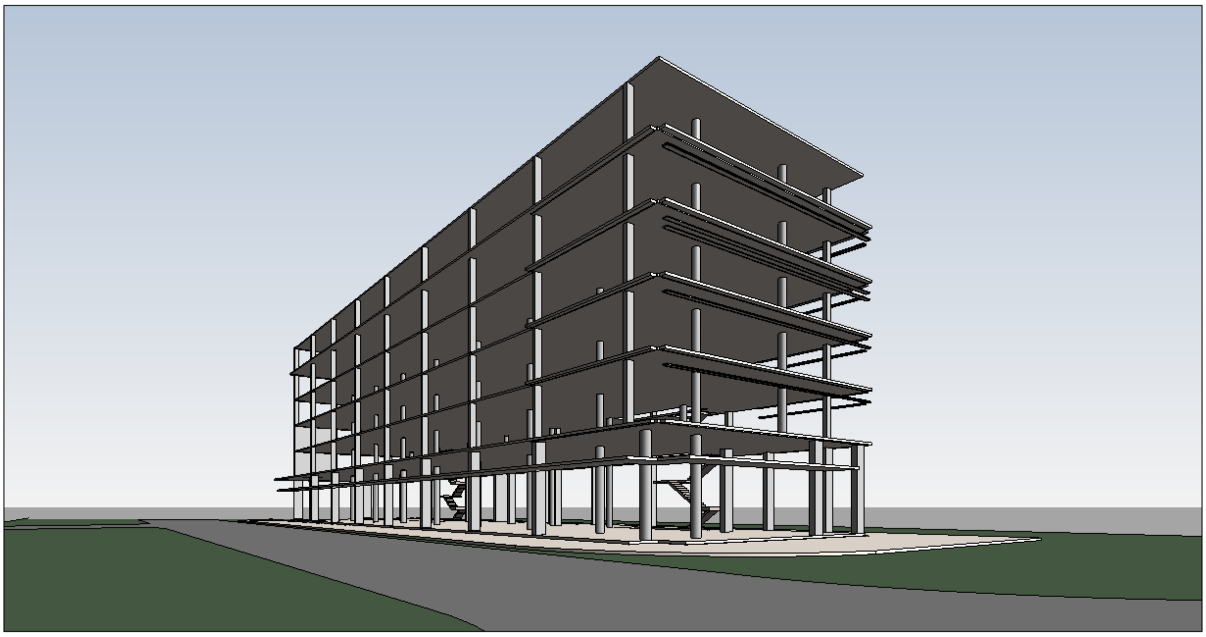


Figure 7.2 Original concrete office design – structure view

7.3 Operational energy and water demand of original concrete design and mass timber redesign

Heating and cooling energy consumption are two key drivers to measure operational energy consumption of a building (Perez Fernandez, 2008). This study also calculated energy used for lighting and other equipment to evaluate the operational energy consumption, which is the energy required during the entire lifetime of a building such as heating, ventilation and air conditioning (HVAC), lighting and other equipment (Azari, 2019). The way that building materials affect operational energy is different from initial embodied energy. Initial embodied energy of each building material varies depending on manufacturing methods, whereas operational energy is governed by the thermal characteristics of building materials (Perez Fernandez, 2008).

Thermal software modelling can predict operational energy consumption of a building before it is constructed and occupied (John et al., 2011). This allows adjustment of the design to optimise the thermal performance of a building. Therefore, thermal software modelling is employed to evaluate and predict thermal performance of the original concrete design and the mass timber redesign, respectively. DesignBuilder version 6 (DesignBuilder-6.1.7.007) with EnergyPlus engine was employed to undertake the energy modelling for the concrete design. Most energy simulation programs for buildings come with a graphical user interface which is used to prepare simulation input files for the simulation engine and to display output simulation results. The EnergyPlus simulation engine is combined within DesignBuilder’s environment, which enables the simulations to be completed without leaving the interface (Maile et al., 2007). This study conducted energy modelling for the concrete design, and the results were used as an energy target and benchmark for the alternative mass timber redesign. Mechanical services, including air conditioning, heating and ventilation systems, must comply with the performance requirements of the design criteria as specified and in accordance with Building Code and Australian Standards (AS/NZS1668.1

& 2). The information used to calculate operational energy consumption, such as internal air conditioning design criteria (Table 7.1), façade and structure criteria (Table 7.2), and schedule of lighting (Table 7.3), are provided by the client. Office operations are planned with a default occupancy density of 0.111 people/m², running daily from 8 am to 6 pm. Assumptions for summer and winter clothing are 0.5 clo and 1.0 clo, respectively. Simulation setpoints for heating, cooling, and lighting are typical for an office building under the following conditions:

- Location: Sydney, New South Wales, Australia
- Ambient conditions: Summer 38ºC Dry Bulb/24ºC Wet Bulb; Winter 5ºC saturated
- Internal conditions: Summer 22.5ºC (Dry Bulb) max ±1.5ºC; Winter 21ºC (Dry Bulb) min ±1.5ºC.

Table 7.1 Internal air conditioning design criteria

Room Description	**Room Conditions (ºC (Dry Bulb)/%RH)**	**Population**	**Equipment (W/m^2)**	**Lights (W/m^2)**
Office areas	22.5ºC±1.5ºC/ 50%RH	1/10 m^2	20 W/m^2	15 W/m^2
Entrance/Lobby	22.5ºC±1.5ºC/ 50%RH	1/10 m^2	5 W/m^2	30 W/m^2
Lift lobby	22.5ºC±1.5ºC/ 50%RH	1/10 m^2	5 W/m^2	20 W/m^2

Car parks (basement levels 1 and 2) are provided with mechanical exhaust and supply systems.

Table 7.2 Façade and structure criteria

Material	**Description**	**Parameter**
Glass	Double glazed performance glass (6mm/12mm gap/6mm) on the east, west and north façades	Shading coefficient SC = 0.32, U-value – 2.6 W/m^2K
Glass	Laminated 13mm thick performance glass on the south façades	Shading coefficient SC = 0.32, U-value – 2.6 W/m^2K
Façade		Thermal coefficient

Material	**Description**	**Parameter**
	Curtain wall with cavity and internal insulation, to architect details	U-value = 0.5 W/m^{2}K
Roof	Insulated concrete slab over office floor Note: sheet metal roof over plant room	Thermal coefficient U-value = 0.5 W/m^{2}K

Table 7.3 Lighting control schedule

Area	**Description**
Basements	100% of the lights shall remain on between 8am and 6pm from Monday to Friday
	50% of the lights in the carriageways shall be un-switched and shall operate as 24 hr security lights
	After hours (outside the above times and weekends), lights other than 24 hr lights shall switch off
Back of house areas	25% of the lights in the back of house corridor are 24 hr security lights
Ground level lift lobby	100% of the lights shall remain on between 8am and 6pm from Monday to Friday
	100% of the lights shall remain on between 8am and 6pm from Monday to Friday
	After hours (outside the above times and weekends), lights shall dim to 50%
Lobbies – Office areas	100% of the lights shall remain on between 8am and 6pm from Monday to Friday
	After hours (outside the above times and weekends), lights shall dim to 50%
Office	Lights switched in 100 m zones
	100% of the lights shall remain on between 8am and 10pm from Monday to Friday
	After hours (outside the above times and weekends), lights other than 24 hr security lights shall switch off
	1 light in each zone shall be a designated 24 hr security light. No dimmable lights shall be 24 hr security lights.
Toilet	100% of the lights shall remain on between 8am and 6pm from Monday to Friday

To ensure a fair comparison and isolate the effect of structural material selection, both the original concrete design and the mass timber redesign were modelled using the same building geometry, glazing specification, HVAC system, lighting controls, internal gains, and occupancy schedules. All façade and roof components were assigned identical thermal performance values, including U-values, shading coefficients, and insulation thickness (Table 7.2). By maintaining consistency in envelope performance across both designs, the only significant variable affecting thermal response was the difference in thermal mass between concrete and mass timber systems.

As mass timber has inherently lower thermal mass than concrete, the energy simulation shows a slightly increased cooling load for the timber redesign. This aligns with existing literature, which indicates that lighter-weight structures with lower thermal storage capacity may respond less effectively to daytime heat gains (Shafigh et al., 2018). Despite this, the overall operational energy demand remains comparable, with only a 0.3% annual difference (Table 7.4), confirming that high-performance insulation and glazing specifications in the timber redesign were sufficient to maintain near-equivalent thermal performance. The simulation results indicate that the difference in annual operational energy demand between the two designs is negligible. The energy consumption of both designs aligns with a 5-Star NABERS Energy Rating. NABERS (National Australian Built Environment Rating System) is a performance-based rating system that measures the environmental performance of Australian buildings, including energy and water efficiency, indoor environment quality, and overall environmental impact (NABERS, 2024)

Table 7.4 Total annual operational energy use

	Concrete design	**Mass timber design**
Heating & Cooling (kWh/yr)	897,547.10	900,239.74
Lighting (kWh/yr)	473,436.84	473,436.84
Equipment (kWh/yr)	329,205.47	329,205.47
Total (kWh/yr)	**1,700,189.41**	**1,702,882.05**
Total (kWh/m^2/yr)	**130.41**	**130.62**

The results show that there is no difference of energy demand from lighting and office equipment. The variation of energy use between the two designs is caused by energy required for heating and cooling. The mass timber structure consumes 2,693 kWh more energy per year for cooling compared to the concrete structure, while the energy demand for heating is nearly identical for both structures (Table 7.5 and Figure 7.3). The main reason behind the difference of cooling and heating energy use is due to thermal mass, which is described as the ability of a material to absorb and store heat energy during day time and release it at night time (Shafigh et al., 2018). Concrete has the highest thermal mass among building materials such as concrete, steel and timber, thus mass timber panels are not as thermally massive as concrete. Hence, building material selection significantly affects the energy required for heating and cooling loads in most climates (Taylor & Miner, 2014).

Table 7.5 Total annual operational energy consumption by categories

	Concrete design	**Mass timber design**
Heating	460,810.55	461,179.20
Cooling	436,736.55	439,060.54
Lighting	473,436.84	473,436.84
Equipment	329,205.47	329,205.47
Total (kWh/yr)	1,700,189.41	1,702,882.05

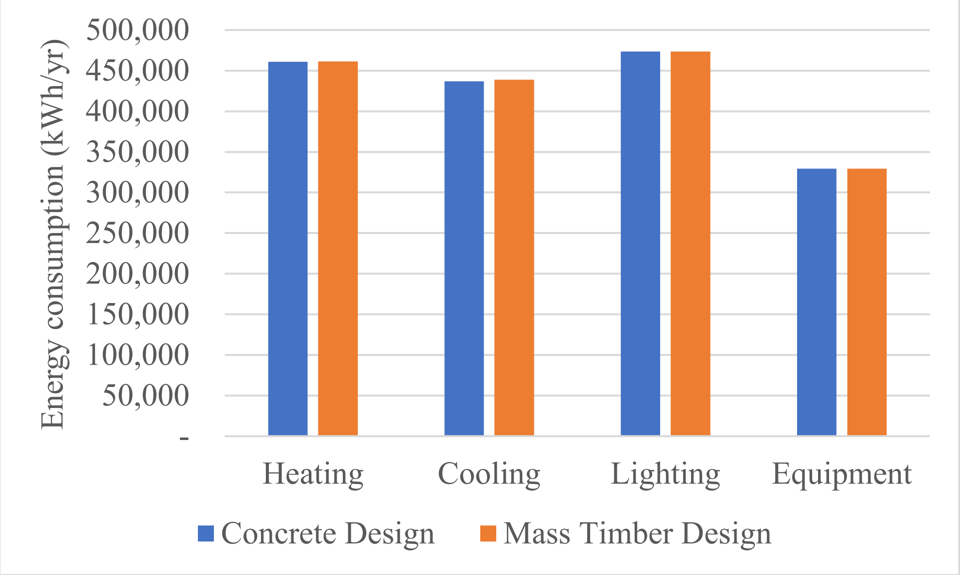


Figure 7.3 Total annual operational energy consumption (kWh) by categories (data from Table 7.5)

Operational water consumption for the two designs is estimated using the NABERS Reverse Calculator, with water intensity based on a 5-star rating. Both designs are occupied for 60 hours per week. The results indicate a maximum water consumption of 4,667 kL/year. Detailed rating information is provided in Appendix D.

The results reinforce findings from semi-structured interviews, in which practitioners noted that properly designed mass timber buildings can offer thermal performance comparable to traditional concrete structures. These operational energy outcomes form the basis of the life cycle assessment analysis presented in the following section.

7.4 Redesigning concrete office building using mass timber as main structural material

To achieve equivalence in structural performance, the original reinforced concrete elements were replaced with prefabricated mass timber components, specifically glulam columns and beams, CLT floor and roof panels, and connections. The mass timber redesign was developed in accordance with Australian structural engineering standards and reviewed by three experienced engineers to validate its feasibility and ensure performance parity with the original concrete structure. While the volume and section sizes of timber components differ from those of concrete due to material density and structural behaviour, the redesign maintained all original spatial arrangements, façade alignments, and vertical and horizontal dimensions. This ensured that no modifications were made to the building envelope, geometry, or internal layout, allowing for a like-for-like comparison of environmental performance. Details of the structural redesign are provided in Appendix C.

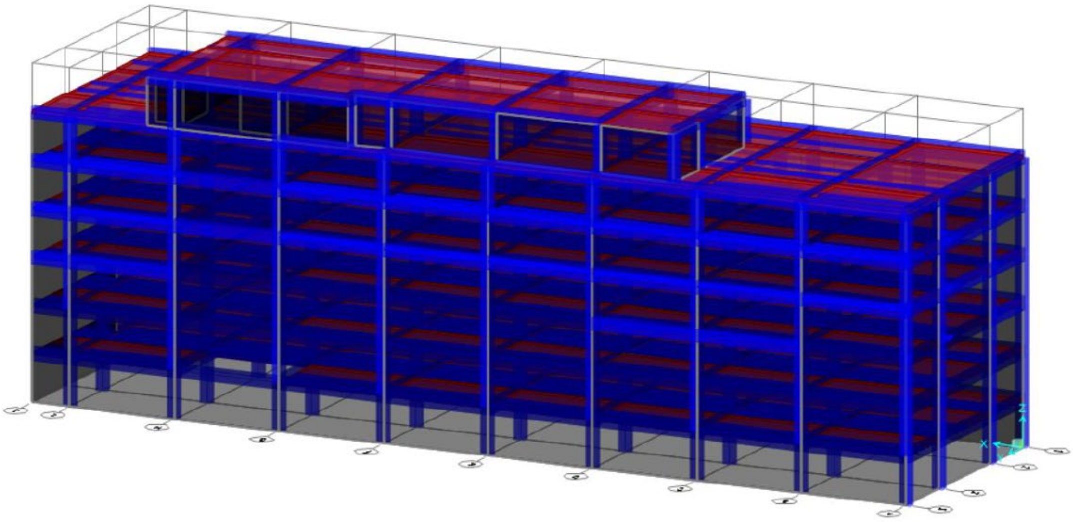


Figure 7.4 Alternative mass timber structural redesign – general view

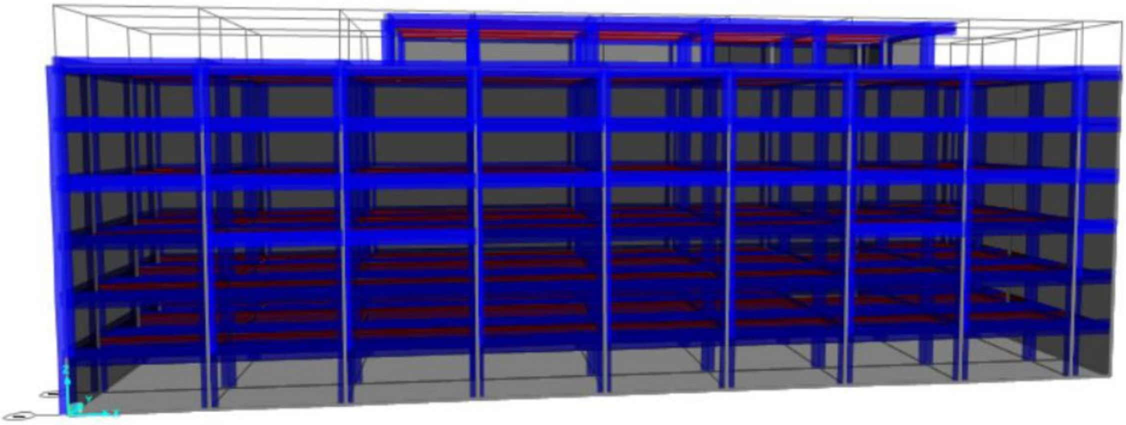


Figure 7.5 Alternative mass timber structural redesign – front view

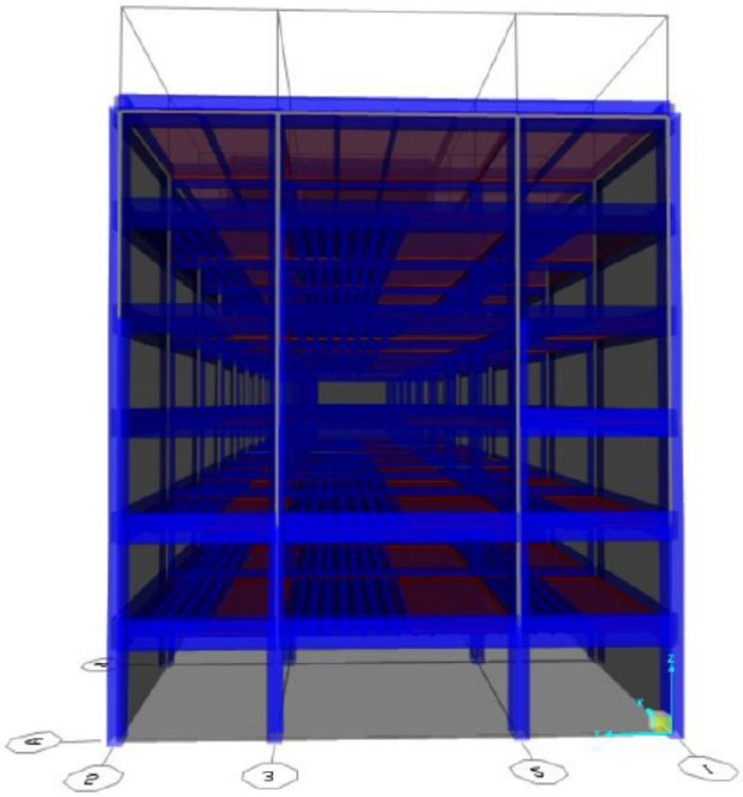


Figure 7.6 Alternative mass timber structural redesign – side view

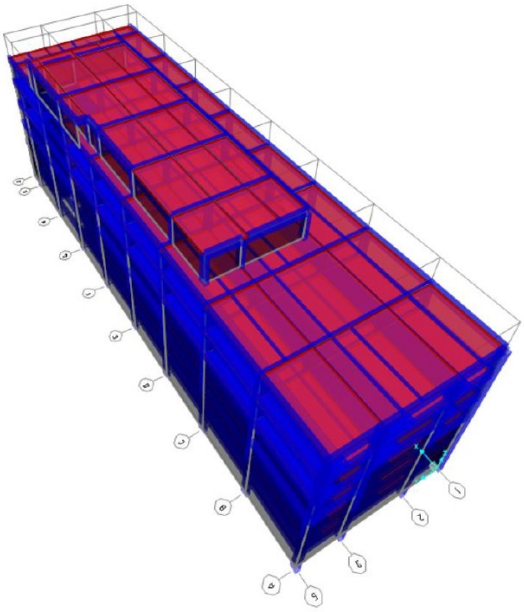


Figure 7.7 Alternative mass timber structural redesign – top view

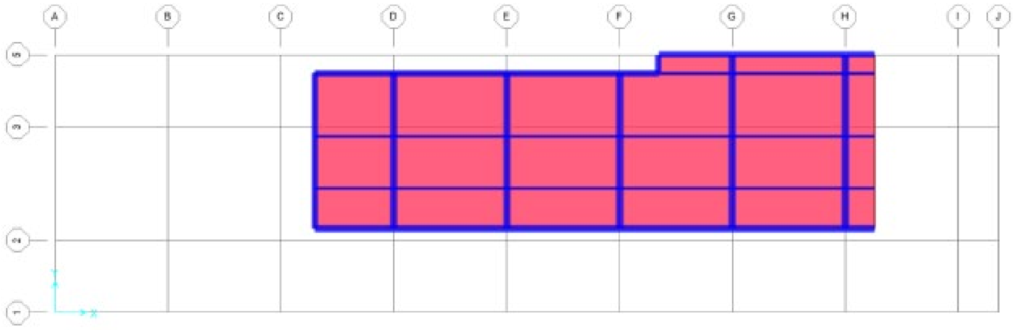


Figure 7.8 Alternative mass timber structural redesign – roof slab

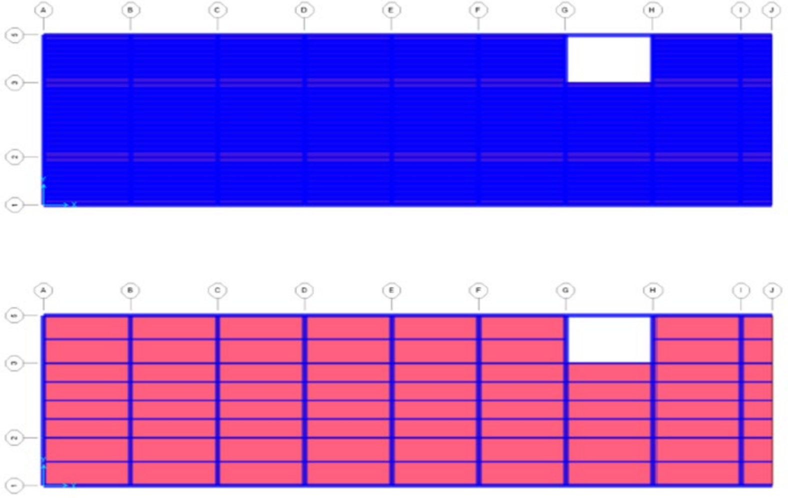


Figure 7.9 Alternative mass timber structural redesign – floor slabs

7.5 Assessment of key performance sub-criteria in sustainable non-residential development model

This section further explains the assessment of other key performance sub-criteria identified in sustainable non-residential development model. The main purpose of key performance sub-criteria assessment, including embodied energy, embodied carbon, operational energy, operational water and end-of-life environmental impacts, and costs for construction, operation, and end-of-life stage, is to prepare for the analysis of key performance criteria. The assessment is carried out for both designs, traditional concrete and alternative mass timber. The results from this section are used for further analysis and discussion in section 7.6.

7.5.1 Life cycle assessment – a comparison between concrete and mass timber designs

a. Goal and scope definition

The goal of this study is to measure the environmental impacts associated with the product, construction, use and end-of-life stages as well as the benefits beyond the service life cycle of the two designs, including conventional concrete office building and the alternative mass timber building, in accordance with EN 15978 (EN 15978, 2011) and EN 15804 (EN 15804, 2012) standards. The LCA study complies with ISO 14040:2006 and ISO 14044:2006 which describes the principles, framework, requirements, and provides guidelines for LCA (ISO 14040, 2006; ISO 14044, 2006).

The scope for the LCA study should align with the proposed goals. The study scope is defined as cradle-to-gate with options, including modules C1 – C4 and D, as well as additional modules A4 – A5 and B6 – B7. The location of the conventional concrete case study building and the alternative mass timber building is Sydney central business district (CBD), New South Wales, Australia.

The description of the inclusion and exclusion of life cycle stages are listed in Table 7.6.

Table 7.6 System boundary (EN 15978, 2011)

Life cycle Stage	Module	Description of life cycle stage	Include/Exclude
Product stage	A1	Raw material supply	✓
	A2	Transport	✓
	A3	Manufacturing	✓
Construction stage	A4	Transport	✓
	A5	Construction process	✓
Use stage	B1	Material emissions from usage	X
	B2	Maintenance	X
	B3	Repair	X
	B4	Replacement	X
	B5	Refurbishment	X
	B6	Operational energy	✓
	B7	Operational water use	✓

Life cycle Stage	Module	Description of life cycle stage	Include/Exclude
End-of-life stage	C1	Deconstruction and demolition	✓
	C2	Transport	✓
	C3	Waste processing	✓
	C4	Disposal	✓
Benefits beyond the system boundary	D	Reuse, recycle or recovery	✓

Table 7.6 shows the stages and modules included in this LCA study, including raw material acquisition to the manufacturing process of building materials, transport of building material to the construction site, construction activities, operational energy and water consumption, and end-of-life stage as well as benefits beyond the building life cycle. Modules B1 and B2 – B5 are excluded, as they are outside the scope of the study. Module B1 pertains to the release of substances from building materials or coated surfaces into the environment during regular use over the building's life cycle. Modules B2 – B5 involve the maintenance, repair, replacement, and refurbishment of materials, including the transport of these materials. Since the study focuses specifically on the structural elements, Modules B1 and B2–B5 are omitted.

b. Functional unit and system boundary

The results of LCA study are shown in the functional unit of per 1m^2 of Gross Floor Area (GFA) from cradle to gate with additional modules A4, A5, C and D over 50 years. A system boundary is drawn based on the definition of the goal and scope in section a. Figure 7.10 below shows the system diagram of this LCA study.

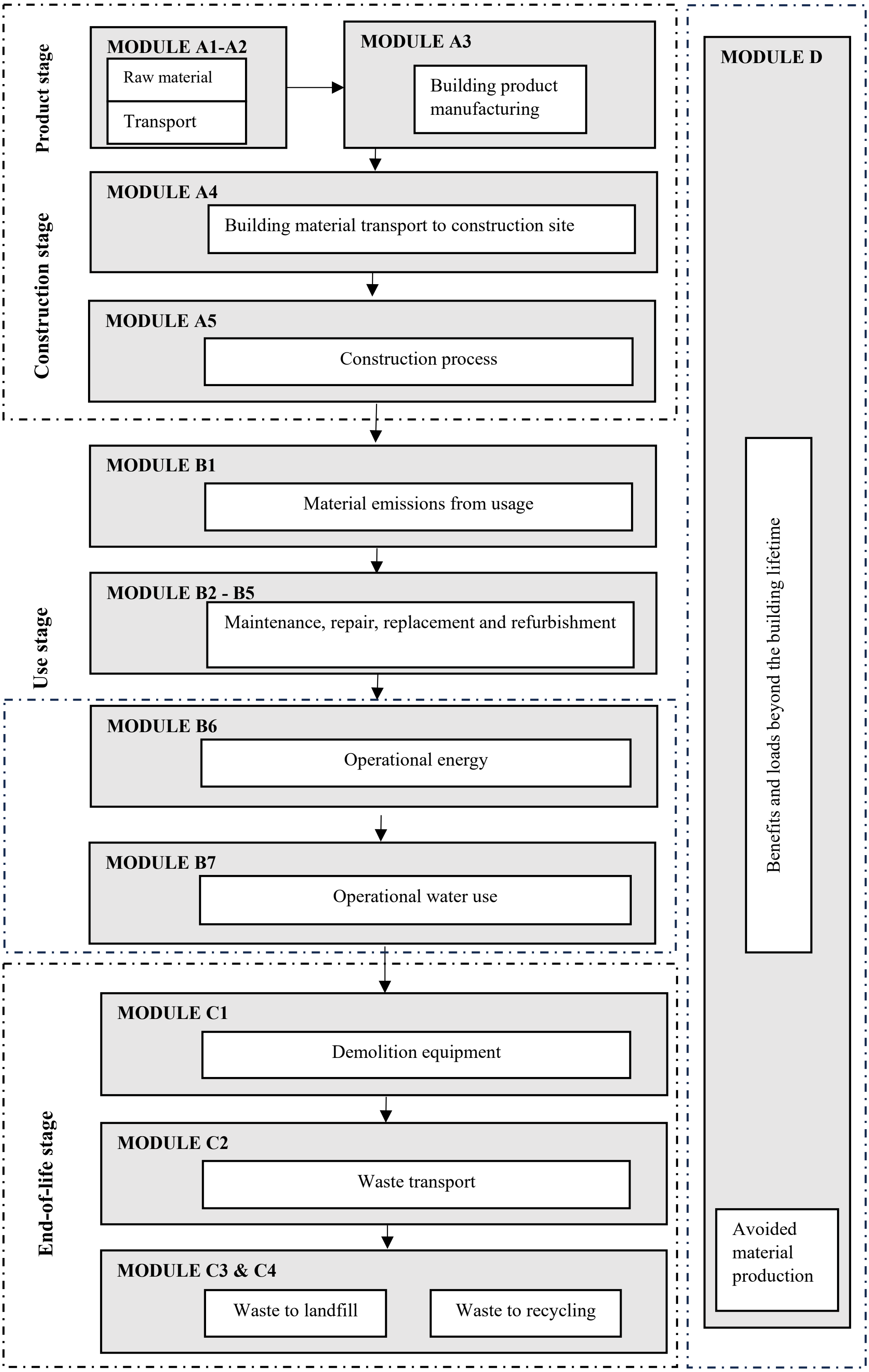


Figure 7.10 System boundary

c. Data quality requirements

According to the standard EN 15978, the key criteria for LCA modelling are as follows:

- Relevance: select sources, data, and methods appropriate to assessing the product's LCI
- Completeness: include all LCI items that provide a material's contribution to a product's life cycle emissions
- Consistency: enable meaningful comparisons in life cycle impact assessment (LCIA) information
- Accuracy: reduce bias and uncertainty as much as is practical
- Transparency: when communicating, disclose enough information to allow third parties to make decisions
- Time coverage: the data collected represents recent practice for the construction of the project
- Geographical coverage: the data collected are representative of the sourcing of materials and are in line with the goal of the study.

The data requirements for the LCA are indicated in Table 7.7

Table 7.7 Data requirements for the LCA

Life cycle stage	**Required data**	**Data sources**	**Primary data quality**
A1-3: Product stage	Materials used for the building.	Bill of quantities from actual project and mass timber redesign	Good
A4: Transport to construction site	Transport mode and distance	Assumption	Medium
A5: Construction energy, water, and waste	Diesel, electricity, and water use during construction	Estimate	Good
B6: Operational energy use	Electricity consumption	Estimate	Good

Life cycle stage	**Required data**	**Data sources**	**Primary data quality**
B7: Operational water use	Water consumption	Estimate	Good
C1: Deconstruction and demolition	Consumption of diesel, electricity, and water during demolition. Current	Estimate	Good
C2: Waste transport	Transport mode and distance (fuel consumption)	Assumption	Medium
C3: Waste processing	Recycling rates of building materials	Bill of quantities National waste report (Department of Agriculture, Water and the Environment, 2020)	Medium
C4: Waste Disposal	Recycling rates of building materials	Bill of quantities National waste report (Department of Agriculture, Water and the Environment, 2020)	Medium
D: Benefits and loads beyond the system boundary	Recycling rates of building materials	Estimate	Medium

d. Criteria for the exclusion of inputs and outputs

According to EN 15978 (2011), the assessment shall accurately quantify the building and the scenarios used at the time of evaluation. The criteria for excluding inputs and outputs for environmental indicators, based on the described object of the assessment, should adhere to the rules set out in the EN 15804 standard (EN 15804, 2012). In line with EN 15804, the following system boundaries have been applied concerning manufacturing equipment and personnel:

- Environmental impacts associated with infrastructure, construction, production equipment, and tools that are not directly consumed during production are excluded from the LCI. These typically account for less than a few percent of the total impacts in most LCIs, a contribution that is often smaller than the inherent inventory data error. For this study, it is assumed that the contribution of capital equipment is negligible, requiring no further analysis (Bauer et al., 2007)

- Employee commuting is excluded from the LCI due to the difficulty of attributing these impacts specifically to this study. Since employees would likely commute to other jobs if not involved in the construction, the associated impacts would occur regardless. Therefore, employee commuting is not considered in this study.
- The environmental impact of transporting construction equipment has been excluded due to a lack of precise data at the time of the study and this impact is assumed to be negligible.

e. Allocation

As per EN 15804, allocation should be avoided wherever possible by breaking down unit processes into sub-processes that can be directly assigned to co-products, ensuring the input and output data collected reflects these specific sub-processes. When subdivision is not feasible, allocation of inputs and outputs among co-products should follow the hierarchy below:

- Physical properties (e.g., mass, volume) are used when co-products exhibit minimal differences in economic value.
- Economic allocation is applied when significant revenue differences exist among co-products.
- Material flows with inherent properties (e.g., energy content, elemental composition) are allocated to reflect actual physical flows.

In this study, the consequential modelling approach is employed to assess the broader system impacts of decisions, reflecting changes in market dynamics and technology adoption. Accordingly, potential loads and benefits from reuse, recycling, and recovery are reported in module D, following EN 15978. These impacts are calculated based on marginal technologies and net system changes, ensuring that results reflect the consequences of material flows exiting the system boundary. For background data, the AusLCI Database, which adheres to EN 15804 requirements, has been prioritised. Where AusLCI data is unavailable, internationally recognized and ISO 14044 compliant datasets have been used.

f. Life cycle impact assessment

This research applies Environmental Footprint version 3.1 to analyse LCA inventory results, with a primary emphasis on abiotic depletion (fossil fuels) and global warming potential (GWP). The GWP is reported both as a total and broken down into fossil carbon (GWP – Fossil) and biogenic carbon (GWP – Biogenic). Environmental impact factors for individual processes, such as materials, energy sources, and transportation modes, were modelled using SimaPro (v9.6.0.1). Details of the impact category, measurement units, and LCIA method are provided in Table7.8.

Table 7.8 Life cycle impact assessment

Impact category	**Unit**	**Assessment Method and Implementation**
Global warming potential – Total	kg CO_2 eq	Baseline model of 100 years of the IPCC based on IPCC 2013
Global warming potential – Fossil	kg CO_2 eq	Baseline model of 100 years of the IPCC based on IPCC 2013
Global warming potential – Biogenic	kg CO_2 eq	Baseline model of 100 years of the IPCC based on IPCC 2013
Abiotic depletion (fossil fuels)	MJ	CML (v4.1)

The impact assessment results are presented in section 7. The environmental impact represented by each indicator can be summarised as follows:

- Global warming potential (GWP) measures the rise in the Earth's average temperature, which can result in serious effects like rising sea levels and more frequent natural disasters. It is a key metric used to evaluate the impact of greenhouse gases, such as carbon dioxide and methane, on climate change, expressed in carbon dioxide equivalents (CO_2 eq) over a 100-year period. GWP contributions originate from both fossil and biogenic sources.

- Biogenic Global Warming Potential (GWP – Biogenic) focuses on the impact of carbon emissions originating from biological sources. This includes carbon absorbed and stored by plants and trees during photosynthesis and later released back into the atmosphere through processes such as decay, combustion, or other forms of biomass processing.
- Abiotic Resource Depletion refers to the consumption of non-living, non-renewable resources, such as fossil fuels and minerals, which are critical to daily life. These resources are often extracted at an unsustainable rate, contributing to their eventual depletion while releasing significant amounts of heat energy into the environment.

g. Life cycle inventory

- **Product stage (Module A1 to A3)**

This section discusses the life cycle inventory data, sources and assumptions used for this LCA study. Table 7.9 shows the source of inventory data for materials, fuel and energy use and emissions flows during the processes of raw material acquisition, manufacturing, transport of building materials from manufacturers to construction site, construction, and end-of-life stages. The inventory data for the process are entered into the SimaPro LCA program (v9.6.0.1) and linked to the existing data for upstream feedstocks and services. The use of Australian data should take precedent over imported data as relevant and where available. Where data for imported products is used, this must be adapted for relevance to Australian conditions such as transport distances and modes and documented to show how the data was adapted.

Table 7.9 Source of inventory data

Material	Source	Region
Concrete	AusLCI Unit Processes version 1.42 (Grant, 2016)	Australia

Material	Source	Region
Reinforcing Steel	AusLCI Unit Processes version 1.42 (Grant, 2016)	Australia
Steel – Welded Beams and Columns	EPD	Australia
Reinforced concrete pipe	EPD	Australia
Electricity	AusLCI Unit Processes version 1.42 (Grant, 2016)	Australia
Diesel	Ecoinvent version 3.10 (Ecoinvent Association, 2019)	Australia
LVL	Carter Holt Harvey LVL Limited EPD	Australia
CLT	XLam CLT Panel EPD	Australia
Glulam	Forest and Wood Products Australia Ltd Glulam EPD	Australia
Plaster board	AusLCI Unit Processes version 1.42 (Grant, 2016)	Australia
Transport	AusLCI Unit Processes version 1.42 (Grant, 2016)	Australia

Table 7.10 and Table 7.11 below show the material quantities for the original concrete office design and mass timber redesign. The material quantities of the two designs were estimated by Rider Levett Bucknall, Australia.

Table 7.10 Material quantities of concrete design

Description		Unit	Qty
SB	**Substructure**		
1	150 mm thick 32 MPa concrete ground slab	m^2	3,521
2	900 wide x 600 mm deep capping beam to East and South East Elevations	m	108
3	800 wide x 600 mm deep capping beam to North Elevations	m	86
4	Core wall to lift pit, 50 MPa	m^3	11
5	Formwork to core walls to lift pit	m^2	97
6	Bored soldier pile, 600 mm diameter	m	51
7	Concrete in pile cap, 32 MPa	m^3	4
8	Bored soldier pile, 1200 mm diameter	m	54
9	Bored soldier pile, 1500 mm diameter	m	24
10	Formwork to sides of pile cap	m^2	7
11	Strip footing, 32 MPa	m^3	27

Description		Unit	Qty
12	Formwork to sides of strip footing	m^2	74
13	Raft footing in lift core, 32 MPa	m^2	10
14	Formwork to sides of raft footing	m^2	9
15	Bar reinforcement	t	786.49
CL	**Columns**		
16	Concrete in columns, 50 MPa	m^3	136
17	Concrete in columns, 40 MPa	m^3	73
18	Formwork to columns	m^2	1,306
19	Bar reinforcement	t	40.68
20	Formwork to 600 mm diameter columns	m	50
21	Formwork to 500 mm diameter columns	m^2	148
22	Formwork to 450 mm diameter columns	m^2	202
23	SC1 - 125 x 125 x 5 SHS Column	t	0.22
24	SC4 - 200 x 100 x 5 RHS Column	t	0.36
25	SC2 - 150 x 150 x 5 SHS Column	t	0.45
26	SC3 - 150 x 150 x 6 SHS Column	t	0.32
27	SC1 - 200 UC 46 Column	t	0.52
28	SC2 - 125 x 125 x 5 SHS Column	t	0.07
UF	**Upper Floors**		
29	Concrete 32 MPa	m^3	1,901
30	Formwork to soffit of suspended slab and beams	m^2	10,811
31	Formwork to side of attached beams	m^2	1,046
32	300 x 600 mm High upstand beam	m	23
33	400 x 400 mm High upstand beam	m	2
34	1000 x 400 mm High upstand beam	m	10
35	300 mm Wide kerb	m	42
36	300 mm Wide kerb	m	6
37	600 mm Wide kerb	m	6
38	Formwork to edge of slab not exceeding 250 mm high	m	1,158
39	Concrete 40 MPa	m^3	447
40	Formwork to edge of step in top and/or soffit of band beam not exceeding 250 mm high	m	385
41	Step/folds in suspended slabs and beams	m^2	1,490
42	Formwork to edge of step in top and/or soffit of band beam 250–500 mm high	m	8
43	Formwork of edge of step in top and/or soffit of suspended slab not exceeding 250 mm high	m	170
44	200 mm wide hob	m	51
45	150 mm thick secondary slab	m^2	68
46	Fold in post tensioned suspended slabs, 32 MPa	m^3	5
47	200 x 300 mm High upstand beam	m	69
48	400 x 600 mm High upstand beam	m	9
49	200 x 765 mm High upstand beam	m	4
50	Bar reinforcement	t	2097.3

Description		**Unit**	**Qty**
51	Post tensioning in suspended slab, band beams and transfer slabs	t	66.13
RF	**Roof**		
52	Concrete 40 MPa	m^3	144
53	Formwork to soffit of suspended slab and beams	m^2	1,207
54	Formwork to side of attached beams	m^2	250
55	Bar reinforcement	t	85.39
56	Post tensioning in suspended slab, band beams and transfer beams	t	7.55
57	Formwork to edge of slab not exceeding 250 mm high	m	232
58	Formwork to edge of step in soffit of band beam 250–500 mm high	m	3
59	300 x 1000 mm High upstand beam	m	18
60	300 mm Wide kerb	m	18
61	Precast concrete for roof slab system	m^2	47
62	Concrete in post tensioned suspended slabs, 32 MPa	m^3	197
63	150 mm thick 32 MPa precast concrete lids to cores	m^2	53
64	RB1 - 200 UB 25 Roof beam	t	1.90
65	RB2 - 310 UB 40 Roof beam	t	1.02
66	STR1 - 114.3 CHS 3.2 Roof strut	t	0.28
67	WB1 - 150 PFC Wind beam	t	0.30
68	RA1 - 100 x 100 x 8 EA Roof bracing	t	0.32
69	HXB1 - 20 mm Dia. rod c/w turnbuckles	m	116
70	R1 - 410 UB 54 Roof beam	t	1.41
71	R2 - 360 UB 45 Roof beam	t	0.82
72	R3 - 200 PFC Roof/Canopy beam	t	1.03
73	B1 - 460 UB 67 Roof beam	t	0.95
74	B2 - 200 x 200 x 9 SHS Roof beam	t	0.86
75	B3 - 200 x 200 x 6 SHS Roof beam	t	2.56
76	TB1 - 250 PFC Canopy beam	t	2.49
77	TB2 - 300 PFC Canopy beam	t	0.59
78	HXB1 - 20 mm Dia. rod Canopy bracing	m	110
79	HXB2 - 16 mm Dia. rod Canopy bracing	m	41
80	S1 - 100 x 50 x 6 RHS Vertical bracing	t	0.10
81	S2 - 100 x 100 x 6 SHS Vertical bracing	t	0.04
82	FB - 50 x 50 x 5 EA Fly bracing	t	0.03
83	P1 - Z20024 Purlins at 1200 cts	m	209
84	P2 - Z20019 Purlin at 600 cts	m	252
85	P3 - C20019 Purlin at 600 cts	m	252
86	Allow for attached and loose connections (10%)	t	1.47
87	Allow for fire proofing to structural steel roof elements as required	m^2	393
88	Waterproofing to roof areas	m^2	1
EW	**External Walls**		

Description		Unit	Qty
89	Retention wall comprising 600 mm dia. piles at 2,100 mm cts, ground anchors and shotcrete (face area given)	m^2	1,806
90	HR2 - 100 x 100 x 4 SHS Wall rail	t	1.03
91	HR1 - 100 PFC Wall rail	t	0.12
92	HR3 - 100 x 100 x 5 SHS Wall rail	t	0.39
93	G1 - C15019 Girt at 600 cts	m	119
94	G2 - C20019 Girt at 600 cts	m	56
95	Allow for attached and loose connections (10%)	t	0.16
96	Allow for fire proofing to structural steel wall elements as required	m^2	50
NW	**Internal Walls**		
97	Concrete 50 MPa	m^3	175
98	125 mm RC dwarf wall	m^2	4
99	Concrete in core wall, 40 MPa	m^3	213
100	Formwork to core walls and walls	m^2	4,367
101	Reinforcement in core walls	t	75.92
102	Reinforcement in walls	t	1.28
103	Concrete in load bearing wall, 40 MPa	m^3	14
CF	**Ceiling Finishes**		
104	Ceiling tiles to Office Levels (to allow for like-for-like comparison with Timber Structure which requires ceiling finish)	m^2	6,663
105	Plasterboard lining to Ground Level ceiling (to allow for like-for-like comparison with Timber Structure which requires ceiling finish)	m^2	1,337

Table 7.11 Material quantities of alternative mass timber redesign

Description		Unit	Qty
SB	**Substructure**		
1	150 mm thick 32 MPa concrete ground slab	m^2	1,761
2	900 wide x 600 mm deep capping beam to East and South East Elevations	m^3	58
3	Bar Reinforcement	t	781.55
4	800 wide x 600 mm deep capping beam to North Elevations	m^3	41
5	Core wall to lift pit, 50 MPa	m^3	11
6	Formwork to core walls to lift pit	m^2	97
7	Concrete in pile cap, 32 MPa	m^3	3
8	Formwork to sides of pile cap	m^2	5
9	Strip footing, 32 MPa	m^3	27
10	Formwork to sides of strip footing	m^2	74
11	Raft footing in lift core, 32 MPa	m^2	10
12	Formwork to sides of raft footing	m^2	9
13	Bored soldier pile, 450 mm diameter	m	51
14	Bored soldier pile, 900 mm diameter	m	54

Description		Unit	Qty
15	Bored soldier pile, 1125 mm diameter	m	24
CL	**Columns**		
16	Concrete in columns, 50 MPa	m^3	58
17	Formwork to columns	m^2	463
18	Bar Reinforcement	t	11.38
19	900 x 700 mm Grade GL18 Glulam Column	m^3	494
20	SC1 - 125 x 125 x 5 SHS Column	t	0.22
21	SC4 - 200 x 100 x 5 RHS Column	t	0.36
22	SC2 - 150 x 150 x 5 SHS Column	t	0.45
23	SC3 - 150 x 150 x 6 SHS Column	t	0.32
24	SC1 - 200 UC 46 Column	t	0.52
25	SC2 - 125 x 125 x 5 SHS Column	t	0.07
UF	**Upper Floors**		
26	Concrete 32 MPa	m^3	337
27	Formwork to soffit of suspended slab and beams	m^2	1,844
28	Formwork to side of attached beams	m^2	70
29	Reinforcement in post tensioned suspended slabs (50 kg/m^3)	t	111.22
30	Post tensioning in suspended slab and band beams (6 kg/m^2)	t	11.07
31	Post tensioning in transfer slabs and beams (10 kg/m2)	t	0.21
32	300 x 600 mm High upstand beam	m^3	4
33	400 x 400 mm High upstand beam	m^3	0.320
34	1000 x 400 mm High upstand beam	m^3	4
35	300 mm Wide kerb	m^3	0.360
36	300 mm Wide kerb curved on plan	m^3	1
37	600 mm Wide kerb	m^3	2
38	Formwork to edge of slab not exceeding 250 mm high	m	50
39	Formwork to edge of step in top and/or soffit of band beam not exceeding 250 mm high	m	10
40	150 mm thick CLT panels, 4,200 / 5,400 mm long x 1,000 mm wide	m^3	1,256
41	Main bearer, 800 x 300 mm deep GL18 beam (running North-South and spanning 8,400 mm long every 1,000 mm cts. in line with CLT panel width)	m^3	854
42	Main bearer, 500 x 300 mm deep GL18 beam (running North-South and spanning 5,400 mm long every 1,000 mm cts. in line with CLT panel width)	m^3	702
43	Main bearer to Plant Levels, 1,400 x 600 mm deep GL18 beam (running North-South and spanning 5,400 mm long every 1,000 mm cts. in line with CLT panel width)	m^3	642
44	Secondary beam, 610 x 90 mm deep LVL 11 beam (running East-West and spanning 8,400 mm long at 5,400 / 8,400 mm cts. in line with CLT panel length)	m^3	108
45	Cantilever beam, 800 x 300 mm deep GL18 beam (running East-West and spanning 3,000 mm long at 5,400 / 8,400 mm cts. in line with CLT panel length)	m^3	17
RF	**Roof**		

Description		Unit	Qty
46	Concrete 40 MPa	m^3	144
47	Formwork to soffit of suspended slab and beams	m^2	460
48	Formwork to side of attached beams	m^2	30
49	Reinforcement in suspended slabs (150 kg/m^3)	t	67.85
50	Post tensioning in suspended slab and band beams (6 kg/m^2)	t	1.85
51	Post tensioning in transfer beams (10 kg/m^2)	t	0.10
52	Formwork to edge of slab not exceeding 250 mm high	m	96
53	Formwork to edge of step in soffit of band beam 250–500 mm high	m	3
54	300 x 1000 mm High upstand beam	m^3	5
55	300 mm Wide kerb	m^3	2
56	Precast concrete for roof slab system	m^3	14
57	150 mm thick 32 MPa precast concrete lids to cores	m^3	8
58	150 mm thick CLT panels, 4,200 / 5,400 mm long x 1,000 mm wide	m^3	205
59	Waterproofing to CLT slabs on roof level comprising vapour permeable membrane flashing	m^2	1,367
60	Main bearer to Plant Levels, 1,400 x 600 mm deep GL18 beam (running North-South and spanning 8,400 mm long every 1,000 mm cts. in line with CLT panel width)	m^3	499
61	RB1 - 200 UB 25 Roof beam	t	1.90
62	RB2 - 310 UB 40 Roof beam	t	1.02
63	STR1 - 114.3 CHS 3.2 Roof strut	t	0.28
64	WB1 - 150 PFC Wind beam	t	0.30
65	RA1 - 100 x 100 x 8 EA Roof bracing	t	0.32
66	HXB1 - 20 mm dia. rod c/w turnbuckles	m	116
67	P1 - Z20015 Purlin at 1200 cts	m	379
68	R1 - 410 UB 54 Roof beam	t	1.41
69	R2 - 360 UB 45 Roof beam	t	0.82
70	R3 - 200 PFC Roof/Canopy beam	t	1.03
71	B1 - 460 UB 67 Roof beam	t	0.95
72	B2 - 200 x 200 x 9 SHS Roof beam	t	0.86
73	B3 - 200 x 200 x 6 SHS Roof beam	t	2.56
74	TB1 - 250 PFC Canopy beam	t	2.49
75	TB2 - 300 PFC Canopy beam	t	0.59
76	HXB1 - 20 mm dia. rod Canopy bracing	t	17
77	HXB2 - 16 mm dia. rod Canopy bracing	t	5
78	S1 - 100 x 50 x 6 RHS Vertical bracing	t	0.10
79	S2 - 100 x 100 x 6 SHS Vertical bracing	t	0.04
80	FB - 50 x 50 x 5 EA Fly bracing	t	0.03
81	P1 - Z20024 Purlins at 1200 cts	m	209
82	P2 - Z20019 Purlin at 600 cts	m	252
83	P3 - C20019 Purlin at 600 cts	m	252
84	Allow for attached and loose connections (10%)	t	1.47

Description		**Unit**	**Qty**
85	Allow for fire proofing to structural steel roof elements as required	m^2	393
EW	**External Walls**		
86	Retention wall comprising 600 mm dia. piles at 2,100 mm cts, ground anchors and shotcrete (face area given)	m^2	752
87	HR2 - 100 x 100 x 4 SHS Wall rail	t	1.03
88	HR1 - 100 PFC Wall rail	t	0.12
89	HR3 - 100 x 100 x 5 SHS Wall rail	t	0.39
90	G1 - C15019 Girt at 600 cts	m	119
91	G2 - C20019 Girt at 600 cts	m	56
92	Allow for attached and loose connections (10%)	t	0.16
93	Allow for fire proofing to structural steel wall elements as required	m^2	50
NW	**Internal Walls**		
94	Concrete in core walls, 50 MPa	m^3	134
95	125 mm RC dwarf wall	m^3	4
96	Concrete in core wall, 40 MPa	m^3	213
97	Formwork to core walls and walls	m^2	3,345
98	Bar Reinforcement	t	54.59
CF	**Ceiling Finishes**		
99	Dry linings and fixings to underside of CLT panels (required to achieve acoustic performance) comprising: - Sound isolation clips, 100 mm high - Metal hat channels, approximate 400 mm spacings - Acoustic insulation - 2 x 13 mm plasterboard lining	m^2	9,713

The mass timber redesign uses a total volume of 4,586.4 m^3 of mass timber, including 1,270.6 m^3 of CLT, 3,207.4 m^3 of Glulam, and 108.4 m^3 of LVL, replacing 4,498.04 m^3 of concrete and 2,051 tons of reinforcing steel from the traditional reinforced concrete design. The outcomes of the LCA will demonstrate whether the redesign contributes to sustainability by reducing reliance on concrete and steel – materials associated with higher carbon emissions.

The timber structure begins at Ground Level, however the roof to the basement (outside of the enclosed Ground Level footprint) remains concrete.

- **The transport of building materials to construction site and construction stage (A4 and A5)**

This section discusses the impact of construction activities, including the transport of building materials to construction site and the erection and installation of building materials and elements. According to Ding (2019), the construction phase accounts for approximately 8% to 20% of the total energy demand in a building's life cycle. However, the energy consumption and associated emissions during on-site activities can be substantial due to their immediate effects. The use of fuels, electricity and heat for plant and equipment, such as a groundwork excavator, concrete pump and crane, were considered.

To calculate the impacts of excavation for groundworks, it is necessary to account for the volume of excavation required for the area and transport of excavated soil to compact in place. Thus, the assumption of soil type is important as it affects the swell factor of excavated soil. Soil tends to swell after excavation and the swell factor is determined by the type of excavated soil (Göktepe et al., 2008). Information from the New South Wales Department of Planning, Industry and Environment indicates that Sydney's two predominant soil types are sandy soil and clay soil. For this study, the soil type was assumed to be dry clay for two reasons: (1) clay soils are prevalent in many urban development areas of Sydney, particularly in western and inner suburbs; and (2) clay generally exhibits a higher swell factor than sandy soil, which provides a conservative estimate for excavation volume and associated costs. The swell factor of dry clay varies from 1.18 to 1.54 (Burch, 1997). Hence, an average swell factor of 1.36 is selected in this model. The calculation of excavation is listed as following:

- Identify the required amount of soil (cubic metre) to be excavated, which is called bank material:

  Volume of bank material = Excavated area = L x W x H (m^3) (7.3)
- Determine the amount of excavated soil to compact in place, which is called loose material:

  Volume of loose material = Bank material x 1.36 (m^3) (7.2)

- Determine the number of dump truck loads, assuming the maximum capacity of a dump truck is 20 tonnes
- Dump truck loads = $\frac{\text{Volume of loose material x density of loose material}}{\text{Maximum capacity of dump truck}}$

  (7.3)

Associated emissions released from transport are calculated based on the following formula:

$$EE_{transport} = \sum_{i=1}^{n} D_i \; x \; T_i \; x \; TF_i \; x \; TEC_i \text{ (Ding, 2019) (7.4)}$$

Where

$EE_{transport}$ = Emissions from fuel consumption in the transport of material (kg CO_2 eq)

D_i = Total distance (km)

T_i = Number of truck loads for transporting building material i (No)

TF_i = Fuel consumption per truck load (litre per km)

TEC_i = Emission coefficient per unit consumption of fuel i (kg CO_2 eq per litre).

A conceptual transport route is shown in Figure 7.11. The assumptions for the transport distance of building materials from manufacturer to construction site are listed in Table 7.12.

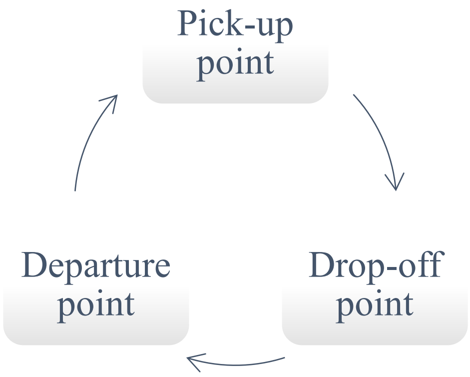


Figure 7.11 Conceptual model of transport route, adapted from Larsen et al. (2009)

Table 7.12 Transport distance of building materials

Transport type	**Distance (km)**	**Assumptions**
Transport of loose material	10	Distance from construction site to compact loose material in place
Concrete mixer truck	25	Maximum capacity per truck is 6 m^3 (14.4 t). Thus, the truck can transport 6 m^3 of concrete each time.
Transport of CLT elements	20	Assume that CLT supplier is 20 km away from the construction site. Additional assumptions regarding the transport of CLT will be explored in a sensitivity analysis to investigate the impact of longer transport distances on the overall life cycle assessment (LCA) results.
Transport of LVL elements	20	Distance from LVL supplier to construction site is 20 km
Transport of Glulam elements	22	Distance from Glulam supplier to construction site is 20 km
Transport of steel including reinforcing steel, prestressing steel, steel low alloyed, chromium steel 18/8; welded steel	30	Assume that all types of steel are purchased from the same factory
Transport of concrete pipes	25	Distance from concrete pipes to construction site is 25 km
Gypsum plasterboard	11	Distance from gypsum plasterboard supplier to construction site is 11 km
Formwork	5.9	Formwork was hired from the supplier located 5.9 km away from the construction site

To calculate the energy demand and associated emissions from the activity of concrete pumping, it is necessary to assume the technical specifications of the concrete pump. A concrete pump is powered by diesel and maximum output capacity ranges from 40 m^3/h to 100 m^3/h, depending on the diesel engine model. The chosen maximum output capacity is 67 m^3/h and diesel engine power is 129 kW. The amount of energy of the concrete pump is calculated based on the following formula:

$$\text{Energy}_{\text{concrete pump}} = \frac{129\,x\ \text{Total volume of concrete}}{67}\ (\text{kWh}) \qquad (7.5)$$

To calculate the energy demand and associated emissions from the activity of the crane to lift mass timber panels, this study assumed that the total capacity of all mechanism features is 24 kW, based on the technical specification of a tower crane. In the technical design guide for cost engineering of mid-rise timber buildings issued by Forest and Wood Products Australia (2019), a total of 26 mid-rise mass timber projects were analysed in terms of activities associated with cost performance such as design, procurement and installation (Forest and Wood Products Australia, 2019b). The guide concluded that seven-storey non-residential projects with an average of 3,770 m^3 engineered wood products required seven crews to complete the installation of 86 m^2 or 18.5 lifts per day. Hence, this study assumed that it took a total of 2,160 lifts to lift 4,587 m^3 mass timber elements in place in 96 days.

- **Use stage (B1 – B7)**

After the completion of construction stage, the building reaches to its operation period which includes the use of the building to meet the specified functional and technical usage over the reference lifespan of the building. The building is maintained, repaired, and refurbished during its life cycle to ensure its functional capacity.

The environmental impacts at the use stage of a building includes the following activities:

- Module B1 refers to the release of substances from the building fabrics or coated surfaces to the environment during the regular use of the building over its life cycle.
- The maintenance, repair, replacement and refurbishment of building fabrics or components during the lifespan of the building (modules B2 – B5).
- The transport for resources used to maintain, repair, replace and refurbish the building and the waste to landfill (modules B2 – B5).

- Module B6, which includes the operational energy consumption for heating, cooling, hot water, lighting, ventilation, and power for occupant activities.
- Module B7 covers operational water use.

The durability of materials is the most important factor affecting recurrent energy use and emissions (Zhang et al., 2013). Over a building's life cycle, one or more maintenance or replacements may occur. The shorter the life expectancy of a material, the greater the frequency of ongoing maintenance and replacement and the greater the recurrent energy and emissions throughout a building's life cycle. Therefore, the selection and use of materials in building for structural elements and interior finishes can influence the embodied energy. It may affect the requirement and frequency of maintenance, repair, replacement, and refurbishment. The material’s lifespan determines how often the material is to be replaced and how frequently the material requires maintenance. The reinforced concrete structural elements of the building have a long lifespan that typically requires no maintenance, repair, replacement and refurbishment during the use stage (RICS, 2006). Treated CLT panels, glulam and LVL are expected to have a long service life with little or no significant change from their original specifications. Only inspection is necessary to be performed on an annual basis (XLam Australia & XLam New Zealand, 2021). This LCA study only focuses on structural elements, the maintenance stage (modules B2 – B5) is therefore omitted.

- **End-of-life stage (modules C1 to C4)**

In the demolition and deconstruction stage of the two designs, diesel consumption from the operation of machinery was considered (module C1). The demolition of the reinforced concrete and mass timber structures is projected to take approximately 16 and 14 weeks, respectively, using an excavator and a wheel loader. The wastes from the demolition were assumed to be transported by truck to waste processing or disposal. The transport distance from the demolition site to recycling plant or landfill (module C2) is assumed to be within 20 km.

Disposal options, such as landfilling, recycling or incineration, vary depending on national policies, regulations and standards (Ding, 2019). The Australian government does not directly legislate the management of construction and demolition waste in Australia, as it is the responsibility of state and territory governments (Department of Sustainability Environment Water Population and Communities, 2012). (Ding, 2019). The Australian government does not directly legislate the management of construction and demolition waste in Australia, as it is the responsibility of state and territory governments (Department of Sustainability Environment Water Population and Communities, 2012). The government’s “2018 National Waste Policy: less waste, more resources” provided an action plan to encourage the use of recycled material and build demand and markets for recycled products (Australian Department of the Environment and Energy, 2018). Building materials from the product stage (A1 – A3) are either recycled (module C3) or sent to landfill (module C4). Average recycling rates for building materials are referred to in the National Waste Report in 2020 (DAWE, 2020).

Table 7.13 shows the average recycling rates for building materials assumed in this study.

Table 7.13 Recycling rates for building materials (DAWE, 2020)

Material	**Recycling rate**
Masonry	82.0%
Metals	90.0%
Organics (including timber)	49.0%
Paper & Cardboard	60.0%
Plastics	13.0%
Glass	59.0%
Glass (design for disassembly)	95.0%

Material	Recycling rate
Hazardous - contaminated soil	24.0%
Hazardous - industrial waste	30.0%
Fly ash	47.0%
Average of all waste	60.0%

Waste processing (module C3) was modelled using the Australian National Life Cycle Inventory Database (AusLCI) Database and EPDs. Recycled materials were categorised and processed based on either material-specific data from the AusLCI database or EPD datasets for construction materials (Table 7.14). Demolished concrete is assumed to be crushed and repurposed as aggregate, replacing virgin gravel. Steel from demolition is modelled as feedstock for steel production, substituting primary iron ore. At the end of the building's life cycle, demolished timber is assumed to be used as biomass for energy recovery, while plasterboard is assumed to be disposed of in a landfill.

Table 7.14 Processes used for material waste processing (module C3).

Material	Process
Concrete	Recycling brick rubble and concrete, at plant/ AU U
Steel	Collection and processing of steel scrap/AU U
LVL	Carter Holt Harvey LVL Limited EPD
CLT	XLam CLT Panel EPD
Glulam	Forest and Wood Products Australia Ltd Glulam EPD

The fraction of non-recycled waste materials was assumed to go to landfill. The impact of landfill disposal (module C4) was modelled using AusLCI database or EPD specific for construction materials (Table 7.15).

Table 7.15 Processes used for materials disposed to landfill (module C4).

Material	Process
Concrete	Disposal, concrete, 5% water, to inert material landfill/CH U/AusSD U
Steel	Disposal, steel, 0% water, to inert

	material landfill/CH U/AusSD U
Plaster board	Disposal, gypsum, 19.4% water, to inert material landfill/CH U/AusSD U
LVL	Carter Holt Harvey LVL Limited EPD
CLT	XLam CLT Panel EPD
Glulam	Forest and Wood Products Australia Ltd Glulam EPD

- **Benefits and loads beyond building lifetime (module D)**

The fraction of non-recycled materials (e.g., concrete, steel and plasterboard) going to the landfill are inert and do not generate methane to be captured for electricity generation. However, landfilled timber generates methane emissions which leads to the avoided impact of electricity production and/or thermal energy recovery from landfill gas recovery (Dodoo et al., 2014a; XLam Australia, 2021). Table 7.16 shows the processes used for the calculations of benefits and loads beyond building life cycle.

Table 7.16 Processes used for module D calculations

Material	**Reprocessing**	**Avoided production**	**Source**
Concrete	Recycling brick rubble and concrete, at plant/AU U	Gravel, crushed, at mine/AU U	AusLCI
Steel	Collection and processing of steel scrap/AU U	Pig iron, at plant/GLO U/AusSD U	AusLCI
CLT	Recycling timber	Avoided impact of electricity generation and thermal energy recovery	XLam Australia (2021)
CLT	Landfilling timber	Avoided impact of electricity production and/or thermal energy recovery from landfill gas recovery	XLam Australia (2021)
LVL	Recycling timber	Avoided impact of electricity generation and thermal energy recovery	(Carter Holt Harvey LVL Limited, 2023)

Material	Reprocessing	Avoided production	Source
LVL	Landfilling timber	Avoided impact of electricity production and/or thermal energy recovery from landfill gas recovery	(Carter Holt Harvey LVL Limited, 2023)
Glulam	Recycling timber	Avoided impact of electricity generation and thermal energy recovery	(Forest and Wood Products Australia Ltd, 2017)
Glulam	Landfilling timber	Avoided impact of electricity production and/or thermal energy recovery from landfill gas recovery	(Forest and Wood Products Australia Ltd, 2017)

According to the EN15804:2012+A2:2019 standard, the benefits and loads beyond a product or a building life cycle are calculated as follows (BSI Standards Limited, 2019)

$e_{module\ D} = e_{module\ D1} + e_{module\ D2} + e_{module\ D3} + e_{module\ D4}$

with:

$e_{module\ D1}$ is the benefits and loads per unit of measurement for module D associated with the export of secondary materials.

$e_{module\ D1} = (M_{MR\ out} - M_{MR\ in})\ (E_{MR\ after\ EoW\ out} - E_{VMSub\ out} * Q_{R\ out}/Q_{Sub})$

with:

$M_{MR\ out}$ is the amount of material exiting the system that will be recovered in a subsequent system.

$M_{MR\ in}$ is the amount of input material to the product system that has been recovered from a previous system

$E_{MR\ after\ EoW\ out}$ is the specific emissions, resources and waste from material made from material recovery.

$E_{VMSub\ out}$ is the specific emissions, resources and waste from material made from primary materials

$Q_{R\ out}/Q_{Sub}$ represents the quality correction factor. $Q_{R\ out}$ is the quality of the outgoing recovered material and Q_{Sub} is the quality of the substituted material.

$e_{module\ D2}$ and $e_{module\ D3}$ are the benefits and loads per unit of measurement for module D related to the export of secondary fuels and the export of energy as a result of waste incineration, respectively. $e_{module\ D2}$ and $e_{module\ D3}$ are not relevant to this study.

$e_{module\ D4}$ is the benefits and loads per unit of measurement for module D related to the export of energy as a result of landfilling.

The detailed calculations of the benefits and loads beyond building life cycle is presented in Table 7.17.

Table 7.17 Benefits and loads beyond building life cycle

Material	**Mass (kg)**	**Recycling rate**	**Processing losses**	**Quality correction factor**	**Recycled content**
Concrete	1	82%	5%	75%	0%
Steel	1	90%	5%	75%	15%
Timber	1	49%	5%	75%	0%

h. Life cycle impact assessment results (A1 to A3, A4, A5, C1 – C4 and D)

- **Product stage (Module A1 to A3)**

The mass timber design demonstrates a significant advantage in reducing global warming impacts. The negative value reflects the carbon sequestration capabilities of the biogenic carbon stored in the mass timber elements. In contrast, the concrete design contributes positively to GWP, largely due to the emissions from the production concrete and steel (Table 7.18 and Figure 7.12). During the product stage, the concrete design consumed more fossil fuels than the alternative mass timber design did by 34%. The reason is not only due to the manufacturing of concrete but also the manufacturing of steel. The manufacturing of steel is responsible for a large amount of energy consumption; even 89% of raw material is recycled steel, according to the Environmental Product Declaration used in this LCA.

Table 7.18 Environmental Impact Results for modules A1 – A3: Comparison of 1 m² GFA in Concrete Design and Mass Timber Redesign

Impact category	**Unit**	**Concrete design**	**Mass timber design**
Global warming potential	kg CO_2 eq	240.61	- 120.36
Global warming potential - Fossil	kg CO_2 eq	240.56	203.46
Global warming potential - Biogenic	kg CO_2 eq	0.05	- 323.81
Abiotic depletion (fossil fuels)	MJ	3,076.25	2,078.79

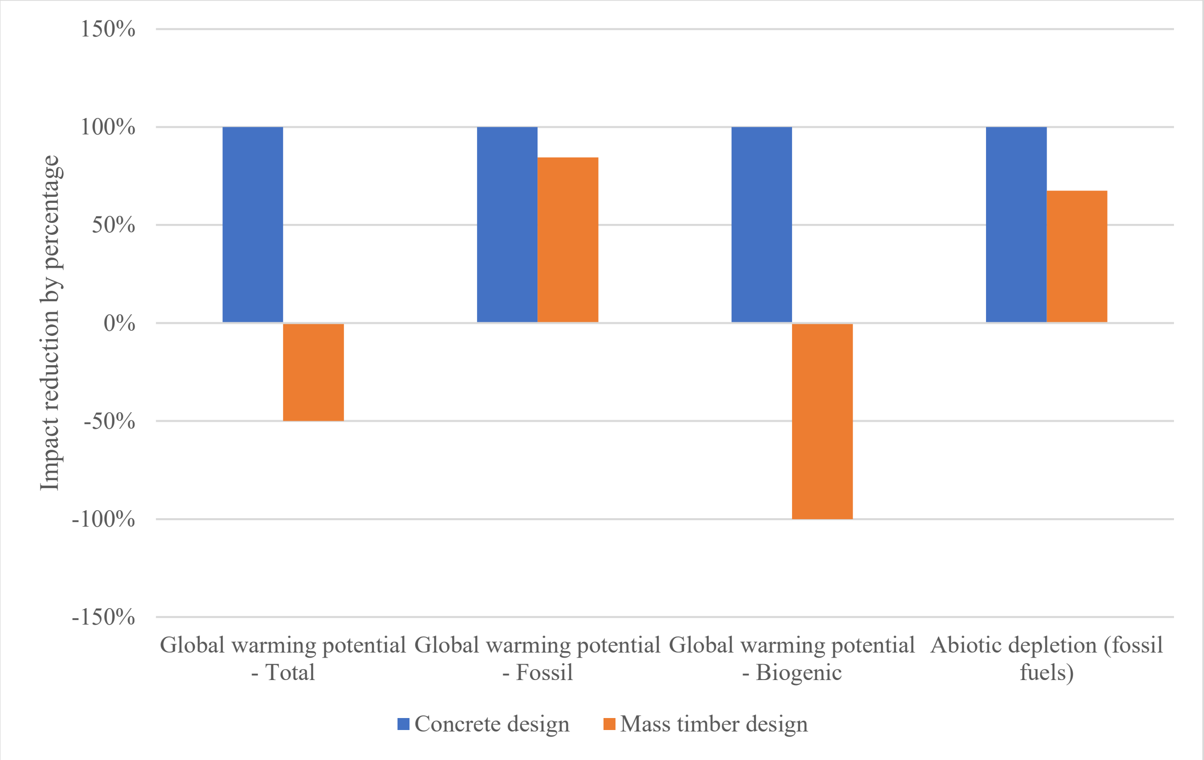


Figure 7.12 Comparison of four impact categories between concrete design and mass timber redesign for modules A1 – A3 per 1 m² of GFA

The negative GWP – Biogenic value for the mass timber design originates from the GWP – Biogenic contributions of 4,587 m³ of mass timber elements, including 1,270.65 m³ of CLT, 108.37 m³ of LVL, and 3,207.39 m³ of Glulam. The GWP – Biogenic values for these materials are -740 kg CO_2 eq/m³ for CLT, -921 kg CO_2 eq/m³ for LVL, and -992 kg CO_2 eq/m³ for Glulam, based on EPD outcomes from XLam, Carter Holt Harvey, and Forest and Wood Products Australia Ltd ((Carter

Holt Harvey LVL Limited, 2023; Forest and Wood Products Australia Ltd, 2017; XLam Australia, 2021)

- **The transport of building materials to construction site and construction stage (A4 and A5)**

Table 7.19 and Figure 7.13 show the impact assessment results for the construction stage, including the impact from transport of building materials to construction site and construction activities.

Table 7.19 Environmental Impact Results for modules A4 – A5: Comparison of 1 m² GFA in Concrete Design and Mass Timber Redesign

Impact category	Unit	Concrete design	Mass timber design
Global warming potential - Total	kg CO_2 eq	5.54	3.83
Global warming potential - Fossil	kg CO_2 eq	5.54	3.83
Global warming potential - Biogenic	kg CO_2 eq	8.68E-05	3.71E-03
Abiotic depletion (fossil fuels)	MJ	80.42	57.26

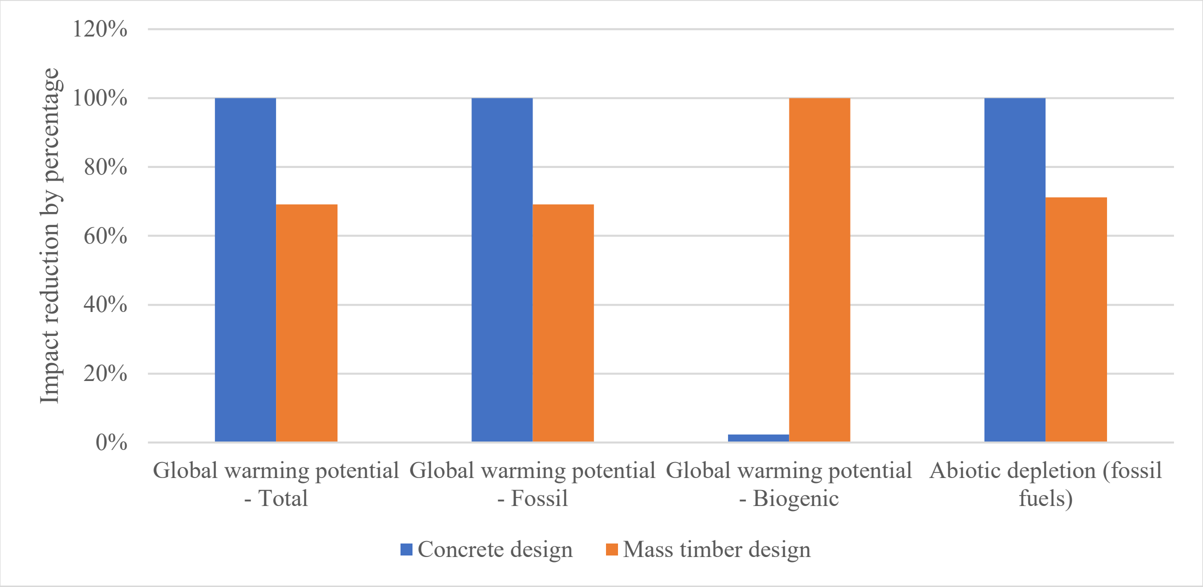


Figure 7.13 Comparison of four impact categories between concrete design and mass timber redesign for modules A4 – A5 per 1 m² of GFA

During the construction stage, the concrete design required considerably more fossil fuels than the mass timber design by approximately 29% per m^2 GFA. At the same time, the concrete design released more CO_2 emissions to the atmosphere in the construction stage than the mass timber design by 31% per m^2 GFA. In cast-in-place reinforced concrete building construction, significant onsite time and labour is exploited for the activities of temporary formwork installation, rebar placing, concrete pumping and concrete curing (Robertson et al., 2012). When factoring in the transport of crews to and from the construction site, the greater environmental impact of concrete building construction compared to mass timber construction becomes even more evident.

- **Use stage (modules B6 and B7)**

The Australian Government's commitment to achieving net zero GHG emissions by 2050 has initiated the transition to this legislated target. The 2023 Emissions Projections for Australia provide updated estimates on the country's GHG emissions trajectory through 2035 (DCCEEW, 2023). This report illustrates Australia's progress toward its 2030 emissions reduction goals by assessing the anticipated effects of policies and initiatives aimed at reducing emissions. In alignment with these national targets, this study's calculations for operational energy (module B6) reflect the Australian Net Zero goal. Table 7.20 presents the projected operational energy consumption over a 50-year lifespan for two designs.

Table 7.20 Operational GHG emissions of two designs

Operating Year	Year of Operation	Scope 2 & 3 combined GHG Emissions Factor ($kgCO_2e/kWh$)	Concrete design Operational emissions ($kgCO_2e/m^2$)	Mass timber design Operational emissions ($kgCO_2e/m^2$)	Emissions factor source
2024	1	0.63	82.16	82.29	(DCCEEW, 2023)
2025	2	0.56	73.03	73.15	(DCCEEW, 2023)
2026	3	0.42	54.77	54.86	(DCCEEW, 2023)

Operating Year	Year of Operation	Scope 2 & 3 combined GHG Emissions Factor (kgCO$_2$e/kWh)	Concrete design Operational emissions (kgCO$_2$e/m^2)	Mass timber design Operational emissions (kgCO$_2$e/m^2)	Emissions factor source
2027	4	0.32	41.73	41.80	(DCCEEW, 2023)
2028	5	0.3	39.12	39.19	(DCCEEW, 2023)
2029	6	0.3	39.12	39.19	(DCCEEW, 2023)
2030	7	0.2	26.08	26.12	(DCCEEW, 2023)
2031	8	0.11	14.35	14.37	(DCCEEW, 2023)
2032	9	0.06	7.82	7.84	(DCCEEW, 2023)
2033	10	0.02	2.61	2.61	(DCCEEW, 2023)
2034	11	0.03	3.91	3.92	(DCCEEW, 2023)
2035	12	0.03	3.91	3.92	(DCCEEW, 2023)
2036	13	0.028	3.65	3.66	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2037	14	0.026	3.39	3.40	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2038	15	0.024	3.13	3.13	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2039	16	0.022	2.87	2.87	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's

Operating Year	Year of Operation	Scope 2 & 3 combined GHG Emissions Factor ($kgCO_2e/kWh$)	Concrete design Operational emissions ($kgCO_2e/m^2$)	Mass timber design Operational emissions ($kgCO_2e/m^2$)	Emissions factor source
					emissions projections 2035 and assuming a net-zero electricity supply from 2050
2040	17	0.02	2.61	2.61	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2041	18	0.018	2.35	2.35	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2042	19	0.016	2.09	2.09	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2043	20	0.014	1.83	1.83	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2044	21	0.012	1.56	1.57	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and

Operating Year	Year of Operation	Scope 2 & 3 combined GHG Emissions Factor ($kgCO_2e/kWh$)	Concrete design Operational emissions ($kgCO_2e/m^2$)	Mass timber design Operational emissions ($kgCO_2e/m^2$)	Emissions factor source
					assuming a net-zero electricity supply from 2050
2045	22	0.010	1.30	1.31	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2046	23	0.008	1.04	1.04	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2047	24	0.006	0.78	0.78	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2048	25	0.004	0.52	0.52	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
2049	26	0.002	0.26	0.26	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050

Operating Year	Year of Operation	Scope 2 & 3 combined GHG Emissions Factor ($kgCO_2e/kWh$)	Concrete design Operational emissions ($kgCO_2e/m^2$)	Mass timber design Operational emissions ($kgCO_2e/m^2$)	Emissions factor source
2050 - 2073	27 - 50	-	-	-	Based on a linear scaling between Australian Government Department of Industry, Science, Energy and Resources (2023), Australia's emissions projections 2035 and assuming a net-zero electricity supply from 2050
	TOTAL (kg CO_2 eq/m² GFA)		**416.02**	**416.68**	

The table demonstrates the gradual reduction in GHG emissions over time for both concrete and mass timber building designs, reflecting Australia's emissions reduction initiatives and the expected progression toward net zero electricity supply by 2050. Initially, in 2024, the combined Scope 2 and 3 GHG emissions factors are high, resulting in significant operational emissions (82.16 kg CO_2 eq/m² GFA for concrete design and 82.29 kg CO_2 eq/m² GFA for mass timber design). However, as the emissions factor decreases over time due to the implementation of cleaner energy sources, the operational emissions for both designs decline correspondingly. For example, by 2030, the emissions factor drops to 0.2 kg CO_2 eq/kWh, resulting in emissions of only 26.08 kg CO_2 eq/m² GFA for concrete design and 26.12 kg CO_2 eq/m² GFA for mass timber design. Post 2035, emissions continue to decrease significantly, aligning with the assumption of a net zero electricity grid by 2050. By 2049, the emissions factor reaches near zero (0.002 kg CO_2 eq /kWh), and the operational emissions for both designs are minimized to just 0.26 kg CO_2 eq/m² GFA. The results illustrate the substantial emissions reductions achievable through a decarbonised energy grid and highlights the potential environmental benefits of adopting sustainable building materials in alignment with national net zero target. Table 7.21 presents the impact assessment results for operational energy consumption (module B6) per m² GFA over a 50-

year life cycle. The findings reveal that the fossil fuel depletion impacts and GHG emissions associated with the operational energy use of the mass timber design are 0.16% higher than those of the concrete design.

Table 7.21 Impact results for operational energy consumption per m^2 GFA of two designs over 50-year life cycle

Impact category	**Unit**	**Concrete design**	**Mass timber design**
Global warming potential - Total	kg CO_2 eq	440.62	441.32
Global warming potential - Fossil	kg CO_2 eq	416.02	416.68
Global warming potential - Biogenic	kg CO_2 eq	24.60	24.64
Abiotic depletion (fossil fuels)	MJ	15,253.67	15,277.83

Table 7.22 shows presents the impact assessment results for operational water consumption (module B7) per m² GFA over a 50-year life cycle. The results indicate that the fossil fuel depletion impacts and GHG emissions related to water consumption are identical for both the concrete and mass timber designs across all assessed categories.

Table 7.22 Impact results for operational water consumption of two designs over 50-year life cycle

Impact category	**Unit**	**Concrete design**	**Mass timber design**
Global warming potential - Total	kg CO_2 eq	8.11	8.11
Global warming potential - Fossil	kg CO_2 eq	7.85	7.85
Global warming potential - Biogenic	kg CO_2 eq	0.27	0.27
Abiotic depletion (fossil fuels)	MJ	150.55	150.55

- **End-of-life stage (modules C1 to C4)**

The impact results of the end-of-life stage for the two designs are shown in Table 7.23, Figure 7.14, and Figure 7.15.

Table 7.23 Associated impacts from end-of-life stage per 1 m^2 GFA of the two designs

End of life stage	Impact category	Unit	Concrete design	Mass timber design
C1	Global warming potential - Total	kg CO_2 eq	24.06	16.12
	Global warming potential - Fossil	kg CO_2 eq	24.05	16.12
	Global warming potential - Biogenic	kg CO_2 eq	3.46E-03	2.32E-03
	Abiotic depletion (fossil fuels)	MJ	337.28	225.98
C2	Global warming potential - Total	kg CO_2 eq	0.10	0.06
	Global warming potential - Fossil	kg CO_2 eq	0.10	0.06
	Global warming potential - Biogenic	kg CO_2 eq	-1.28E-05	-7.59E-06
	Abiotic depletion (fossil fuels)	MJ	1.57	0.93
C3	Global warming potential - Total	kg CO_2 eq	39.36	184.43
	Global warming potential - Fossil	kg CO_2 eq	39.27	8.25
	Global warming potential - Biogenic	kg CO_2 eq	8.92E-02	1.77E+02
	Abiotic depletion (fossil fuels)	MJ	480.86	102.08
C4	Global warming potential - Total	kg CO_2 eq	1.21	11.87
	Global warming potential - Fossil	kg CO_2 eq	1.21	11.30
	Global warming potential - Biogenic	kg CO_2 eq	9.07E-05	0.58
	Abiotic depletion (fossil fuels)	MJ	30.14	168.15

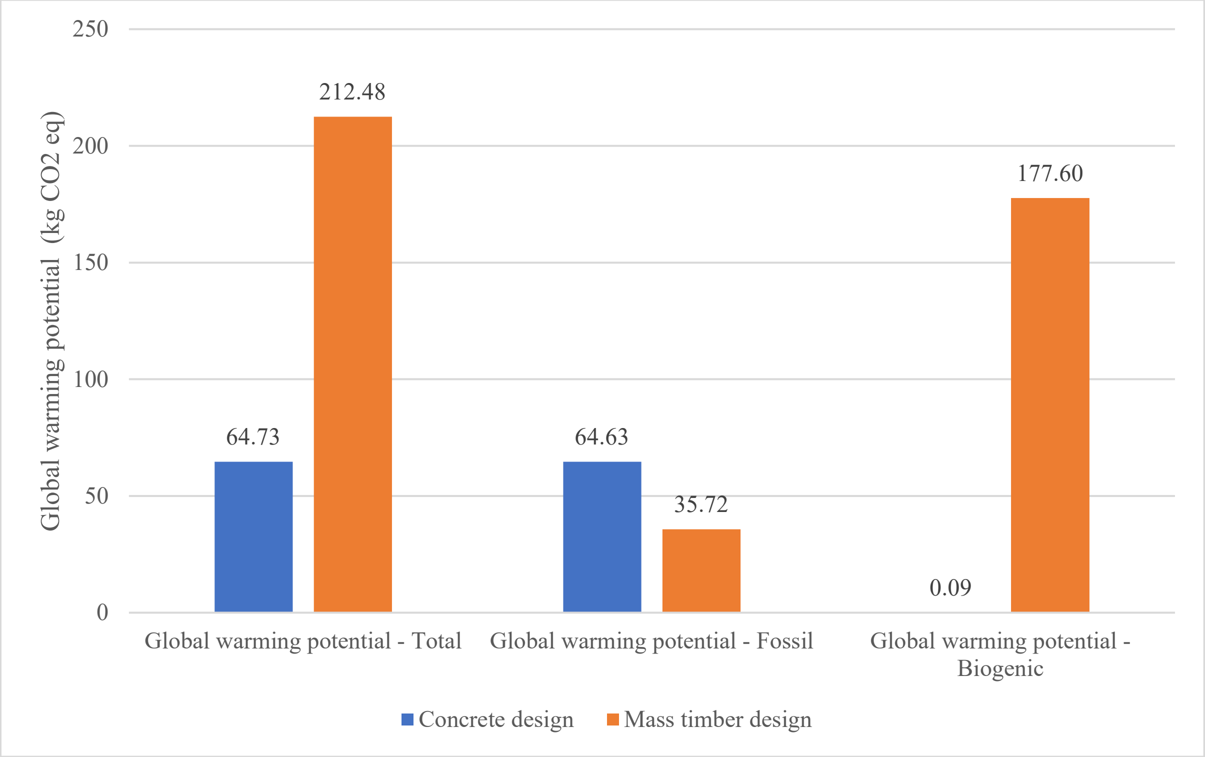


Figure 7.14 Associated CO_2 emissions from end-of-life stage (modules C1 – C4) per 1 m^2 GFA of the two designs.

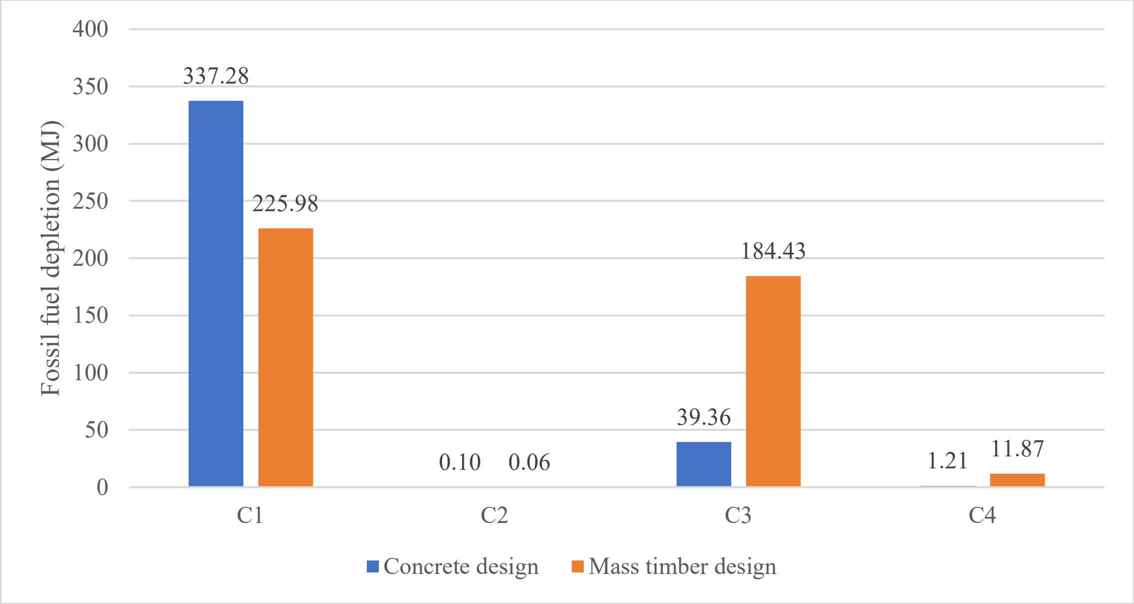


Figure 7.15: Fossil fuels consumption for end-of-life stage per 1 m^2 GFA of the two designs.

The total global warming potential and abiotic depletion (fossil fuels) of modules C1 – C4, mass timber design are higher than concrete design by 70% and 11%, respectively.

The global warming potential and abiotic depletion (fossil fuels) for demolition machinery of two designs account for 4% – 19% and 54% – 89% respectively, while transport energy constitutes only less than 1%. Since concrete design requires more resources and energy for demolition compared to mass timber design, the global warming potential and fossil fuel depletion associated with demolishing concrete are 33% higher than those of mass timber.

- **Benefits and loads beyond building lifetime (module D) per m^2 GFA**

Table 7.24: Benefits and loads beyond building lifetime per m^2 GFA

Impact category	**Unit**	**Concrete design**	**Mass timber design**
Global warming potential - Total	kg CO_2 eq	-164.49	-139.90
Global warming potential - Fossil	kg CO_2 eq	-164.63	-140.24
Global warming potential - Biogenic	kg CO_2 eq	1.45E-01	2.94E-01
Abiotic depletion (fossil fuels)	MJ	-1,283.29	-2,194.56

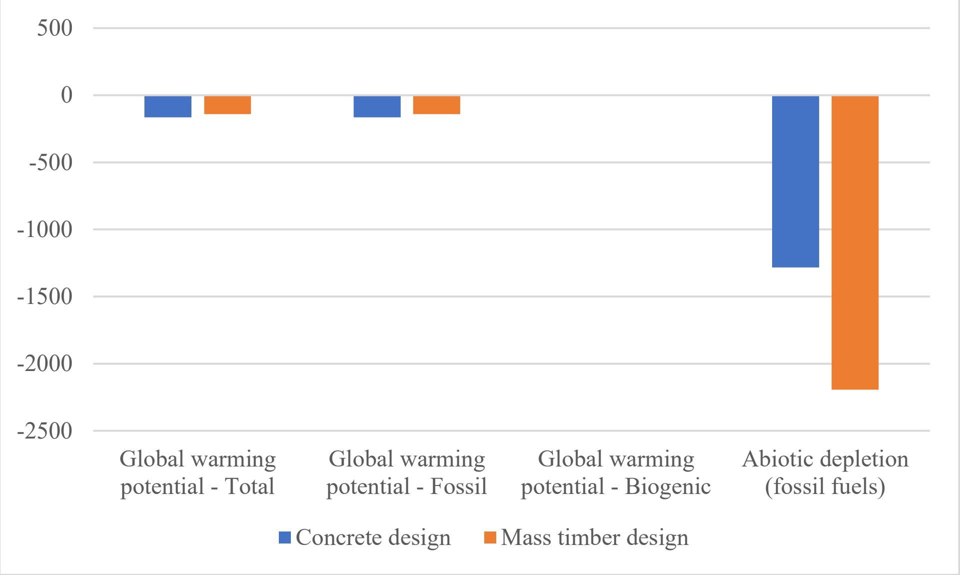


Figure 7.16: Benefits and loads beyond building lifetime per m^2 GFA

The recycling rate of steel and concrete is significantly higher than that of timber, resulting in greater CO_2 emissions avoidance benefits from the recycling of the concrete design compared to the alternative mass timber design, even when accounting for the benefits of landfilled timber. However, because waste mass timber elements are utilised as biomass for energy recovery, the mass timber design achieves a 42% greater avoidance of fossil fuel depletion compared to the concrete design.

i. Sensitivity analysis

The main purpose of sensitivity analysis is to study the sensitivity to uncertainty factors and the robustness of assumptions and results in LCA (Wei et al., 2015). Due to the limited number of CLT manufacturers in Australia, material decision-making can be impacted by availability, which in turn affects the total life cycle energy and associated CO_2 emissions of mass timber projects. To assess the influence of CLT transportation on the construction stage and its further impact on life cycle energy consumption and associated CO_2 emissions, this analysis assumes a transport distance of 565 km from the manufacturer to the construction site. Table 7.25 compares eight environmental impact indicators, including CO_2 emissions and fossil fuel consumption, for the construction stage between the original concrete design and the mass timber redesign under two scenarios: the original transport distance of 20 km for CLT panels and the newly assumed distance of 565 km. The results show that transportation significantly affects CO_2 emissions and fossil fuel consumption during the construction stage. When the transport distance for CLT panels increases by 565 km, CO_2 emissions and fossil fuel consumption are 27% and 25% higher than those of the concrete design, respectively. However, despite this substantial increase, the impact of transportation during the construction stage remains minor compared to the overall life cycle, including the product stage, end-of-life phase, and the benefits and loads beyond the building life cycle (less than 5%). Therefore, the transport distance has an insignificant effect on the overall LCA results.

Table 7.25 Influence of CLT transport from manufacturer to construction site on environmental impacts from construction stage

Impact category	**Unit**	**Concrete design**	**Mass timber design**	**Mass timber design with 565 km CLT transport distance**
Global warming potential - Total	kg CO_2 eq	5.54	3.83	6.32
Global warming potential - Fossil	kg CO_2 eq	5.54	3.83	6.32
Global warming potential - Biogenic	kg CO_2 eq	8.68E-05	3.71E-03	3.39E-03
Abiotic depletion (fossil fuels)	MJ	80.42	57.26	94.88

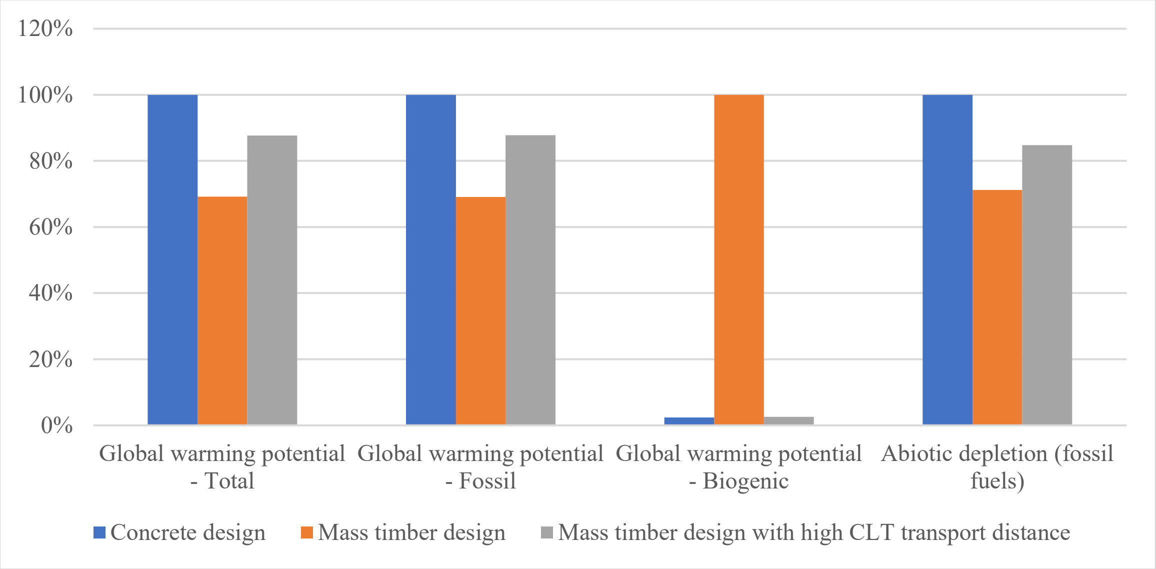


Figure 7.17 Influence of CLT transport from manufacturer to construction site on environmental impacts from construction stage

j. Benchmarking

Skullestad et al. (2016) investigated the GHG emissions reduction potential in the building industry by substituting mass timber for conventional structural materials like concrete and steel. The study compared the GWP – Total of 3- to 21-story reinforced concrete buildings with alternative mass timber structures, using both attributional and consequential modelling approaches. In the consequential approach, Module D was included to account for avoided impacts from the recycling and reuse of waste materials at the end of the buildings' life cycle. Similar to the assumptions in this thesis regarding end-of-life scenarios, Skullestad et al.'s study assumed that timber was incinerated to replace natural gas. However, the recycling rate differed – 90% in Skullestad et al.'s study compared to 49% in this thesis, due to differences in waste management regulations between Norway and Australia.

In addition to Skullestad et al., the study by Kumar et al. (2024) contributes valuable benchmarking data by comparing the embodied environmental impacts of mid- and high-rise residential buildings constructed using mass timber, structural steel, and reinforced concrete. Their study modelled three building heights (8, 12, and 18 storeys) within a cradle-to-grave system boundaries, including Module D. While the structural design was kept functionally equivalent across materials, the study revealed that mass timber buildings consistently demonstrated GWP than their reinforced concrete buildings. Their results are shown in Table 7.26 and provide additional context for this thesis's findings, with reinforced concrete GWP values ranging from 338.95 to 352.18 kg CO_2 eq/m² GFA, and corresponding mass timber values between -28.83 and -79.23 kg CO_2 eq/m² GFA, highlighting substantial reductions attributed to biogenic carbon storage and material substitution benefits.

Table 7.26 Comparison with other studies

	Number of storeys	**Concrete design (Modules A1 - A3 & D) GWP - Total (kg CO_2 eq/m^2 GFA)**	**Mass timber design (Modules A1 - A3 & D) GWP - Total (kg CO_2 eq/m^2 GFA)**
This thesis	5	76.12	-260.26
Skullestad et al. (2016)	3	151.1	-139.7
	7	138.5	-142.8
	12	139	-167.4
	21	403.8	-226.8
Kumar et al. (2024)	8	352.18	-79.23
	12	338.95	-57.31
	18	349.89	-28.83

The results across all three studies consistently affirm the environmental advantages of mass timber construction over traditional RC systems. The inclusion of biogenic carbon (Module D) in the LCA framework captures the critical role of mass timber as a carbon sink, sequestering CO_2 during forest growth and retaining that storage throughout the material's life in the built environment. This mechanism significantly offsets emissions generated during upstream and downstream processes. By incorporating biogenic carbon flows and realistic end-of-life scenarios, these studies collectively demonstrate the capacity of mass timber to deliver net carbon savings, thereby reinforcing its role as a viable strategy for decarbonising the building sector and advancing toward more sustainable construction practices.

7.5.2 Calculation of initial construction cost, operational cost and end-of-life cost

This section aims to explore cost performance of the two designs of traditional concrete and alternative mass timber over a 50-year lifespan. The cost of the two designs is compared in terms of initial cost, operational energy cost and end-of-life disposal cost.

Non-construction costs such as land purchase, design consultant and legal services are omitted from this study. In addition, interior fit out and maintenance cost are not considered, as explained in section 6.3.2.

$$LCC = PV_{CP.C} + PV_{OP.C} + PV_{EoL.C} \text{ (Robati et al., 2018)} \quad (7.6)$$

Where

LCC: Life cycle cost

PV_{CP}: Present value of capital cost (or initial cost including material, transport and construction costs)

$PV_{OP.C}$: Present value of operational cost during 50 years of building lifetime

$PV_{EoL.C}$: Present value of end-of-life disposal costs.

a. Calculation of initial cost

The initial cost of a building comprises expenses associated with building materials and construction activities such as labour and construction and installation costs. Input data for the calculation of initial cost came from different sources. Material quantities were the same as used in section 7.4.2. The building material price list, construction time and labour cost were acquired from a variety of sources including material suppliers, costing guidelines, peer-reviewed literature, a professional consultant and two site visits to a residential building project and a commercial office building project in Sydney, Australia (Forest and Wood Products Australia, 2019a; John et al., 2011; Rawlinsons, 2018; Robati et al., 2018; Waugh Thistleton Architects, 2018a). Table 7.27 presents the base unit costs for the primary materials used in both the concrete and mass timber design options.

Table 7.27 Material base cost

Materials	**Unit**	**Base cost**
Concrete 50 MPa	m^3	$248.00
Concrete 40 MPa	m^3	$246.00
Concrete 32 MPa	m^3	$233.00
Concrete 25 MPa	m^3	$221.00
Rebar Steel	t	$770.00
Steel - Structural Sections & Beams	t	$945.00
CLT	m^3	$810.00
LVL	m^3	$603.80
Glulam	m^3	$445.50
Gypsum Plasterboard	sheet	$43.20
Concrete pipe 600 mm	m	$195.10
Concrete pipe 1200 mm	m	$895.50
Concrete pipe 1500 mm	m	$1,408.00
Concrete pipe 450 mm	m	$123.00
Concrete pipe 900 mm	m	$542.30
Concrete pipe 1125 mm	m	$714.60
Martini Absorb HD 1200x15m (1 Roll 25 mm thickness)	$18m^2$	$137.37

The lighter weight of the mass timber design significantly reduces the extent of groundworks and the volume of heavy materials, such as concrete and steel, required for construction. This results in savings in both material quantities and associated costs when compared to a conventional reinforced concrete design. In addition, mass timber structures require less formwork than traditional concrete structures, further reducing material use. Although the unit cost of CLT (\$810/m³) is approximately 69.4% higher than the cost of 50 MPa concrete (\$248/m³), the smaller material volumes needed for the mass timber option offset much of this difference.

When the total material costs for the building are considered (Table 7.28), including all elements, the mass timber design totals \$4,335,306.36, compared to \$4,340,988.07 for the concrete design. This represents a marginal difference of approximately 0.13%, with the mass timber option being slightly less expensive overall. This percentage is calculated from the total material cost for the complete building in each scenario, not from a per-unit volume comparison. The result demonstrates that, despite the higher price per cubic metre of CLT, the reduced overall material requirements of the mass timber design make it cost competitive with concrete.

Table 7.28 Material cost of concrete design and alternative mass timber design

Element	**Mass timber design**	**Concrete design**
Substructure	\$752,956.65	\$857,922.65
Columns	\$252,151.46	\$110,807.30
Upper Floors	\$2,257,126.69	\$2,610,474.09
Roof	\$536,707.27	\$235,807.46
External Walls	\$102,856.71	\$241,873.63
Internal Walls	\$180,386.80	\$226,044.45
Ceiling Finishes	\$253,120.78	\$58,058.49
Total	**\$4,335,306.36**	**\$4,340,988.07**

In terms of construction program, the installation speed of the mass timber structure is faster than a conventional concrete system. When the first level is completed, prefabricated mass timber panels are immediately craned and lifted into place for quick connection using hand-held tools. Conventional in-situ concrete construction includes formwork installation, placing reinforcing bars, pumping and pouring concrete as well as waiting time for concrete to cure before starting to erect the next floor. Subsequently, mass timber systems are quicker to build than traditional concrete systems. Concrete structures can be constructed at a rate of 500 m^2 per week compared to the mass timber system installation rate of 86 m^2 per day with 50 – 70% fewer crews than concrete structures (Forest and Wood Products Australia, 2019a; Waugh Thistleton Architects, 2018a). Table 7.29 shows details of other related costs to calculate the construction cost of the two designs, including construction time, number of crews, wage rate, base rate of concrete pumping and tower crane hiring.

Table 7.29 Details of related costs for the construction of the concrete design and mass timber design

	Concrete design	**Mass timber design**
Construction time (days)	130	96
Average wage rate of construction labourer ($/hour/person)	$35.63	$35.63
Number of crews onsite	16	8
Working hours per day (hours)	8	8
Concrete pumping rate ($/per cubic metre pumped)	$7	$7
Tower crane hire rate ($/per month)	$15,000	$15,000

Overall, the total initial cost for the construction of the concrete design is 4.1% higher than that of the mass timber design (Table 7.30).

Table 7.30 Total other related costs and initial cost of the two designs

	Concrete design	**Mass timber design**
Labour cost	$592,883.20	$218,910.72
Crane cost	$97,500.00	$288,000.00
Pumping	$31,565.10	$12,544.00
Total other related costs	**$721,948.30**	**$519,454.72**
Total material cost	**$4,340,988.07**	**$4,335,306.36**
Total initial cost	**$5,062,936.37**	**$4,854,761.08**

b. Calculation of operational cost

Operational costs are calculated on an annual basis using prevailing market rates and then converted into a 50-year total using the present value method with a discount rate of 8%. The discount rate reflects the time value of money, recognising that future expenses have a lower worth today due to factors such as inflation, the opportunity cost of capital, and investment risk. The choice of 8% is consistent with values commonly applied in Australian building life cycle cost studies, where rates between 6% and 10% are typical depending on the nature of the project, economic conditions, and perceived financial risks over the building's life (John et al., 2011; Thomas, 2015). This rate accounts for a combination of the expected long-term real interest rate and a margin to address uncertainties in operational costs over a 50-year period. It also reflects a balanced and conservative approach in line with industry practice for evaluating sustainable building and infrastructure projects, ensuring comparability with other studies in the Australian context.

$$PV_{OP.C} = \sum_{n=1}^{50} \left(C_n \frac{1}{(1+r)^n} \right) \quad \text{(John et al., 2011; Robati et al., 2018) (7.7)}$$

Where

$PV_{OP.C}$: Present value of operational cost

$C_{1,2\ldots n}$: Operational cost in year 1, 2, …n

r: discount rate

n: building lifetime.

The electricity cost is calculated based on the market rate in New South Wales, Australia. Table 7.31 shows the results of the annual operation cost for the concrete and alternative mass timber designs.

Table 7.31 Annual operational cost for concrete and alternative mass timber buildings

Total annual operational cost			
Calculation of annual electricity usage		**Concrete building**	**Mass timber building**
Average electricity per quarter (kWh)		425,047	425,721
First 4000 kWh usage per quarter	28 cents per kWh	$1,120.00	$1,120.00
Next 4000 kWh usage per quarter	27 cents per kWh	$1,080.00	$1,080.00
Remaining usage per quarter	24 cents per kWh	$100,091.36	$100,252.92
Electricity cost per quarter		**$102,291.36**	**$102,452.92**
Annual operational cost (I)		**$409,165.46**	**$409,811.69**

Table 7.32 Operational cost over 50-year lifetime

Year	Factor for discount rate 8%	Concrete design	Mass timber design
1	0.926	$378,856.91	$379,455.27
2	0.857	$350,793.43	$351,347.47
3	0.794	$324,808.73	$325,321.73
4	0.735	$300,748.83	$301,223.83
5	0.681	$278,471.14	$278,910.95
6	0.630	$257,843.64	$258,250.88
7	0.583	$238,744.12	$239,121.19
8	0.540	$221,059.37	$221,408.51
9	0.500	$204,684.60	$205,007.88
10	0.463	$189,522.78	$189,822.11
11	0.429	$175,484.05	$175,761.21
12	0.397	$162,485.23	$162,741.86
13	0.368	$150,449.29	$150,686.91
14	0.340	$139,304.90	$139,524.92
15	0.315	$128,986.02	$129,189.74
16	0.292	$119,431.50	$119,620.13
17	0.270	$110,584.72	$110,759.38
18	0.250	$102,393.26	$102,554.98
19	0.232	$94,808.57	$94,958.31
20	0.215	$87,785.72	$87,924.36
21	0.199	$81,283.07	$81,411.45
22	0.184	$75,262.10	$75,380.97
23	0.170	$69,687.13	$69,797.19
24	0.158	$64,525.12	$64,627.03
25	0.146	$59,745.48	$59,839.84
26	0.135	$55,319.89	$55,407.26
27	0.125	$51,222.12	$51,303.02
28	0.116	$47,427.89	$47,502.80
29	0.107	$43,914.71	$43,984.07
30	0.099	$40,661.77	$40,725.99
31	0.092	$37,649.79	$37,709.25
32	0.085	$34,860.92	$34,915.97
33	0.079	$32,278.63	$32,329.61

Year	Factor for discount rate 8%	Concrete design	Mass timber design
34	0.073	$29,887.62	$29,934.82
35	0.068	$27,673.72	$27,717.43
36	0.063	$25,623.81	$25,664.28
37	0.058	$23,725.75	$23,763.23
38	0.054	$21,968.29	$22,002.99
39	0.050	$20,341.01	$20,373.14
40	0.046	$18,834.27	$18,864.01
41	0.043	$17,439.14	$17,466.68
42	0.039	$16,147.35	$16,172.85
43	0.037	$14,951.25	$14,974.86
44	0.034	$13,843.75	$13,865.61
45	0.031	$12,818.29	$12,838.53
46	0.029	$11,868.78	$11,887.53
47	0.027	$10,989.61	$11,006.97
48	0.025	$10,175.57	$10,191.64
49	0.023	$9,421.82	$9,436.70
50	0.021	$8,723.91	$8,737.69
Total energy cost for 50 years		**$5,005,519.35**	**$5,013,425.04**

Table 7.32 shows the operational cost over a 50-year lifetime using an 8% discount rate. The total energy cost over 50 years is $5,005,519.35 for the concrete design and $5,013,425.04 for the mass timber design. The overall difference is 0.16%.

To assess the effect of the discount rate on NPV calculations, a sensitivity analysis was conducted using lower (6%) and higher (10%) discount rates. At 6%, total 50-year energy costs are $6,449,208.93 (concrete) and $6,459,394.78 (mass timber) (Table 7.33). At 10%, total 50-year energy costs are $4,056,799.61 (concrete) and $4,063,206.90 (mass timber) (Table 7.34).

Table 7.33 Operational Cost over a 50-Year Lifetime Using a 6% Discount Rate

Year	Factor for discount rate 6%	Concrete design	Mass timber design
1	0.943	$386,005.15	$386,614.80
2	0.890	$364,155.80	$364,730.95
3	0.840	$343,543.21	$344,085.80
4	0.792	$324,097.37	$324,609.24
5	0.747	$305,752.23	$306,235.14
6	0.705	$288,445.50	$288,901.07
7	0.665	$272,118.40	$272,548.18
8	0.627	$256,715.47	$257,120.93
9	0.592	$242,184.41	$242,566.91

Year	Factor for discount rate 6%	Concrete design	Mass timber design
10	0.558	$228,475.85	$228,836.71
11	0.527	$215,543.26	$215,883.69
12	0.497	$203,342.70	$203,663.86
13	0.469	$191,832.73	$192,135.71
14	0.442	$180,974.28	$181,260.11
15	0.417	$170,730.45	$171,000.10
16	0.394	$161,066.46	$161,320.85
17	0.371	$151,949.49	$152,189.48
18	0.350	$143,348.58	$143,574.98
19	0.331	$135,234.51	$135,448.10
20	0.312	$127,579.72	$127,781.22
21	0.294	$120,358.23	$120,548.32
22	0.278	$113,545.50	$113,724.83
23	0.262	$107,118.40	$107,287.58
24	0.247	$101,055.09	$101,214.70
25	0.233	$95,334.99	$95,485.56
26	0.220	$89,938.67	$90,080.72
27	0.207	$84,847.80	$84,981.81
28	0.196	$80,045.10	$80,171.52
29	0.185	$75,514.24	$75,633.51
30	0.174	$71,239.85	$71,352.37
31	0.164	$67,207.41	$67,313.55
32	0.155	$63,403.21	$63,503.35
33	0.146	$59,814.35	$59,908.82
34	0.138	$56,428.63	$56,517.76
35	0.130	$53,234.56	$53,318.64
36	0.123	$50,221.28	$50,300.60
37	0.116	$47,378.57	$47,453.40
38	0.109	$44,696.76	$44,767.36
39	0.103	$42,166.76	$42,233.36
40	0.097	$39,779.96	$39,842.79
41	0.092	$37,528.27	$37,587.54
42	0.087	$35,404.02	$35,459.94
43	0.082	$33,400.02	$33,452.77
44	0.077	$31,509.46	$31,559.22
45	0.073	$29,725.90	$29,772.85
46	0.069	$28,043.30	$28,087.59
47	0.065	$26,455.95	$26,497.73
48	0.061	$24,958.44	$24,997.86
49	0.058	$23,545.70	$23,582.89
50	0.054	$22,212.92	$22,248.01
Total energy cost for 50 years		**$6,449,208.93**	**$6,459,394.78**

Table 7.34 Operational Cost over a 50-Year Lifetime Using a 10% Discount Rate

Year	Factor for discount rate 10%	Concrete design	Mass timber design
1	0.909	$371,968.60	$372,556.08
2	0.826	$338,153.27	$338,687.35
3	0.751	$307,412.06	$307,897.59
4	0.683	$279,465.51	$279,906.90
5	0.621	$254,059.56	$254,460.82
6	0.564	$230,963.23	$231,328.02
7	0.513	$209,966.58	$210,298.20
8	0.467	$190,878.71	$191,180.18
9	0.424	$173,526.10	$173,800.16
10	0.386	$157,751.00	$158,000.15
11	0.350	$143,410.00	$143,636.50
12	0.319	$130,372.72	$130,578.63
13	0.290	$118,520.66	$118,707.85
14	0.263	$107,746.05	$107,916.23
15	0.239	$97,950.96	$98,105.66
16	0.218	$89,046.33	$89,186.96
17	0.198	$80,951.20	$81,079.06
18	0.180	$73,592.00	$73,708.24
19	0.164	$66,901.82	$67,007.49
20	0.149	$60,819.84	$60,915.90
21	0.135	$55,290.76	$55,378.09
22	0.123	$50,264.33	$50,343.72
23	0.112	$45,694.84	$45,767.01
24	0.102	$41,540.77	$41,606.38
25	0.092	$37,764.33	$37,823.98
26	0.084	$34,331.21	$34,385.44
27	0.076	$31,210.19	$31,259.49
28	0.069	$28,372.90	$28,417.72
29	0.063	$25,793.55	$25,834.29
30	0.057	$23,448.68	$23,485.72
31	0.052	$21,316.98	$21,350.65
32	0.047	$19,379.07	$19,409.68
33	0.043	$17,617.34	$17,645.17
34	0.039	$16,015.76	$16,041.06
35	0.036	$14,559.79	$14,582.78
36	0.032	$13,236.17	$13,257.07
37	0.029	$12,032.88	$12,051.89
38	0.027	$10,938.98	$10,956.26
39	0.024	$9,944.53	$9,960.24
40	0.022	$9,040.48	$9,054.76
41	0.020	$8,218.62	$8,231.60
42	0.018	$7,471.47	$7,483.27

Year	Factor for discount rate 10%	Concrete design	Mass timber design
43	0.017	$6,792.25	$6,802.98
44	0.015	$6,174.77	$6,184.52
45	0.014	$5,613.43	$5,622.29
46	0.012	$5,103.12	$5,111.18
47	0.011	$4,639.20	$4,646.52
48	0.010	$4,217.45	$4,224.11
49	0.009	$3,834.05	$3,840.10
50	0.009	$3,485.50	$3,491.00
Total energy cost for 50 years		**$4,056,799.61**	**$4,063,206.90**

The results confirm that the difference between the two designs remains 0.16% under all discount rate scenarios.

c. Calculation of end-of-life demolition cost

Demolition costs are costs associated with labour, plants and trucks used during the demolition process. In this study, costs for labour, plants and truck hiring are calculated based on the market rate. Other costs related to insurance, administration and maintenance of equipment as well as profits from selling recycled materials are not taken into account. Demolition expenses are summarised in Table 7.33.

Table 7.35 Demolition expenses of the concrete design and alternative mass timber design

Demolition expenses	Concrete design	Mass timber design
Labour	$306,633.60	$160,992.00
Excavator	$327,600.00	$240,800.00
Wheel loader	$25,740.00	$18,920.00
Truck	$56,160.00	$41,280.00
Total demolition expenses	**$716,133.60**	**$461,992.00**

Because a mass timber structure is mostly built with lightweight prefabricated timber elements, the demolition process requires less labour and equipment than that of a conventional concrete structure. The demolition cost of the concrete structure and alternative mass timber structure is \$55 per m^2 and \$35.44 per m^2, respectively. The results indicate that the demolition expenses of the concrete structure cost 35% more than the demolition process of a mass timber structure.

7.6 Discussion

This section discusses the assessment results of the main criteria identified in Chapter 6 for the sustainable non-residential development (SNRD) model. Three main criteria of quality performance, cost performance and environmental performance were derived from the analysis of the literature review and semi-structured interviews with Australian construction practitioners. The validation of the SNRD model has been verified by using mass timber as an alternative to traditional heavy concrete design. A comparison between the material flows of the two designs during their lifetime in terms of energy demand, including energy used for building construction, operation and demolition stages and associated CO_2 emissions, was investigated. The following sections discuss the results of life cycle energy demand and associated CO_2 emissions as well as life cycle cost of the two designs. These results allow further discussion to determine how mass timber as a sustainable building material behaves against the selected main criteria of the SNRD model.

7.6.1 Quality performance

Structural performance, durability, fire performance, acoustic performance, aesthetics and thermal performance were identified as sub-criteria of quality performance. Among these sub-criteria, thermal performance was selected to test the performance of the alternative mass timber design against a conventional concrete design in the sustainable non-residential development model. The alternative mass timber structure was redesigned with thermal performance as close as possible to that of the conventional concrete design. The two designs were then used as the case studies to investigate thermal performance. The results showed that life cycle operational energy consumption of the two designs is fairly equal (Table 7.34).

Table 7.36 Annual operational energy consumption and total operational energy consumption in 50-year lifetime

	Annual operational energy consumption	**Operational energy consumption in 50 years**
Concrete design	130.41 kWh/m^2 GFA	6,520.63 kWh/m^2 GFA
Mass timber redesign	130.62 kWh/m^2 GFA	6,530.96 kWh/m^2 GFA

This has shown that mass timber structure can achieve the same thermal performance as a traditional concrete structure.

7.6.2 Cost performance

The calculations for the construction cost, operation cost and end-of-life demolition cost were made in order to understand how mass timber performs against concrete in non-residential project development. The results from the semi-structured interviews revealed that early engagement among design teams, the offsite manufacturer and the builder could significantly enhance the design and subsequently improve the initial cost of mass timber structures even though the supply chain of CLT in Australia is not as well-established as that of concrete. Table 7.35 presents the total life cycle cost in 50 years of the concrete design and alternative mass timber redesign.

Table 7.37 Life cycle cost of concrete design and alternative mass timber redesign

Life cycle cost of concrete design and mass timber redesign
50-year lifetime with 8% discount rate

		Concrete design	**Mass timber redesign**
Initial cost (I)	$	$5,062,936.37	$4,854,761.08
Annual operational cost	$/year	$409,165.46	$409,811.69
Operational cost for 50 years (II)	$PV	$5,005,519.35	$5,013,425.04

Life cycle cost of concrete design and mass timber redesign 50-year lifetime with 8% discount rate			
		Concrete design	**Mass timber redesign**
End-of-life demolition cost (III)	$	$716,133.60	$461,992.00
Total life cycle cost (I)+(II)+(III)	$	**$10,784,589.32**	**$10,330,178.12**

The results demonstrated that the total life cycle cost of the alternative mass timber redesign outperforms that of the concrete design in the 50-year lifetime. The total life cycle cost of the concrete design is higher than the mass timber redesign by approximately 4%. Hence, even if maintenance costs were accounted for, the total life cycle cost of the alternative mass timber design would be still lower than the concrete design due to the small portion of the maintenance cost in the total life cycle cost. Additionally, advancement in timber engineering may play a crucial role in increasing the durability of engineered wood products and thus reducing maintenance cost over a 50-year lifetime.

7.6.3 Environmental performance

In the sustainable non-residential development model, fossil fuel depletion and associated CO_2 emissions were tested to investigate the performance of the concrete design and alternative mass timber redesign. Three major energy contributors and associated CO_2 emissions were taken into account in the model, including initial embodied energy, operational energy and water consumption, end-of-life and benefits and loads beyond building lifetime. Table 7.36 and Figure 7.18 reveals the total fossil fuel depletion for the concrete design and alternative mass timber redesign.

Table 7.38 Total life cycle fossil fuel depletion of two designs

Life cycle stage	**Unit**	**Concrete design**	**Mass timber redesign**
Product stage	MJ/m^2 GFA	3,076.25	2,078.79
Construction stage	MJ/m^2 GFA	80.42	57.26

Life cycle stage	**Unit**	**Concrete design**	**Mass timber redesign**
Use stage	MJ/m^2 GFA	15,404.23	15,428.38
End-of-life	MJ/m^2 GFA	377.95	422.34
Benefits and loads beyond building lifetime	MJ/m^2 GFA	-1,283.29	-2,194.56
Life cycle fossil fuel depletion	**MJ/m^2 GFA**	**17,655.56**	**15,792.22**
Life cycle fossil fuel depletion of whole building	GJ	**230,193.24**	**205,898.92**

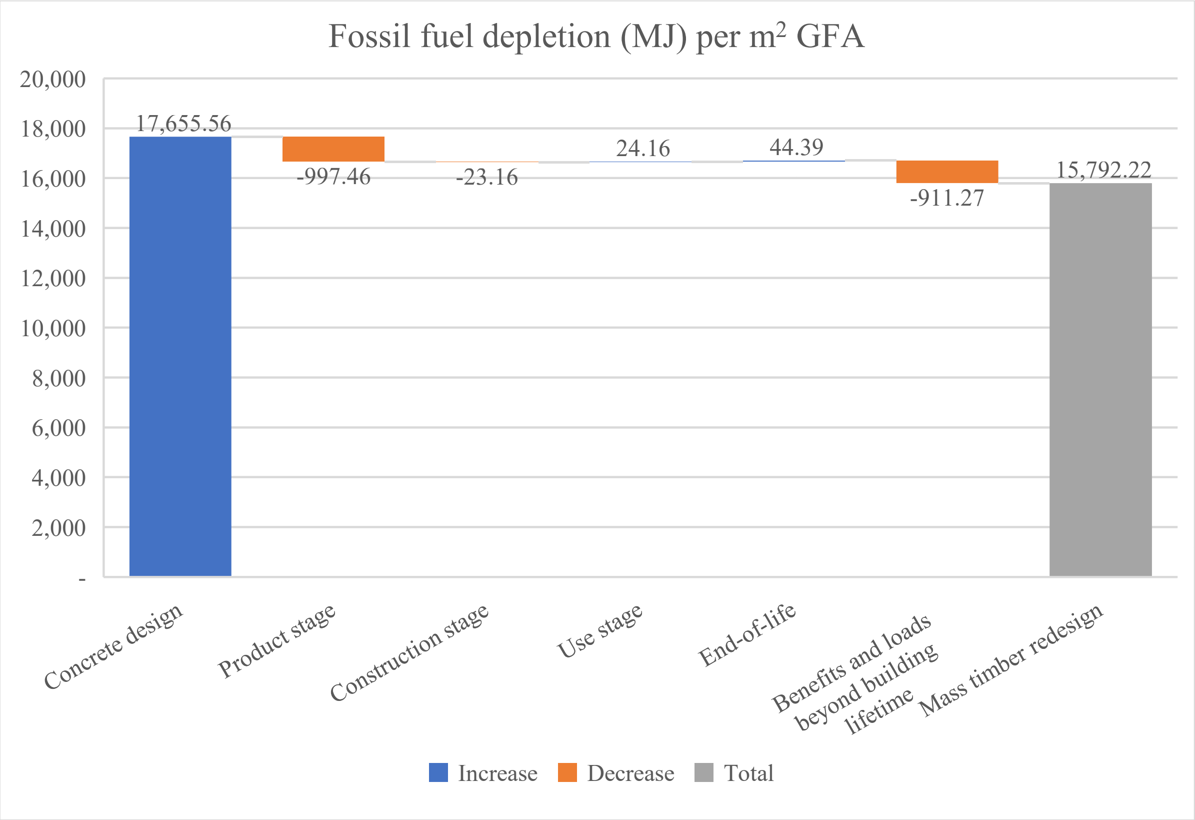


Figure 7.18 Total life cycle fossil fuel depletion of two designs

The results show that fossil fuel depletion for the product stage, construction stage and end-of-life stage of concrete design is higher than the alternative mass timber redesign by 29% – 32%. The total lifecycle fossil fuel depletion of concrete design is higher than that of the alternative mass timber design by 11%, primarily due to the higher recycling rate of concrete and steel (Table 7.36). The total life cycle CO_2 emissions of the concrete design are significantly higher than the alternative mass timber redesign by 32% (Table 7.37 and Figure 7.19). This highlights the substantial environmental impact of manufacturing concrete and reinforcing steel, particularly in terms of CO_2 emissions.

Table 7.39 Total life cycle CO_2 emissions from the two designs

Life cycle stage	Unit	Concrete design	Mass timber redesign
Product stage	kg CO_2 eq/m^2 GFA	240.61	-120.36
Construction stage	kg CO_2 eq/m^2 GFA	5.54	3.83
Use stage	kg CO_2 eq/m^2 GFA	448.73	449.43
End-of-life	kg CO_2 eq/m^2 GFA	64.73	212.48
Benefits and loads beyond building lifetime	kg CO_2 eq/m^2 GFA	-164.49	-139.90
Total life cycle CO_2 emissions	**kg CO_2 eq/m^2 GFA**	**595.13**	**405.49**
Total life cycle CO_2 emissions of whole building	**t CO_2 eq**	**7,758.69**	**5,286.41**

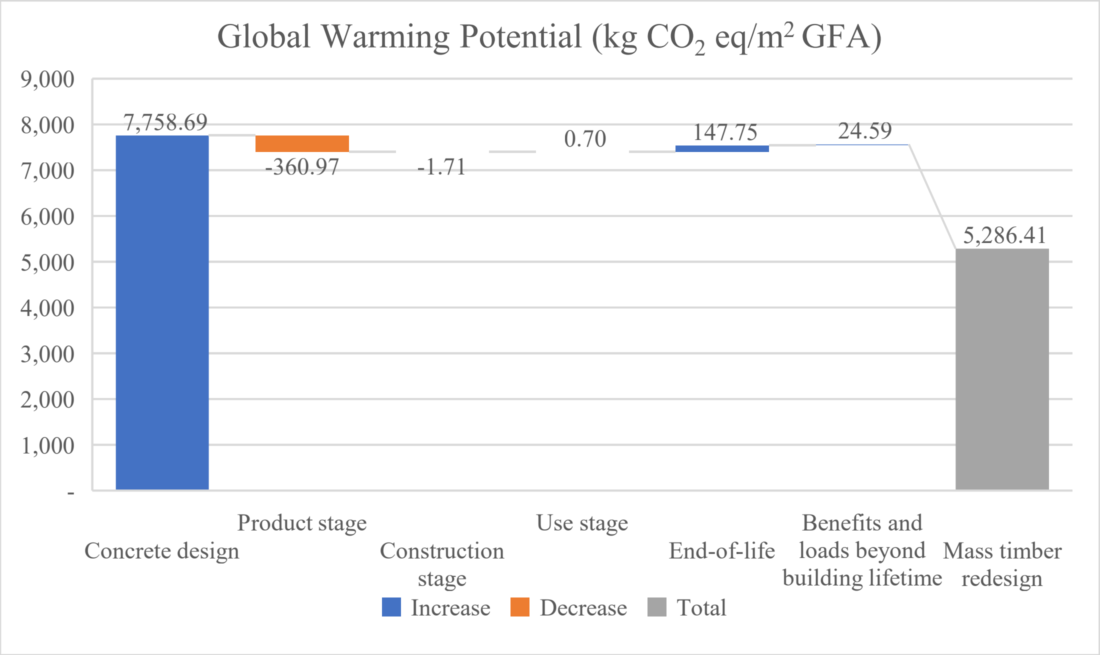


Figure 7.19 Total life cycle CO_2 emissions from the two designs

On the whole, the mass timber design outperforms the traditional heavy design in terms of environmental performance when considering the two largest contributors to the environmental impact including fossil fuels consumption and CO_2 emissions.

7.7 Conclusion

This chapter discussed the use of mass timber in the sustainable non-residential development model. Through the use of an actual conventional concrete office case study design and the alternative mass timber redesign, this chapter tested three main criteria of thermal performance, cost performance and environmental performance, in order to investigate how mass timber performed against concrete in non-residential development. The assessment demonstrated the following results:

- A mass timber structure can achieve equivalent thermal performance to a concrete structure. This allowed equitable comparison for life cycle non-renewable fossil energy demand and associated life cycle CO_2 emissions as well as the life cycle cost between the two designs.
- Although the operational energy cost of the mass timber structure is slightly higher than the concrete structure (by approximately 0.16%), the life cycle cost of the mass timber office structure is lower than the traditional reinforced concrete structure when considering construction, operation and end-of-life demolition stages. Both construction and end-of-life costs of the mass timber structure are lower than for a traditional concrete structure as a result of the lightweight structure of the mass timber design and the design for manufacture and assembly (DfMA) program. The mass timber structure minimised the use of equipment, material, construction time and labour, compared to concrete structure. Overall, the verification has demonstrated that a mass timber non-residential structure can offer comparable cost to a traditional concrete non-residential structure.
- Life cycle fossil fuel depletion and associated CO_2 emissions were used to compare the environmental performance of the selected case study buildings. The mass timber non-residential structure outperforms a

traditional concrete structure in terms of environmental performance, especially since mass timber elements can store carbon even beyond the building life cycle. While concrete and steel can be raw materials for recycled concrete and reinforcing steel, there are more options for recycling or reusing mass timber elements, such as using timber for wood pellets or particle board production or for non-structural timber elements. This study also assessed the impacts of transport on the environment. At the present time, there are only a few CLT manufacturers in Australia and thus transport of CLT has raised concerns about associated fossil fuel depletion and CO_2 emissions. If the CLT supply chain was as well-established as other materials such as glulam, LVL, concrete and steel, it would be easier to have CLT within the state and its transport would pose minimal impacts on the environment. Otherwise, transport of CLT to the site may put more pressure on the energy use. Thanks to the calculation of carbon sequestration, the impact of transport of CLT to site on the global warming potential is negligible.

- The traditional concrete structure emitted approximately 32% more CO_2 than the alternative mass timber structure did during a 50-year lifetime. It can be clearly seen that the mass timber structure saved a huge amount of CO_2 cost during its life cycle.
- In conclusion, using mass timber in non-residential construction can provide a building of similar quality to that of heavy material and achieve cost savings and energy efficiency and can reduce a large amount of CO_2 released into the atmosphere. End-of-life demolition of mass timber structures not only consumes less energy, labour, heavy equipment and cost, but it also reduces wastage compared to an equivalent concrete structure.

Chapter 8 Conclusions and Recommendations

This chapter summarises the findings of this research and reviews the research aims and objectives. Limitations of this research and recommendations for further research are also discussed.

8.1 Summary of research

In Chapter 1, the research questions and problems were identified. Research problems were the lack of a model for non-residential development that suits the sustainable building sector and considers addressing the current challenges of mass timber construction in the Australian context. Through semi-structured interviews conducted with 17 construction practitioners experienced in mass timber construction in Australia, emerging advantages, disadvantages and strategies to increase the uptake of mass timber usage in Australia were explored. These benefits and barriers were categorised into different aspects in terms of key performance indicators, which were then used to assess the success of a building project through cost, time, quality and environment performance. In conjunction with benefits and barriers identified from the literature review, the three most important indicators of quality, cost and environmental performance were selected to develop a sustainable non-residential development model. This model provides strategies to adopt the use of sustainable building material in non-residential development. The proposed model was demonstrated by using an actual concrete office design and an equivalent alternative mass timber redesign to compare selected key performance indicators. The purpose of the comparison was to assess how mass timber performs against heavy material, such as concrete, in the model. The results demonstrated that the use of mass timber in non-residential construction can provide fairly similar quality as heavy material and achieve cost saving and energy efficiency and can reduce a large amount of CO_2 released into the atmosphere. End-of-life demolition of a mass timber structure not only consumes less energy, labour, heavy equipment and cost but it also reduces wastage compared to an equivalent concrete structure.

This research has contributed to the body of knowledge in the use of timber in sustainable non-residential development. To date, limited studies have examined changing the traditional heavy material to accommodate sustainable timber use in non-residential development to provide benefits in all key performance areas of the construction industry. Analysis of the interviews indicated the lack of an Australian Standard for the design teams, such as architects, structural engineers and fire engineers, to apply when working with mass timber projects. The sustainable non-residential development model, in which the offsite manufacturer and builder can be involved in the design stage due to the change of the building procurement process, potentially solves the difficulties facing the design teams. Therefore, this is indirectly beneficial for the selection of mass timber in non-residential development projects in Australia. Consequently, the client or the owner also benefits by having a building with the same thermal performance as a traditional concrete building but with better cost and environmental performance.

8.2 Review of research aims and objectives

8.2.1 Benefits and current obstacles of using mass timber as an alternative to traditional heavy materials

The first objective of this research was to investigate the benefits and current obstacles of using mass timber as an alternative to traditional heavy materials such as concrete and steel. In Chapter 2, a comprehensive literature review was conducted to understand the benefits and challenges that mass timber construction currently faces. The key benefits of using mass timber in construction include the possibility of carbon storage during the building and throughout the life cycle and the reduction of embodied energy and associated CO_2 emissions during the production, construction, operation and maintenance stages.

In addition, using mass timber in construction brings economic benefits through the increased use of forests for raw material supply. Compared to heavy building materials like concrete and steel that are non-renewable, timber is a renewable resource that is abundant and can be regenerated through sustainable forest management practices. Replacing 1 tonne of steel with timber in building structures results in approximately 1 tonne less of carbon being released into the atmosphere. There is also significant scope for higher carbon storage in houses by increasing the use of timber and timber products for the construction of sub-floor and wall cladding systems. The community may be concerned that using mass timber in construction may cause deforestation, yet the advance technology of wood products not only increases forest plantations but also improves forest carbon management.

There are challenges in using mass timber in construction that the industry needs to overcome. Major challenges are the fire performance of timber buildings, lack of emerging technologies in timber construction, and lack of information and evidence relating to constructability and technical guidelines such as prefabrication and standardised connection details, particularly for mid to high-rise non-residential buildings. In addition, the supply chain in timber is not yet as well organised as other building materials such as concrete and steel.

8.2.2 Perceptions of Australian construction practitioners on mass timber construction, particularly for non-residential development

Chapter 5 analysed semi-structured interviews conducted with 17 construction practitioners in Australia. There are concerns with cost performance due to potential delays in legislation and lack of early involvement of manufacturers in the planning and design stage, which potentially increases cost in the tendering process. Early engagement of structural engineers, builders and offsite manufacturers in the preliminary stage could potentially save materials and take advantages of DfMA strategies in the construction process. Offsite manufacture, coupled with DfMA, offers a reduction in onsite labour cost, site risk and construction time. Understanding the limits of an individual manufacturer's machinery can make huge differences in the cost of the project. Builders are currently becoming more familiar with the installation of mass timber structures and the logistics of importing material from overseas. Hence, there are likely to be difficulties or delays due to logistics and lack of installation experience. However, these participants are pioneers in mass timber construction and they are becoming more familiar with the system. It is necessary to educate skilled labour, especially when the demand for mass timber construction increases. Currently, the lack of suppliers may affect cost competitiveness and the availability of material. Most of the completed mass timber projects in Australia used overseas CLT, mainly imported from Europe. Although the results of the interviews show that there is no delay in logistics, relying on imported material has raised concerns about a significant amount of embodied energy and CO_2 contribution due to transport. Participants agreed that most completed mass timber projects have an equivalent thermal and acoustic performance to traditional heavy material structures despite high requirements. Nevertheless, the technical understanding of construction practitioners is still one of the hurdles in mass timber development in Australia. This is because there are not many Australian construction practitioners who already have experience with mass timber construction. Importantly, there is a lack of Australian standards and testings, particularly related to fire performance, for construction practitioners to apply. Insurance premiums are rated based on historical data. Therefore, it potentially hinders the implementation of mass timber in construction as construction practitioners may hesitate to take risks with new technology. This is understandable because mass timber is not yet as well established as heavy materials such as brick, steel or concrete. It naturally takes time and effort from different stakeholders in the industry. According to the results of the interviews, sustainability is nominated as one of the most important criteria in non-residential development. While construction speed is recognised as a big advantage of mass timber construction to enhance cost and safety benefits to the construction site, sustainability needs to be attached to cost and quality performance.

8.2.3 Key criteria to assess the performance of mass timber in non-residential development

Chapter 6 consolidated the key performance criteria identified in the literature review of Chapter 3 and the key performance criteria identified from the analysis of the interviews with construction practitioners. The results revealed that the three most important indicators used to develop the sustainable non-residential development model, including cost performance, quality performance and environmental performance. These main criteria were divided into the following sub-criteria:

- Cost performance includes the initial construction cost, operation cost, maintenance cost, and end-of-life cost.
- Quality performance includes the considerations of aesthetics, structural, fire, acoustic and thermal performance.
- Environmental performance includes life cycle fossil fuel depletion and CO_2 emissions with the consideration of carbon sequestration and benefits and loads beyond the building life cycle.

The sub-criteria were selected to use for the case study and model verification, including initial construction cost, operation cost, and end-of-life cost, thermal performance, life cycle fossil fuel depletion and CO_2 emissions with the consideration of carbon sequestration, and benefits and loads beyond the building life cycle.

8.2.4 Current building procurement process using heavy materials and suggested suitable building procurement process for mass timber construction

Chapter 6 also reviewed the current building procurement process used for traditional heavy material building construction. However, this building procurement process was not suitable for the case of mass timber construction, as identified in the results of the interviews with construction practitioners. In mass timber construction, as part of DfMA technology, the success rate relies highly on the collaboration among design teams, manufacturers and assemblers. These experts should have a mutual level of commitment and willingness to engage with DfMA technology. According to the interview results, one of the current obstacles in mass timber construction in Australia is that builders and mass timber manufacturers do not have the opportunity to be involved early in the planning and design stage. Hence, it is crucial to adjust the conventional building procurement process by integrating the design team, offsite manufacturing and construction contractor. This enables the contractor to be selected at an earlier stage to choose an appropriate offsite manufacturer and builder.

8.2.5 Development of a non-residential development model using sustainable material as key structural materials

Chapter 6 also proposed the sustainable non-residential development model using mass timber as an alternative to traditional heavy materials, such as concrete. The proposed model used the circular economy concept in its application to construction by viewing material inputs from a life cycle perspective. This perspective incorporates the energy used to create, operate, demolish and recycle materials in non-residential development. It requires the consideration of sustainability from the beginning of the project or design stage for efficient substitution of mass timber for heavy materials.

8.2.6 Verification and testing of the sustainable non-residential development model

Through the use of an actual conventional concrete office case study design and the alternative mass timber redesign, three main criteria including thermal performance, cost performance and environmental performance were tested in order to investigate how mass timber performed against concrete in non-residential development.

- The results showed that using mass timber in non-residential construction can provide a fairly similar quality as heavy material and achieve cost saving and prevent a large amount of CO_2 released into the atmosphere. The traditional concrete structure emitted approximately 32% more CO_2 than the alternative mass timber structure did during a 50-year lifetime. The total life cycle fossil fuel depletion of concrete design is higher than that of the alternative mass timber design by 11%, primarily due to the higher recycling rate of concrete and steel.

8.3 Contribution of the sustainable non-residential development model

The sustainable non-residential development model is a strategic model that provides an alternative model to the traditional heavy material model. This model suits the current circumstances of mass timber construction in Australia when highlighting the early involvement of the builder contractor and offsite manufacturer in the design stage. This helps reduce the design time, saving costs through the mitigation of uncertainties during the installation stage and saving materials. The model has proved that using mass timber in non-residential construction can provide a fairly similar quality as heavy material and achieve cost saving and energy efficiency as well as reducing a large amount of CO_2 released into the atmosphere. End-of-life demolition of a mass timber structure not only consumes less energy, labour, heavy equipment and cost but also produces less waste than an equivalent concrete structure. This matches the principles of sustainability when increasing industrial and economic growth without harming the environment and human health.

8.4 Research limitations

This research demonstrated that the sustainable non-residential development model applied to the Australian context reduces the life cycle cost, life cycle fossil fuel depletion and CO_2 emissions when compared to the traditional model using heavy materials. A number of limitations of this research have been recognised and these relate principally to the collection of data, case study scope and cost results.

The interviews were conducted with a wide range of construction professionals who provided a range of perspectives while access to construction practitioners who had worked on mass timber construction was limited because not many Australian companies had completed mass timber projects. Some practitioners had less than 5 years of experience or had not worked on a sufficient number of mass timber projects.

Another limitation of this research is that if a mass timber structure was better designed, it might result in better thermal performance compared to the traditional concrete design. In addition, the scope was limited to the case study in Sydney, NSW, with costs sourced in NSW only. There are slight differences across the climate zones in Australia in the approach to construction and the materials dominating the construction process in each state.

The final limitation of this study is in the circular sustainable model in the recycling part of the end-of-life stage. As there is no legal obligation for demolishers to reuse or recycle all materials from the demolition of buildings, there is limited literature or industry data on this part of the life cycle. Therefore, the LCA modelling of the end-of- life in this study relied on the national recycling rate for organic products, including timber, which stands at a relatively low (49%). It is also difficult to predict the policies that will exist at the end of the 50-year building lifetime. This part of the sustainable non-residential model will need future evaluation as research develops in the area of construction waste, recycling and reuse and as tighter legislation is implemented.

8.5 Recommendations for further research

Section 8.4 discussed some limitations of the research, which in turn lead to the opportunities for further research.

The scope of the case study has the potential to broaden its focus on a comparison between a prefabricated concrete structure and a prefabricated mass timber structure, examining the differences in construction speed between the two systems utilising the same construction method.

Further research should investigate the criteria in the SNRD model that were not explored in this study. Examining thermal comfort, which is relevant to indoor temperature, humidity levels and occupant comfort in different climate conditions, would provide insights into how mass timber buildings perform in comparison to concrete building across different climate zones in Australia. Additionally, the environmental impacts and cost associated with fitouts and the maintenance activities should be carried out in further research to understand the performance of concrete and mass timber buildings.

In conjunction with the model, the development of an excel-based tool to support the decision-making of material selection in the early design stage would be beneficial for different stakeholders such as building owners, designers, engineers, and builders who have limited access to emissions factors and appropriate GHG emissions accounting tool.

Examining different reuse and recycling scenarios to optimise the benefits of avoiding the use of virgin materials. This can be a foundation for a strategy and management plan contributing to a circular economy in building construction industry. Moreover, future research should deep dive into the methodology of carbon credits creation as well as estimate the potential cost benefits that can be obtained by the mass timber case study structure. In fact, the University of Washington's new campus building, which is a mass timber building, has recently become a pilot carbon offsets project. The University successfully has successfully sold the carbon credits derived from the carbon stored in its mass timber campus building (Hirji, 2023). This is a significant advantage of mass timber buildings, which potentially bring the cost benefits over the building's life cycle.

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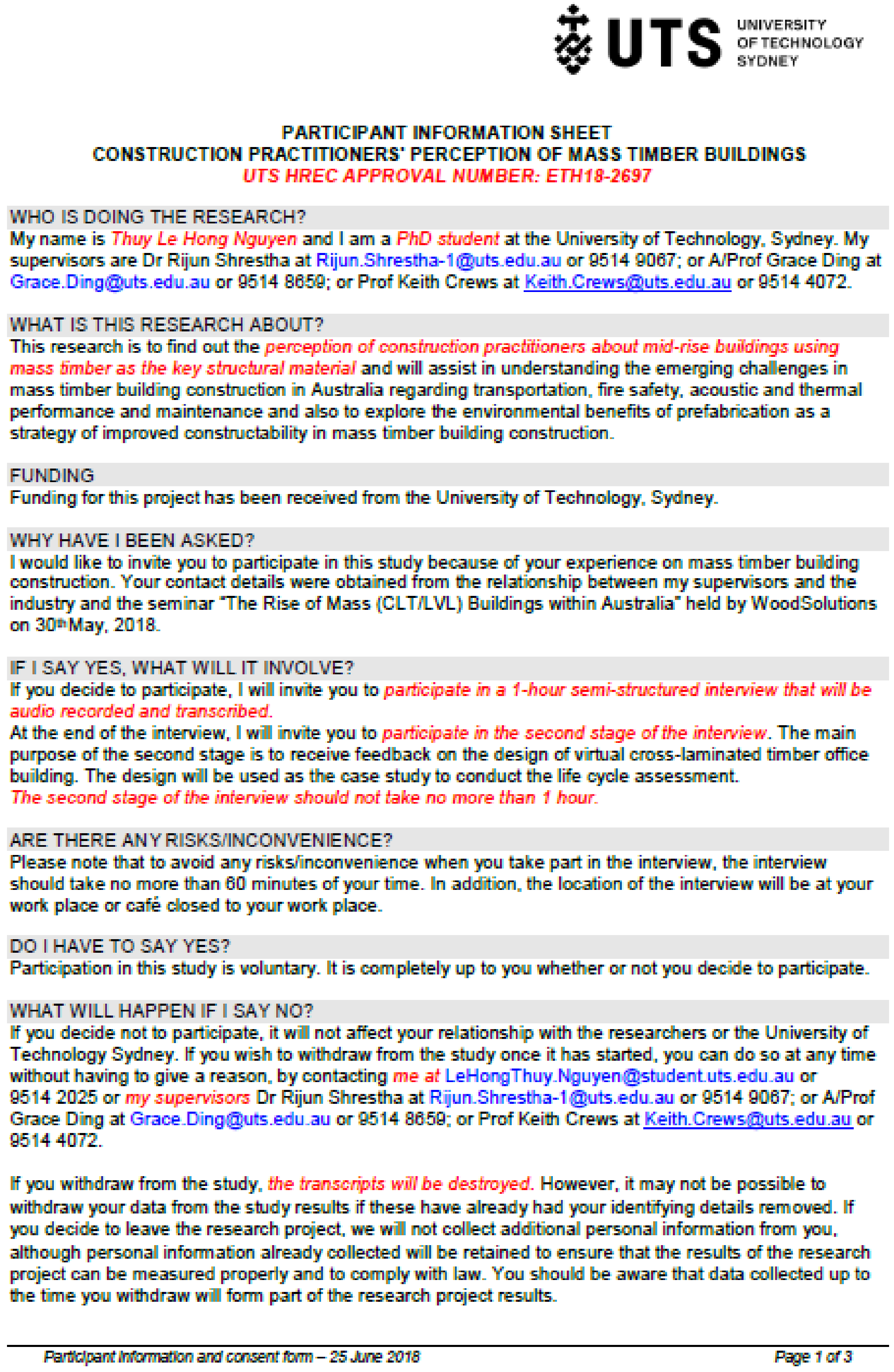
Appendices

Appendix A Participant information sheet and consent form



UTS UNIVERSITY OF TECHNOLOGY SYDNEY

PARTICIPANT INFORMATION SHEET
CONSTRUCTION PRACTITIONERS' PERCEPTION OF MASS TIMBER BUILDINGS
UTS HREC APPROVAL NUMBER: ETH18-2697

WHO IS DOING THE RESEARCH?

My name is *Thuy Le Hong Nguyen* and I am a *PhD student* at the University of Technology, Sydney. My supervisors are Dr Rijun Shrestha at Rijun.Shrestha-1@uts.edu.au or 9514 9067; or A/Prof Grace Ding at Grace.Ding@uts.edu.au or 9514 8659; or Prof Keith Crews at Keith.Crews@uts.edu.au or 9514 4072.

WHAT IS THIS RESEARCH ABOUT?

This research is to find out the *perception of construction practitioners about mid-rise buildings using mass timber as the key structural material* and will assist in understanding the emerging challenges in mass timber building construction in Australia regarding transportation, fire safety, acoustic and thermal performance and maintenance and also to explore the environmental benefits of prefabrication as a strategy of improved constructability in mass timber building construction.

FUNDING

Funding for this project has been received from the University of Technology, Sydney.

WHY HAVE I BEEN ASKED?

I would like to invite you to participate in this study because of your experience on mass timber building construction. Your contact details were obtained from the relationship between my supervisors and the industry and the seminar "The Rise of Mass (CLT/LVL) Buildings within Australia" held by WoodSolutions on 30th May, 2018.

IF I SAY YES, WHAT WILL IT INVOLVE?

If you decide to participate, I will invite you to *participate in a 1-hour semi-structured interview that will be audio recorded and transcribed.*

At the end of the interview, I will invite you to *participate in the second stage of the interview*. The main purpose of the second stage is to receive feedback on the design of virtual cross-laminated timber office building. The design will be used as the case study to conduct the life cycle assessment.

The second stage of the interview should not take no more than 1 hour.

ARE THERE ANY RISKS/INCONVENIENCE?

Please note that to avoid any risks/inconvenience when you take part in the interview, the interview should take no more than 60 minutes of your time. In addition, the location of the interview will be at your work place or café closed to your work place.

DO I HAVE TO SAY YES?

Participation in this study is voluntary. It is completely up to you whether or not you decide to participate.

WHAT WILL HAPPEN IF I SAY NO?

If you decide not to participate, it will not affect your relationship with the researchers or the University of Technology Sydney. If you wish to withdraw from the study once it has started, you can do so at any time without having to give a reason, by contacting *me at* LeHongThuy.Nguyen@student.uts.edu.au or 9514 2025 or *my supervisors* Dr Rijun Shrestha at Rijun.Shrestha-1@uts.edu.au or 9514 9067; or A/Prof Grace Ding at Grace.Ding@uts.edu.au or 9514 8659; or Prof Keith Crews at Keith.Crews@uts.edu.au or 9514 4072.

If you withdraw from the study, *the transcripts will be destroyed*. However, it may not be possible to withdraw your data from the study results if these have already had your identifying details removed. If you decide to leave the research project, we will not collect additional personal information from you, although personal information already collected will be retained to ensure that the results of the research project can be measured properly and to comply with law. You should be aware that data collected up to the time you withdraw will form part of the research project results.

CONFIDENTIALITY

By signing the consent form you consent to the research team collecting and using personal information about you for the research project. All this information will be treated confidentially and will only be used for the purpose of this research project. It will not be disclosed to any parties beyond the researchers named below. The outcome of the interview will be used as part of my PhD thesis and academic journals. If you are interested in reviewing your transcripts or receiving the final results of this research there is an opportunity for you to provide your contact details at the end of the interview. In any publication, information will be provided in such a way that you cannot be identified.

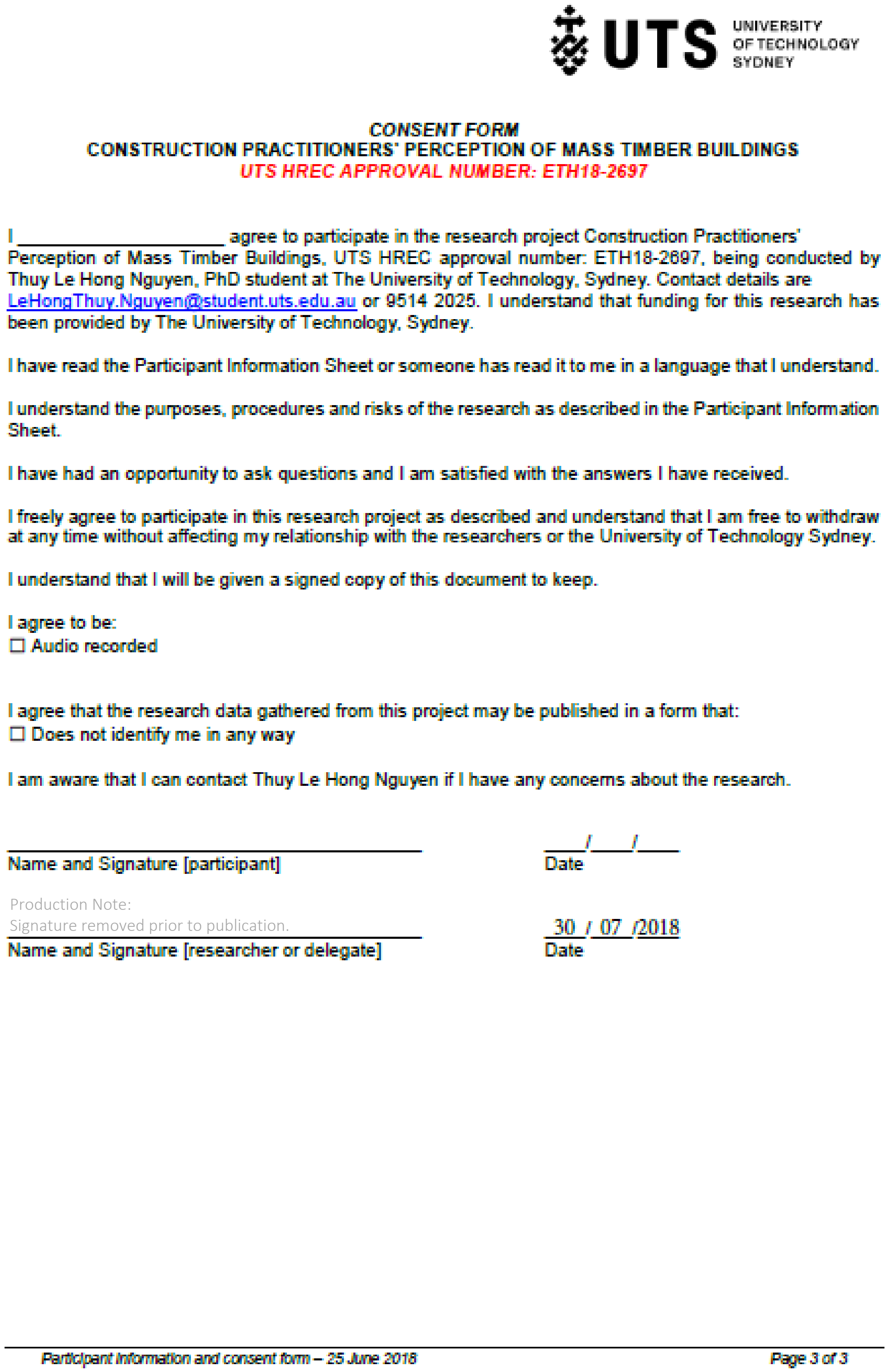
WHAT IF I HAVE CONCERNS OR A COMPLAINT?

If you have concerns about the research, please feel free to contact me at LeHongThuy.Nguyen@student.uts.edu.au or 9514 2025 or my supervisors Dr Rijun Shrestha at Rijun.Shrestha-1@uts.edu.au or 9514 9067; or A/Prof Grace at Grace.Ding@uts.edu.au or 9514 8659; or Prof Keith Crews at Keith.Crews@uts.edu.au or 9514 4072.

You will be given a copy of this form to keep.

NOTE:

This study has been approved by the University of Technology Sydney Human Research Ethics Committee [UTS HREC]. If you have any concerns or complaints about any aspect of the conduct of this research, please contact the Ethics Secretariat on ph.: +61 2 9514 2478 or email: Research.Ethics@uts.edu.au], and quote the UTS HREC reference number. Any matter raised will be treated confidentially, investigated and you will be informed of the outcome.



CONSENT FORM

CONSTRUCTION PRACTITIONERS' PERCEPTION OF MASS TIMBER BUILDINGS

UTS HREC APPROVAL NUMBER: ETH18-2697

I ____________________ agree to participate in the research project Construction Practitioners' Perception of Mass Timber Buildings, UTS HREC approval number: ETH18-2697, being conducted by Thuy Le Hong Nguyen, PhD student at The University of Technology, Sydney. Contact details are LeHongThuy.Nguyen@student.uts.edu.au or 9514 2025. I understand that funding for this research has been provided by The University of Technology, Sydney.

I have read the Participant Information Sheet or someone has read it to me in a language that I understand.

I understand the purposes, procedures and risks of the research as described in the Participant Information Sheet.

I have had an opportunity to ask questions and I am satisfied with the answers I have received.

I freely agree to participate in this research project as described and understand that I am free to withdraw at any time without affecting my relationship with the researchers or the University of Technology Sydney.

I understand that I will be given a signed copy of this document to keep.

I agree to be:
☐ Audio recorded

I agree that the research data gathered from this project may be published in a form that:
☐ Does not identify me in any way

I am aware that I can contact Thuy Le Hong Nguyen if I have any concerns about the research.

____ ____/____/____
Name and Signature [participant] Date

Production Note:
Signature removed prior to publication.
Name and Signature [researcher or delegate] 30 / 07 /2018
Date

Participant Information and consent form – 25 June 2018 *Page 3 of 3*

Appendix B Semi-structured interview questions

INTERVIEW QUESTIONS

CONSTRUCTION PRACTITIONERS' PERCEPTION OF MASS TIMBER BUILDINGS

This research is to find out the perception of construction practitioners about mid-rise buildings using mass timber as the key structural material and will assist in understanding the emerging challenges in mass timber building construction in Australia regarding transportation, fire safety, acoustic and thermal performance and maintenance and also to explore the environmental benefits of prefabrication as a strategy of improved constructability in mass timber building construction.

Questions to company:

1. What do you think are the usefulness of conducting the LCA for each mass timber project?
2. What are the challenges have your company faced in previous mass timber projects?
3. Have you ever experienced any delays in receiving CLT panels from Europe?
4. How do you plan to store CLT panels once in Australia?
5. What are the difficulties when CLT are mostly imported from Europe?
6. What are the challenges in installing the prefabricated timber structure?
7. What do you think are the environmental benefits of prefabrication in mass timber projects? (Wastage, dust?)
8. What do you think are the strategies to improve the uptake of mass timber usage in Australia?

Questions to designers, structural engineers, fire engineers:

1. What do you think are the advantages of using engineered timber as a key structural material in mid-rise projects?
2. What are the challenges in designing multi-story building with engineered timber as a structural material?
3. What are the difficulties of designing mass timber structures to meet the building codes related to fire safety and acoustic requirements?
4. What are the challenges to repair, replace or remain in-service of mass timber structures from fire damage?
5. How is engineered timber's thermal performance compared to concrete and steel?
6. What do you think are the strategies to improve the uptake of mass timber usage in Australia?

Questions to construction managers:

1. What are the challenges to repair, replace or remain in-service of mass timber structures from fire damage?
2. Have you ever experienced any delays in receiving CLT panels from Europe?
3. What are the difficulties when CLT are mostly imported from Europe?
4. How do you plan to store CLT panels once in Australia?
5. What do you think are the environmental benefits of prefabrication in mass timber projects? (Wastage, dust?)
6. What are the challenges in installing the prefabricated timber structure?
7. What do you think are the strategies to improve the uptake of mass timber usage in Australia?

Question to CLT plants:

1. Are your CLT panels produced from Australian sustainable forests?
2. What is the potential development of CLT in Australian market?
3. What are the potential obstacles of CLT in Australian market?
4. Do you think CLT can be a viable alternative to concrete and steel in mid-rise building construction?
5. How do you advise designers to improve constructability in CLT structures construction?
6. What do you think are the strategies to improve the uptake of mass timber usage in Australia?

Appendix C Technical details of mass timber redesign

Beams Design

The following are the suggested beams which are used for all floors.

Secondary Beams	**Span:** 8.4m **Dimensions:** 610 x 90mm **Material:** LVL 11 **Manufacturer:** Nelson Pine
Main Bearers	**Floor:** GF & UF **Span:** 8.4m **Dimensions:** 800 x 300mm **Material:** GL18 **Manufacturer:** Any
Main Bearers	**Floor:** GF & UF **Span:** 5.4m **Dimensions:** 500 x 300mm **Material:** GL18 **Manufacturer:** Any
Main Bearers	**Floor:** PF **Span:** 8.4m & 5.4m **Dimensions:** 1400 x 600mm **Material:** GL18 **Manufacturer:** Any
Cantilever	**Floor:** All floors **Span:** 3m **Dimensions:** 800 x 300mm **Material:** GL18 **Manufacturer:** Any

Columns Design

The following are the suggested columns which are used to support beams in all floors.

Suggested Columns

Span: 3.6m
Restraints: Pinned from both sides
Dimensions: 900 x 700mm
Material: GL 18
Manufacturer: Any

Other Possible Options

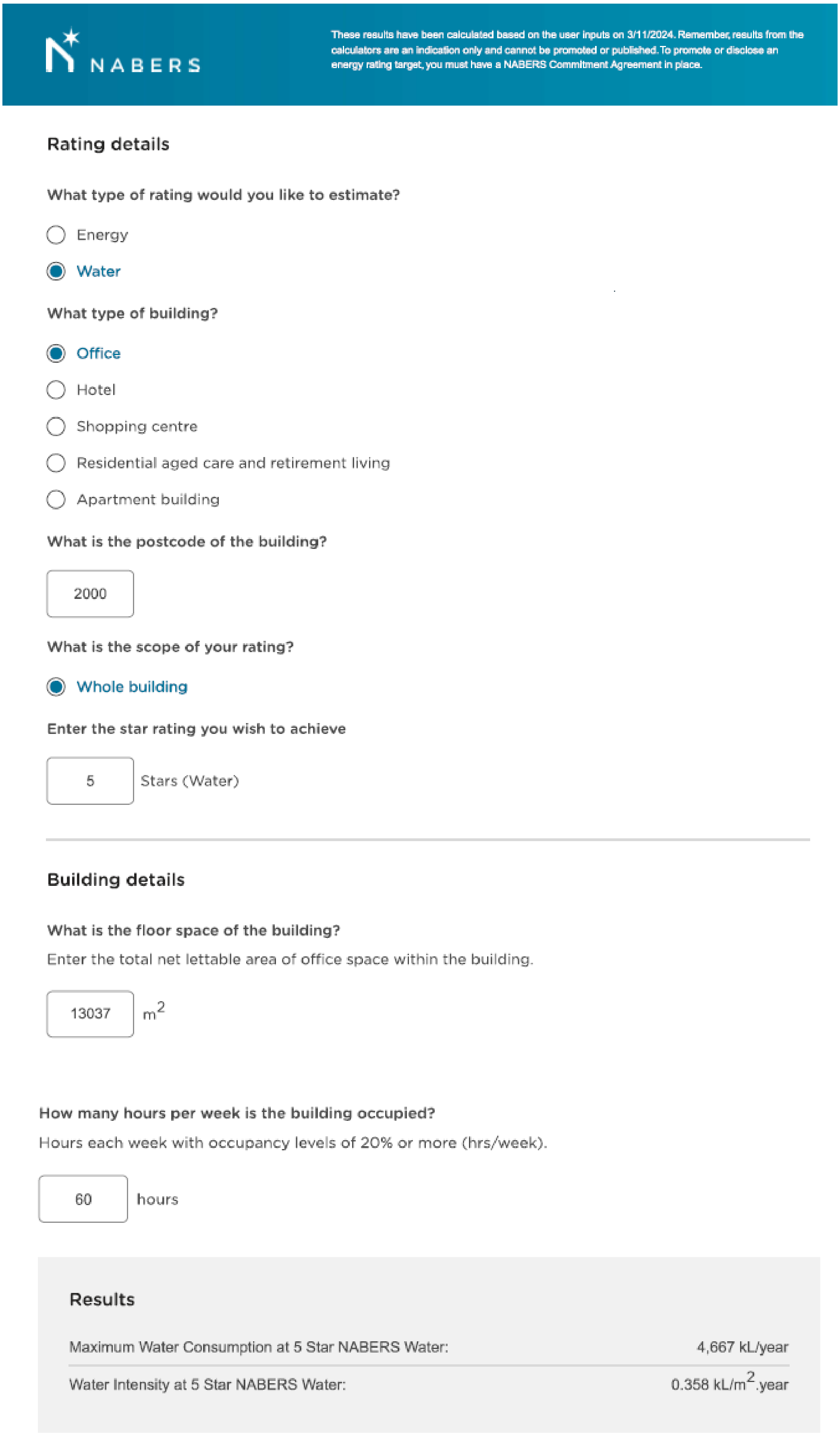
Span: 3.6m
Restraints: Pinned from both sides
Dimensions: 1000 x 600mm
Material: GL21
Manufacturer: Hyne Timber

Connections Design

The following are the suggested connections which are used for all floors.

Slab-to-Slab Connection	**Joint Type:** Screws **Design Joint:** 1 JD5 screw per metre **Screw Type:** JD5 **Screw Diameter:** 6.3mm **Manufacturer:** Any
Joist-to-Bearer	**Joint Type:** Bolts with Steel Plates **Design Joint:** 2 brackets 12 mm thick with 9 M16 Bolts on each side of Secondary beams **Bolt Type:** JD4 **Bolt Diameter:** 16mm **Manufacturer:** Any
Bearer-to-Column	**Joint Type:** Screws with Steel Plates simply supporting the bearer **Design Joint:** 2 brackets 12 mm thick with 16 Spax screws **Screw Diameter:** 16mm **Manufacturer:** Spax
Column-to-Slab	**Joint Type:** Screws with Steel Plates **Design Joint:** 2 brackets 12 mm thick with 6 screws on two opposite sides of the column **Screw Diameter:** 16mm **Manufacturer:** Spax

Appendix D Operational water use – NABERS Reverse Calculator



NABERS

These results have been calculated based on the user inputs on 3/11/2024. Remember, results from the calculators are an indication only and cannot be promoted or published. To promote or disclose an energy rating target, you must have a NABERS Commitment Agreement in place.

Rating details

What type of rating would you like to estimate?

○ Energy
● Water

What type of building?

● Office
○ Hotel
○ Shopping centre
○ Residential aged care and retirement living
○ Apartment building

What is the postcode of the building?

2000

What is the scope of your rating?

● Whole building

Enter the star rating you wish to achieve

5 Stars (Water)

Building details

What is the floor space of the building?

Enter the total net lettable area of office space within the building.

13037 m^2

How many hours per week is the building occupied?

Hours each week with occupancy levels of 20% or more (hrs/week).

60 hours

Results

Maximum Water Consumption at 5 Star NABERS Water:	4,667 kL/year
Water Intensity at 5 Star NABERS Water:	0.358 kL/m^2.year