UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

The role of Mass Engineered Timber in the decarbonisation of the built environment.

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Abstract

As urbanisation accelerates globally, the built environment faces the critical challenge of decarbonisation to mitigate the impacts of climate change. With cities expanding at an unprecedented rate, the demand for sustainable construction methods is more pressing than ever. This research explores decarbonisation pathways in the construction industry by examining the potential of Mass Engineered Timber (MET) as an alternative to conventional building materials for medium-rise urban buildings.

The study investigates how geographic location influences buildings' Global Warming Potential (GWP), hypothesising that MET buildings exhibit significantly lower embodied emissions than reinforced concrete (RC) buildings. Factors such as energy grid composition and supply chain logistics are examined in two geographic scenarios: Cape Town, South Africa, and Perth, Australia. A standardised Life Cycle Assessment (LCA) methodology is employed to perform a comparative analysis of functionally identical buildings in these locations through computational modelling. Scenarios involving vertical extensions of existing buildings are also modelled to assess their decarbonisation potential compared to redevelopment.

By integrating qualitative and quantitative insights, the research highlights the importance of context-specific strategies in emissions reduction. It underscores the benefits of utilising local materials and adopting standardised LCA methodologies to advance sustainable urban development. The findings indicate that MET offers a viable alternative to conventional construction materials and methods, providing actionable recommendations for stakeholders to mitigate the environmental impact of the built environment.

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List of Abbreviations

AAC	Autoclaved Aerated Concrete
AEMO	Australian Energy Market Operator
ALCA	Attributional Life Cycle Assessment
BAU	Business as Usual
CLCA	Consequential Life Cycle Assessment
CLT	Cross-Laminated Timber
CO_2	Carbon Dioxide
CRC	Crushed Recycled Concrete
DCCEEW	Department of Climate Change, Energy, the Environment and Water
FSC	Forest Stewardship Council
FU	Functional Unit
GFA	Gross Floor Area
GHG	Greenhouse Gas
GJ	Giga Joule
GLT	Glue-laminated Timber
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
ILCD	The International Reference Life Cycle Data System
ISO	International Organisation for Standardisation
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LEED	Leadership in Energy Efficient Design
MET	Mass Engineered Timber
PRASA	Passenger Rail Agency of South Africa
PV	Photo Voltaic
RC	Reinforced Concrete
SABS	South African Bureau of Standards
SCM	Supplementary Cementitious Material
SLTS	Solid Laminate Timber Systems
TFR	Transnet Freight Rail
UN	United Nations

Definition of key terms

Life Cycle Analysis (LCA):

Life Cycle Assessment (LCA), also known as Life Cycle Analysis, is a comprehensive methodology employed in the context of the built environment to evaluate the environmental impact of a structure throughout its entire life cycle (International Organization for Standardization, 2006). This encompasses all stages, from raw material extraction and manufacturing through construction and use to eventual demolition and waste management. In the pursuit of decarbonisation, LCA is a vital tool for assessing the total environmental impact of buildings. The method considers embodied emissions in materials, operational energy use, and end-of-life impacts. An LCA can be conducted from early design stages, providing a holistic perspective to inform sustainable decision-making in the built environment. An LCA model typically provides a standardised result of the total cumulative Global Warming Potential of a building in the form of kg-CO_2-eq/m^2.

kg-CO_2-eq:

The measurement of emissions and environmental impacts in kilograms of Carbon Dioxide equivalent (kg-CO_2-eq) is a standard unit used to express the total greenhouse gas emissions associated with a particular activity, product, or process. This metric offers a standardised measure by converting the emissions of various greenhouse gases into the equivalent amount of carbon dioxide that would have the same global warming potential over a specified time frame. For instance, methane and nitrous oxide, which have higher global warming potentials than carbon dioxide, are converted into CO_2-e for a more uniform comparison. Expressing emissions and environmental impacts in kg CO_2-e allows for a consistent and comprehensive assessment of the emissions impact associated with building construction, operation, and eventual decommissioning. This measurement aids in understanding the broader environmental consequences and enables comparisons between materials and building strategies.

Global Warming Potential:

Global Warming Potential (GWP) is a critical metric for comparing the impact of different greenhouse gases (GHGs) on climate change. It quantifies how much heat a specific greenhouse gas traps in the atmosphere over a certain period (usually 100 years) relative to carbon dioxide (CO_2), the baseline reference gas. GWP is expressed as a factor of CO_2, assigned a GWP of 1. Other GHGs, such as methane (CH_4) or nitrous oxide (N_2O), have higher GWP values because they trap more heat, even in smaller quantities. For instance, methane has a GWP of 28-36 over 100 years, meaning that 1 kg has the same global warming effect as 28-36 kg of CO_2 over that period. The unit kg-CO_2-eq is a standard measure used to express the global warming potential of various gases in terms of the equivalent amount of CO_2.

Functional Unit (FU) of measurement:

The functional unit of measurement in the context of a building, such as expressing it in square meters (m^2), defines a standardised measure applied to evaluate the environmental performance of a construction project. The functional unit serves as a reference point against which the environmental impacts and emissions associated with the entire life cycle of the building are evaluated. This allows for a consistent basis of comparison between the two structures and facilitates the assessment of the emissions intensity per measured unit of usable space. This study utilises an accepted industry standard output of kg-CO_2-eq/m^2 of building GFA.

Scope 1 Emissions:

Scope 1 emissions, within the framework of environmental assessments like Life Cycle Assessment (LCA) in the built environment, pertain to direct greenhouse gas emissions originating from sources directly owned or controlled by the entity under examination. This category is integral to understanding and mitigating the immediate environmental impact of construction and operational stages, as it enables a focused exam of emissions directly attributable to the project itself.

Scope 2 Emissions:

Scope 2 emissions are indirect greenhouse gas emissions associated with generating purchased or externally supplied energy. These emissions are generated off-site from the electricity, heat, or steam a building consumes during its life cycle. Recognizing and quantifying Scope 2 emissions is essential for a comprehensive understanding of a building's environmental impact. It contributes valuable insights to the broader LCA and aids in developing strategies to reduce the overall emissions intensity of structures in the built environment.

Scope 3 Emissions:

Scope 3 emissions, within the built environment context, encompass indirect greenhouse gas emissions associated with a building's life cycle but occur outside the direct control of the entity undertaking the construction or operation. These emissions extend beyond the boundaries of the building itself and include factors such as the extraction, production, and transportation of raw materials, as well as end-of-life processes and occupants' commuting. This broader perspective is essential for a comprehensive understanding of the environmental impact, allowing for a more nuanced evaluation of the emissions intensity associated with the entire life cycle of the structures, considering factors beyond the immediate control of the building project.

Materiality Cut-off/Material Significance:

When Considering Life Cycle Assessment (LCA) studies for buildings, a materiality cut-off refers to a threshold set to exclude certain materials or components from a detailed assessment based on their relatively low environmental impact (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010, p. 40). This cut-off is implemented to streamline the analysis and focus on the most significant contributors to the overall life cycle environmental performance of the building. Modelling in software tools like OneClickLCA requires the incorporation of materiality cut-offs to enhance the efficiency of the assessment process. By excluding materials or components that have a negligible influence on the overall results, LCA practitioners can concentrate on thoroughly evaluating the environmental impacts of the most substantial elements, ensuring that the study remains relevant and actionable. The criteria for materiality cut-offs vary based on the goals of the LCA and the selected software tools. Still, they are generally set to exclude materials with <0.1% of the overall impact (Pomponi & Stephan, 2021, p. 7).

Vertical Extension:

The Vertical Extension (VE) of existing building stock denotes the addition of new floors or levels to an existing building. This development involves expanding upwards, increasing the structure's height while maintaining its footprint. Vertical extensions are a strategic approach to optimising urban space, especially in densely populated areas with limited horizontal expansion.

Chapter 1 Introduction

1.1 Aim

The world is currently undergoing an unprecedented rate of urban growth. As of 2018, more than half of the global population resides in concentrated urban areas (UN DESA, 2018). Projections suggest that by 2050, urban areas will be home to more than two-thirds of a global population estimated to reach 10 billion (ibid.). The United Nations (2017) Estimate that cities must add 230 billion m² to the global building stock by 2060 to accommodate this urban expansion. This expansion is equivalent to doubling the existing building stock (ibid.; (Pomponi & Moncaster, 2016, p. 688).

Chau et al. (2015, p. 396) outline a well-established figure in the literature indicating that the built environment is responsible for approximately 40% of global energy consumption and 30% of raw material use. Given the rapid urbanisation rates and the anticipated expansion of city areas, the built environment must explore and implement more effective and efficient methods in both construction and operation to become more sustainable.

This research project compares the Global Warming Potential (GWP) from embodied energy-associated emissions of primary building frames across select building scenarios within distinct contexts and markets in South Africa and Australia, respectively. This geographic distinction examines the life cycle impact of functionally identical buildings within their respective geographic and market contexts. Although the designs and functions are similar, the differences in energy grids, material supply chains, and construction practices in these regions are expected to influence the Life Cycle Assessment (LCA) modelling outcomes. This comparison highlights how local factors, such as energy intensity and transportation logistics, can impact the environmental performance of Mass Engineered Timber (MET) buildings, particularly regarding embodied emissions.

The research further seeks to understand the market factors influencing Mass Engineered Timber (MET) adoption in these regions while providing insights into LCA material modelling strategies and outcomes. The project aims to refine existing building designs to align with LCA requirements and conduct comparative LCA modelling exercises for different building scenarios within each context. Lastly, it seeks to explore the potential for vertical expansion of existing building stock and assess its implications on embodied emissions.

1.2 Background

Historically, timber was a predominant construction material for multi-story buildings, favoured for its abundance, cost-effectiveness, and ease of use. Its popularity declined significantly, especially in urban areas, following notable fire incidents such as the Great Fire of London in 1666 and the Great Chicago Fire in 1871 (Planning and Housing Committee, 2010). These events underscored the vulnerability of timber structures to rapid and devastating fires, leading to extensive destruction. In response, stringent building regulations were developed to mitigate fire risks, contributing to timber falling out of favour as the primary material for tall structures (ibid.). Therefore, the industry regards recent advancements in classifying engineered timber as equivalent to traditional timber types because they are both derived from timber. However, insufficient consideration is given to acknowledging the engineered nature of these products.

Mass Engineered Timber (MET) is a Solid Laminate Timber Systems (SLTS) collection. It includes, among other, Cross-Laminated Timber (CLT) and Glue-Laminated Timber (GLT or Glulam), which are gaining traction as a viable alternative to more conventional materials like steel and concrete (Andersen, et al., 2022, p. 1). These engineered timbers offer numerous benefits, such as the potential of being a renewable resource, having lower embodied emissions, faster construction times through prefabrication and modularity, and providing better thermal performance. Nonetheless, a detailed comparative analysis of the performance and feasibility of engineered timbers versus steel and concrete in different geographic contexts could offer further insights to the built environment professionals.

Embodied energy is estimated to constitute as much as 70% of the total building life energy use (Pomponi & Moncaster, 2016, p. 688), influenced by factors like construction methodology, material supply chain, and operational energy efficiency (Koezjakov, et al., 2018). This research utilises Life Cycle Assessment (LCA) modelling to explore the potential of CLT and GLT as alternative structural systems that could reduce the embodied energy in building frames in different geographic contexts. The use of CLT is specifically examined in structural floor and wall panels, combined with GLT columns and beams to offer a potentially lower-emission alternative to traditional materials.

The study examines scenarios of new building construction (greenfield or total redevelopment brownfield opportunities) and vertical extensions of existing buildings with significant refurbishments. These scenarios are modelled using LCA software to compare the impacts of different value chains in two distinct economies on the impacts associated with constructing MET buildings in Cape Town, Western Cape, and Perth, Western Australia, respectively. The selected geographies offer contrasts in alternative building material adoption, decarbonisation efforts, economies, alternative policies, and value chains.

1.3 Problem Statement

Life Cycle Assessments (LCAs) of buildings began to gain notable popularity in the 1990s. During this period, various organisations initiated the development of methodologies to assess the environmental impacts of buildings throughout their entire life cycle, encompassing stages from raw material extraction to demolition or deconstruction. (Guinée, et al., 2011). An LCA methodologically evaluates the environmental impact of a product or an assembly of products over its entire lifespan, including considerations of energy, water, material use, and broader environmental impacts (Andersen, et al., 2022) European Standards EN 15978 and EN 15804 (Hafner & Schäfer, 2017, p. 632) typically guide these assessments. The comprehensive stages of a building's LCA generally encompass raw material extraction and processing, manufacturing and transportation, construction, operation, and end-of-life disposal or recycling (ibid.). Employing a standardised LCA modelling approach can effectively demonstrate how a Mass Engineered Timber (MET) structure may significantly reduce both the embodied and whole-of-life emissions impact of a building.

Recently, MET has started emerging as a leading and sustainable material in the construction sector, heralding a new era in building practices (Andersen, et al., 2022, p. 1). Gong (2019) discusses CLT and GLT as two of the four major lumber-based mass-engineered timber products. Cross Laminated Timber (CLT) is a prefabricated wood product crafted by bonding perpendicular layers of lumber in alternating directions, creating panels with superior strength, stability, and fire resistance. Similarly, the second commonly used MET, Glue Laminated Timber (GLT), is an engineered timber product made by bonding parallel structural timber sections with a moisture-resistant adhesive. The uptake of CLT and GLT as core components of the MET structural system has enabled the design and construction of taller buildings and innovative architectural forms, potentially supporting a more sustainable urban development. In practical applications, CLT is typically used for structural walls and floors and GLT for columns and beams. Due to its high structural performance and potential for reducing embodied emissions, MET has garnered significant attention as a viable alternative to conventional construction materials and systems like steel and concrete framed buildings.

Furthermore, the supply chain and local geographic context of a building and its materials are critical factors in determining the embodied energy of a building. The component of the overall embodied energy can vary significantly depending on the building's location. Factors influencing this include the distance materials travel, modes of transportation used, production methods, energy consumption during production, and waste generation. Therefore, a thorough analysis of the supply chain for building materials is imperative. Such an analysis identifies opportunities for improving energy efficiency, subsequently reducing greenhouse gas emissions and promotes more sustainable practices within the built environment as a whole. An in-depth understanding of these factors is essential for architects, engineers, and policymakers to make informed decisions that could better support environmental sustainability targets in building construction.

1.4 Rationale

Regulatory requirements for calculating and reporting the reduction of GWP from embodied emissions in buildings remain limited. Reducing energy consumption can be achieved by targeting embodied energy in buildings, rather than focusing solely on operational energy. Embodied energy can constitute as much as 70% of a building's life cycle energy consumption (Andersen, et al., 2022, p. 7). Figure 1 Typical building energy make-up below illustrate typical buildings and their energy composition, comparing business-as-usual construction, improved operational energy use, and combined operational and embodied energy improvements (Younis & Dodoo, 2022).

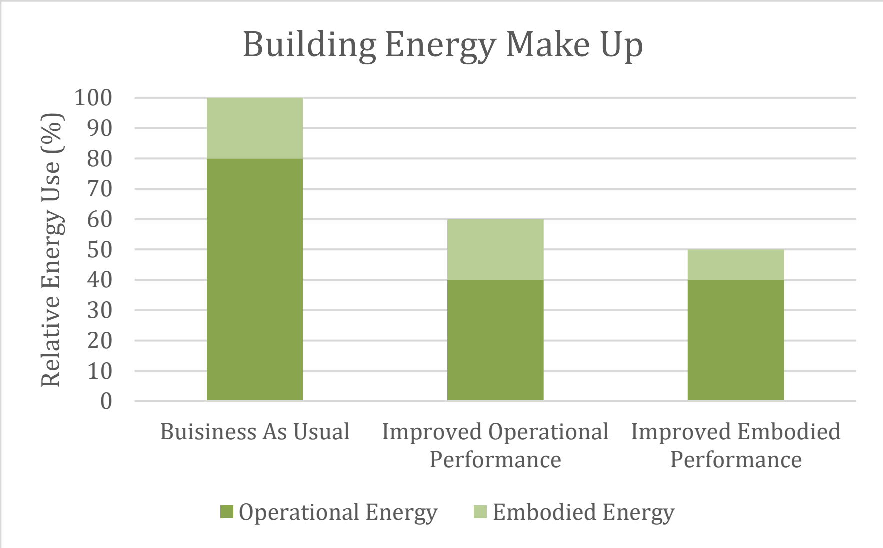

Figure 1 Typical building energy make-up (Younis & Dodoo, 2022)

The majority of a building's embodied energy is concentrated in primary structural components such as foundations, walls, floors, columns, beams, and roof systems (Leonard, 2023). These elements are traditionally heavy masses of large material quantities like concrete and steel and often require significant amounts of energy during their production, manufacturing, transportation, and installation processes.

With the growing need for urban densification and sustainable urban development, utilising engineered timber for entire building frames or adding floors on top of existing structures has gained considerable attention (Argenziano, et al., 2021, p. 1). This innovative approach provides several benefits, including shorter construction times, reduced disruption to occupants, and enhanced carbon sequestration potential. Moreover, engineered timber's lightweight nature enables adding extra floors without requiring extensive structural modifications in carefully considered base buildings (Julistiono, et al., 2023, p. 9).

Several papers conducting comparative life cycle analyses were reviewed by Younis et al. (2022, p. 6) to further the field of study. However, relatively few studies have focused on comparative analysis based on the geographic location of the target building. Jayalath (2020) conducted a comparative LCA in three distinct geographic locations. However, the study included three functionally identical buildings on the Eastern Coast of Australia. The locations were Melbourne, Sydney, and Brisbane, respectively, and the study covered not only LCA emissions of an MET and RC building but also a Life Cycle

Cost (LCC) component. Specific gaps were identified for a comparative study of two functionally identical buildings in similar climate zones but falling under distinct international geographical contexts to understand better how developed and developing economies impact the embodied emissions of their respective built environments.

This study aims to explore the role of MET in reducing GWP in building frames in South Africa and Australia, emphasising the necessity of sustainable building practices in the context of rapid urbanisation. By utilising LCA modelling, the research should evaluate MET's effectiveness in lowering embodied energy and emissions compared to more conventional systems and materials like steel and concrete, considering the built environment's significant energy and raw material demands. The focus on MET, a renewable resource with potentially lower emissions, underscores the urgent need for policies encouraging sustainable urban development and construction, aiming to mitigate GWP through improved material efficiency.

1.5 Embodied Emissions in Buildings

Embodied emissions in the built environment encompass all greenhouse gas emissions over the lifecycle of building materials, from raw material extraction and processing to transportation, installation, demolition, and disposal. These emissions are quantified as carbon dioxide equivalents (CO_2-e) per m^2 of building area, providing a measure of the environmental impact of construction materials and methods. Authors offer differing viewpoints on the significance and measurement of embodied emissions. Atmaca and Atmaca (2015, p. 418) The operational stage is a crucial consideration in the lifecycle analysis, as it dominates residential buildings' primary energy use and CO_2 emissions. In contrast, embodied energy constitutes a significant but smaller portion—conversely, Rodrigues et al. (2018, p. 421) focus on the impact of building materials and product components on total embodied emissions, emphasising the need for detailed LCAs to understand and mitigate these emissions effectively.

Embodied emissions refer to the total greenhouse gas emissions (measured in carbon dioxide equivalents) resulting from the extraction, manufacture, transportation, installation, maintenance, and disposal of building materials throughout the entire lifecycle of a building (Pomponi & Moncaster, 2016). The embodied emissions encompass all upstream and downstream emissions directly tied to the construction and eventual deconstruction of buildings and infrastructure. Andersen (2022, p. 2)outlines that embodied and operational emissions are typically measured in units of carbon dioxide equivalents (CO_2-e) per functional unit (FU) of floor area and are essential to analyse an emissions profile. Understanding and reducing embodied emissions is crucial for setting and achieving sustainability goals in the construction industry, as it directly contributes to the environmental impact of buildings.

In contrast, the operational emissions component of whole-of-life emissions refers to the emissions associated with the day-to-day energy consumption of a building throughout its operational stage. This operational energy includes the energy required for thermal controls, HVAC, lighting, equipment, appliances, and any other form of energy consumption within the building (Karimpour, et al., 2014, p. 107). Operational emissions are often the most significant contributor to a building's emissions footprint over its operational life, especially for buildings with high energy demands as outlined by numerous studies by but not limited to Andersen (2022), Younis (2022), Atmaca et al. (2015) and Pomponi (2016). While embodied emissions are correlated with the building's construction and materials, operational emissions are tied to its ongoing energy use. Sustainable building practices aim to minimise embodied and operational emissions to create efficient structures with less associated whole-of-life emissions.

Reducing embodied emissions in buildings involves strategies such as design optimisation, whole-of-life planning, material minimisation, alternative material selection, and value chain optimisation (Leonard, 2023). Hemati et al. (2024) highlight a primary strategy to select low-embodied-emissions building products, which may include certified sustainably sourced (FSC) timber, recycled content materials, and alternatives to emission-intensive materials like Portland cement-based concrete. Focussing on efficient design for construction methods, Hemati et al. (2024) also states modular and prefabricated construction can help reduce material waste and energy use during the construction process. Optimising transportation logistics to minimise the distance materials travel to the construction site can also lower embodied emissions. Recycling and repurposing materials from existing structures can also effectively reduce embodied emissions in renovations or adaptive reuse projects. Furthermore, considering materials' entire life cycle, from raw material extraction to ultimately reuse or disposal, supports a holistic approach to embodied emissions reduction. Ultimately, combining material choices, construction techniques, and sustainable design principles plays a pivotal role in achieving significant reductions in embodied emissions in buildings and contributes to more environmentally responsible and sustainable construction practices.

1.6 Context of Life Cycle Analysis in the Built Environment

Life Cycle Analysis (LCA) plays an increasingly important role in the built environment, covering planning, design, construction, operation, and the eventual demolition or decommissioning of buildings and infrastructure. With urbanisation and construction activities rising globally, the built environment has become a major contributor to resource extraction, energy consumption, waste generation, and greenhouse gas emissions (Volk, et al., 2023, p. 2). In this context, LCA is considered a robust methodology and tool for quantifying the environmental impacts associated with construction materials, building systems, and architectural choices during the entire life cycle of the built environment.

The position of LCA in the built environment helps stakeholders, including architects, engineers, contractors, developers, policymakers, and building owners, make more informed decisions about sustainable construction and design. An LCA enables a comprehensive quantitative examination of the environmental impacts of various design options, such as material choices (e.g., wood vs. concrete), energy systems (e.g., passive vs. active), and design strategies (e.g., energy-efficient vs. conventional). Analysis through an LCA framework helps decision-makers identify and prioritise opportunities for improvement, contributing to the development of sustainable, resilient, and environmentally responsible buildings and infrastructure.

Additionally, LCA underpins sustainability frameworks such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and other certification systems. These frameworks encourage the integration of LCA data into their certification processes, reinforcing the importance of life cycle thinking in building projects. As environmental regulations become stricter and public awareness of sustainability grows, LCA is poised to become an even more integral part of the built environment's decision-making processes. It helps balance economic, social, and environmental considerations, enabling the shift toward greener and more resource-efficient construction practices in an increasingly urbanised world.

1.7 Challenging the 'Business-as-Usual' Building

Mass-Engineered Timber (MET) buildings, incorporating Cross-Laminated Timber (CLT) and Glued Laminated Timber (GLT) as key structural components, signify a significant advancement in construction practices prioritising sustainability, efficiency, and design flexibility (Jayalath, et al., 2020). As illustrated in Figure 2 below, CLT panels, made of wood layers bonded perpendicularly with adhesive, are well-suited for walls, floors, and roofs. Its notable strength-to-weight ratio enables the construction of tall, structurally stable buildings. On the other hand, GLT, made by bonding layers of dimensional lumber, offers impressive load-bearing capabilities and is often employed for large beams and columns, contributing to the overall structural integrity of these timber buildings.

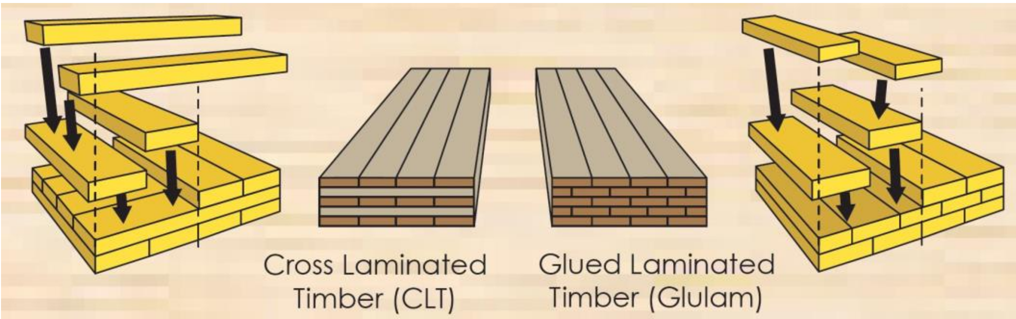

Figure 2 CLT and GLT make-up (Brooshakian, 2016)

One of the most compelling aspects of MET buildings is their role in reducing the impact of emissions on the built environment. CLT and GLT offer substantially lower embodied emissions than traditional materials such as steel and concrete (Younis & Dodoo, 2022). These timber products are derived from a renewable resource and store carbon absorbed by the trees during growth, contributing to carbon sequestration. As the construction industry grapples with the urgency of climate change mitigation, these timber solutions offer a viable alternative without compromising structural integrity.

Moreover, MET buildings embrace a sustainable construction approach characterised by precision manufacturing, shorter construction timelines, and reduced off-site and on-site waste. The prefabricated nature of CLT and GLT components facilitates efficient assembly, reducing disruption to urban areas and their surroundings (Van Der Westhuyzen & Wium, 2020). These buildings often exemplify modern architectural designs, with exposed timber surfaces creating warm and inviting interior spaces. In essence, mass-engineered timber buildings showcase the harmonious integration of sustainable materials and advanced construction techniques, offering the potential to reshape urban landscapes in the future.

1.8 Main Research Question

What role can Mass Engineered Timber (MET) play in decarbonising the built environment as an alternative to conventional materials, specifically in reducing embodied emissions in functionally identical buildings located in Cape Town, South Africa, and Perth, Western Australia, respectively?

1.8.1 First Sub-question

Which life cycle stage contributes the most significant volume of emissions in the built environment?

1.8.2 Second Sub-question

What factors contribute to certain life cycle stages having significantly higher emissions?

1.8.3 Third Sub-question

Which current and emerging initiatives offer the greatest potential for emissions reductions?

1.8.4 Fourth Sub-question

What is the potential for vertical expansion of existing buildings with low-emissions, lightweight materials such as MET?

1.9 Expected Findings (working hypothesis)

It is expected that higher embodied emissions would be observed in the case of RC building scenarios, likely due to the energy-intensive processes associated with cement production and the manufacturing of steel reinforcement components. The higher emissions intensity during the material extraction and production stages of concrete—particularly the Portland cement content—is expected to result in a higher Global

Warming Potential (GWP) compared to MET, irrespective of the geographical market being considered.

Supporting the main hypothesis, MET building scenarios are expected to exhibit lower embodied emissions than RC scenarios, given the renewable nature of wood and the potential for carbon sequestration. The manufacturing process for MET may involve lower energy requirements and fewer emissions, contributing to a reduced environmental impact during both the production and construction stages.

As a further supporting hypothesis of regional material emissions intensity, it is expected that regional variations in material sourcing, waste management, local energy grid factors, and construction practices may exacerbate differences in embodied emissions. These factors will likely influence Life Cycle Assessment (LCA) further results if functionally identical buildings are constructed in two distinct geographic locations. For instance, the local availability of sustainably sourced materials and the emissions intensity of the energy grid in each location would impact the overall embodied emissions.

As this study does not consider operational energy use in its conclusions, it is essential to note that local climate conditions, which influence operational energy requirements, could affect the overall environmental impact of the respective buildings. A comprehensive evaluation that includes operational energy use, end-of-life considerations, and other relevant factors would offer a more holistic understanding of the environmental performance of the two building materials.

Based on the findings of this study, it is expected that the MET building in Perth, Australia, would have the lowest environmental impact, while the RC building in Cape Town, South Africa, would have the highest. This expectation is primarily due to known differences in material impacts between RC and MET and the compounding differences between the two locations.

1.10 Research Concept Approach and Delimitation of Scope

Understanding associated emissions is required to further our comprehension of the decarbonisation or emissions abatement of the built environment. This would help to understand where large pockets, or ‘hotspots’ of emissions are situated. When we cross-reference the now-known emissions with potential emissions reduction opportunities, emission reduction strategies can be implemented effectively and efficiently. Emissions are expected to vary based on the material types and the geographic locale of a building to be studied, and a better understanding of these materials and geographic nuances could enable more sustainable decision-making in the wider built environment. Determining quantitative building-associated emissions is achievable by implementing a comparative LCA modelling exercise.

Comparative LCA of buildings in distinctly different geographic locations was researched to present insights into the sustainability and environmental impact of construction products, materials, and practices in each location and ultimately answer the questions posed in this research paper. This methodology particularly supports comparing the environmental performance of buildings that are functionally identical but located in different built environments and value chain contexts - Cape Town, South Africa and Perth, Western Australia, respectively.

Scenario definitions summarised in Table 1 below outline the distinct differences modelled using the comparative LCA methodology. The distinction between the two geographic locations is identified using ‘A’ for Cape Town-based scenarios and ‘B’ for Perth-based scenarios, respectively:

Table 1 Modelling scenario description summary

Scenario	Description
1	Comparison of standard conventional Reinforced Concrete buildings.
2	Comparing functionally identical MET buildings.
3	Vertical extension of existing buildings compared.

In Scenario 1 from Figure 3 Research approach - scenario modelling below, the LCA comparison between two conventional RC buildings in the respective cities would focus on the energy requirements and greenhouse gas (GHG) emissions associated with the materials, construction process, and any logistic aspects unique to each location (Vossberg, et al., 2014).

Scenario 2 from Figure 3 Research approach - scenario modelling below involves comparing functionally identical MET buildings in the same cities as the RC buildings above. The focus would shift to the environmental impacts of using lumber or engineered wood products as a primary construction material; the analysis would include the same impact categories as the RC building and have the embodied emissions in the raw material extraction, production, transportation, and operational energy efficiency. Lastly, Scenario 3 compares the environmental impact of constructing mass timber vertical extensions on existing reinforced concrete buildings. This scenario highlights the balance between utilising existing structures and the additional benefits or burdens of the vertical extension. The scenario will be assessed by considering the same impact categories as the RC and MET buildings from Scenario 1 and 2, respectively, considering both the original and the extension construction materials and methods.

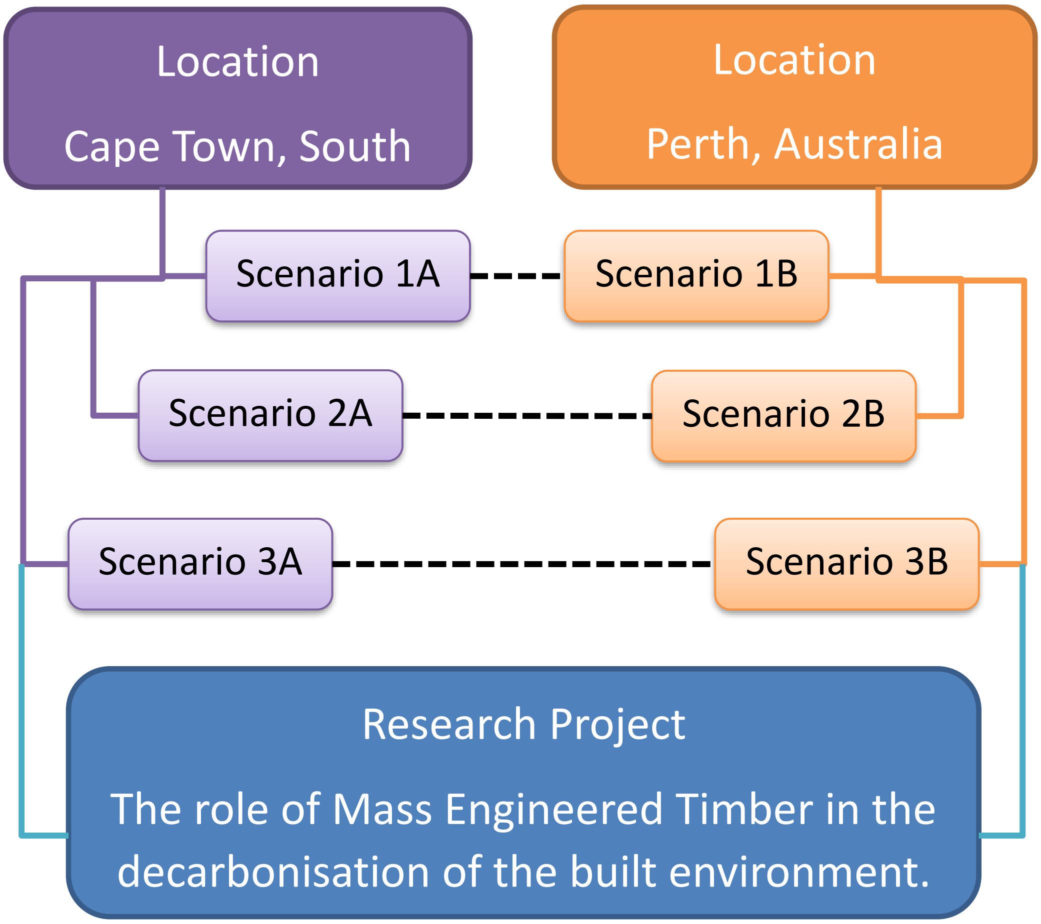

Figure 3 Research approach - scenario modelling

Key: – – – – Direct Comparison of LCA modelling results between scenarios.

The project modelling is ring-fenced only to consider the direct impacts of the embodied emissions-associated GWP for each respective building modelled. Only the building structural frames are considered for the comparison – as detailed in Chapter 3. This is due to the expected similarities in the building envelopes, which would have similar outputs to those from LCA modelling. Furthermore, the study does not consider operationally associated emissions for analyses; it only finds them for perspective. The LCA modelling is constructed on strict frameworks outlined in the ICLD Handbook (2010)

The study is thus structured to directly compare embodied emissions associated with functionally identical MET with RC buildings in a like-for-like manner; the study further investigates the impacts associated with a vertical extension using MET. Alternative construction methods are not considered, and the buildings selected are distinctly located in or around the Central Business District area around Cape Town, South Africa and Perth, Australia, respectively.

1.10.1 Study Limitations

The scoping of this study results in numerous limitations, with the most significant and notable limitations stated and discussed in the following section to enable the reader to understand certain assumptions and results better. The limitations include, but may not be limited to:

Building design

The building designs developed for a financial, comparative study by Van Der Westhuizen (2020, p. 59) are considered viable and compliant with the required standards. Only minor refinements were made to model material impacts more accurately. The building designs are discussed in detail in Chapter 4. Further design optimisation exercises are not considered in the scope or resources of this study.

Energy mix

The national energy mix for South Africa and Australia is accepted as currently captured in the relevant LCI databases. The Australian National Greenhouse Gas Account Factors Workbook 2023 (2023) provides a high confidence level in the emissions intensity of the relevant national and regional grids. Uncertainties in the South African national energy grid are not considered separate from projections implemented in the relevant LCI databases.

Available data and data quality

The modelling software implemented utilises the latest emissions associated with the relevant templates from various international databases. The templates defined for modelling are listed in descending order, starting with the templates most pertinent to the building locale. The most relevant templates were thus implemented for modelling.

Timber market capacity

This research comments on but notes that market readiness is excluded from the study. Both countries have CLT projects being built, and both have CLT being manufactured locally (Llewellyn, 2023), both countries also still rely heavily on imported CLT (Harding, 2023) – or would be heavily reliant on imports if bigger projects were implemented.

Chapter 2 Literature Review

A literature review serves as a critical foundation for any research project, aiming to establish the background and context of the subject matter, synthesise the current body of knowledge, and identify gaps or areas requiring further investigation. In the context of this study, which explores the role of Mass Engineered Timber (MET) in the decarbonisation of the built environment, the literature review has been designed to examine the prevailing discourse, methodologies, and findings surrounding sustainable construction practices, life cycle assessments (LCA), and material-specific impacts of MET compared to conventional building materials. An overarching theme of specific geographical context comparative studies was implemented as part of the literature review and, subsequently, the output of this research paper.

The methodology for this literature review entailed a systematic search and selection process. Peer-reviewed journal articles, industry reports, and standards documentation were sourced from the relevant academic databases. These formed the foundation to explore and understand the research gap and subsequent methodology used for this research. Direct keyword searching and citations within research articles were followed to examine the existing research. Although the principle of this field of research has been explored over decades, more recent studies proved most valuable in terms of method development and data availability – older research sources were included for foundational context. A thematic analysis approach was employed to organise the literature into key themes relevant to this study: decarbonisation of the built environment, understanding MET as a new and evolving material, life cycle assessment methodologies, the life cycle impact of supply chains, and the emerging role of MET in vertical extensions of existing buildings.

These themes were selected based on their alignment with the research objectives, which aim to evaluate MET's potential to reduce embodied emissions, compare its performance across distinct geographic contexts, and explore its application in vertical building extensions. Decarbonisation is critical to addressing climate change and understanding the built environment's role in emissions reduction requires an analysis of both operational and embodied emissions. The use of LCA as a methodological tool forms the backbone of this research, as it provides a quantifiable means to assess environmental impacts. Additionally, understanding material-specific characteristics and the supply chain—factors that vary significantly between regions—is essential to contextualising MET's viability as a sustainable alternative to conventional materials like reinforced concrete. Finally, the theme of vertical extensions addresses urban densification challenges, positioning MET as a solution that minimises additional land use while leveraging its lightweight and potentially lower-emissions profile.

This review identifies a significant gap in comparative studies considering the geographic and contextual nuances influencing MET adoption and environmental impact. While the body of literature extensively covers LCA studies, limited research explores these dynamics in developing economies or cross-continental comparisons. Moreover, the integration of vertical extensions into LCA frameworks remains underexplored, particularly in regions like South Africa and Australia. This study aims to contribute to the broader understanding of sustainable construction practices by exploring the gaps. It offers practical insights for policymakers, architects, and engineers seeking to decarbonise the built environment through innovative material choices.

2.1 Decarbonisation of the Built Environment

Decarbonising the built environment is crucial in mitigating the sector's overall environmental impact on climate change due to the building sector's substantial contribution to global energy-related emissions (He & Prasad, 2022). Several sections of the building development process could be considered to reduce the emissions associated with the embodied and operational-related components.

As outlined by He et al. (2022), an array of targets, pathways, and methods adds to the challenge of understanding where efforts should be applied and highlights that primary attention is given to operational emissions as the largest portion of whole-of-life emissions for a building. In addressing operational emissions, targets range from 60% to 100% reduction of operational energy-related emissions by 2030 for various governments and industry bodies and some 40% reduction in embodied emissions. Jayalath (2020) highlights the lack of policy enforcement or specific pathways to measuring, reporting, and reducing embodied emissions-associated methods. Early adoption of voluntary disclosure and reporting based on public perception is the primary driver at this time (He & Prasad, 2022). Still, a lack of policies enforcing more robust decarbonisation measures is evident.

Reducing the whole-of-life emissions by designing a building differently may include operational design optimisation principles and distinct material and construction methodology considerations. The selection of specific building materials not only impacts the embodied emissions of a building but could also impact the operational emissions. Guo et al. (2017).

Chen (2020, p. 1) notes the two strategies available for decarbonising the built environment: design optimisation and material selection, and operational building energy use optimisation. One of the primary strategies to decarbonise embodied emissions is to consider the carbon content or intensity of materials during the design phase (ibid.). Depending on the energy standard used to design a building, Cheng (2020, p. 1) further states that the operational energy consumption of a building accounts for 45% to 80% of the total carbon equivalent emissions associated with a building over its lifetime – implying that 20% to 55% of carbon-equivalent emissions are from the building structure. Addressing the non-operational energy use scope involves choosing materials with lower energy-intensive production processes, lower direct construction stage emissions, and a reduced end-of-life. Sustainable and innovative materials, such as recycled or bio-based materials, can also significantly decrease embodied emissions through use past the framed building end-of-life.

Carefully considered products with energy-efficient production techniques, shorter supply chains, and simplified constructability could be regarded as to decarbonise the embodied energy-associated emissions in the built environment as the products inherently have lower embodied emissions associated with production and construction. Pierbon et al. (2019, p. 10) found the product stage constituted 75% to 92% of the total upfront embodied emissions between varying construction methods for CLT buildings. Adopting alternative materials and better manufacturing methods, such as using renewable energy sources and implementing process optimisations, can substantially reduce the emissions associated with the extraction and production of building materials.

Minimising transportation distances of raw materials, products, and construction waste can further lower the embodied emissions in the built environment. Chen et al. (2019, p. 9) focussed on sourcing materials locally and showed that transportation-related emissions can be reduced by 95% during the product stage. Additionally, implementing circular economy practices, such as recycling, reusing, and repurposing materials, can extend their lifespan and decrease the demand for new raw materials, thereby reducing the environmental impact of materials and products over their entire functional life cycle.

Thus, decarbonising the built environment is a critical step in mitigating its significant contribution to global energy-related emissions. Addressing both operational and embodied emissions is essential, with operational emissions often comprising the larger share of a building's whole-of-life emissions. Governmental and industry targets aim for reductions in operational energy emissions by up to 100% and embodied emissions by 40% by 2030, but achieving these goals is hindered by insufficient policy enforcement and reliance on voluntary disclosure (Jayalath, et al., 2020). Strategies to reduce whole-of-life emissions include optimising operational design, selecting low-carbon materials, and improving construction methodologies, as material choice directly affects both embodied and operational emissions. The product stage, often constituting up to 92% of upfront embodied emissions (Pierobon, et al., 2019), can be decarbonised through energy-efficient manufacturing, shorter supply chains, and the adoption of renewable energy sources. Transportation and end-of-life practices also play a pivotal role in reducing embodied emissions. Adopting a whole-life approach to building design and construction enables emissions reduction for buildings.

2.2 Understanding Mass-Engineered Timber

Mass-engineered timber (MET), particularly Cross-Laminated Timber (CLT) and Glue Laminated Timber (GluLam or GLT) is increasingly considered a highly competitive alternative construction method for medium- to high-rise residential buildings instead of more conventional RC buildings. Its increasing popularity in structural applications stems from potential environmental benefits, architectural and engineering flexibility, and structural efficiency and safety. MET buildings are characterised by a reduced weight compared to traditional concrete and steel structures, leading to lower foundation costs and potentially more efficient construction processes. In his research, Van Der Westhuizen (2020, p. 67) notes that a functionally similar MET building was 3.6 times lighter than its RC counterpart. Despite its lighter weight, MET offers considerable strength and stability, making it a viable option for mid-rise to high-rise constructions.

The structural properties of MET, such as engineered wood products and CLT, are being leveraged in various residential and non-residential applications. These applications are potentially more environmentally sustainable due to timber's natural properties and meet the structural demands posed by taller constructions. Mass timber buildings can efficiently handle lateral forces from phenomena like wind and earthquakes, a crucial factor in the stability of taller structures (Tannert & Loss, 2022).

In Figure 4 Existing standards structure for MET across the world below, the development of Cross-Laminated Timber (CLT) standards across different regions is demonstrated, highlighting established standards in some nationalities, ongoing efforts in regions where standards are under development, and current timber standards being used in other countries. This visual contextualises the global progress and disparities in CLT standardisation, providing insights into the respective South African and Australian standards contexts.

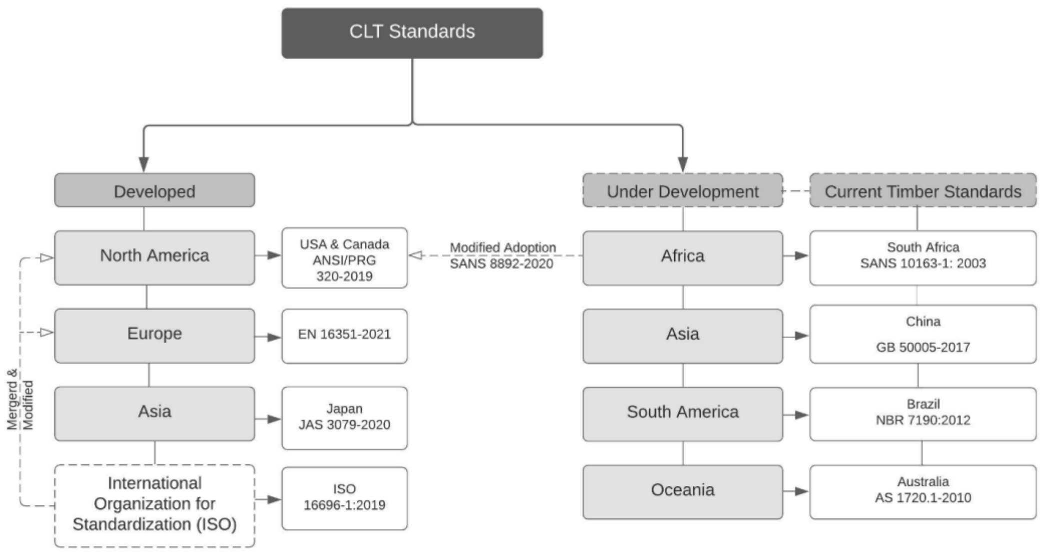

Figure 4 Existing standards structure for MET across the world (Kurzinski, et al., 2022)

In South Africa, the development of Cross-Laminated Timber (CLT) became recognised through the release of a manufacturing standard in 2020 – GLT or variants thereof have been manufactured for many years. The key standard in focus is the SANS 8892-2020, a performance standard for CLT adapted from the ANSI/APA PRG 320-2017. These standards address various aspects of CLT, including timber grading, adhesive requirements, and finger jointing processes (Kurzinski, et al., 2022, p. 3). It also refers to other South African National Standards like SANS 10163-2003 and SANS 1783-2/1783-5, which are pivotal in determining timber's grading and structural requirements, particularly South African Pine, a widely used species in local construction. The push towards developing a unique South African CLT classification system highlights the country's commitment to establishing standards that resonate with its local construction practices, market demands, and available resources.

In contrast, Australia's CLT and mass timber industry is marked by a growing interest, especially in utilising locally grown pine for CLT panel fabrication. However, specific CLT standards are yet to be established. The most relevant standard currently in use is AS 1720.1-2010, titled "*Timber Structures - Part 1: Design Methods.*" (Standards Australia, 2010). This standard provides guidelines on the design of timber structures, addressing various stresses and strength properties. The AS/NZS 1328 standard for GLT, which shares similarities with CLT, is also applied. This standard includes performance requirements and installation guidelines. The Australian standards development process, involving submissions and reviews by relevant committees, indicates ongoing efforts to integrate CLT standards more comprehensively into the national building codes, ensuring the adoption and effective use of this sustainable building material in the built environment (Kurzinski, et al., 2022).

2.2.1 Fire Safety

Fire safety is a critical aspect and perceived barrier of using mass timber in medium to build medium- to high-rise buildings. Despite the combustible nature of wood, extensive research has shown that MET buildings can be designed to meet stringent fire safety standards. An increasing number of countries have developed their own or adopted several North American and European building standards for use in their respective building regulatory framework. Numerous industry organisations have also published and regularly update their respective MET design guides, like a popularly referred manual from WoodSolutions (2023).

One key attribute of MET that contributes to its fire safety is the formation of a char layer during the burning process. This char layer on the surface of the timber acts as an insulation layer, protecting the inner core of the wood and slowing down the burning process. This phenomenon not only preserves the structural integrity of the building during a fire but also offers more time for evacuation and firefighting efforts (Pierobon, et al., 2019). Barber's (2017) research on the fire safety of MET buildings highlights this aspect, emphasising the importance of understanding the behaviour of exposed MET in fire scenarios (ibid.). Effective use of protective covering and fire suppression systems is critical, and recent studies have investigated the functional performance of such systems in MET buildings, demonstrating their effectiveness in maintaining safe conditions during a fire and reducing damage to timber structures (Ko & Elsagan, 2023).

Furthermore, extensive fire testing and analysis have been conducted to assess the fire dynamics in mass timber building compartments. This research provides crucial data on critical temperatures, fire flows, and the burning characteristics and behaviour of MET structures, contributing to a better understanding of how mass timber behaves during fires and informing fire engineering processes (Gorska, et al., 2021).

The combination of natural charring characteristics, effective fire suppression systems, and ongoing research into fire dynamics supports the safety of MET as a suitable construction material for building frames of medium to high-rise residential buildings, provided proper design and engineering practices are followed.

2.2.2 Building Life Span

Building lifespan is a commonly raised concern when considering MET as a primary construction material; however, studies suggest the expected lifespan of a mass timber building could be more than 100 years (Chen, et al., 2020), but could vary significantly. The lifespan is generally accepted as comparable to conventional RC buildings, designed for a minimum service life of 50 years. Pomponi et al. (2016, p. 697) note that LCA studies typically vastly underestimate the building service life, which could, on average, be 132 years, and as a result, modelling outputs could be skewed. Studies indicate that with proper design, maintenance, and environmental conditions, mass timber buildings can achieve similar, if not longer, lifespans than RC buildings exceeding 100 years (Younis & Dodoo, 2022, p. 1). Research in this field is evolving as mid to high-rise MET buildings forming significant research contributions of MET have been constructed only as recently as 2016 in the case of Brock Commons Tallwood house in Vancouver, Canada. A Swedish CLT manufacturer, Enso (Andersen, et al., 2022, p. 3), states that ‘‘With the right building physics construction methods, there is no limit to lifetime” when commenting on the expected lifespan of a CLT building. Published studies have shown varying MET lifespans, all acknowledging the evolving nature of this technology. Duan et al. (2022, p. 7), in their review of 41 relevant research papers covering LCA studies on MET buildings, noted the impact of the building lifespan unknowns and assumptions. Their research states that dynamic LCA models can span 0 to 300 years, including forestry activities of 80 years, building service life of 50 years (assumed in their study), and effects after an additional 100 years of pulsed emissions. Duan et al. (2022, p. 8) state that an Athena survey found that 60% to 80% of buildings were either demolished or redeveloped within 50 years for RC, and 65% of timber buildings were only redeveloped or demolished after 75 years. The timber buildings demolished within 75 years do not include MET buildings, which is considered an emerging method. A sensitivity study by OneClickLCA (2023) notes that a building life span of only 25 years results in the materials-driven impacts being 120% higher than the same building with a 60-year lifespan.

The lifespan of a building, whether mass timber or RC, is primarily influenced by material quality, construction methods, maintenance practices, and environmental conditions. For instance, a study on the seismic performance of MET versus RC buildings in highly active seismic regions showed that mass timber could have advantages in terms of flexibility and mass, which could influence its durability and longevity under certain conditions (Timmers & Jacobs, 2018, p. 722). Additionally, the susceptibility to environmental factors like moisture and pests and the quality of protective treatments are critical in determining the longevity of mass timber buildings.

Environmental factors such as corrosion, extreme heat and cold cycles, and chemical erosion play a significant role in estimating the longevity of RC structures. Maj et al. (2020, p. 1) highlight that RC structures are susceptible to environmental impacts, with durability being a key factor in design. Over time, exposure to aggressive environmental conditions can alter the mechanical performance of steel reinforcing bars and concrete, resulting in a general decrease in the bearing capacity of structural elements. This deterioration by factors like chloride-induced corrosion, climate change, and cyclic loading can exacerbate deterioration, which, when combined, can significantly reduce the lifetime of RC structures.

Similarly, MET structures face environmental challenges, which may be inherently different. While mass timber is more susceptible to biological factors like mould, decay, and insect infestation, modern treatment methods and construction techniques have greatly improved its durability. The susceptibility of MET to moisture and pests is a key consideration, and the quality of protective treatments plays a vital role in its longevity.

However, the natural resilience of timber, combined with advancements in protective treatments, can make MET structures comparably durable to their RC counterparts. It is essential to prevent traditional timber structures from damage and structural performance reduction, highlighting the need for effective treatment, protection against the elements and reinforcement methods to enhance the durability of MET constructions.

Both RC and MET structures require careful consideration of environmental factors to ensure their durability and longevity. While RC structures must be designed and maintained to prevent corrosion and structural degradation, MET structures benefit from modern treatment and construction methods that mitigate their natural susceptibility to biological degradation. The differences in how these materials respond to environmental factors underscore the importance of tailored approaches to ensure the durability of buildings constructed with either material.

In summary, Mass Engineered Timber (MET), particularly Cross-Laminated Timber (CLT) and Glue-Laminated Timber (GLT), is emerging as a viable alternative to conventional materials like reinforced concrete (RC) due to its potential environmental, structural, and construction advantages. Considered to have lower embodied emissions, carbon sequestration capabilities, and efficient construction processes, MET presents a compelling solution for sustainable building practices. However, challenges such as fire safety, durability, and developing region-specific standards highlight the need for continued research and adaptation. Despite these considerations, MET's potential to balance performance and sustainability positions it as a key material in transitioning to a decarbonised built environment.

2.3 Life Cycle Assessments

Life Cycle Assessments (LCAs) have emerged as a crucial tool for quantifying the environmental impacts of products, materials, and operations in the built environment during various stages of the building development process. In the context of a sustainable built environment, LCAs offer a thorough quantitative approach to analyse the entire life cycle of buildings and infrastructure, from the extraction of raw materials to construction, operation, and eventual disposal. Based on standards outlined in AS ISO14040:2019 and EN 15978 (Jayalath, et al., 2020; Duan, et al., 2022), an LCA quantifies the energy consumption, resource use, and emissions associated with different stages of a building's entire life cycle by modelling specific material quantities and properties in a specialised software package. LCAs aid decision-makers in identifying hotspots for improvement and formulating effective strategies to minimise the environmental impact of the built environment across the complete life cycle of the built form.

Conducting an LCA can be a timeous and costly exercise and is often neglected due to lacking regulatory requirements. Duan (2022) found that the vast majority of 32 studies were conducted in developed countries, with more than 50% in Northern Europe. Duan (ibid.) specifically noted that not a single LCA that studied the use of MET have been conducted in Africa. An LCA could play a pivotal role in responsible practices and support informed, evidence-driven decision-making in the built environment if the modelling process is undertaken. As the demand for more sustainable buildings continues to rise, LCAs provide an evidence-based framework for architects, engineers, and policymakers to make informed decisions.

2.3.1 Modelling methods and life cycle inventories

Life Cycle Assessment (LCA) studies commonly use two distinct approaches: the attributional LCA (ALCA) and the consequential LCA (CLCA). These approaches differ in focus and methodology, impacting their suitability for comparative studies on building materials.

Attributional LCA primarily assesses the environmental impacts of a specific product or system as it currently functions without considering potential changes in the system caused by decisions (Collinge, et al., 2018). It attributes environmental burdens to specific products or processes and is often used to understand the direct impacts of a particular product or process. For example, in a study comparing steel and concrete, ALCA would look at the environmental impacts as they are currently, including factors like energy use and emissions during production (Kua & Maghimai, 2017).

Consequential LCA, conversely, assesses the environmental impacts of changes in production levels or technologies, considering broader system-level changes. The consequential method is concerned with the environmental consequences of decisions, such as a shift from one building material to another on a macroscale and not at a micro, building-level scale. For instance, CLCA would examine the potential changes in environmental impacts if there was a switch from reinforced concrete to mass timber in building construction, including indirect effects like changes in forest management or the concrete industry (Fauzi, et al., 2021, p. 8).

For a comparative LCA study on MET and RC buildings, the choice between ALCA and CLCA depends on the study's objective. If the goal is to understand these materials' current direct environmental impacts in construction, ALCA is appropriate. However, if the aim is to assess the broader environmental implications of a shift from reinforced concrete to mass timber in the construction industry, including potential market and supply chain reactions, CLCA would be more suitable. Considering dynamic interactions and systemic changes, CLCA can provide insights into the potential environmental impact reduction or drawbacks of such a shift.

The use of ALCA is particularly well-suited for directly comparing the environmental impacts of two buildings based in distinct geographic locations for their immediate impact (Bruce-Hyrkäs, 2018). This approach focuses on the environmental burdens directly attributable to a specific product or system within its current functioning context, making it ideal for such direct and location-specific comparisons.

In ALCA, the assessment is grounded in the existing state of production and processes captured in the relevant LCI databases, providing a clear and direct evaluation of the quantified environmental impacts associated with each individual building or development. For example, when comparing buildings in different geographical areas, ALCA can effectively account for the specific energy mixes, local construction practices, and material sourcing and value chains unique to each location. This specificity is crucial, as the environmental impact of building materials can vary significantly based on regional factors, including energy sources used in material extraction and production, and transportation distances (Kua & Maghimai, 2017).

Moreover, ALCA's focus on current systems and processes allows for a more standardised comparison between the two buildings. It effectively isolates the environmental impacts of each building based on its specific construction and operational characteristics. This isolation is essential for accurately assessing and comparing the immediate environmental impacts of each building without the influence of potential systemic changes or future scenarios, as would be the case in CLCA (Fauzi, et al., 2021).

Therefore, ALCA provides a targeted and location-specific assessment approach for a comparative study to determine the immediate environmental impacts of two buildings in different geographic locations. This approach allows for unique environmental factors and direct impacts associated with each building to be accurately captured and compared, making ALCA a more appropriate choice for such studies.

2.3.2 Considering Biogenic Carbon

When considering MET as a primary construction material for a building frame, a large portion of emission reduction opportunity lies within the carbon sequestration within the timber as biogenic carbon. Including biogenic carbon in lifecycle assessment (LCA) studies when comparing reinforced concrete and mass timber construction is critical for accurately assessing the whole-of-life impacts of building materials to compare different construction methodologies directly. Mass-engineered timber construction, in particular, benefits from the carbon sequestration capabilities of wood, offering a lower emissions impact than traditional reinforced concrete construction.

Guest et al. (2013) and Andersen et al. (2022, p. 4) estimate the biogenic Global Warming Potential over a storage period for the resources implemented in the product. They based the estimation on the rotation period of the wooden products and the resources used to create them. Andersen (2022, p. 4) states that net carbon sequestration would occur if the sequestration period exceeded the regeneration of the natural resources used to produce the products. The resultant net negative is expected as the building lifecycle is modelled as 100+ years, and the regeneration of timber resources for the products used is expected to exceed the rate at which the built form would be decommissioned.

When timber reaches the end of its functional life, the stored biogenic carbon can be re-released into the atmosphere as CO_2 through decomposition or combustion processes. However, if the timber is reused, recycled or repurposed, the embodied emissions remain stored for the duration of the new product's life. Incinerating timber waste can generate energy but re-releases the stored carbon as CO_2. Alternatively, disposing of timber in landfills results in a slow decomposition process, with part of the emissions being released as methane, a greenhouse gas considered four times as potent as CO_2. However, some emissions remain stored in the landfill for extended periods as organic mulch. Recycling or upcycling timber waste into new products can extend the emissions storage period and reduce the need for virgin materials. Reuse scenarios, including manufacturing particleboard or engineered wood products, can mitigate environmental impacts by conserving resources and storing emissions for longer durations.

The end-of-life consideration of timber buildings and the associated biogenic carbon release have significant implications for the overall environmental impact of timber as a construction material. While incineration and landfilling release stored emissions, recycling and upcycling present opportunities to maintain emissions storage and reduce the demand for new materials. Adopting dynamic LCA methods that account for these complexities is crucial for accurately evaluating the sustainability of timber construction and informing policy and practice to enhance the circular economy and mitigate climate change. A review by Hoxha et al. (2020, p. 519) identifies the discrepancies in LCA methods for assessing the biogenic carbon in buildings. It emphasises the need for a consensus on modelling the end-of-life scenarios for timber waste.

Andersen et al. (2022, p. 8) confidently conclude that the emissions storage horizon in the built form is sufficiently long to reflect the net-negative emissions as typical LCA studies do. The natural resources would replenish multiple times over the sequestration period within the built form. As such, the emissions sequestered would exceed the embodied emissions re-released at the end of product life. A study by Breton et al. (2018, p. 3) discusses the challenges in assessing the impacts of biogenic carbon in the built environment. It suggests that dynamic approaches to LCA could more accurately reflect the benefits and impacts of biogenic materials like timber. Julie Lyslo Skullestad et al. (2016, p. 122) highlights the need for consistency of biogenic carbon inclusion in LCA studies, as different standards have different recommendations for accounting for biogenic carbon.

2.4 The Impact of Materials and the Supply Chain on Embodied Emissions

Understanding the impact of material supply chains on Life Cycle Assessment (LCA) results is crucial for promoting sustainable practices within the built environment. The supply chain of materials encompasses the various stages involved in the extraction, production, transportation, and disposal of building products or materials, and each stage can pointedly influence the overall environmental performance of a product or construction project. To conduct a comprehensive LCA, it is vital to consider the embodied energy, emissions, and resource use associated with each material's journey from extraction to end-of-life. This understanding helps stakeholders identify potential hotspots for environmental impact and devise targeted strategies for reducing emissions impacts and resource consumption.

Raw material extraction and transportation (A1 – A2):

The choice of materials and sourcing strategies directly affect the outcomes of an LCA. Opting for locally sourced materials can lower transportation emissions and resource consumption (Chen & Pierobon, 2019). The study by Chen (2019, p. 2) projects that a region in the Pacific Northwest with growing interest in MET would require 187 000m3 of CLT panels to satisfy the demand just for mid to high-rise developments by 2035. The area of the study mentioned above excluded GLT requirements and shares characteristics similar to those in the regions studied in this paper. Moving vast volumes of products through road transport or over long distances could negate the gains of the sequestered emissions in the timber itself. However, it is often excluded from the modelling system boundary (Pierobon, et al., 2019) and thus not accounted for.

Manufacturing (A3)

The energy supply mix of the national grid is a crucial component in manufacturing products, particularly concerning the impact of embodied emissions. The emissions intensity of the electricity used in manufacturing directly impacts the overall emissions embedded in the products.

Fact sheets from the Australian Energy Market Operator (AEMO) indicate that Australia's national grid for the reporting year 2022/23, on average, was made up of 68% fossil fuel-based generation and 32% of renewable energy generation (Australian Government Department of Climate Change, Energy, the Environment and Water, 2023, p. 7). The same report notes that the state of Western Australia, where Perth is located, achieved only 17% of renewable generation on average. Notably, 57% of the Western Australian energy generation mix was from Natural Gas. Comparing Scope 1 emissions for Natural Gas to Bituminous Coal generation shows that Natural Gas produces 51.53 kg CO_2-e/GJ as opposed to 90.24 kg CO_2-e/GJ from Bituminous Coal (Australian Government Department of Climate Change, Energy, the Environment and Water, 2023,

p. 13). As a result, the emissions intensity could be considered lower than that of other comparable fossil fuel grids.

A significantly higher fossil fuel-based generation is noted in the South African energy production market, as reported in the 2019 South African Energy Sector Report. The South African grid was powered by 84% heavy carbon-based fuels, including coal and crude oil, with only 11% of renewables (Directorate: Energy Economics and Statistics, 2022). The South African grid also implements a small portion of natural gas generation capacity that comprised 2% of generation for the same year (ibid.).

While the Western Australian electricity grid may be less carbon-intensive than its South African counterpart, it is crucial to consider the influence of localised factors on manufacturing processes. Increased adoption of renewable energy sources at a manufacturing facility or within the regional grid can significantly mitigate the emissions intensity of products. This underscores the importance of analysing the broader energy mix and the specific measures taken at the local level to enhance sustainability.

Finished product logistics (A4)

To fully comprehend its sustainability potential, it is crucial to analyse the impact of material logistics, encompassing sourcing, transportation, and processing, on CLT's overall environmental impact. Additionally, choosing a wood species mix in CLT production is vital in determining its ecological impact and resilience (Chen & Pierobon, 2019).

In studying the locations of CLT manufacturing facilities and the use of lighter wood species, Chen (2019) outlined an additional reduction in the GWP of up to 14% less of CLT panels. Patula Pine and sub-variants, most commonly produced in South Africa (Morris, 2022), have a relative density of 500kg/m3 at 12% moisture content (Protea Timber), in line with the heavier timbers studied by Chen (2019). Mass Timber Technologies and XLam are the only two manufacturers currently operating in South Africa, and their respective production facilities are located in Germiston and Cape Town, respectively. However, the bulk of the lumber produced in South Africa is grown in the Mpumalanga Highveld, Lowveld, and KwaZulu-Natal regions (Morris, 2022) – adding to the length of the logistical supply chain and subsequent emissions.

In the opposing Australian timber production environment, softwood lumber is produced near populous cities on both the Eastern and Western coasts, respectively, with the main species being Pinus Radiata (May, et al., 2012) with a higher relative density of 550kg/m3 (U Tasmania). XLam is currently producing cross-laminated timber at their facility in Woodonga, situated on a main route roughly halfway between the two major populous cities of Sydney and Melbourne. NeXTimber also manufactures CLT and is based at the port in Adelaide, South Australia, positioning itself well to serve the Australian market through rail or ocean freight. Crosslam, which manufactures CLT from Western Australian timber sources, serves the western coast of Australia.

The two opposing markets present opposing timber supply chains. As outlined by Chen (2019), the impact on the GWP of a building could be significantly impacted by the respective metrics presented, i.e., the length of the supply chain and relative density of the choice of timber species specified.

In South Africa, the rail system, including operators like Transnet Freight Rail (TFR) and the Passenger Rail Agency of South Africa (PRASA), faces safety, infrastructure, and efficiency challenges. Maluleke (2013) notes that safety concerns and collisions have been significant issues within the South African rail network, which can impact the reliability of timber transportation. Furthermore, Havenga (2012) discusses that the most dense, long-distance freight in South Africa is transported by road, indicating underutilisation and potential inefficiencies in the rail system. These factors can affect the environmental performance of rail transport, possibly leading to higher emissions compared to more efficient systems (Maluleke, 2013).

In contrast, the rail system in Australia, particularly for freight transport, has been undergoing modernisation and efficiency improvements. The integration of solar photovoltaic systems on locomotive rooftops, as explored by Lencwe et al. (2016), is an example of how renewable energy technologies are being incorporated to enhance the sustainability of rail transport. Adopting clean energy sources in the rail sector can significantly reduce the impact of emissions from mass timber transportation by rail in Australia compared to traditional diesel-powered trains.

Therefore, while the rail transportation of mass timber in South Africa faces challenges that could increase its environmental impact, the Australian rail system shows potential for lower emissions associated with integrating renewable energy sources and modernisation efforts. This difference in the energy supply and reliability of the rail systems in these countries is a determining factor in the overall embodied emissions of mass timber transportation by rail.

Following Section 2.4, building materials' environmental impact is deeply influenced by their supply chains, encompassing raw material extraction, manufacturing processes, and transportation (LCA stage A1 – A5). Key strategies to reduce embodied emissions include sourcing materials locally, improving energy efficiency in production, and minimising transportation distances. The carbon intensity of national energy grids further affects the emissions profile of manufacturing processes, noting that regional disparities could positively or negatively impact product stage emissions. Adopting circular economy principles, such as recycling and reusing materials, can also extend the lifecycle of resources and reduce emissions. An understanding of the material supply chains of a project is therefore vital to managing the overall embodied emissions of the built environment.

2.5 Using Mass Engineered Timber for Vertical Expansion of Buildings

Urban densification is a significant challenge in most cities due to the migration to urban areas; as discussed in Chapter 1, the option to increase usable GFA without the associated additional land pressure is the vertical extension or expansion (VE) of existing buildings, particularly tertiary buildings, due to their abundance in the existing building stocks. Dind et al. (2018) introduce the 'Working Space' project, which aimed to design and develop a prefabricated modular timber construction system for the vertical extension of suitable buildings. This system is adjustable to various structural grids and typological organisations. Being inspired by bioclimatic architecture, the system offers high-performance insulation and large surfaces for photovoltaic energy production (Dind, et al., 2018). The successful application of a similar concept in Lausanne, Switzerland, serves as a precedent for other cities facing similar urban densification challenges. This approach not only maximises the use of existing spaces but also enhances the energy efficiency and sustainability of the urban landscape, paving the way for future developments in sustainable urban architecture (ibid.).

Julistiono et al. (2023, p. 68) investigate the suitability of buildings to be vertically extended during a major renovation or functional conversion project rather than a complete demolition of an existing base building followed by the construction of a new building. Figure 5 Functional changes in buildings in vertical extensions (Julistiono, et al., 2023) below demonstrates from their research how the 172 VE projects reviewed, a significant number of 71 of the base buildings functioned as residential buildings from the original number of 42. Furthermore, the research found that 96 and 54 of the VE project components functioned as residential and office buildings, respectively. Notably, Julistiono et al. (2023, p. 74) conclude that the occurrence of VE projects and their use of timber over conventional materials has been accelerating significantly in the past decade.

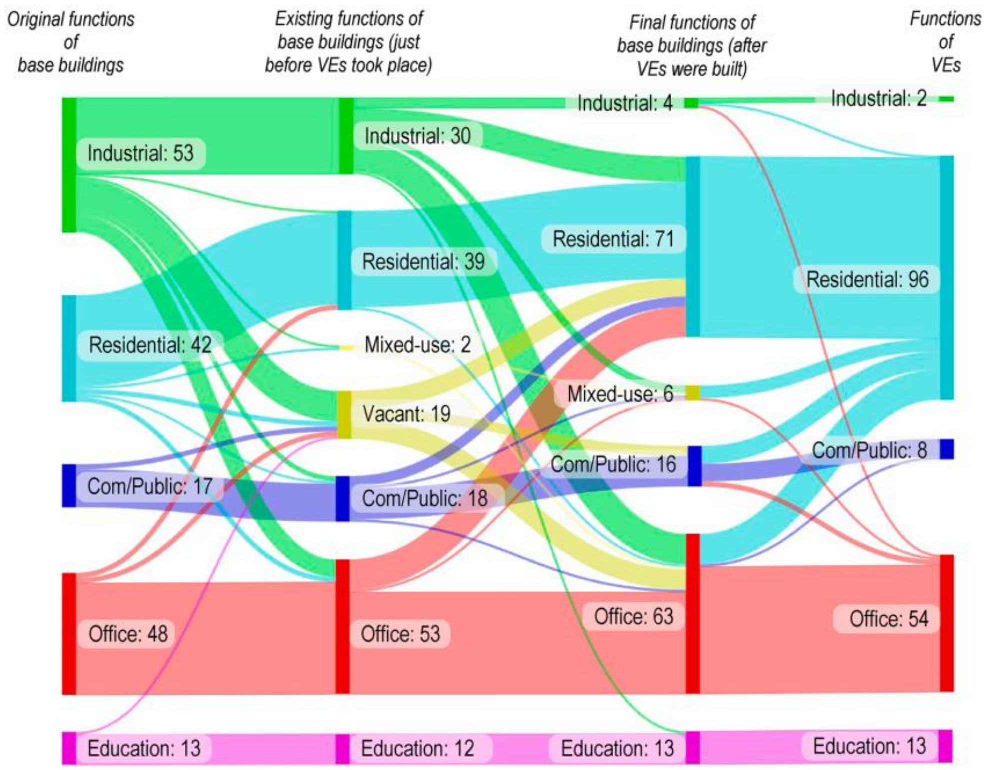

Figure 5 Functional changes in buildings in vertical extensions (Julistiono, et al., 2023)

Considering the embodied emissions of an existing base building are a critical factor in LCAs for vertical extensions. These emissions, encompassing all the energy and resources consumed in constructing the original base building, could be a sunk environmental cost. By incorporating the existing building into a new construction project, some of these costs can be effectively amortised over a longer building life, improving overall sustainability. The work by Dind et al. (2018) discuss an innovative, modular MET system for vertical extension focusing on sustainable materials, indirectly stressing the role of embodied emissions in older buildings.

In considering the operational emissions in a vertical extension, Ingrao et al. (2019) highlight the role of LCA in evaluating energy efficiency and environmental performance, indicating the importance of embodied emissions in assessing overall sustainability for a vertical extension context. Perini et al. (2021, p. 3) evaluate the sustainability of Vertical Greening Systems (VGS) in building retrofits. This becomes more relevant when considering the existing structure's embodied emissions. The implementation of VGSs has the potential to sequester emissions incurred when the original building was constructed and vastly improve the operational efficiency of the existing and extended structure. The strategy ultimately lowers the whole-of-life emissions for the entire building. Perini et al. (2021, p. 1) modelled a 56% operational energy improvement in their study but noted an increased impact in the water scarcity category.

Hafner and Storck (2019)emphasise the need for frameworks and rules in LCA that consider the existing building's impact, particularly when assessing the environmental impacts of different material selections in storey additions, as gaps in the frameworks will result in other projects reporting different boundaries and ultimately higher or lower emissions figures.

2.6 Chapter Conclusion

The literature review chapter underscores the urgent need for the built environment sector to address its substantial contribution to climate change and environmental degradation. Through a comprehensive examination of current practices, policies, and methodologies, particularly the implementation of Life Cycle Assessments (LCAs), the review discusses the challenges and opportunities in pursuing sustainability within the sector.

The examination of MET within this review reveals its transformative current use and future potential in sustainable construction, balancing environmental performance potential and innovation in a traditionally slow-evolving industry. Mass Engineered Timber's appeal lies in its emissions sequestration capacity, which significantly contributes to the decarbonisation of the built environment and its structural and aesthetic versatility. Considering concerns regarding fire safety, advancements in material science and fire design have led to the development of fire-resistant treatments, monitoring systems and construction methods that enhance MET's fire safety, aligning it with relevant safety standards. Furthermore, the longevity of Mass Timber structures is underscored by these innovations, promising a durable solution that rivals traditional construction materials. The understanding of MET - through its environmental benefits, fire safety enhancements, and extended lifespan - underlines its potential for the future built environment, offering a pathway to more sustainable, safe, and long-lasting buildings in the pursuit of reducing the industry's emissions and impact on climate change.

The review highlights the critical role that LCAs play in the built environment, serving as a pivotal tool for quantifying the environmental impacts linked to building construction, operation, and demolition. By offering a holistic view of environmental impacts throughout the entire lifecycle of a building, LCAs facilitate informed decision-making to enable stakeholders to identify strategies that significantly reduce emissions impact and promote resource efficiency. The evidence suggests that integrating LCAs into construction projects not only aids in achieving regulatory compliance but also supports the broader goal of sustainable development by minimising negative environmental impacts.

The literature also reveals significant barriers to the widespread use of LCAs in the built environment. These include, but may not be limited to, a lack of standardised methodologies, insufficient data availability, and the high costs associated with conducting comprehensive assessments. Furthermore, the findings point to a gap in the knowledge and skills required among professionals in the sector to implement and interpret LCAs effectively. There is a need for enhanced collaboration between researchers, industry professionals, policymakers, and educational institutions to standardise LCA methodologies and improve the accessibility of LCA tools and data. Areas for future research identified in the literature review are discussed in the recommendation section in Chapter 7.

The transition towards a more sustainable built environment requires integrating innovative materials like MET, applying comprehensive assessment tools like LCAs, and reevaluating construction practices to reduce emissions and environmental impacts.

Exploring MET, particularly its application in vertical extensions, alongside the strategic use of LCAs presents a promising pathway to achieving improved sustainability goals in the sector. As the construction industry continues to evolve, the insights gained from this literature review are expected to contribute to developing more sustainable, efficient, effective, and practical building practices.

Chapter 3 Research Method

The method used in this research project is based on utilising detailed quantitative models of the Life Cycle Analyses of two respective buildings in their respective contexts to answer research sub-questions and, finally, a comprehensive response to the main research question. The study will deliver qualitative findings to conclude the embodied emissions reduction potential using MET based on modelling specific building design scenarios in their respective contexts.

The proposed building designs to be modelled are located in Cape Town, South Africa, and Perth, Western Australia, to distinguish how localisation factors impact the embodied emission levels of MET and RC buildings. The building construction methods directly compare a building frame constructed primarily from Business as Usual (BAU) materials, i.e., cast-in-situ reinforced concrete, and the proposed MET method. The identified scenarios for building comparison include the construction of a medium-rise (8 floors) building as a greenfield development and the vertical expansion of an existing base building.

The comparative factors are generally considered essential to research development, as they seek to place similar buildings in similar environmental and climatic conditions. The differentiating factors function as a like-for-like comparison method to demonstrate how the geographical context impacts a building's whole-of-life impact. Table 2 below are some of the significant factors that are distinguished in the research and modelling outcomes.

Table 2 Comparative factors expected to impact research outcomes

Topic	Cape Town, South Africa	Perth, Western Australia
Climate Zone	Moderate temperate coastal climate zone.	Moderate temperate coastal climate zone.
Electricity Supply (Assume on-site renewables are not applicable)	Carbon intensive and uncertain future.	Rapidly decarbonising and extensively planned further decarbonisation.
Raw Materials	Strong and sustainable raw material supply available.	Uncertain raw material supply future. Currently, practices are considered sustainable.
Logistics Systems	Carbon intensive and primarily road-based, and uncertain future decarbonisation.	Less carbon-intensive road-based operations and strong railway options. Notable road and

		rail freight decarbonisation plans.
Built environment policy and standards	Generally, slow evolving and reactive. Communities of practice influencing and driving MET evolution.	Somewhat slow evolving and reactive.

As a comparative LCA, only primary building frame components are modelled and compared based on the case that buildings will have similar envelopes and finishes specified and will not present an advantage for one building method over another in terms of embodied emissions (Andersen, et al., 2022). In modelling the primary building frames, the methods implemented follow the ILCD (International Reference Life Cycle Data System) handbook guideline for a standardised approach in model setup. The model development method is critical for comparable data outputs through consistent measures to compare modelling scenarios based on a functional measuring unit (FU) selected as $kgCO_2eq/m^2$ (ibid.)

3.1 Tools Used for LCA Modelling

The study requires a consistent method and evidence-based output to compare building scenarios on a FU level. The tools used to arrive at consistent model outputs include the ILCD handbook as a methodology guideline and a cloud-based, scientifically credible LCA modelling platform. The cloud-based modelling software implements various applicable certified LCI databases, as outlined in the LCI database section below, for the model back-end to provide reliable and credible model impact outputs.

In LCA modelling platforms, material quantities are typically modelled using predefined templates built on LCI databases that contain environmental impact data for various building materials such as CLT, GLT, steel reinforcement, concrete, etc. These templates are based on extensive research and data collection regarding the life cycle impacts of these materials, including their extraction, manufacturing, transportation, installation, use, and disposal stages. Figure 6 LCA modelling below outlines the process flow on material quantities that are typically modelled in a platform:

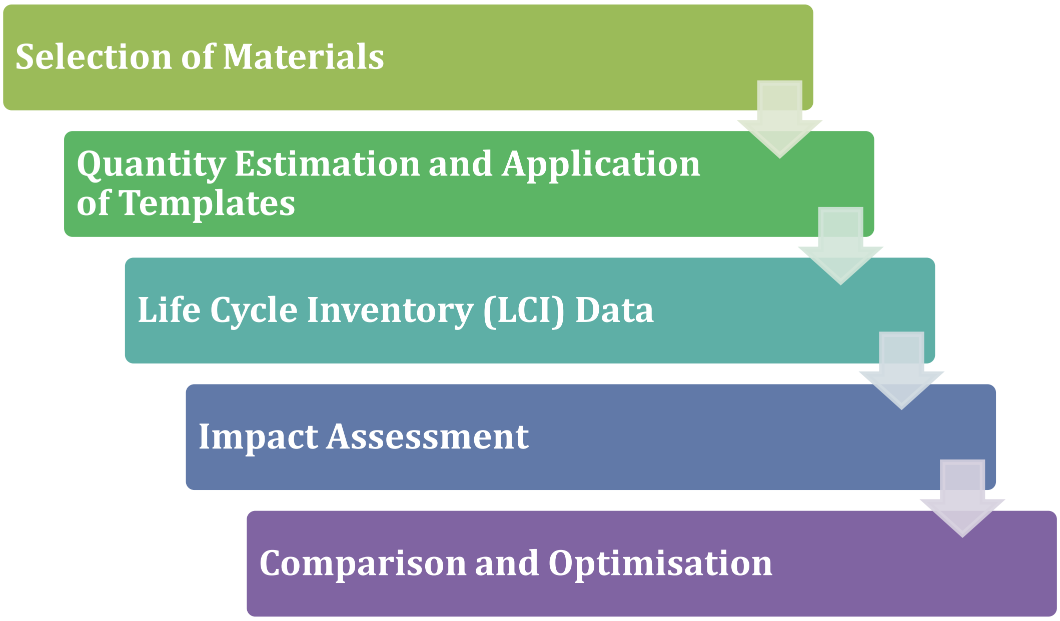

Figure 6 LCA modelling process.

The various steps in the modelling process are outlined in Figure 1 above are:

Selection of Materials: The first step is selecting the materials for the building project. The user can choose from a list of available options for each material or enter custom data if necessary.

Quantity Estimation: Once the materials are selected, the next step is to estimate the quantities required for the project. That can be based on architectural drawings, bills of quantities, or other relevant documentation. Depending on the material, the quantities may include dimensions such as volume, area, or weight.

Application of Templates: LCA platforms use templates or databases for each material type to calculate the environmental impacts associated with its extraction, production, transportation, and ultimate disposal. Each template contains data on energy intensity, associated greenhouse gas emissions, water usage, and other environmental indicators.

Life Cycle Inventory (LCI) Data: The templates in LCA modelling platforms are populated with LCI data, representing each material's environmental impacts throughout its life cycle. This data in an LCI is collected from empirical reports, academic studies, and government databases.

Impact Assessment: Once you input the quantities and LCI data into the model, the LCA model performs impact assessments to quantify the specific environmental impacts of each building material individually. This includes assessing impacts such as global warming potential, acidification, eutrophication, and finite resource depletion.

Comparison and Optimisation: Finally, the LCA model's results allow users to compare the environmental impacts of different material options and identify opportunities for optimisation. This could involve selecting materials with lower environmental impacts, optimising design parameters, or implementing alternative construction techniques.

For materials like CLT, GLT, steel reinforcement, and concrete, we use specific templates or databases within LCA modelling platforms, as discussed in the LCI database sub-section in this chapter. These templates are continuously updated to reflect the latest research and industry practices, ensuring that the LCA results are accurate and reliable for decision-making in sustainable building design and construction.

Building LCAs, as outlined above, are guided by established standards such as the ILCD Handbook by the European Commission, EN 15804 for sustainability in construction, and the ISO 14040 and 14044 standards. These frameworks collectively ensure a uniform and scientific approach to assessing the environmental impacts of buildings, broken down into specific life cycle stages. These stages provide standardised boundaries for evaluating all stages of a building's life, from raw material extraction to end-of-life uses, ensuring that environmental performance is assessed consistently and comparably. Figure 7 Below, followed by discussions for each category, insights into the specific life cycle stages are provided.

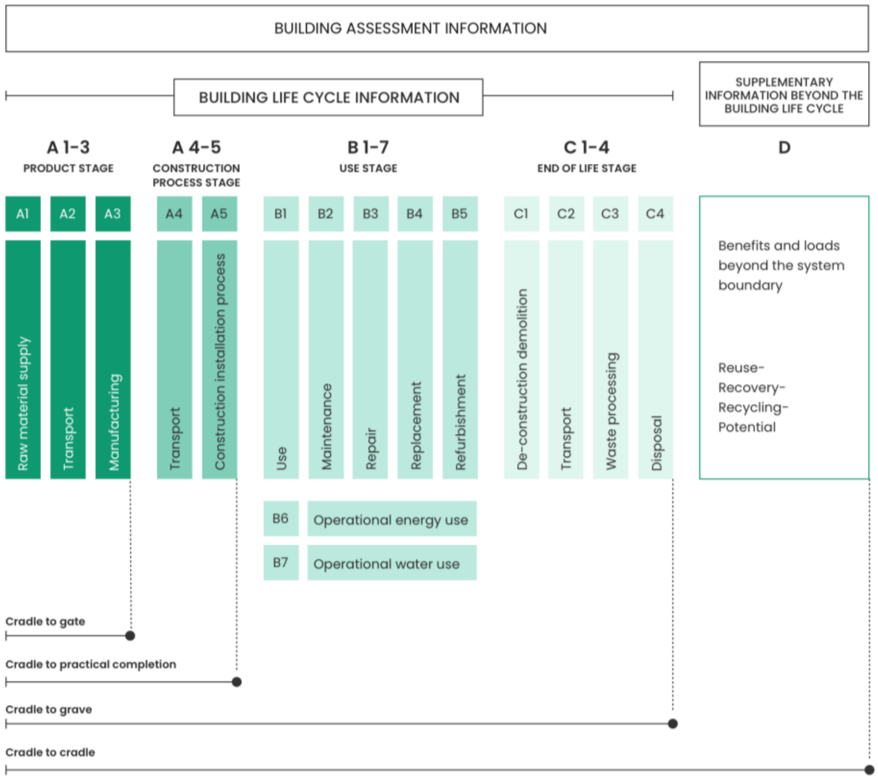

Figure 7 Life Cycle Stages (Masson, 2023)

Product Stage - A:

A1-A3: These stages are significant because they involve extracting raw materials and preparing and manufacturing them into construction products. Each step has its environmental impact, such as greenhouse gas emissions from transport and energy use in manufacturing processes. The assessment in these stages can help select materials with lower environmental impacts, like sourcing locally to reduce transport impacts or choosing materials processed using renewable energy.

Use Stage - B:

B1-B5: The use stage is critical as it can span several decades, during which the building will require energy for heating, cooling, and lighting. Maintenance and repairs are also considered here, reflecting the resource and energy needs over time. Strategies to reduce impact in this stage include designing for durability and energy efficiency.

B6 and B7: These subcategories are particularly crucial as they represent the ongoing consumption of resources. Focusing on energy-efficient building designs and incorporating water-saving technologies can significantly reduce the impact of the operational stage.

End of Life Stage - C:

C1-C4: The end-of-life stage involves deconstruction and the potential reuse, repurposing, upcycling, or recycling of materials or products. This stage's impacts can be mitigated by planning for deconstruction rather than demolition, allowing materials to be disassembled and repurposed. Waste processing and disposal can also be optimised to minimise landfill use and encourage materials recycling.

Supplementary Information Beyond the Building Life Cycle - D:

This category recognises that a building's impact extends beyond its immediate use. Materials that can be recycled or repurposed can offset the need for new raw materials. The potential for recovering energy from waste materials is also considered. This stage encourages adopting a circular economy approach, where the end of one building's functional or useful life can be the beginning of another's resource life cycle.

The LCA framework provides a comprehensive view, enabling architects, engineers, and builders to make informed choices that can reduce environmental impacts. By considering each stage's impacts, from the extraction of raw materials to end-of-life disposal, stakeholders could implement strategies that promote sustainability throughout a building's life cycle.

3.1.1 ILCD Handbook

The International Reference Life Cycle Data System (ILCD) handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) is a fundamental guide and reference for practitioners, researchers, and policymakers engaged in LCA endeavours. Representing a comprehensive compilation of standardised methodologies, data sets, and guidelines, the ILCD handbook (ibid.) provides a structured framework for conducting consistent and credible LCA studies across diverse sectors. Its wealth of information spans from methodological considerations to inventory data and impact assessment indicators, offering a universally recognised foundation that enhances the transparency, comparability, and reliability of LCA modelling. As a cornerstone of LCA practice, the ILCD handbook (ibid.) underwrites the proper methodology to accurately evaluate this comparative LCA study's environmental impacts.

3.1.2 Software Solution - OneClickLCA

The software utilised in this study, OneClickLCA, is a cloud-based LCA software that offers comprehensive tools for conducting LCA modelling in sustainability and environmental assessment. The specific LCA software employed, such as OneClick LCA, is considered less significant than the databases used within these tools. The differentiation in results and accuracy stems from the relevance, comprehensiveness, and regional specificity of the databases referenced by the software. This highlights that LCA modelling can be considered somewhat software-agnostic, with the database being the critical factor influencing the robustness and validity of the findings.

The selected software provides a user-friendly interface to model building materials, products, and projects while integrating various localisation factors and region-specific data from more than 62 relevant LCI databases, such as Ecoinvent, Athena, AusLCI, OpenLCI, etc. (OneClickLCA, 2023). The software produces detailed results that aid the evaluation of the environmental impact across the entire life cycle of a design and material choices. Results from OneCickLCA modelling include data from life cycle stages A1-A3, A4-A5, B1-B5, and C1-C4 – only seeing operational energy and water use stages B6 and B7 excluded. All building life cycle stage boundaries in OneClickLCA are set up according to industry-wide accepted European Standards EN 15978 and EN 15804.

3.2 LCA Methodology Classification

The LCA models are set up using the guidelines in the ILCD Handbook and include the cradle-to-grave modelling results that span the entire life cycle stage spectrum. According to the ILCD handbook, the decision context is defined according to 'Situation B', where the results of an LCA may introduce meso- and macro-level deciding factors. Resultant structural design decisions may be informed by the outcome defined by the final LCA study according to the methodology of 'Situation B' (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010, p. 40). In the specific application of this study, the results may influence the theoretical design decision to implement a BAU concrete and steel building frame or the MET alternative. The Attributional Approach for constructing the LCA is then deemed appropriate;

however, the structural design decision of this and future buildings could impact the timber and concrete material manufacturing and supply industries. A consequential LCA could be conducted as further research to determine the up-and downstream impacts of the sector's evolution (Andersen, et al., 2022).

This study assesses embodied emissions of various building scenarios in two respective predetermined contexts. The scope of the study is specifically designed to exclude operational energy and water use, defined as life cycle stages B6 and B7, respectively, in EN15978. Operational energy is modelled on expected average usage data to provide perspective on the scale of whole-of-life emissions.

3.3 Data Requirements

Reliable data is the bedrock of a meaningful and effective life cycle assessment (LCA), serving as the cornerstone upon which accurate environmental insights and informed decisions are built. LCA's objective is to comprehensively quantify the environmental impacts of materials or products across their complete life cycle. Data inputs must accurately reflect these elements' real-world attributes and behaviours to achieve that. Reliable data ensures the assessment's results are trustworthy, enabling stakeholders to confidently make choices that align with sustainability goals. With dependable data, the credibility of the LCA process is maintained, potentially leading to misguided decisions, skewed priorities, and misinterpretation of environmental implications. By sourcing and utilising high-quality data, LCA practitioners uphold the integrity of the assessment, promote transparency, and foster informed environmental strategies.

Key data requirements include the building location, building designs to a relevant detail level, and design specifications, including material specifications and quantities. The information mentioned above is required as inputs to the modelling software, which uses the appropriate LCI databases to provide impact factors for the models. In both cases, the building lifespan is modelled for a 100-year life span, representing the expected functional lifespan for various typical building typologies according to Marsh (2016, p. 2) and Andersen (2022, p. 2) as discussed in the building life span section in Chapter 2.

Finally, similar to the comparative LCA study conducted by Andersen et al. (2022) and Fauzi (2021), an attributional LCA with marginal process data methodology was used, and data from EPD's implementing average value data still proved valuable. Specific material densities could still be obtained from EPD's implementing average data. All modelling data is sourced from the relevant Life Cycle Inventory (LCI) databases through implementing OneClickLCA software.

3.3.1 LCI Database

Life Cycle Inventory (LCI) databases form the foundation for LCA modelling software, serving as invaluable repositories of meticulously collected and curated data. These databases comprehensively compile environmental impact information for various products, materials, processes, energy sources, and activities. By providing standardised data on factors such as energy intensity, associated emissions, and resource use at various stages of a product's or building life cycle, LCI databases streamline the data collection process for LCA modelling. The selected LCA modelling software leverages these databases to ensure consistency and accuracy in environmental impact calculations, reducing the need for manual data entry and minimising the risk of errors.

Integrating LCI databases into LCA modelling software significantly enhances the efficiency and reliability of assessments. These databases facilitate a systematic approach to assembling data, ensuring practitioners can access up-to-date and verified information without spending excessive time and effort on data compilation. Moreover, LCI databases contribute to the comparability and credibility of LCA studies, as they provide a standardised reference point for conducting assessments across different sectors and contexts (Fauzi, et al., 2021). Databases of note utilised by OneClickLCA include Ecoinvent, Athena, AusLCI, and others similar to the software implemented in the study by Andersen (2022) and studies reviewed by Duan et al. (2022, p. 7).

3.4 Localisation Factors

There is a lack of available data and previous LCA studies on the African continent, and insufficient data is available for all products in the modelling process (He & Prasad, 2022). The selected LCA software, OneClickLCA, incorporates essential localisation factors (Steven, 2023) to ensure accurate and context-specific environmental assessments in the absence of sufficient data for their 200 000+ (OneClickLCA, 2023) verified data points across their 62 databases. These factors are critical as the environmental impact of materials, products, processes, or buildings can differ significantly across different regions and locations. One of the primary localisation factors is the composition of the regional energy grid. LCA software takes into account the specific mix of energy sources used in the electricity grid of the project's location. This factor influences assessing a product or building's emissions impact, as regions with higher proportions of renewable energy produce lower emissions than those heavily reliant on fossil fuels.

Additionally, LCA software considers regional material production data. Each region might have distinct processes and sources for extracting, manufacturing, and transporting building materials, resulting in varying environmental impacts. By incorporating localised material production data, the software can provide more accurate insights into the sustainability of construction projects and help stakeholders make informed decisions about material choices and sourcing strategies. Moreover, some LCA software includes transportation distances as a localisation factor. By accounting for the distances materials and products travel from their origin to the project site, the software can capture the environmental consequences associated with transportation, such as fuel consumption and emissions. This factor emphasises the importance of choosing locally sourced materials to reduce the overall emissions of a project and promote regional sustainability. Some of the common localisation factors that OneClickLCA may implement include:

3.4.1 Regional Energy Grid Factors

As discussed in section 2.2 in the literature review chapter, regional energy grid factors significantly impact the outcomes of an LCA model, as they play a central role in determining the environmental impact of energy consumption throughout a product's or project's life cycle (Collinge, et al., 2018). The energy grid composition of a specific region influences the mix of energy sources used to generate electricity, which can vary widely from one location to another. Regions heavily reliant on fossil fuels, such as bituminous coal or natural gas, will have higher emission intensities than those with a more significant proportion of renewable energy sources, like hydro, solar, wind, or nuclear power. Consequently, the regional energy grid factor affects a product or project's emissions impact and overall environmental performance, mainly when energy-intensive processes or operations are involved.

The consideration of regional energy grid factors in an LCA model is crucial for making context-specific sustainability assessments in static or dynamic, attributional or consequential, or hybrid modelling approaches (Collinge, et al., 2018). By accounting for the regional mix of energy sources, LCA models can provide more accurate and relevant results that reflect the unique environmental characteristics of a particular location. That enables decision-makers to understand the environmental implications of energy use intensity in their specific region and to identify opportunities for reducing energy use, increasing energy efficiency, and reducing overall emissions. Moreover, regional energy grid factors can influence a project's choice of energy sources, highlighting the importance of transitioning to cleaner and more sustainable energy options to minimise environmental impacts. As regions adopt different energy policies and shift towards greener energy alternatives, incorporating up-to-date and location-specific data on energy grids becomes essential for reliable LCA analyses and promoting sustainable practices.

3.4.2 Regional Material Production Data

The software and model include data on the environmental impacts associated with the production and transportation of building materials specific to the project's location. Different regions may have variations in raw material availability, transportation distances, and manufacturing processes. Both contextual scenarios have similar parameters regarding regional factors, and the primary differentiation in the models is based on the energy of each respective context.

3.4.3 Transportation Distances

The transportation stage involves moving raw materials, components, and finished goods between various supply chain stages, including sourcing, production, distribution, and consumption. The longer the transportation distances, the greater the energy requirements and associated greenhouse gas emissions, primarily if fossil fuels power the transportation. As a result, transportation can significantly contribute to a product's or project's emissions impact and overall environmental impact. The software automatically adjusts or allows users to adjust the transportation distances and modes to suit local factors.

Moreover, transportation distances can also affect the choice of materials and sourcing strategies in a life cycle assessment (Chen & Pierobon, 2019, p. 4). When evaluating different materials or suppliers, considering their proximity to the production site or construction location becomes vital. Opting for locally sourced materials can lower transportation emissions and reduce environmental burdens. By assessing the embodied impacts of transportation, LCA models encourage stakeholders to make more informed decisions about supply chain optimisation, promoting sustainability through reduced transportation distances and supporting regional economies. Additionally, transportation distance consideration fosters a broader understanding of the interconnectedness of global supply chains and how choices at one stage of the life cycle can influence environmental outcomes throughout the entire product or project lifespan (ibid.).

3.4.4 Waste Management Data

The software accounts for the specific waste management practices and recycling rates of the respective regions where the modelled buildings are located. Different regions have significantly varying capabilities for waste recycling and disposal at the end of a building's functional life.

3.4.5 Operational Data

OneClickLCA uses local climate data to assess the energy consumption and HVAC requirements of the building, as well as the impact of materials under specific climatic conditions. The same applies to the local water impact factors. However, being operational data, it is irrelevant or included in this study's scope. Still, an assumed operational energy use value is modelled to provide an order of magnitude for embodied versus operational associated emissions.

3.5 Comparative Study

The utilisation of LCA modelling software presents a dynamic avenue for modellers to engage in comprehensive design optioneering. This process involves refining and optimising building design choices by employing a systematic approach. Modellers initiate the optioneering process by establishing a foundational base case model that reflects a standard BAU building configuration. With this base case, modellers can develop a spectrum of proposed model options through adjustments, modifications, and substitutions to variables such as materials, construction methods, energy systems, and more. This iterative approach enables the consideration of a diverse range of options, allowing for the comparison of how different design choices impact the holistic environmental performance of a development. Through the iterative refinement of the base case in accordance with varying model options, modelling enables modellers to demonstrate the relationship between design decisions and their associated impacts.

3.6 Study Challenges

While comprehensive in its exploration of MET and LCAs within sustainable construction, this research encountered several challenges and limitations that are important to acknowledge. These challenges influenced the study's approach and highlighted areas for further investigation and improvement in future research.

A challenge encountered and addressed during the study was the limited availability of standardised data concerning MET's environmental impact and the application of LCAs in construction projects. The variability in data sources often made it difficult to draw consistent conclusions, underscoring the need for more data points and reporting practices within the industry on more localised levels. This limitation points to a broader issue of data accessibility and standardisation in LCI databases, which could significantly enhance the reliability and comparability of sustainability assessments in construction.

The focus on MET and LCAs, though crucial for the study's objectives, also needs to be revised in terms of the broader context of sustainable construction materials and methodologies. The built environment's decarbonisation involves many factors and potential solutions, of which MET and LCAs are but a part. Recognising this, the study's conclusions should be considered within the context of a larger ecosystem of sustainable construction practices. Furthermore, the study focuses on the technological and methodological aspects of MET and LCAs, with less emphasis on the socio-economic barriers to adoption and implementation. Factors like market readiness, regulatory frameworks, and stakeholder perceptions significantly influence the adoption of sustainable construction practices, though they were not the primary focus of this research. Future studies could investigate these aspects more comprehensively, offering a more integrated perspective on the challenges and opportunities in sustainable construction.

Acknowledging these challenges and limitations is crucial for the study's findings and could provide insights and support to guide future research. By addressing these gaps, subsequent studies can build on the foundation laid by this research, contributing further to the advancement of sustainable construction practices.

3.7 Chapter Summary

The research method chapter sets out the framework for assessing the environmental impact of selected building methods and their potential for reducing embodied emissions in specific context scenarios. The modelling scenarios evaluate the environmental impact of two distinct construction methods, MET and traditional RC, across two locations: Cape Town, South Africa, and Perth, Western Australia. These scenarios are designed to explore how localisation factors influence the embodied emission levels of buildings constructed with the selected construction methods and materials. The modelling aims to compare the environmental impacts of a medium-rise building (eight floors) constructed as a greenfield development and the vertical expansion of an existing base building, respectively. The modelling is isolated to primary building frame components and utilising a standardised approach for LCA modelling as outlined in 'Situation B' (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010, p. 40).

The study aims to provide a comprehensive quantitative comparative analysis that isolates the impact of the construction material from other variables, such as building envelopes and finishes, due to the functional similarities of the buildings. This methodological approach allows for a focused assessment of the embodied emissions reduction potential by using MET over traditional RC within the specific context of each location's environmental, economic, and regulatory landscape.

The critical importance of reliable data sources in conducting an LCA for comparative analyses is discussed - emphasising the need for accurate, verified data to ensure credible results. Key data requirements include detailed building designs, material specifications and quantities, supported by Life Cycle Inventory (LCI) databases like Ecoinvent and Athena to provide impact factors for LCA models. The method discusses the adoption of a 100-year building lifespan to standardise comparisons and acknowledges the evolving nature of MET in terms of building lifespan. Finally, the method outlines the significance of localisation factors, such as regional energy grids and material production data, in tailoring LCA to specific contexts.

Adopting OneClickLCA, a cloud-based modelling platform, alongside the International Reference Life Cycle Data System (ILCD) handbook, provides a robust, repeatable methodology for the required modelling and analysis. The ILCD handbook guides the methodology with standardised frameworks, including EN 15978 and EN 15804, ensuring the credibility and comparability of the LCA studies. At the same time, OneClickLCA integrates region-specific data and certified inventories from LCI databases to facilitate comprehensive environmental assessments. This standardisation is critical for the comparative analysis, allowing for a clear, functional comparison of MET and RC based on a consistent measuring unit of $kgCO_2eq/m^2$.

Chapter 4 Building Design

This section outlines the design concept and explains how the corresponding building designs were developed to facilitate a comparative study. A subsection describes the design decisions and material impacts that will be modelled as material quantities in the LCA software for each building typology.

4.1 Design Concept – Whole Building

The building design was adapted from a design developed and used by S. van der Westhuyzen (2020, p. 50) for a research project comparing the financial feasibility of a Reinforced Concrete (RC) and a Mass Engineered Timber (MET) counterpart building. The designs were developed with several stakeholders to ensure the two building variants are functionally identical. Stakeholders contributing to the original building design include professional quantity surveyors, CLT and GLT manufacturers, component suppliers, construction schedulers, and professional structural engineers. The designs are detailed and discussed extensively in Chapter 4: Structural Development and Design of the Research Paper by Van Der Westhuizen (ibid.).

The buildings are designed on a 6m x 6m grid and have a 24m ×30m footprint, resulting in a gross floor area (GFA) of 5 472 m^2 over a total of 8 floors. Each building has a floor-to-floor design height of 3.5 m and is 28m high. Structural building cores are designed in three sections, including space for stairs, an elevator shaft, and an HVAC and services shaft. This design has been repeated for Reinforced Concrete and Mass Engineered Timber buildings.

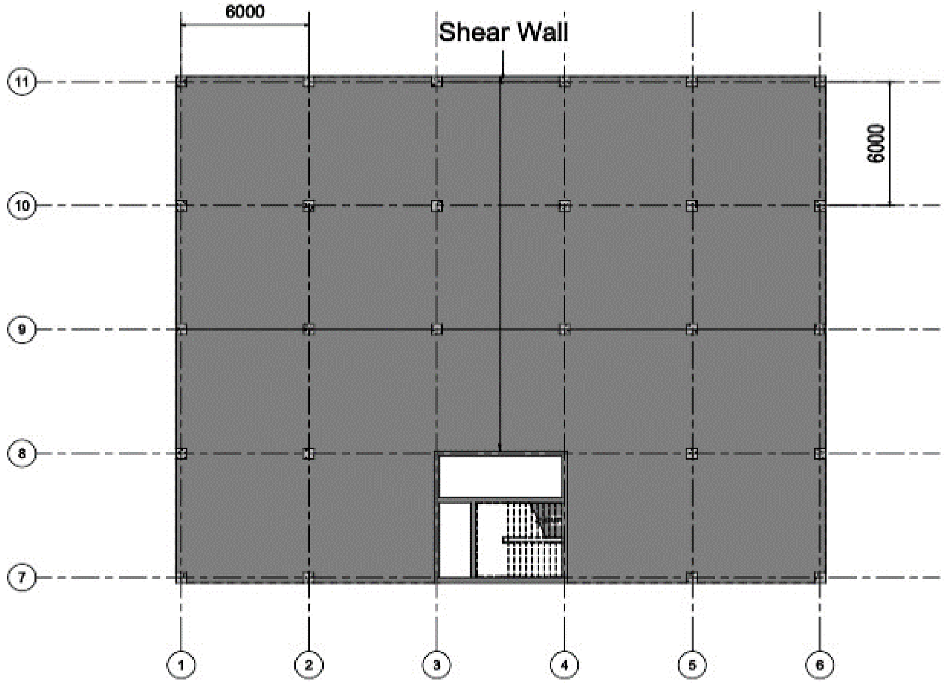

Figure 8 Building plan showing size and grid spacing (Van Der Westhuizen, 2020)

The building frames are designed with an open layout when considering building use cases. They could be further refined to have a suitable envelope and internal layout for office space, mixed or multi-unit residential, or purpose-built student accommodation fit-out.

The original building concept considered rational fire designs for both cases, and we can assume that both building frames comply with a level of rational fire design. Fire design is not a specific criterion for this study, and the standalone building frames were modelled as structurally sound and considered the relevant levels of fire safety. Building fit-outs would require further fire design and potential modelling. However, these factors do not impact the study on the building frames.

4.1.1 Reinforced Concrete Building Design

Developed to be structurally feasible and compliant with relevant codes, the reinforced concrete building is presented in Figure 9 Revit model of the proposed RC building below from the original 3D Revit software model.

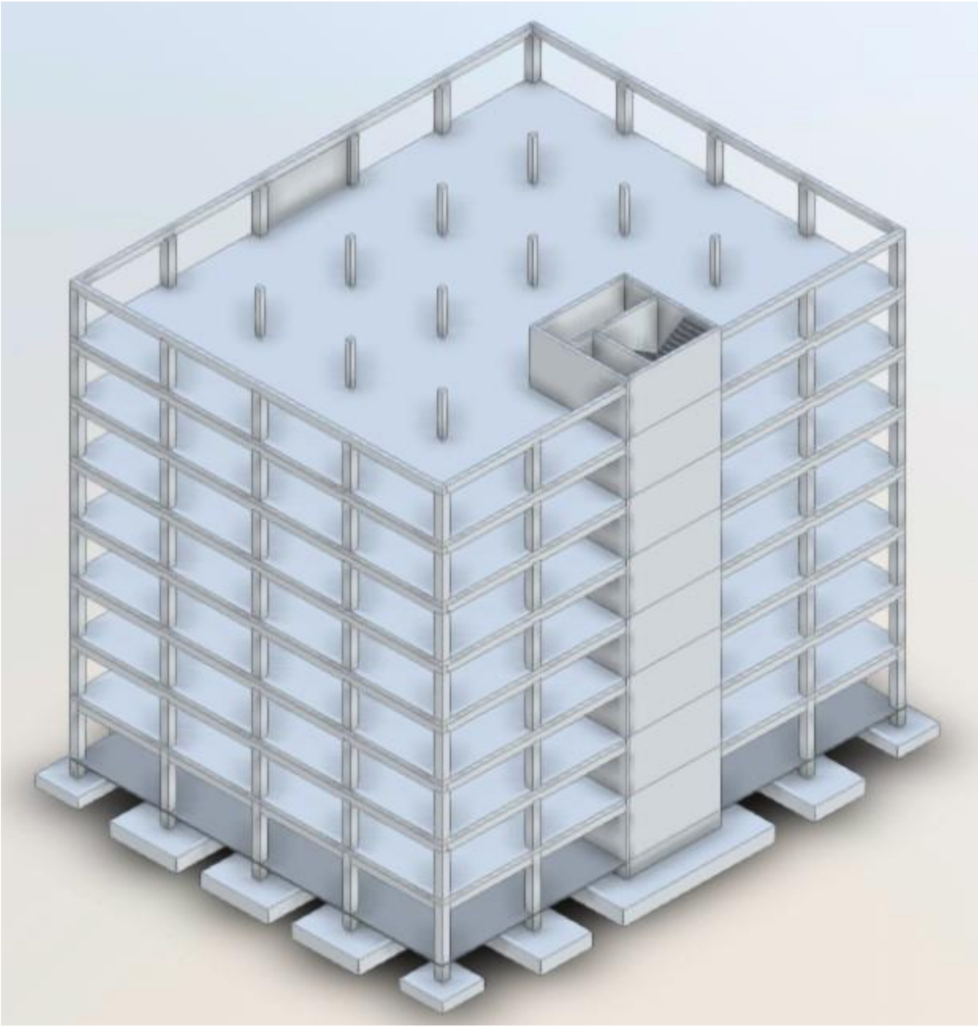

Figure 9 Revit model of the proposed RC building (Van Der Westhuizen, 2020)

The building core on one side was designed as 250mm thick reinforced concrete walls to provide lateral stability and a shear wall at the opposite end. To maintain a simplified design for comparison purposes, the building includes regular reinforced concrete floors of 300mm thick instead of more efficient and cost-effective post-tensioned concrete slabs. Normal cast-in-situ reinforced concrete is still the most commonplace in the construction industry. An alternate post-tensioned slab design is not considered to impact the embodied emissions for this study significantly, but it is more so for the original research of cost feasibility. Concrete floors were specified as 35MPa concrete, whereas the remaining concrete elements were specified as 30MPa.

Concrete reinforcement was beyond the scope of the initial study as it would not have significantly impacted the cost or construction time of the building. However, standard concrete templates from the OneClickLCA software included a 2% by-volume reinforcement as standard. The reinforcement content is considered material value in the overall embodied emissions figure. A summary of the material quantities extracted from the modelling design for the reinforced concrete building is presented in Table 3 RC Building Material Quantities adapter from Van Der Westhuizen (2020, p. 55) below:

Table 3 RC Building Material Quantities (Van Der Westhuizen, 2020)

Reinforced Concrete Building		Depth (m)	Width (m)	Length (m)	Quantity	Volume (m^3)
Footings (30MPa)	Inner	0.8	5.1	5.1	10	208.08
	Outer	0.7	3.2	4.1	10	91.84
	Corner	0.6	3	3	4	21.6
	Shear Wall	0.8	4	8	1	25.6
	Core	0.8	1	10	1	8
Inner Columns	1--2	0.5	0.5	3.5	20	17.5
	3--5	0.4	0.4	3.5	20	11.2
	6--8	0.3	0.3	3.5	20	6.3
Outer Columns	G-8	0.5	0.5	3.5	16	14
Slab (35MPa)	Surface Bed	0.12	24	30	1	86.4
	Flat Slab 1-8	0.3	24	30	7	1512
Ringbeam	2-Roof	0.5	0.3	108	8	129.6
Walls	Core	0.25	33.8	3.5	8	236.6
	Shear	0.25	5.5	3	8	33
Summary				30MPa		803
				35MPa		1598

Subsection 3.1 Tools used for LCA Modelling in the Research Methods chapter details how the material quantities, as in Table 3 above, are modelled into specific templates. The templates are selected for each material and model variation and then populated with material quantities. These templates interface in the back-end with the relevant LCI databases to provide impact results for each material.

4.1.2 Mass Engineered Timber Building Design

Chapter 2 discusses previous successful MET residential building developments and their respective designs and determining factors. With many solutions available for MET buildings, a simplified design considers geographic location, local climate, manufacturability, and constructability. Development size, purpose, and cost are additional factors determining a specific design solution. For this research, a building method was selected based on the attainability of products and materials in the respective contexts. In some instances, more advanced or locally suitable options were available; however, to retain the comparability of the study, options were selected to be suited to the lesser advanced option.

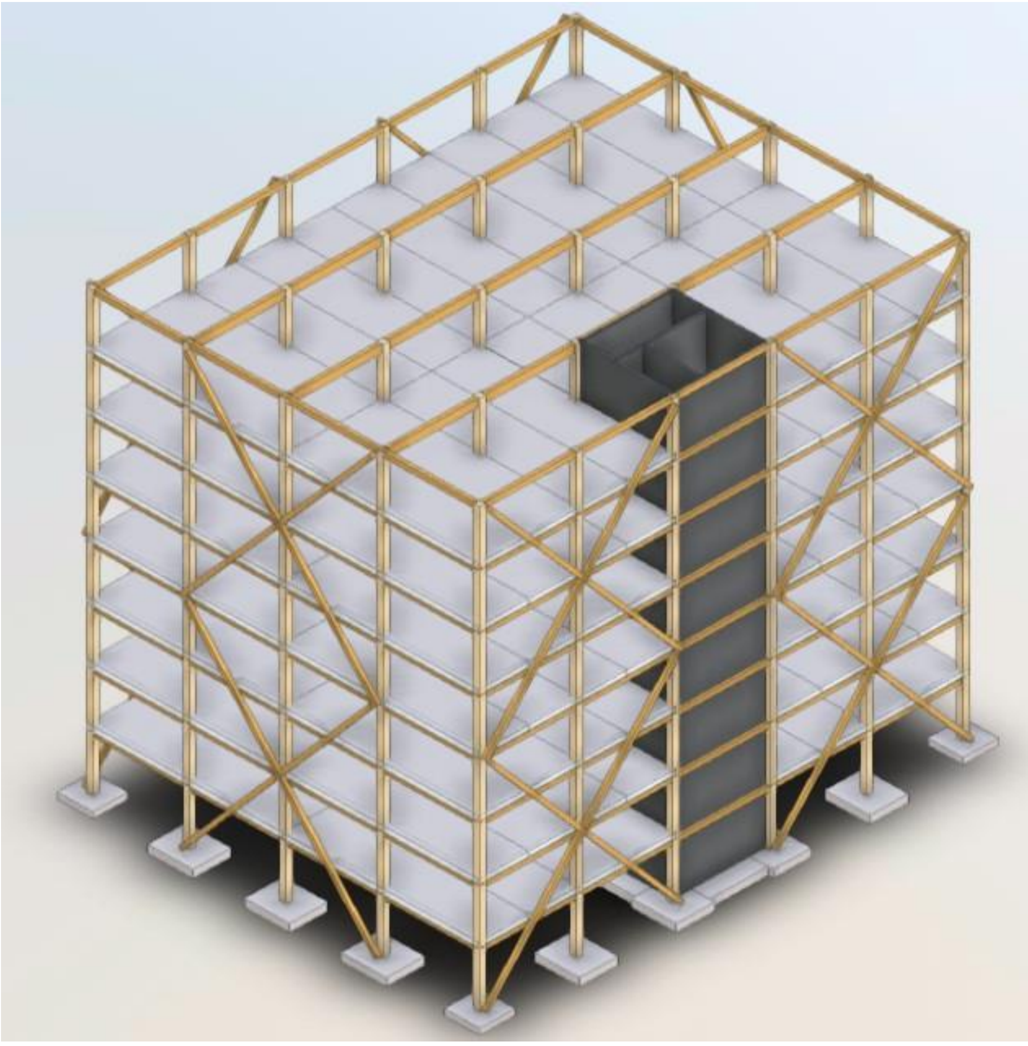

Figure 10 3D Revit model of the proposed MET building (Van Der Westhuizen, 2020)

To retain the comparative nature of this study and model a viable real-world scenario, the following design specifications were used in the MET building to comply with a relevant international code referred to as the Eurocode:

Like the RC building, the MET building frame is designed to comprise a 6m x 6m grid, a CLT core, and lateral bracing through GLT beams instead of a shear wall in the RC building. Unidirectional spanning CLT floor panels are 220mm thick and assembled in a 60-30-40-30-60 structure with overall dimensions of 6m x 3m – resulting in ~4m^3 of MET per panel. The building core was designed using 180mm thick CLT wall panels, which provide lateral stability to the structure, similar to the RC building design.

The GLT beams implemented in the design measured 520mm x 240mm for all internal beams, and the edge beams of the structure were designed to have dimensions of 320mm x 240mm. The GLT columns throughout the building are specified as square columns of 400mm x 400mm. Further lateral stabilisation is achieved through bracing around the building frame with GLT beams of 260mm x 240mm.

Table 4 MET Building Material Quantities (Van Der Westhuizen, 2020)

		Depth (m)	Width (m)	Length (m)	Quantity	Volume (m^3)
Footings (30MPa)	In	0.6	3.2	3.2	10	61.44
	Out	0.5	2.4	2.8	10	33.6
	Cor	0.4	2.2	2.2	4	7.744
	Core	0.5	8	8	1	32
Columns (GL24h)	1--8	0.4	0.4	3.5	240	134.4
Internal Beams (GL24h)	1--8	0.52	2.4	6	120	898.56
Ring Beam (GL24h)	1--8	0.32	0.24	6	144	66.3552
Bracing Beams (GL24h)	1--8	0.26	0.24	18.3	24	27.40608
CLT Floors (220L75-2)	1--8	0.22	3	12	126	997.92
CLT Floors (220L75-2)	1--8	0.22	3	6	14	55.44
CLT core (180 C24)	1--8	28	0.18	32.1	1	161.784
Steel connections kg	Prlm kg					5000
Summary				Concrete (30MPa)		134
				GLT		1126
				CLT		1215

Subsection 3.1 Tools used for LCA Modelling in the Research Methods chapter details how the material quantities, as in Table 4 MET Building Material Quantities above, are modelled into specific templates. The templates are selected for each material and model variation and then populated with quantities of material. These templates

interface in the back end with the relevant LCI databases to provide impact results for each material.

4.2 Constructability

The structural integration of mass timber extensions onto existing reinforced concrete buildings involves addressing the compatibility and load transfer between the two materials. Loss et al. (2016) highlight this critical aspect of construction, discussing the engineering challenges and solutions for combining timber with concrete. The focus is on ensuring structural integrity through appropriate joint design and load distribution. The work also considers differential movements due to material properties, such as thermal expansion and shrinkage, providing a seamless and safe connection between the old and new structures. Given that this study does not consider constructability, it is an essential factor impacting the overall feasibility of the practical application of MET as a suitable vertical extension to consider in future research.

The constructability of non-traditional building systems like MET in contexts such as Cape Town and Perth depends significantly on local factors like available skills, equipment, and supply chains. In regions like Cape Town, the transition to innovative construction methods may be challenged by the need for skilled labour and modern equipment (Clarke, 2018). With its more developed construction sector, Perth might have an advantage in existing expertise and technology for such projects (Lovell, 2012). Both locations require an adaptation of the construction industry to embrace new materials and techniques, necessitating investment in training, equipment, and supply chain development.

4.3 Chapter Conclusion

The Building Design chapter outlines the concept and development of building designs for the comparative LCA study. Building typologies are detailed, and design decisions and the impact of materials are discussed, which are to be modelled as material quantities in LCA software. The design concept for the whole building and vertical extension is adapted from a design by Van Der Westhuyzen (2020), which was used in a research project comparing the financial feasibility of a traditional RC versus MET. This section aims to provide insight into the rationale behind the design choices and their environmental implications.

The chapter also emphasises that while real-world considerations such as constructability, engineering compatibility, and local factors like skills, equipment availability, and supply chain efficiency are critical for the practical adoption of non-traditional building systems, they do not form part of the life cycle assessment (LCA) modelling conducted in this research. Instead, the study focuses on the comparative environmental impact of adopting Mass Engineered Timber (MET) through LCA methodologies. This highlights the distinction between the theoretical modelling approach, which isolates environmental performance metrics, and the broader contextual realities that influence the feasibility of implementing MET in diverse geographical settings.

Chapter 5 Whole Building

Following the design and modelling methodologies from Chapters 3 and 4, the material quantities for the functionally identical Vertically Extended buildings were modelled using OneClickLCA. As previously detailed, the software uses quantities and/or volumes of materials and produces results quantifying the mass of material implemented and the subsequent Lifecycle impacts. Similar to the method employed for modelling the whole building in Chapter 4, the materials were grouped and modelled into their relevant design functions so that the software could output values against structural building functions like foundations, columns, and floors.

Similar to the approach in Chapter 4, the LCA modelling results are reported in impact per square meter (m^2) of the building area as a Functional Unit (FU) to facilitate simplified comparability between different buildings and construction materials (Andersen, et al., 2022, p. 2). This approach standardises the assessment outlined in the ILCD Handbook (2010, p. 60), by providing a common unit of measurement, allowing for a direct comparison of environmental impacts on a per-unit-of-space basis as outlined in Chapter 3.

Australian-Based Building Results Overview:

Depicted in Figure 11 Whole building's overall impact summary below is a summary comparing the building models based in Perth, Western Australia. The results explicitly compare the modelled RC building for a redevelopment project and the impacts of a MET Vertical Extension. The results suggest that most embodied emissions are contained within the product materials (A1 – A3) stage. The significant impact reduction is reflected in a comparative review conducted on 30 studies by Younis (2022, p. 7), which found that all cases considering an entire MET structure or specific MET components over conventional construction materials had an impact reduction averaging 40%.

The impact reduction observed in this model was 74%, primarily attributed to the decrease in the material's impact (A1 – A3) and the reduction in material quantity used due to the nature of MET projects. The results underscore the findings from Younis (2022, p. 7) as a baseline reduction, and highlights the further potential reduction in opting for a MET building option.

South African-Based Building Results Overview:

Similar to the results in the Australian-based building comparison, the MET building in the Cape Town region in South Africa presents a similar saving primarily attributed to the materials' life cycle stage (A1 -A3) and quantity required. The overall impact of both building versions is still higher in the South African-based model due to the localisation factors—similar to the outcomes in the whole building models in Chapter 4.

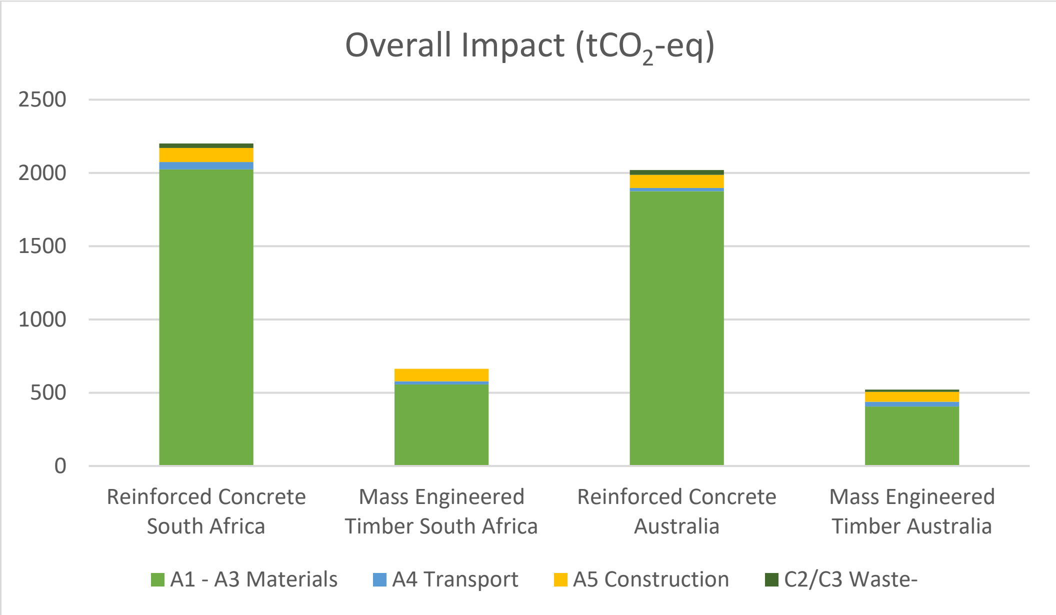

Figure 11 Whole building's overall impact summary

The most notable differences in embodied emissions are during the product stage, encompassing building materials' extraction, manufacturing, and transportation. These metrics pertain to the emissions intensity of the local supply chains, energy sources, and transportation methods that contribute to distinct embodied emissions. In the various modelled scenarios, the product stage (A1 – A3) contributed 78% to 92% of all the embodied emissions associated with the building frames. The impact contributions from the product stage are consistent with the findings from Younis (2022), and as highlighted, the nature of VE projects results in significantly less material required for the same amount of GFA that redevelopment may yield.

5.1 Product and Construction Stage (A1 – A5)

Chen (2020) notes that regular Portland cement-based concrete production potentially generates the highest amount of GHG emissions pertaining to the entire life cycle of a reinforced concrete building frame. The study by Cheng (2020, p. 5) states that the 92% material mass of an RC building may account for up to 85% of its total GHG emissions, excluding operational emissions.

In this study, the models for the South African and Australian-based buildings have been analysed to distinguish between the Product Stage (A1 – A3) and the Construction Stage (A4 – A5). In analysing the two stages (and other minor subsequent stages) separately, it is possible to discuss the impact of the materials themselves and the impact the selection of each construction method would have on the construction activities.

5.1.1 Product Stage (A1 – A3)

Figure 12 shows distinct differences across the cumulative product-stage life-cycle categories, evident between the modelled buildings' geographic distinctions. The software does not explicitly distinguish between stages A1 – A3; however, as outlined in the localisation factors in Chapter 3, the variation is not expected to be in life cycle stage A1 – Raw Material Supply. Instead, it is expected for the difference in transport distances of raw materials and, more importantly, the emissions intensity level of the energy used to process the raw materials into products during the A3 – Manufacturing stage.

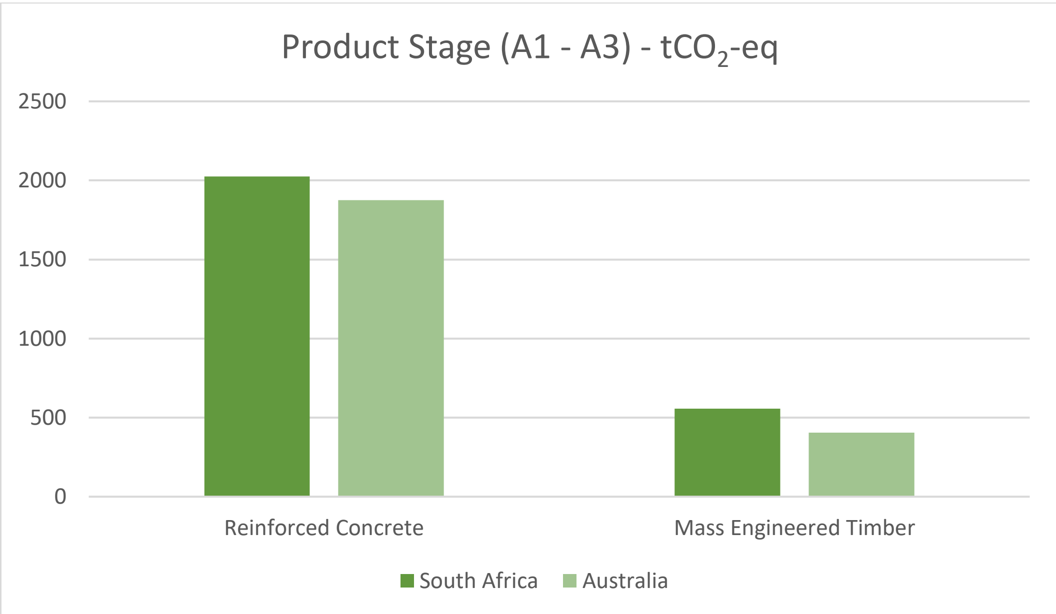

Figure 12 Product stage comparison

When considering the A1 – Raw Materials Supply stage in isolation, wood's upfront emissions sequestration potential contributes to a more favourable environmental profile for the MET buildings, irrespective of their contexts. In contrast, concrete production involves extracting raw materials, including limestone and clay, and the energy-intensive process of manufacturing Portland cement releases substantial emissions. Therefore, when considering the A1 stage of the life cycle, mass timber buildings tend to have a lower environmental impact due to the renewable nature of wood and the less energy-intensive process in manufacturing MET when compared to concrete. In stage A1, minor discrepancies in the timber may be noted based on the relative density of the lumber as discussed in section x, the distance the lumber is transported, and the forestry practices employed by the sawmill. These discrepancies can be noted as negligible.

As part of the product stage of the LCA, the transportation of raw materials becomes a factor when you consider significant distances. As shown in Figure 14 the map below shows that the transport distance from the sawmill to the MET manufacturing facility is >350km, which would differ slightly if the lumber was sourced from other sawmills. The same distance for the Australian-based MET shows that suitable lumber could be sourced as close as 25km from a potential manufacturing facility. The distance from the manufacturing facility to the building site is considered under life cycle stage A4. The transportation of raw material lumber is also considered to be a minor contributor to the product stage of the lifecycle; it may, however, start to demonstrate differentiating factors in compounding embodied emissions (Chen & Pierobon, 2019).

The final contributing factor to the product life cycle stage is the actual manufacturing process of the MET components in stage A3. The process involves selecting lumber members, planning and sanding to achieve desired specifications, and arranging and glueing lumber to a suitable thickness based on layer specification. The assemblies are compressed and clamped in place to cure (heat may be applied). Finally, the cured assemblies are finished to specification and ultimately machined for assembly based on design specifications. Arguably, the most significant contributor to the emissions in this category, as the manufacturing process could be assumed to be similar in either geography, is the make-up of the energy mix used to manufacture the final product. As discussed in section 2.2, the energy grids supplying energy to a factory in South Africa differ significantly from those supplied to a factory in Australia. The localisation within the LCA modelling software accounts for each country's generic energy supply grid but does not consider localised renewable energy generation specific to a manufacturing facility.

Integrating local renewable energy sources at the factory level, like rooftop solar PV, significantly influences the manufacturing environmental impact assessed in an LCA study. By sourcing energy locally from renewable sources such as solar, wind, or hydropower during the manufacturing process of MET building materials, greenhouse gas emissions and environmental impact can be reduced. The reliance on renewable energy minimises the emissions intensity associated with electricity consumption, mitigating the environmental impact of manufacturing.

5.1.2 Construction Activities Stage (A4 – A5)

The construction stage includes Life Cycle stages A4 and A5, which are the transportation of products to the site and, ultimately, the construction stage activities, respectively. A similar trend can be observed in both categories: the RC and MET options in the South African setting produce higher emissions.

Due to the locality of Portland cement, aggregate and sand supplies, and batched concrete production plants in South Africa and Australia, only slight discrepancies can be noted in transport emissions for RC. Both entities are modelled to use similar transport modes and a difference in distance results in a subtle difference in emissions. Chen (2020) notes that due to the popularity of RC construction, a well-established supplier network would be found within 50km of most large metros. An opportunity to lower the emissions for MET further is to establish the building methodology as commonplace and competitive in the commercial market as an option for RC and steel frame buildings. If MET becomes a well-established competitor, arguably, more localised production of components could result. Once more robust localised production is established, transport distances may be reduced, resulting in lower embodied emissions. It was found that most MET buildings in South Africa and Australia have been constructed to date from imported timber CLT panels (Llewellyn, 2023).

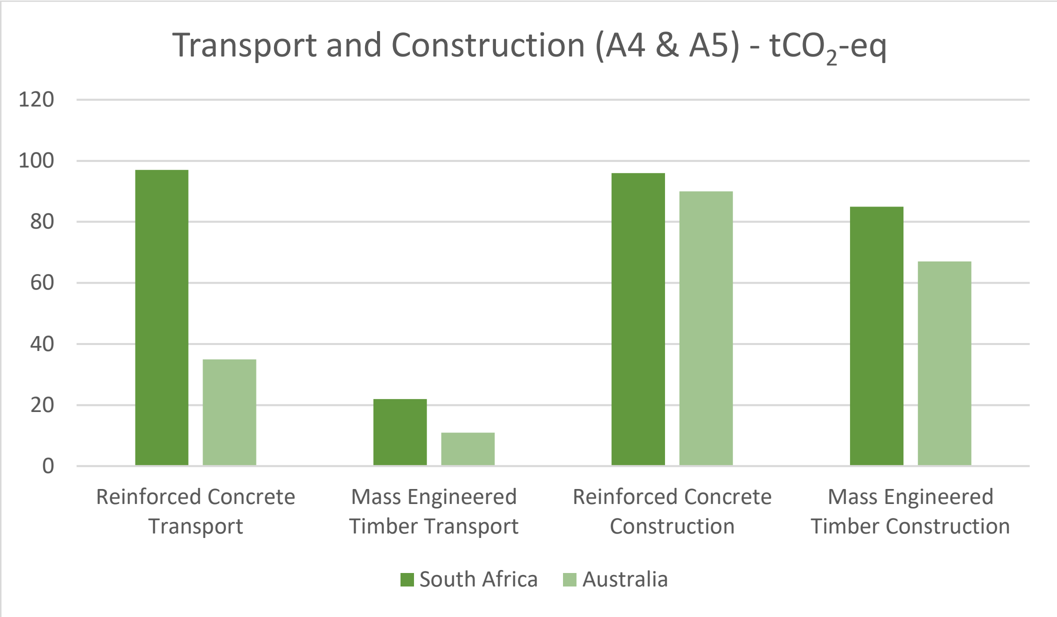

Figure 13 Transport and construction stage-associated emissions

Building on the transport distance sensitivity study conducted by Chen et al. (2019) the proximity of lumber species mixes significantly impacts the transport emissions from the product stage (A1 – A3) and the final transportation to the site. The impact is expected to change and potentially reduce over time as MET products evolve; however, transportation emissions are still considered a minor contributor when considering the overall building impacts.

Figure 14 The respective transportation distances for MET are below, as discussed in the previous two sub-sections. The first transportation leg for the South African-based study covers the transportation of raw materials (A2) from the forestry operations to the facility where the end product is developed, which is just over 350km. The second transportation section covers the transportation of the product to the construction site – totalling just over 1400km for the South Africa-based study. Conversely, these two distances for the Australian-based study are 25km and 42km, respectively.

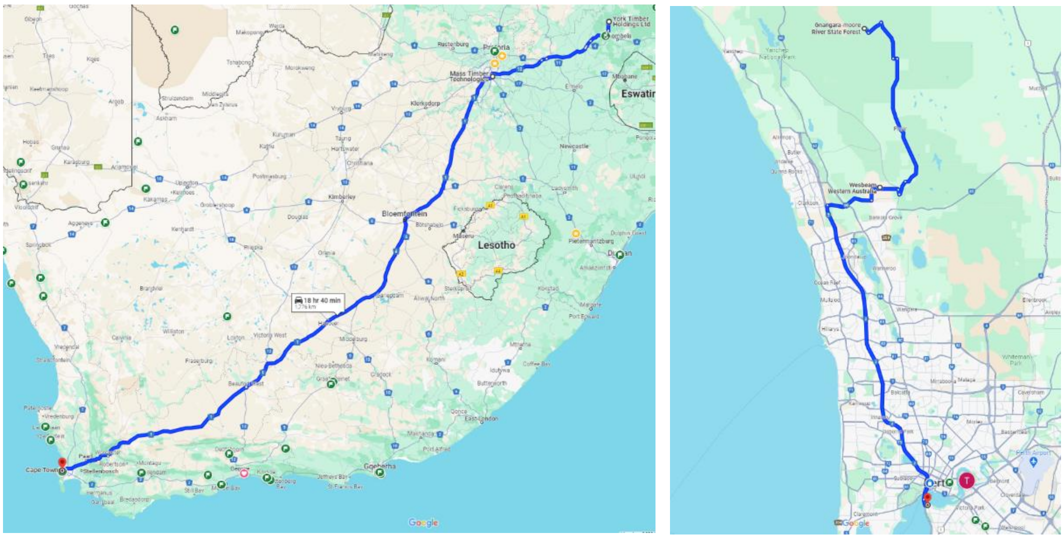

Figure 14 South African and Australian MET Transport Distances (A2 and A4) Google Maps LLC

Adopting electric construction equipment, biofuels, and hydrogen fuel cells in the construction stage (A5) could further lower the emissions associated with the building life cycle. Electric construction equipment powered by renewable electricity reduces reliance on fossil fuels during construction, leading to lower direct emissions on-site. Introducing biofuels as an alternative to traditional fossil fuels for machinery and vehicles contributes to reducing emissions, as these fuels are derived from renewable biological sources. Furthermore, hydrogen—particularly in fuel cells—offers a clean energy option, producing only water vapour when burned. By adopting these technologies, we can reduce emissions from construction and adhere to sustainable practices, tackling the embodied emissions associated with building materials. Consequently, integrating electric construction equipment, biofuels, and hydrogen into the construction stage offers a tangible pathway towards achieving lower overall emissions in building LCAs, contributing to the broader objectives of sustainable and environmentally conscious construction practices.

While electric construction equipment, biofuels, and hydrogen offer promising avenues for reducing construction stage emissions in building projects, careful consideration is crucial due to several factors. The environmental impact of these technologies heavily depends on the source of electricity or feedstock used to produce biofuels and hydrogen. The intended emissions reduction benefits will be diminished if the electricity used for charging electric equipment or producing hydrogen comes from non-renewable sources. Similarly, the sustainability of biofuels relies on responsible sourcing and/or cultivation practices.

Considering the required infrastructure for electric construction equipment, biofuels and hydrogen may not be universally available, which could pose logistical challenges and affect the practicality of implementation. Adequate charging or refuelling infrastructure and the availability of sustainable feedstocks are vital. The production of batteries for electric equipment and the overall life cycle of hydrogen production methods also need to be assessed for their environmental impacts.

5.2 Use Stage (B1 – B7)

Similar as noted by Chen (2020, p. 10), the use or operational stage of the model excludes life cycle stages B1 (Use), B3 (Repair), B5 (Refurbishment), B6 (Operational Energy), and B7 (Operational Water) due to the presumed functional equivalency of the RC and MET buildings. Chen (2020, p. 10) further notes the lack of empirical data for Repair (B3) and Refurbishment (B5) for MET buildings.

The impact on GWP during the use stage of a building can be influenced by Repair and Refurbishing activities, mainly if the waste stream generated from these activities is significant. However, in this study, the absence of relevant data from this emerging building sector led to the exclusion of such considerations. Instead, the analysis focused solely on maintenance components (B2) and the replacement of building materials (B4). The MET and RC buildings produced minimal greenhouse gas (GHG) emissions for modules B2 and B4, deeming them materially insignificant. Notably, emissions during this stage were slightly higher for the MET building when compared to the RC building, attributed to the wood's increased maintenance requirements to comply with fire codes, prevent moisture ingress, and manage biological risk.

Due to the scope of this study only focussing on the primary building frame and excluding the building envelope, most materials that could affect the operational elements are not modelled. The exclusion of building materials from the model that would have been exposed to the elements like the building envelope or internal walls, results in use (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment

(B5) reflecting negligible to no emissions. As a result, these life cycle categories are not discussed in further detail.

5.2.1 Operational Energy (B6)

Operational energy (B6) is excluded from this LCA as the focus is on the embodied emissions of the modelled buildings due to the distinct nature of these two stages in a building's life cycle. The primary objective of an embodied energy assessment is to quantify the energy consumed and associated environmental impacts during the raw material extraction, product manufacturing, transportation, construction, and end-of-life stages. In contrast, operational energy is the energy used by the building users during the building's operational life, encompassing activities like heating, cooling, lighting, and appliances. Operational energy is excluded from the scope of embodied energy. By excluding operational energy, the LCA emphasises the energy invested in creating and maintaining the main physical structure rather than its day-to-day energy consumption. It provides a focused perspective that aligns with the specific objectives of examining embodied energy in the built environment. As outlined in the research method in Chapter 3, the study assumes the building envelopes to be similar across all building variants in this study. The building envelope design is a primary contributor to operational energy efficiency. If the building envelope is excluded from the study, so would the operational energy be.

In assessing the operational energy use for a mid-rise residential building in a temperate coastal climate zone, as demonstrated for both locations in Figure 15 below, we can make certain assumptions to derive a representative estimate. Given the temperate climate for both building locations and similar latitudinal placement, it's reasonable to assume a reliance on similar building service systems during occupation. Considering the implementation of energy-efficient technologies, building insulation, and the utilisation of renewable energy sources, assumed operational energy use of 50-70 $kWh/m^2/year$ could be anticipated (Andersen, et al., 2022, p. 4); (He & Prasad, 2022, p. 6). Melo (2023, p. 10) found a global average of mixed residential buildings to use a median of 88$kWh/m^2/year$ and scaled to 65$kWh/m^2/year$, accounting for more efficient mid-rise buildings at the lower end of energy use as opposed to single-family residential buildings also included in the study.

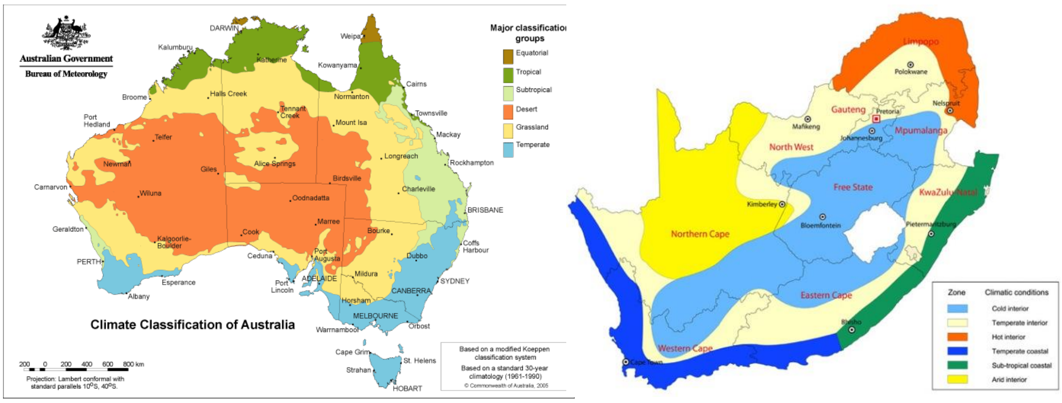

Figure 15 Australian (Australian Bureau of Meteorology, 2005) and South African Climate Zones (South African Bureau of Standards, 2011)

The operational energy use figures values consider the moderate temperate coastal climate, aiming for an equilibrium between heating and cooling demands, lighting loads, and hot water systems. Specific factors like building orientation, envelope efficiency, and the efficiency of installed systems would further refine this estimate. Utilising LCA modelling with these assumptions provides a better understanding of the operational energy impact in the context of each respective building to give a perspective of the overall embodied and operational emissions.

However, as the study aims to determine the role MET could play in decarbonising the built environment, it is essential to gain perspective on the sizable embodied emissions of various building scenarios. The building model has been adjusted to include operational energy consumption, as outlined before, over the entire lifespan of the building. Figure 16 below shows the same rate of operational energy for each of the respective building scenarios, outlining the proportion of embodied emissions as opposed to operational emissions.

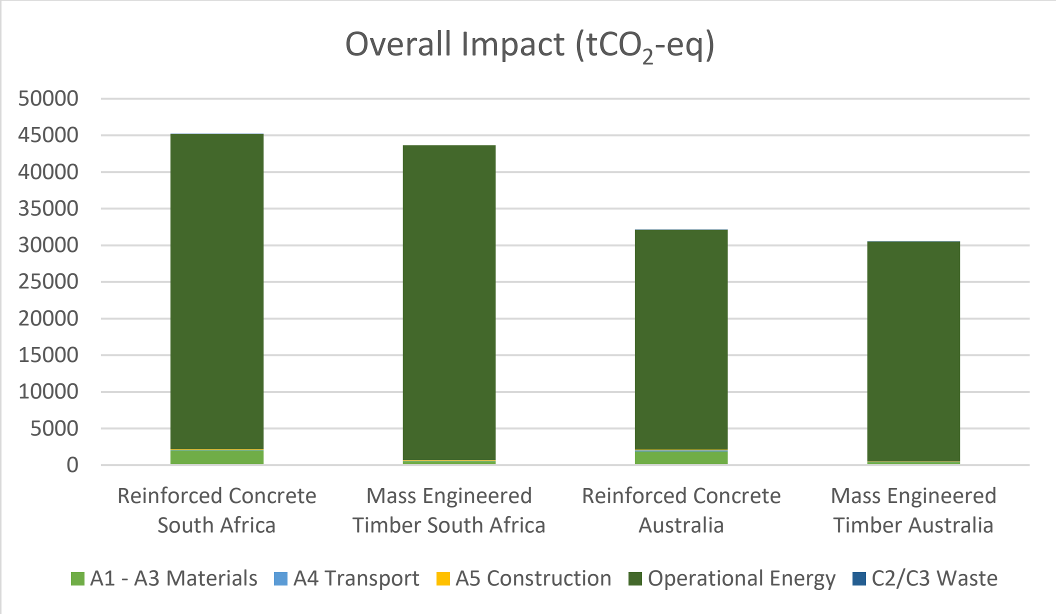

Figure 16 Overview of whole-of-life building emissions

Looking into more detail, the respective embodied vs. operational split varies between 7%/93% and 2%/98% across all the modelled scenarios. Even though the operational energy use has not been refined in a detailed model, the figures from high-level modelling show that embodied emissions are still a significant portion, considering the modelled materials only include the primary building frame materials.

As the models only include the building frame and not the entire building fit-out materials, the embodied energy will ultimately form a more significant portion of each building's overall whole-of-life emissions. **Error! Reference source not found.** in A ppendix A, compiled by Younis (2022, pp. 6 - 8), summarises similar studies that cover the whole-of-life emissions from the cradle to the grave for similar building scenario models and finds that embodied emissions contribute 7 to 15 % of the whole-of-life emissions. The whole-of-life emissions vary significantly across the studies based on the geographic location of a building being studied and the varying construction methods analysed.

Figure 16 above shows a much lower impact for the Australian-based buildings, demonstrating the significant role of the decarbonisation of the energy supply in the built environment. As discussed in section 2.5, Production Energy Mix, the Australian national grid operates at a much lower emissions intensity than the comparable South African national energy grid. The lower emissions intensity in the grid reflected in the models is based on national averages and does not consider more localised low-emissions solutions like a regional microgrid or behind-the-meter renewables that a building could use.

Table 5 Relative emissions per life cycle stage below breaks Figure 16 above into emissions per lifecycle stage, each as a percentage of the overall emissions of the building it pertains to.

Table 5 Relative emissions per life cycle stage

	Reinforced Concrete South Africa	Mass Engineered Timber South Africa	Reinforced Concrete Australia	Mass Engineered Timber Australia
A1 - A3 Materials	4.5%	1.3%	5.8%	1.3%
A4 Transport	0.1%	0.1%	0.5%	0.1%
A5 Construction	0.2%	0.2%	0.3%	0.2%
Operational Energy (B6)	95.1%	98.5%	93.3%	98.3%
C1, C2, C3 Waste	0.1%	0.0%	0.1%	0.0%

With the Operational energy modelled consistently across all models, it serves as a reference point for interpreting the improved embodied emissions. In the relative percentage scenarios above, it could be deduced that the Australian RC products have a less severe impact on the RC buildings. We also know the Australian energy grid results in lower operational emissions, yet the embodied emissions for the RC materials reflect higher relative to the South African RC materials. The above demonstrates the balance between embodied and operational emissions and the impact of the energy supply mix.

Decarbonising the energy grid would have twofold benefits: lowering the embodied emissions of building products and processes and reducing the impact of a building's operational energy consumption.

5.3 End-of-Life (C1 – C3)

As discussed in Section 2.3.2, biogenic carbon is considered sequestered in this study, as outlined by Younis et al. (2022, pp. 11 -12). The assumed building life and product rotation, forest rotations, and waste management constitute the impacts not to be considered as re-released. As a result, Table 5 above shows minimal to negligible impact on the buildings' end-of-life stage, depending on the waste management practices associated with each respective context.

It should be noted that impacts considered in LCA stage "D" – Beyond building life, are not included in the scope of this study.

5.4 Alternative Material Modelling Sensitivity

To further understand how the embodied emissions of a MET or RC building could be impacted by the use of lower emissions and less conventional material substitutions, the research explored the use of Supplementary Cementitious Materials, Crushed Recycled Concrete, and steel with high recycled content. Supplementary Cementitious Materials (SCM), recycled crushed concrete, and recycled content steel can potentially substantially lower the embodied emissions of a building during the construction stage due to their lower associated Product Stage (A1-A3) emissions. The product descriptions below outline how such materials could be circular and result in less raw material extraction and processing.

Supplementary Cementitious Materials: Incorporating SCM, including fly ash or blast furnace slag, into concrete mixtures can significantly reduce the reliance on traditional Portland cement, a significant source of emissions in concrete production. SCM materials often require lower energy inputs during manufacturing. They are considered a byproduct of a different primary product and require only minor additional processing, reducing the concrete's overall embodied emissions.

Recycled Crushed Concrete: Using recycled crushed concrete as an aggregate in concrete mixes offers a sustainable alternative to traditional aggregates, reducing the need to extract new virgin material. That not only diverts construction waste from landfills but also lessens the impact on natural systems of extracting and processing natural aggregates. Concrete recycling requires less energy than producing new aggregates, resulting in lower embodied emissions in the construction materials.

Recycled Content Steel: Utilising recycled content steel in construction, such as reinforcing bars, reduces the need for virgin steel production, which is energy-intensive and emits a substantial amount of carbon dioxide. Recycling steel requires less energy, and raw materials are used to produce new steel. Incorporating recycled content steel into the building's structural elements contributes to lowering the embodied emissions associated with steel components.

Modelling scenarios were adjusted to reflect the use of SCMs and recycled content, respectively, and results are outlined in Figure 17 below.

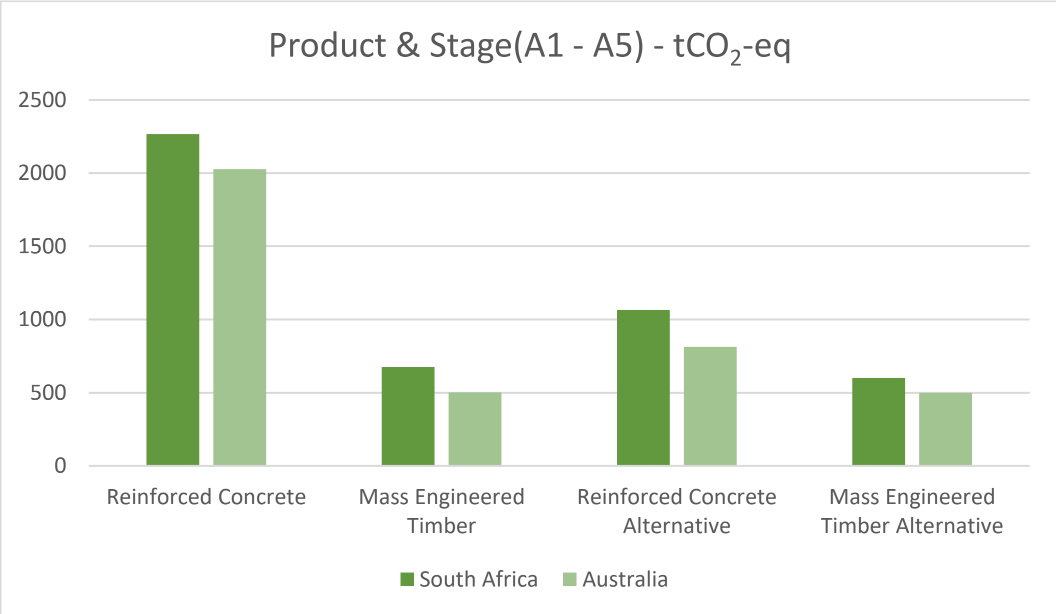

Figure 17 SCM - Combined product and construction stage emissions

While SCMs are generally considered sustainable due to their potential to reduce the impact of concrete emissions, certain aspects could limit their sustainability credentials. The SCM's source and production methods could depend on fossil fuel-driven industries. For example, if producing an SCM like fly ash involves coal combustion at a coal-fired power station to attain the SCM byproduct, the product would not be attainable once coal-fired power stations become redundant.

Similar to the originally modelled materials, SCM's sustainability or reduced environmental impact benefit can be influenced by the distance from the source to the building site. If the SCM needs to be transported over longer distances, an increase in energy consumption and emissions would ensue, offsetting the emissions reduction benefits achieved by implementing the material.

5.5 Modelling Limitations

In conducting a directly comparable LCA to determine the overall impact of buildings situated in two distinct locations, a simplified model was built as outlined in Chapter 3 based on the design development in Chapter 4. This simplified model allowed for a systematic and standardised assessment with results reported in the relevant FU, enabling a direct comparison (Andersen, et al., 2022) between the buildings in their respective geographies. By utilising this approach, the modelling aimed to pinpoint the specific differences in environmental performance attributed to the geographic variations. This approach was followed to provide insights into how location impacts the overall sustainability profile of buildings using MET instead of RC as primary building materials for a building frame.

The models only consider the primary materials constituting the primary building frame and do not account for more minor elements deemed materially insignificant, which were thus excluded from modelling and reporting. As discussed in Chapter 3, the modelling only considers the main building frame elements based on the assumption that facades and fit-outs could be specified to be functionally similar for both building frame types and, as a result, not influence the embodied energy differential. Model localisation is based on empirical quantitative or estimated data for local production and manufacturing and is not based on importing any materials.

5.6 Chapter Conclusion

The modelling shows that a cleaner energy grid indirectly influences the embodied emissions of the raw material extraction and product stage of building materials (A1 - A3). The production of construction materials often relies on energy-intensive processes. If the manufacturing facilities transition to cleaner energy sources, the embodied emissions of materials, including those like CLT and GLT, would be reduced. The product stage does not consider on-site renewables in the manufacturing emissions modelling. However, the associated product stage emissions could be significantly lowered if a manufacturer implements on-site renewables.

Transitioning to a decarbonised or lower-carbon energy grid or implementing behind-the-meter renewables on site also significantly impacts the life cycle emissions of a building in the operational stage. The intensity of the local energy supply mix's emissions directly influences the emissions from electricity consumption for building functions in 100% electrified buildings. In regions with a cleaner energy grid, characterised by a higher share of renewable sources like wind, solar, or hydropower, the operational emissions of buildings automatically decrease.

Discrepancies in transport distances for stage 4A and 5A emissions modelling are discussed and attributed to the potential supply of products in each respective context even though significant transport distance differences are noted, excluding potentially imported products results in negligible product transport emissions.

The modelling results chapter ultimately allows a response to two of the research sub-questions initially targeted in Chapter 1 of this paper. Considering the modelling results, analyses and discussions, the first sub-question:

" *Which life cycle stage contributes the most significant volume of emissions in the built environment*?"

This chapter answers that question: the research indicates that the most significant volumes of emissions in the built environment are predominantly emitted during the material production stage (A1-A3) in the cases modelled above where operational energy (A6) is not considered.

The second sub-question:

" *What factors contribute to certain life cycle stages having significantly higher emissions*?"

That could be answered as follows: The proposed subject of this research, replacing traditional RC buildings with MET building methods, indicates significant potential for lowering the embodied emissions associated with the construction of mid- to high-rise buildings. Timber's renewable nature and the associated emissions sequestration potential prove it to be a worthy adversary to RC.

However, the models were adjusted to demonstrate the potential substitution of traditional RC construction methods to include higher recycled content and SCM products. The latter strategies in RC construction also proved to lower the embodied emissions of the modelled building frames. The building frame-associated emissions were reduced by roughly 50% and 60% for the South African and Australian contexts, respectively.

Chapter 6 Vertical Extension

Vertical expansion of an existing multi-storey building refers to the process of adding additional floors or levels to an already constructed structure to increase its height and overall capacity. This expansion strategy offers a practical solution to the challenges of urban density and the need for more space in densely populated areas. Instead of opting for new construction on limited available land, property owners and developers can capitalise on the existing building's foundation and infrastructure by extending it vertically.

Urban densification, achieved by applying lightweight construction methods to expand existing building stock vertically, represents a strategic approach to address the growing urban space demand. With limited available land, especially in densely populated cities like Cape Town and Perth, the vertical expansion of existing structures becomes an attractive solution. Lightweight construction materials, such as Cross-Laminated Timber (CLT) and Glue-Laminated Timber (GLT), provide the structural strength necessary for vertical expansion while minimising the additional load on existing foundations. This approach optimises land use and contributes to creating sustainable and vibrant urban environments by accommodating increased population density without sacrificing green spaces or compromising the aesthetic integrity of neighbourhoods.

Beyond the potential for urban densification, lightweight construction methods offer significant environmental advantages. Timber, in particular, is a potentially sustainably renewable resource with reduced embodied energy than more conventional building materials like concrete and steel. The production of CLT and GLT involves sequestering emissions within the building components, acting as a carbon sink rather than contributing to greenhouse gas emissions. Additionally, lightweight construction methods typically require less energy during manufacturing and construction, reducing the environmental impact. Integrating sustainable practices in urban development aligns with the broader goal of decarbonisation in the built environment, making it a compelling solution for expanding existing building stock while minimising the environmental impact.

6.1 Design Concept – Vertical Extension

Based on the same building design used for the whole building, modelling was adapted from a design developed and used by S. van der Westhuyzen (2020) for a research project comparing the financial feasibility of a Reinforced Concrete and Mass Engineered Timber building. The MET building design was adapted to suit a vertical extension scenario.

The existing base building layout was assumed to be an existing RC frame building utilising a structural grid matching that of the MET design. The base building and the vertical extension are designed to a 6m x 6m grid with a 24m ×30m footprint, resulting in a gross floor area (GFA) of 2 880 m^2 for four storeys to be added by implementing MET construction.

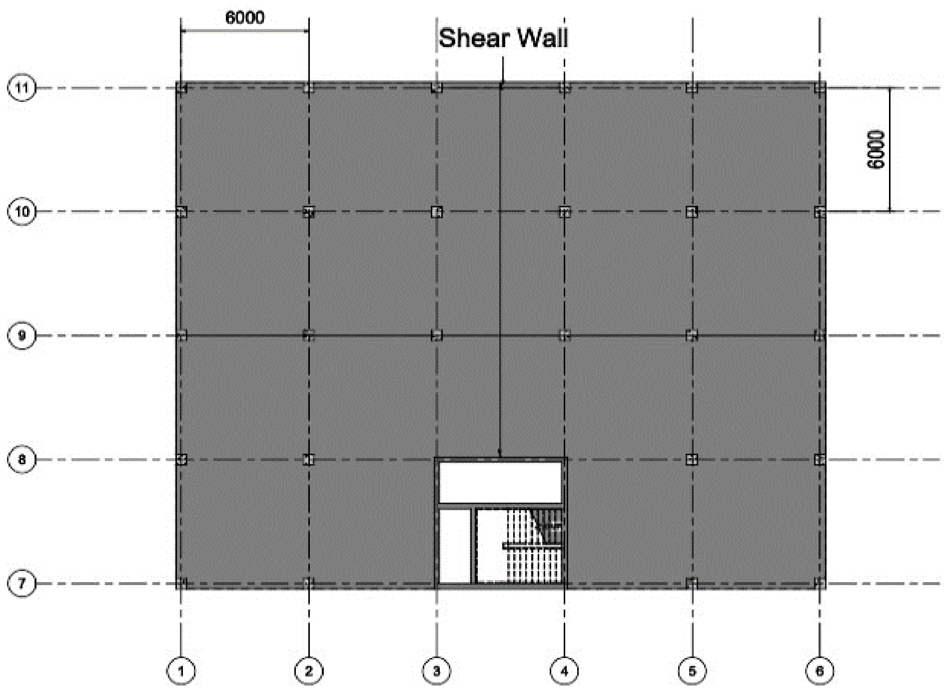

Figure 18 Building plan showing size and grid spacing (Van Der Westhuizen, 2020)

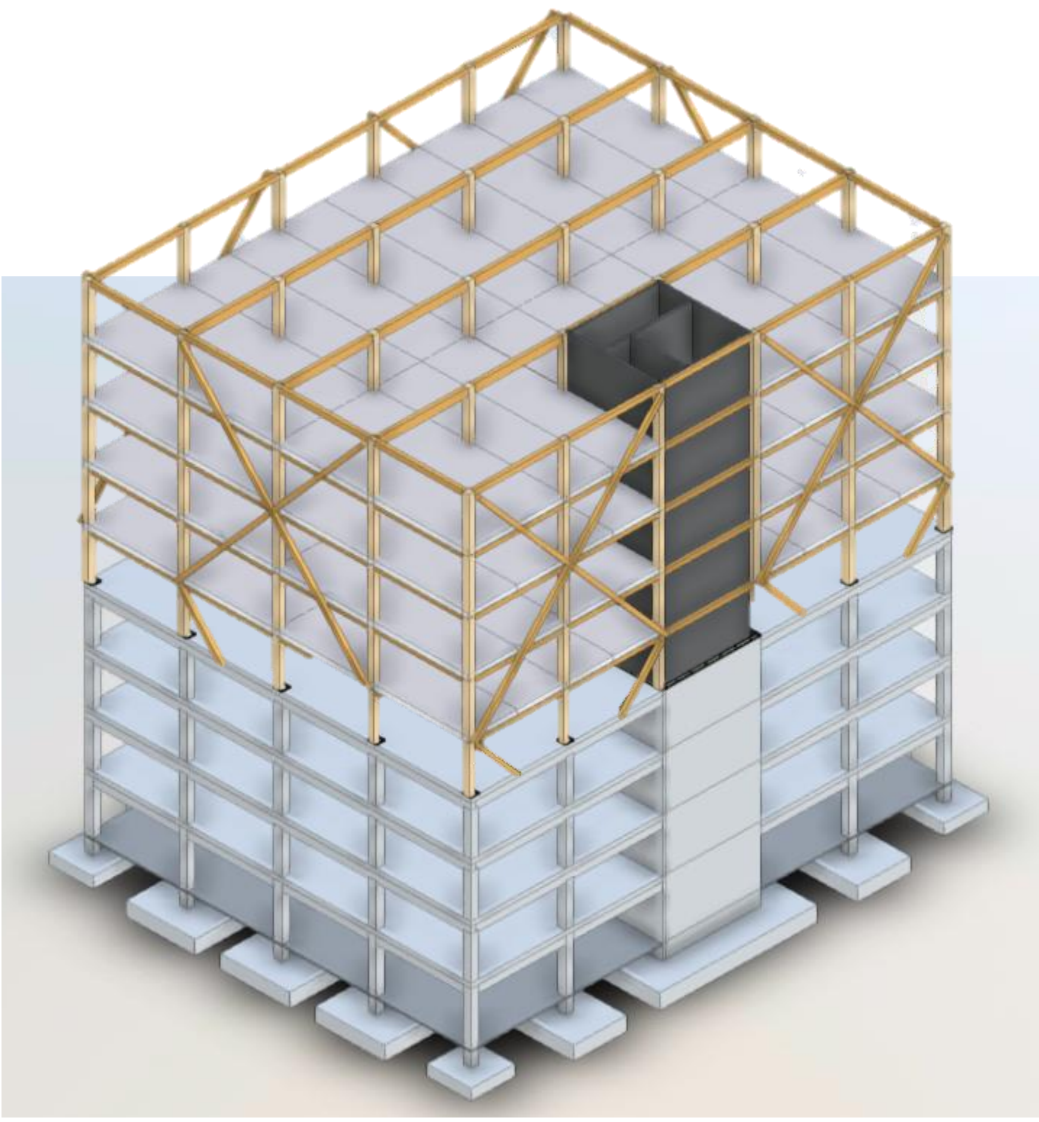

Figure 19 Vertical extension illustration adapted from (Van Der Westhuizen, 2020)

Considering the materials to be added, the vertical expansion option would not require concrete for foundation footings. Material quantities have also been adjusted to reflect the quantities in Table 6 below in the LCA modelling software.

Table 6 Vertical extension material quantities adapted from (Van Der Westhuizen, 2020)

		Depth (m)	Width (m)	Length (m)	Quantity	Volume (m^3)
Footings (30MPa)	Nil					
Columns (GL24h)	4--8	0.4	0.4	3.5	120	67.5
Internal Beams (GL24h)	1--8	0.52	2.4	6	60	450
Ring Beam (GL24h)	4--8	0.32	0.24	6	72	33

Bracing Beams (GL24h)	4--8	0.26	0.24	18.3	12	14
CLT Floors (220L75-2)	4--8	0.22	3	12	63	500
CLT Floors (220L75-2)	4--8	0.22	3	6	7	25
CLT core (180 C24)	4--8	28	0.18	32.1	1	80
Steel connections kg	Prlm kg					2500
Summary				Concrete (30MPa)		-
				GLT		563
				CLT		607

Subsection 3.1 Tools used for LCA Modelling in the Research Methods chapter details how the material quantities contained in Table 6 above are modelled into specific templates. The templates are selected for each material and model variation and then populated with material quantities. These templates interface in the back-end with the relevant LCI databases to provide impact results for each material.
It is assumed that the base structure can support the additional load with only minor modifications to footings through potential directional micro-piling (Babu, et al., 2004, p. 7) and column bracing.

6.2 Vertical Extension Modelling Results

Like the full building models detailed in Chapter 4, the material quantities for the functionally identical buildings were modelled using OneClickLCA. The modelling results are reported in the same impact per square meter and reported in tCO_2-eq/m^2.

The vertical extension models were only conducted by implementing a MET extension atop an existing RC building for Cape Town, South Africa, and Perth, Australia. The modelling did not include alternative lightweight construction methods like autoclaved aerated concrete (AAC) blocks, lightweight steel or timber frames, or several hybrid options that could be used for vertical extension.

Figure 20 below summarises the impact reduction for the vertical extension of an existing base building. The RC impact is the projected amortised embodied emissions for the existing RC building to be redeveloped, while the MET emissions are associated with the building frame extension activities. The base buildings were assumed to be 30 to 50 years of age and to have an additional 80-year life span remaining.

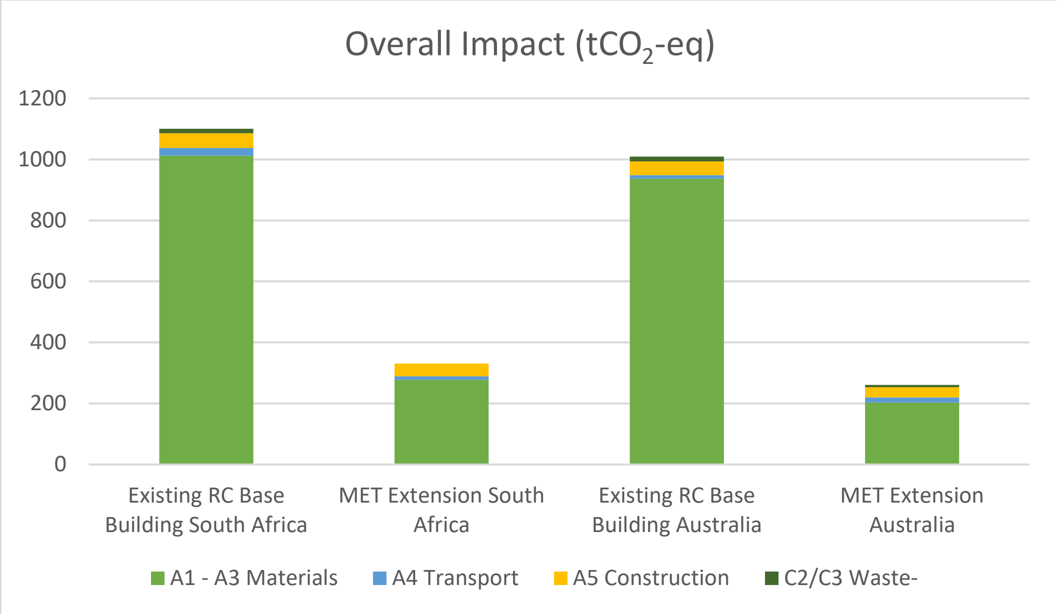

Figure 20 Overall emissions impact - vertical extension

Like the whole-building comparative models, the most significant impact or savings are realised in the product stage when operational energy is not considered. Utilising mass timber for adding floors to an existing building results in a lower embodied impact, as assessed in an LCA, compared to the alternative of demolishing the current structure and constructing an entirely new reinforced concrete building to have the same GFA ultimately. Extending vertically with mass timber capitalises on the inherent sustainability of MET construction, a renewable resource with a lower emissions impact than conventional concrete. Retaining the existing structure minimises the demand for additional raw materials. It reduces the environmental impact associated with manufacturing, while the faster construction process with mass timber minimises overall construction-related emissions and site disruption.

6.3 Life Cycle Assessment Stages

Conditions considered for the life cycle modelling of the vertical extension portion of this study are identical to the conditions and assumptions used for the whole building development in the previous section. The following subsections highlight key differences in findings for the respective life cycle stages.

6.3.1 Product and Construction Stage (A1 – A5)

The Product and construction stage is expected to correlate linearly with the new building models constructed and discussed in the previous section. The material volumes are scaled based on m^2 of floor area constructed and modelled accordingly.

As previously discussed, the model assumes that the base building frame requires minimal modifications to accommodate the vertical expansion. Any minor changes are not considered to have a materially significant impact and have been excluded. There are, however, notable differences in the construction stage (A5) effort required to prepare the base building for the vertical extension.

As this study only considered the building frame impact of a new building and existing building extension, the opportunity for commentary on the building envelope and upgrades to an existing building is limited. However, it is essential to note the vertical extension project will have significant embodied emissions not associated with the extended portion but rather the retrofitting of the 'older' base building (Artés, et al., 2017).

Improving thermal insulation of the base building envelope (walls, windows, window frames, airtightness) is a key aspect of energy-efficient retrofitting. While enhancing the thermal performance of the building, it also contributes to the embodied emissions associated with the building retrofit and, ultimately, the vertical extension. Additionally, subsequent equipment upgrades could be installed, such as HVAC systems, fire safety equipment and services, electrical equipment, and other general building service upgrades – all of which will contribute to the associated embodied emissions.

When these retrofitting measures are included in an LCA, they initially increase the embodied emissions due to the materials and processes involved. However, when evaluating the building's performance over its entire life cycle, these improvements often lead to decreased total emissions. The operational energy savings achieved through better insulation, efficient windows, and modern HVAC systems contribute to a reduced environmental impact over time, thus potentially outweighing the initial increase in embodied emissions. That highlights the importance of a holistic approach in LCA studies, considering both the immediate impacts of retrofitting and the long-term benefits.

6.3.2 Use Stage (B1 – B7)

Similar to the Use Stage modelling in the previous section for the building development, the embodied emissions categories with available data include only maintenance components (B2) and the replacement of building materials (B4). However, with only the main structural frame of the building being modelled, the impacts from these categories are materially insignificant and make <0.1% of the emissions modelled (Pomponi & Stephan, 2021, p. 3). That is because the building envelope has been excluded from the study due to the functional equivalency of the materials for different building frame typologies. The building envelope would have formed a more significant embodied category impact due to its extensive exposure to the elements to keep the occupants comfortable and protect the main building structure.

Further studies may consider modelling the building extension envelope, the base building, and the base building retrofitting activities to provide a holistic indication of the overall impact of the vertical extension. Literature on this topic was found to lack specificity, particularly in extending medium to higher-rise buildings.

Operational Energy (B6)

The operational energy use assumptions are similar to that of the whole building model in that the energy use per floor area and the climate zones are consistent. The model does not consider the energy use for the base building as it is undetermined which improvements would be made to the base building. We could assume that retrofitting would be conducted to bring the base building up to an improved performance level, as considered for the vertical extension section. However, in this case, it would not be viable to determine the interventions required for the hypothetical base building. Thus, modelling the embodied emissions associated with the retrofitments is impossible.

In the case of the vertical building extension, the modelled operational energy set does not provide significant insights, as it correlates to the same usage per m^2 of floor area as the whole building. Subsequently, further discussion of the operational energy use is abandoned.

6.3.3 End-of-Life (C1 – C3)

As discussed in Section 2.3.2, the consideration of biogenic carbon is considered sequestered in this study, as outlined by Younis et al. (2022, pp. 11 -12). The assumed building life and product rotation, forest rotations, and waste management constitute the impacts that should not be considered as re-released. As a result, modelling results show minimal to negligible impact for the end-of-life stage of the buildings, depending on the waste management practices associated with each respective context.

It should be noted that impacts considered in LCA stage “D” – Beyond building life, are not included in the scope of this study.

6.4 Alternative Material Modelling Sensitivity

Due to the limited use of 'conventional' construction materials in the vertical extension scenario, the alternative material modelling sensitivity presents a different relevance than all building construction options. Alternative materials primarily focus on reducing embodied emissions in traditionally energy-intensive materials. Such initiatives include replacing large volumes of Portland Cement in RC with SCM alternatives, virgin aggregate with crushed recycled concrete, and high recycled content steel options. None of the typical alternative material tactics would be applicable or have a materially significant impact in the case of a vertical extension.

6.5 Modelling Limitations

Similar to the models built for the whole-building developments in Chapter 5, the building modelling assumes a material cutoff of materially insignificant building elements. The requirement for structural modifications to foundations, footings, floors, columns, and beams of an existing building to be vertically extended would differ significantly in each real-world scenario. It is assumed that the target building for vertical expansion would require minimal structural modifications to allow the MET development to be placed on top. Minor structural modification could potentially not be considered materially significant when modelled in the LCA software and have less than a 0.1% impact on the overall embodied emissions as outlined in the ILCD Handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010, p. 110).

6.6 Chapter Conclusion

Vertical expansion with MET offers potential environmental benefits and contributes significantly to asset value improvement in the real estate sector. Through a low emissions building extension, the overall embodied emissions account is divided by a larger GFA, ultimately resulting in a lower CO_2-e/m^2 ratio. The efficient and streamlined construction process associated with MET ensures quicker project timelines, minimises the duration of disruptions, and enables a faster return on investment. Van Der Westhuyzen noted up to 33% reduction in the construction schedule (Van Der Westhuyzen & Wium, 2020, p. 44). The adaptability of mass timber to modern design preferences and its positive impact on the building's overall environmental performance position it as a valuable asset enhancement strategy, contributing to increased GFA and the property's market competitiveness and long-term value.

This chapter also enables answering the fourth and final research sub-question:

" *What is the potential for vertical expansion of existing buildings using low emissions lightweight materials like MET*?"

That could be answered: "Vertical extensions using MET construction methods could support urban densification where previously impossible or feasible". Based on the literature review on the specific topic, this paper makes assumptions regarding the structural suitability of base buildings. In assuming structural suitability based on the ability of a base building, material properties of MET, like its relatively lightweight, modular prefabrication abilities and low embodied emissions, are considered favourable for less disruptive and effective intervention.

Chapter 7 Conclusion and Recommendations

This research explored the role of Mass Engineered Timber (MET) in decarbonising the built environment in densely populated urban areas within South Africa and Australia, emphasising the urgency for more sustainable construction and operational methods due to rapid urbanisation. With urban areas expected to accommodate two-thirds of the global population by 2050 (UN DESA, 2018) and the built environment accounting for significant energy and raw material consumption, the study aims to assess the environmental benefits of MET over traditional materials like steel and concrete. Using comparative LCA modelling, the research investigates MET's potential to lower embodied energy and associated emissions in the construction and operations of a building, considering different supply chains' impacts on embodied energy. The rationale for focusing on MET stems from its potential renewable nature, lower embodied emissions, and the potential for urban densification and sustainable development through vertical extension, as outlined in the Literature Review section. It highlights the need for regulatory frameworks to encourage reduced GWP through operational and embodied energy efficiencies in the construction sector.

Primarily based on quantitative methods like computational LCA modelling, the research also explores some qualitative factors evident from the literature reviews that impact buildings' potential whole-of-life emissions profile in their distinct context. This approach enabled a holistic understanding of the current landscape of sustainable construction, identifying gaps in knowledge and practice while highlighting MET's potential to revolutionise the sector. Through this approach, the research explored the complexities of integrating innovative materials into established construction practices, contributing insights into pursuing a more sustainable and environmentally responsible built environment.

A total of 52 similar studies were reviewed by Younis et al. (2022, pp. 5 - 8) and Duan et al. (2022, p. 6) of similar scope, found that the embodied energy associated emissions contribute between 7% and 15% of the whole-of-life emissions by a MET building when compared to conventional building methods. Their findings are consistent with the modelling outcomes conducted for this research piece. These findings provide support for answering the main research question of the research conducted in this study:

"*What role can Mass Engineered Timber (MET) play in decarbonising the built environment as an alternative to conventional materials, specifically in reducing embodied emissions in functionally identical buildings located in Cape Town, South Africa, and Perth, Western Australia respectively?*"

With the above question being answered as:

With the embodied emissions comprising up to 15% of the whole-of-life emissions for a conventional building, implementing a low-emissions alternative like MET could significantly reduce the embodied emissions component. Industry and research focus on the built environment's operational energy and associated emissions, which form the most significant portion of building impacts. However, as operational emissions lower due to increased building operating efficiency and decarbonisation of energy supply, the relative proportion of embodied emissions for a building becomes larger if left unconsidered.

Considering the results of this study, the embodied emissions for a MET building in Perth, Western Australia, and Cape Town, South Africa, were 74% and 70% lower than their reinforced concrete counterparts, respectively. The embodied emissions from the reinforced concrete and MET buildings were 8% and 21% lower in Perth, Western Australia, than in Cape Town, South Africa.

It is important to note that fit-for-purpose applications of MET have the potential to lower the embodied emissions of a building, as this study discussed the sensitivity of energy supply mix and supply chain logistics on the overall results. If the products are manufactured using a high emissions intensity energy supply and transported over long distances, the emissions sequestration capabilities of timber become effectively negated. Ultimately, the widespread adoption of MET as a construction method can potentially cumulatively reduce the built environment's whole-of-life emissions depending on the supply and manufacture of the products.

7.1 Key Findings

The utilisation of MET for decarbonising the built environment has highlighted its significant potential alongside the challenges accompanying a shift toward more sustainable construction practices. The core emissions reduction opportunity from the research findings is the environmental potential of MET, demonstrated through its emissions sequestration capability. This attribute enables the storage of emissions within the building materials themselves and facilitates a reduction in greenhouse gas emissions by displacing conventional construction materials like RC. Such displacement is pivotal in decarbonising the built environment, positioning MET and vertical extensions, and using MET as an efficient and effective material and method in the quest for a more sustainable built environment.

The use of MET over RC showed a 70% and 74% reduction in embodied emissions for modelled building frames located in South Africa and Australia, respectively, with most of the savings attributed to the Product Stage (A1 - A3) of the building lifecycle. This reduction is evident in Figure 21 below depicting the reduction from RC to MET in the two respective locations. The Product stage, including the raw material supply, transportation of the material to the manufacturer, and the manufacturing of the final product for construction, constituted between 78% and 93% of the modelled embodied emissions for the various building scenarios.

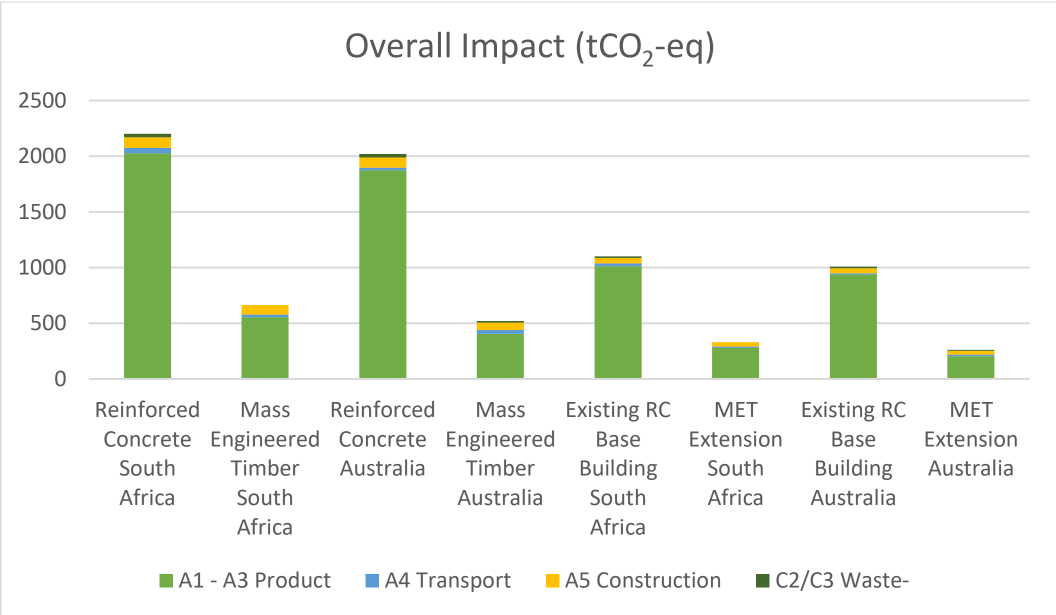

Figure 21 Overall emissions impact - whole building and vertical extension

The VE modelling in Chapter 6, depicted in the last four scenarios in Figure 21 above, showed similar impact reduction potential for MET in relation to the whole building modelling in Chapter 5. The differentiation should be noted in that the effective CO_2-e/m^2 was nearly halved if the base building is considered as a 'paid for' sunk environmental cost. The final vertically extended building will have the same floor area as the whole building modelled in Chapter 5. However, only four new floors were added. The comparative modelling demonstrates that an RC building in South Africa has the highest embodied emissions, and a functionally identical vertically extended building in Australia would have the lowest emissions.

As detailed in section 5.4, to further understand product stage sensitivity, potentially more sustainable products like SCM, CRC aggregates, and increased recycled steel products showed a 53% and 60% reduction in South Africa and Australia, respectively, for the RC buildings. Even though the alternative RC options presented significant savings over the conventional RC construction, the MET buildings still had a 37% and 39% reduction in South Africa and Australia, respectively, as shown in Figure 22 below.

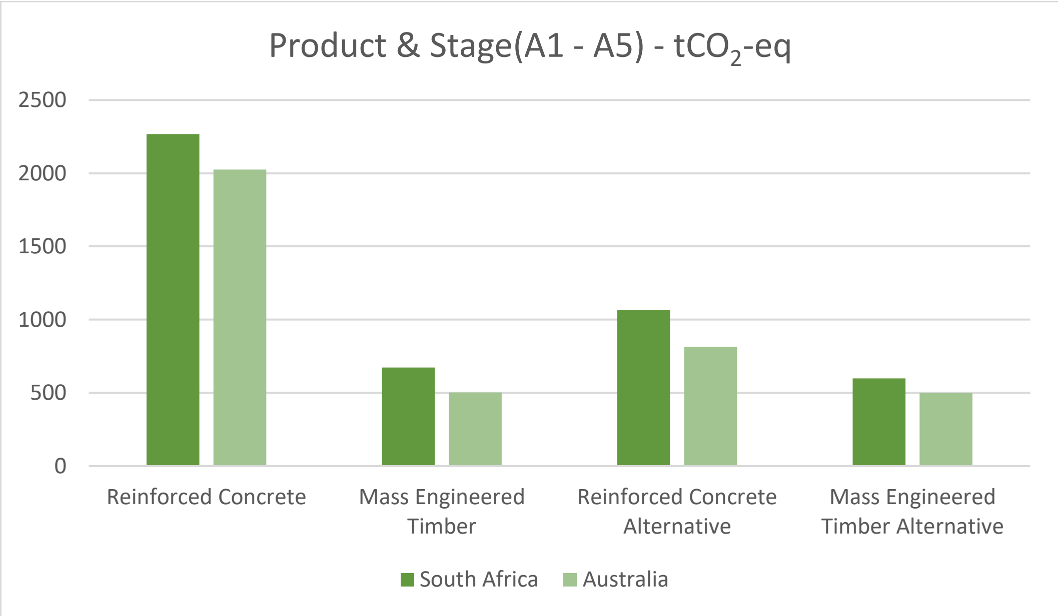

Figure 22 Reinforced concrete alternatives implemented

Historically, fire safety concerns have hindered MET's adoption. Yet, current advancements, including fire-resistant treatments and the development of comprehensive monitoring systems, have significantly mitigated these concerns. These innovations ensure MET's compliance with rigorous safety standards, addressing one of the primary barriers to adoption. Due to the nature of this research and the development of the design concept, fire retardants applied to exposed MET were not modelled.

The role of LCAs in construction emerged as another critical area of focus. LCAs offer a holistic perspective on a building's environmental impact throughout its lifecycle, empowering stakeholders to make informed choices that minimise ecological impacts. This comprehensive approach is essential for fostering the adoption of fit-for-purpose sustainable practices within the construction industry. However, the implementation of widespread LCA integration has its challenges. The research pinpointed several barriers, such as the absence of standardised methodologies, a rigorous data quality requirement, and the prohibitive costs of conducting thorough assessments. Furthermore, a notable gap in the requisite knowledge and skills among industry professionals underscores the urgency for enhanced educational initiatives to bolster LCA utilisation.

These insights highlight the transformative potential of MET in revolutionising sustainable construction and underscore the indispensable role of LCAs in steering the industry toward more holistic, environmentally responsible practices. They delineate the essential challenges that must be overcome to enable the broader adoption of these innovations, paving the way for a detailed exploration of their implications for policy, practice, and future research directions.

7.2 Significance of the Research

This research critically compares construction methods and materials against each other in a like-for-like building scenario in different geographical contexts. The focus of the comparisons is on establishing the potential role of MET in the decarbonisation of the built environment. Even though much research on comparative LCA modelling exists, little research has been found comparing building LCAs across geographic contexts. This provides significant insights as to how local factors influence the environmental impact of a functionally identical building in two different locations.

At the core of the research is the environmental imperative of reducing the emissions associated with built environment activities. The study's detailed examination of MET contributes to a growing body of evidence supporting the material's potential to sequester emissions and replace more emissions-intensive construction materials. This dual capacity positions MET and vertical extensions using MET as pivotal elements in the construction industry's transition to more sustainable practices, offering a tangible solution to one of the sector's most pressing challenges.

The kg-CO_2-e/m^2 comparison in Figure 23 below highlights the impact of the building materials and the distinction between the geographies of the buildings.

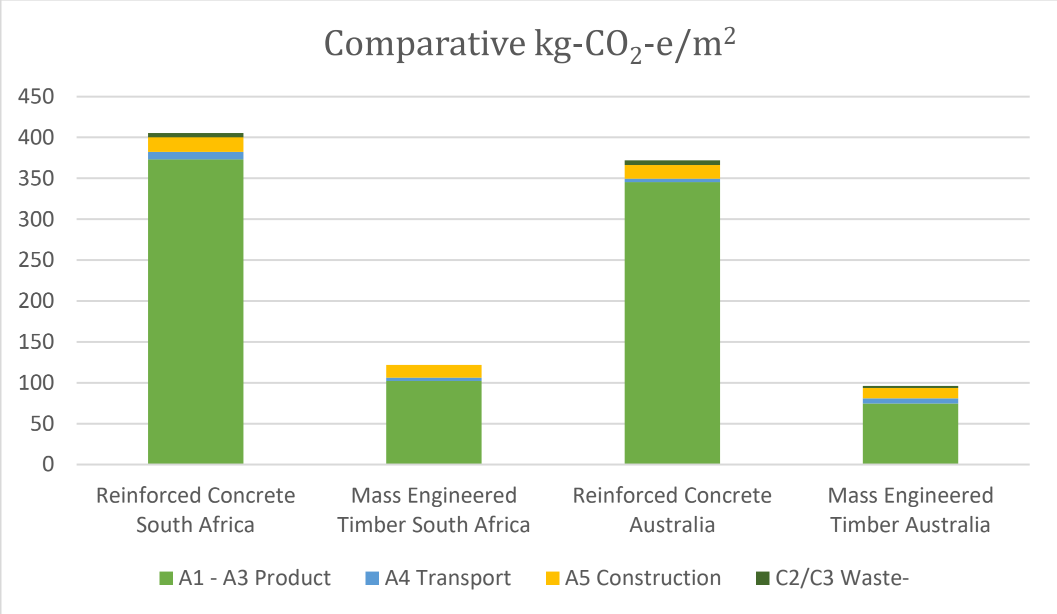

Figure 23 Comparative kg-CO2/m2 for building scenarios

Beyond its environmental and technological considerations, the research highlights other potentially significant socio-economic implications. Adopting MET in construction practices can shift the industry's economic dynamics, fostering the growth of new markets and industries related to sustainable building materials. The emphasis on LCAs underscores the importance of holistic approaches to environmental impact assessment, promoting transparency and accountability in construction projects. This shift towards more sustainable practices is beneficial for the environment and could support the long-term socio-economic sustainability of the construction industry.

The research enriches the academic and practical understanding of potentially sustainable materials and methodologies. By articulating the benefits, drawbacks, and potential challenges of using MET and LCAs, the study significantly contributes to the field, encouraging theoretical and practical advancements towards a more sustainable built environment.

7.3 Implications for Policy and Practice

The findings from this study on the utilisation of MET and the application of LCAs in construction carry potential implications for both policy and practice within the built environment. With the construction sector potentially standing at a crossroads, facing the urgent need to reduce its environmental impact and associated emissions, the insights garnered through this research support sustainability integration into various facets of construction, from design and material selection to project execution.

The environmental benefits of MET and vertical extension of buildings using MET, highlighted by its emissions sequestration capability and the potential to replace more emissions-intensive materials like RC, underscore the necessity for policy frameworks that encourage its adoption. Governments and regulatory bodies are urged to develop incentives for using sustainable materials like MET in construction projects. These incentives could take various forms, including tax benefits, subsidies, or streamlined approval processes for projects demonstrating a commitment to sustainability. Noting from the literature reviewed in section 2.3.1, the differing standards of LCA methodologies must be considered when used to inform policy framework decision-making.

For industry professionals, the advancements in MET technology, vertical extensions and fire safety protocols present new opportunities for innovation in construction. Architects, engineers, and builders are encouraged to explore the use of MET in their projects, benefiting from its environmental and aesthetic advantages. However, transitioning to MET and integrating LCAs into project planning requires a shift in mindset and a deepening of knowledge across the sector. This necessitates targeted educational programs and continuous professional development opportunities that equip practitioners with the skills to implement these sustainable practices effectively.

The study identified barriers to LCA adoption, such as the lack of accessible data and the cost implications of comprehensive assessments. These challenges highlight the need for collaborative efforts to overcome them. Industry stakeholders, academic institutions, and government agencies must collaborate to improve the availability of LCA tools and data, making it easier for professionals to incorporate these assessments into their work.

7.4 Future Research Recommendations

The use of Mass Engineered Timber (MET) as a building material and Life Cycle Assessments (LCAs) as a comparative tool are two distinct opportunities to improve sustainability in the built environment. While providing valuable insights, each of the two concepts also opens numerous avenues for future research. Addressing the challenges and limitations identified in this study is essential for advancing the field and further contributing to decarbonising the built environment. The following areas represent key directions for future research:

Empirical Studies on MET Implementation: A need for empirical research that examines the real-world application of MET in construction projects in specific geographical contexts is identified. Evidence-based studies that analyse actual case studies of MET projects may provide robust data on MET's environmental impact, cost-effectiveness, and performance over time. By documenting and analysing case studies of MET implementation, researchers can offer more definitive guidance on its benefits and challenges, contributing to a holistic understanding of MET's role in sustainable construction. The data from these empirical studies could also further serve to improve the quality and accuracy of LCA modelling.

Standardisation of LCA Methodologies: The variability in LCA methodologies emerged as a potential barrier to their effective application in assessing construction projects' environmental impacts. Future research could be more explicit on their standardised, industry-wide LCA protocols that ensure consistency and comparability of results. This effort could involve collaborations between academic institutions, industry stakeholders, and regulatory bodies to agree on common standards and practices. Agreement on standard criteria used in the industry could improve data reliability, provide robust and consistent assessment, and provide a better like-for-like comparison.

Socio-Economic Barriers to New Construction Practices: While this study touched on technological and methodological aspects of sustainable construction, further research is needed to explore the socio-economic factors influencing the adoption of practices like MET and LCA in specific geographical contexts. Case studies could investigate the impact of regulatory frameworks, market dynamics, and stakeholder perceptions on the uptake of sustainable construction materials and methodologies, providing insights into how these barriers have been or can be overcome.

Material Science Research: Continuing advancements in material science are crucial for enhancing MET's properties and applications. Future research could explore new treatments, composites, and construction techniques that improve MET's fire resistance, structural integrity, and aesthetic versatility. Such innovations could broaden MET's applicability in diverse construction contexts. Lifecycle Impact Assessments Beyond Environmental Metrics: Expanding the scope of LCAs to include more comprehensive assessments of social and economic impacts represents an important future research direction. By developing methodologies that capture a broader range of sustainability metrics, researchers can provide a more holistic view of the impacts of construction materials and practices, supporting more informed decision-making in the industry.

Impact on the Global Forestry Industry: An essential avenue for future research lies in examining the effects of the widespread adoption of Mass Engineered Timber (MET) on the global forestry industry. As the demand for MET increases, understanding its implications for forestry management practices, biodiversity, and the emissions cycle becomes paramount. This research could explore how sustainable forestry practices can be optimised to support the escalated use of lumber in buildings while ensuring the health and resilience of forest ecosystems. Key questions might include the effects of MET demand on deforestation rates, the potential for afforestation and reforestation initiatives to offset these impacts, and the role of certification schemes in promoting sustainable timber harvesting.

The potential impact of circular economy: Future research could explore how advancements in circular economy practices within South Africa and Western Australia influence buildings' life cycle assessment (LCA). Circular economy principles, such as material reuse, recycling, and closed-loop supply chains, could significantly impact embodied carbon calculations by reducing material extraction and manufacturing emissions. For instance, increased adoption of deconstruction techniques over demolition may enable higher recovery rates of materials, including structural components like timber, thereby extending their useful life and reducing waste sent to landfills. Similarly, developing regional recycling infrastructure and policies in both geographies could improve the availability and quality of secondary materials, directly impacting the embodied carbon associated with material production.

These benefits will likely vary depending on local factors such as resource availability, existing recycling technologies, and policy frameworks. For instance, Cape Town's efforts to integrate informal recycling networks into formal waste systems may present unique challenges and opportunities distinct from Perth's focus on industrial-scale recycling and waste management strategies.

By pursuing these and other related research topics, the academic and professional communities can continue to build on the foundational knowledge established by this study. Such efforts will advance the sustainable construction field and contribute to the broader goal of mitigating climate change through innovative and responsible building practices.

7.5 Concluding Remarks

As this research journey exploring the role of Mass Engineered Timber (MET) in decarbonising the built environment concludes, it's clear that the path towards sustainable construction is both promising and fraught with complexities. This study has illuminated MET's significant potential to support the development of a more sustainable, effective and efficient built environment while highlighting the indispensable role of Life Cycle Assessments (LCAs) in evaluating and guiding these practices. The findings underscore the urgent need for the construction sector to embrace innovative materials and methodologies that align with global sustainability goals, particularly amid the ongoing climate crisis.

Exploring METs and LCAs has revealed their potential and the challenges that must be navigated to realise their benefits entirely. From technological advancements and methodological standardisation to socio-economic and regulatory barriers, the path forward requires a multifaceted approach that engages all stakeholders in the construction ecosystem. This research's significance lies in its contribution to academic knowledge and its practical implications for industry practices, policy development, and environmental stewardship.

Looking ahead, ongoing research and innovation will undoubtedly shape the future of sustainable construction. The directions for future research outlined in this study offer a roadmap for addressing the current limitations and expanding our understanding of sustainable construction practices. As the industry moves forward, it is imperative that stakeholders across the spectrum—from policymakers to practitioners and from academics to industry leaders—work collaboratively to support the uptake of sustainable materials like MET and the integration of comprehensive assessment tools like LCAs.

In conclusion, this research reaffirms the critical role of more sustainable construction practices in mitigating the built environment's environmental impacts. By embracing the challenges and opportunities METs and LCAs present, the construction sector can support the global pursuit of sustainability. The quest for a more sustainable built environment continues, and this study marks progress in comprehending and addressing the intricacies of this vital issue endeavour.

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Appendix A: LCA Modelling Results

Main > Decarbonisation of the built environment (South African building)

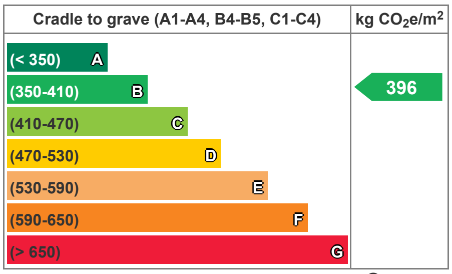
Decarbonisation of the built environment (South African building)

General information

Results and benchmarking - Design: 2 - Reinforced Concrete

Select design

Embodied carbon benchmark



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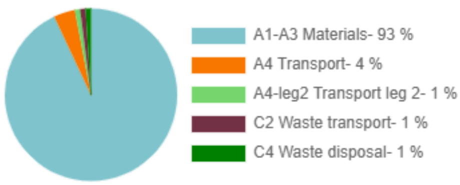
Embodied carbon by life-cycle stage



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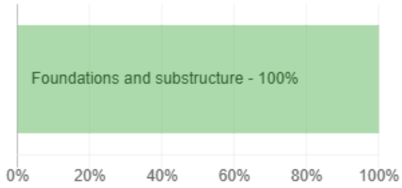
Embodied carbon by structure - A1-A3



Download as image

Project level parameters are not defined. Set them under the Parameters menu. Changing them later on will lead to results being recalculated.

Design phase: 3 designs

Parameters | Add a design | Compare data | Carbon Designer 3D | Tools

Tool	Unit	2 - Mass Engineered Timber Frame	2 - Reinforced Concrete	2 - RC - sustainable
Level(s) life-cycle assessment (EN15804 +A1) ? Help	kg CO_2e	43 542 822	45 135 790	43 935 05
Level(s) life-cycle assessment (EN15804 +A2) (new version available) ? Help	kg CO_2e	Ready	Ready	Reac
Building Circularity (unsupported - new version available) ? Help	%	33	3	5

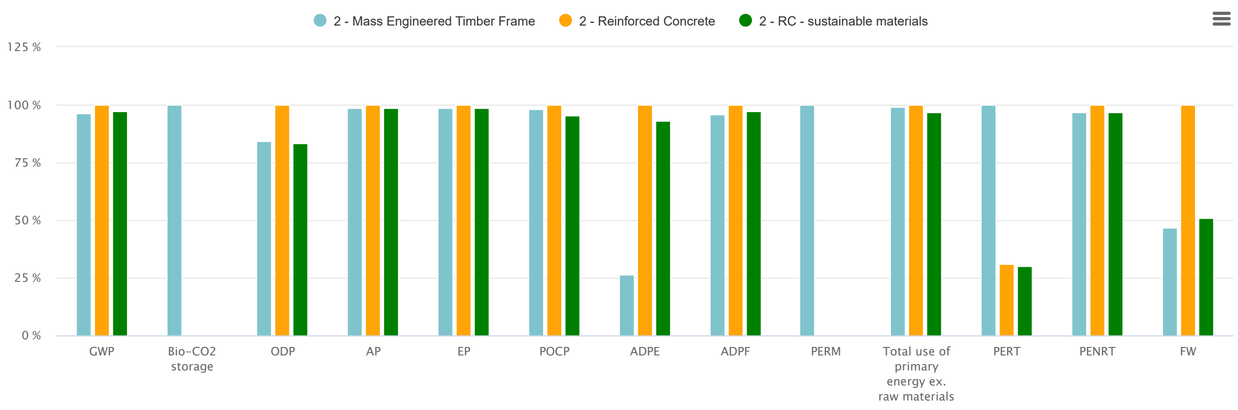
Graphs Level(s) life-cycle assessment (EN15804 +A1), Glob...

Showing: 3 / 3 Designs | Classification | Change tool and impact category

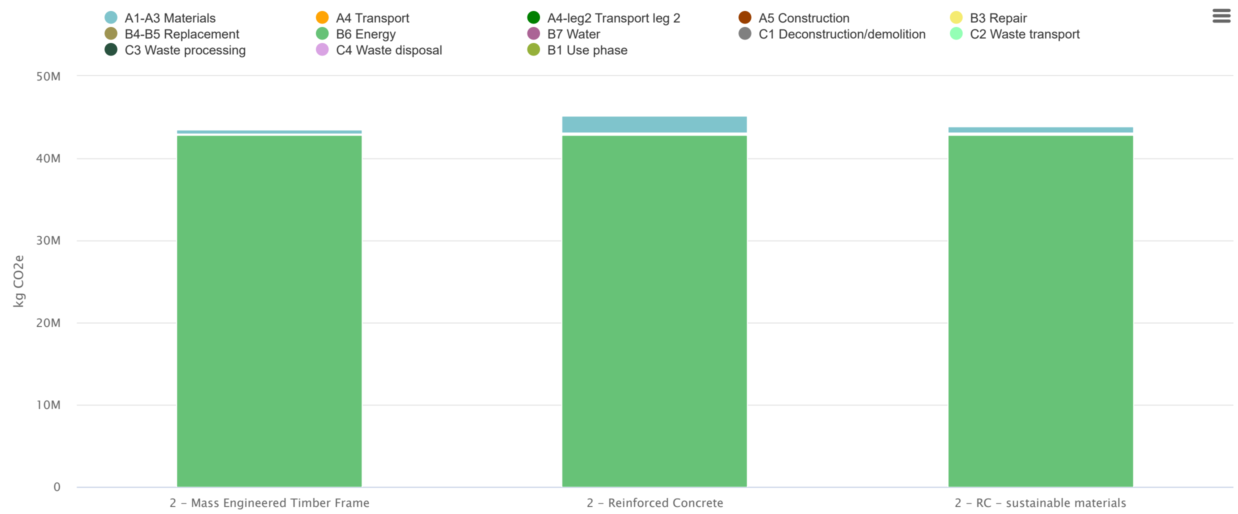
All impact categories | Life-cycle stages | Elements | Compare elements | Elements and life-cycle stages | **All graphs**

How can we help?

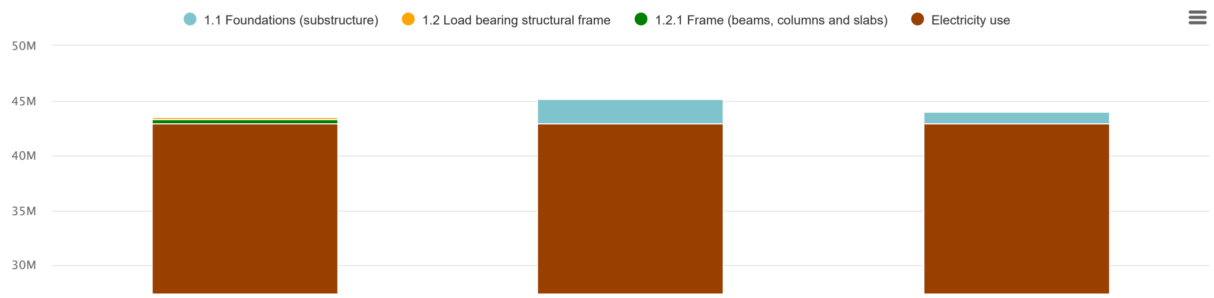
Level(s) life-cycle assessment (EN15804 +A1) - All impact categories

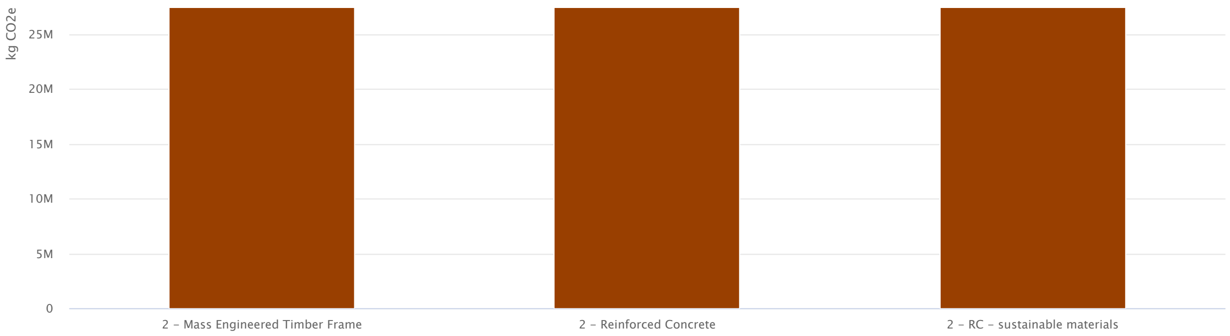


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Life-cycle stages



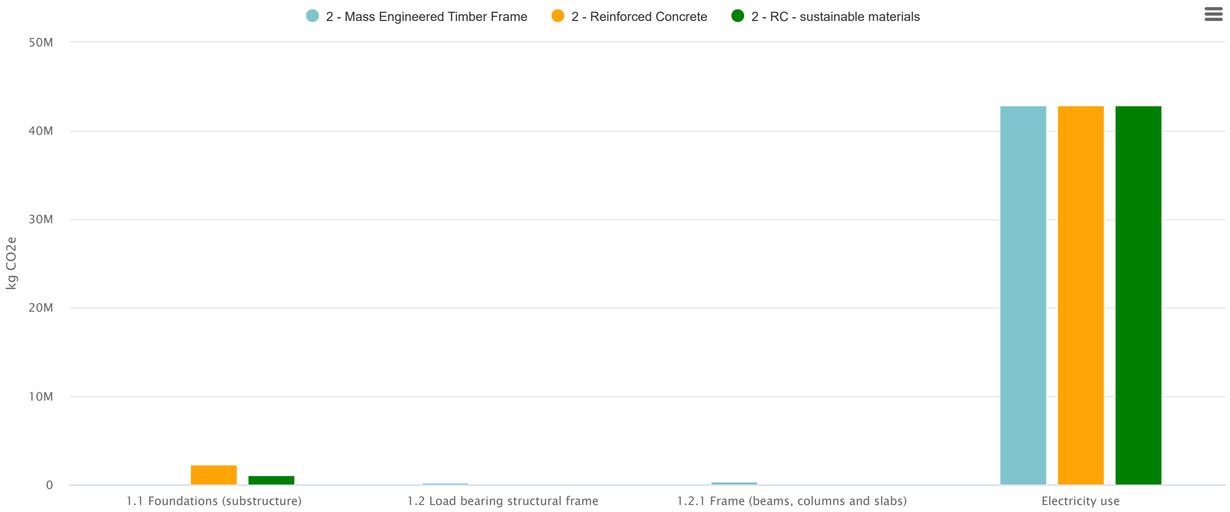
Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements



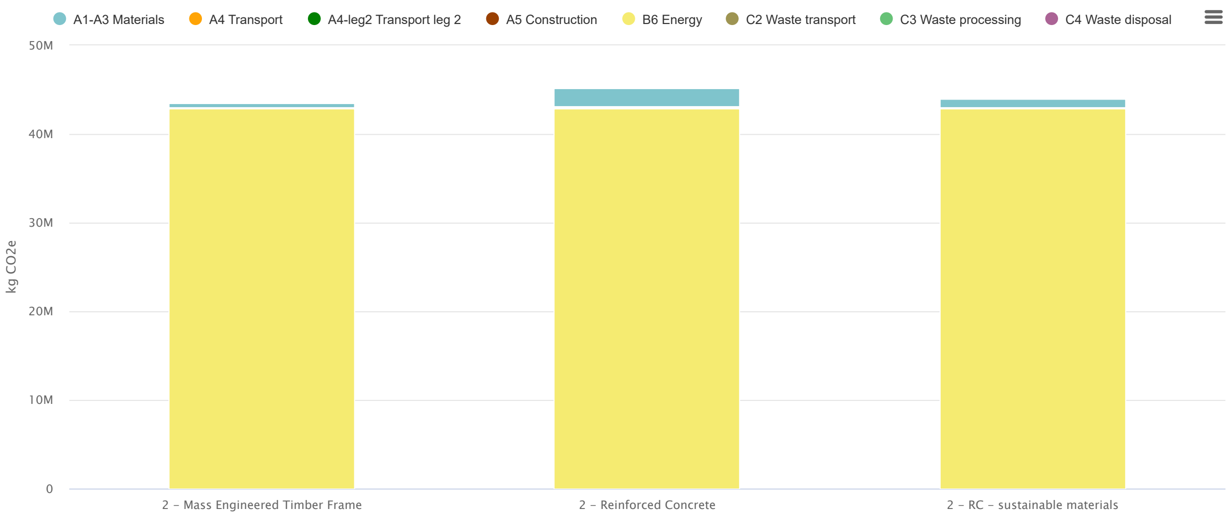


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Compare elements

Select groupings



Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements and life-cycle stages



Main > Decarbonisation of the built environment (South African building)

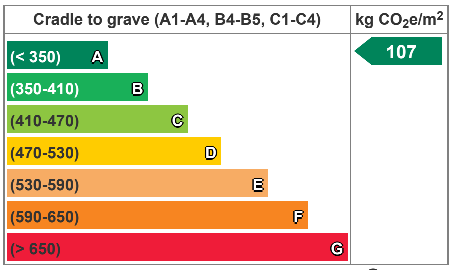
Decarbonisation of the built environment (South African building)

General information

Results and benchmarking - Design: 2 - Mass Engineered Timber Frame

Select design

Embodied carbon benchmark



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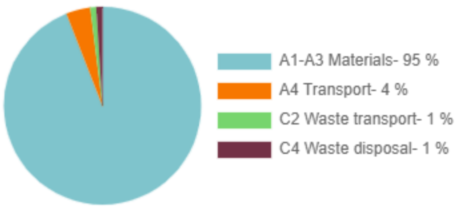
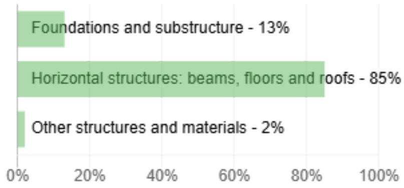
Embodied carbon by life-cycle stage



Download as image

Embodied carbon by structure - A1-A3



Download as image

Project level parameters are not defined. Set them under the Parameters menu. Changing them later on will lead to results being recalculated.

Design phase: 3 designs

Parameters | Add a design | Compare data | Carbon Designer 3D | Tools

Tool	Unit	2 - Mass Engineered Timber Frame	2 - Reinforced Concrete	2 - RC - sustainable
Level(s) life-cycle assessment (EN15804 +A1) ? Help	kg CO_2e	43 542 822	45 135 790	43 935 05
Level(s) life-cycle assessment (EN15804 +A2) (new version available) ? Help	kg CO_2e	Ready	Ready	Reac
Building Circularity (unsupported - new version available) ? Help	%	33	3	5

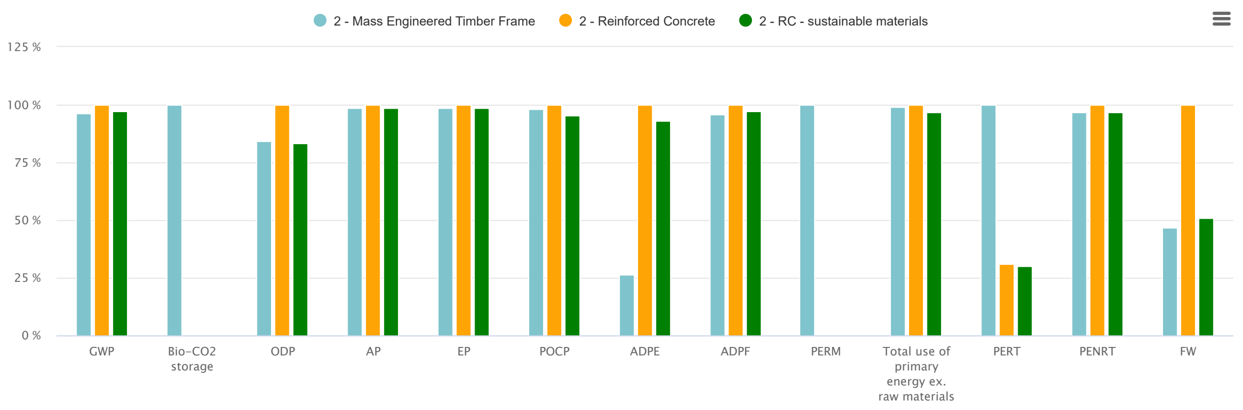
Graphs Level(s) life-cycle assessment (EN15804 +A1), Glob...

Showing: 3 / 3 Designs | Classification | Change tool and impact category

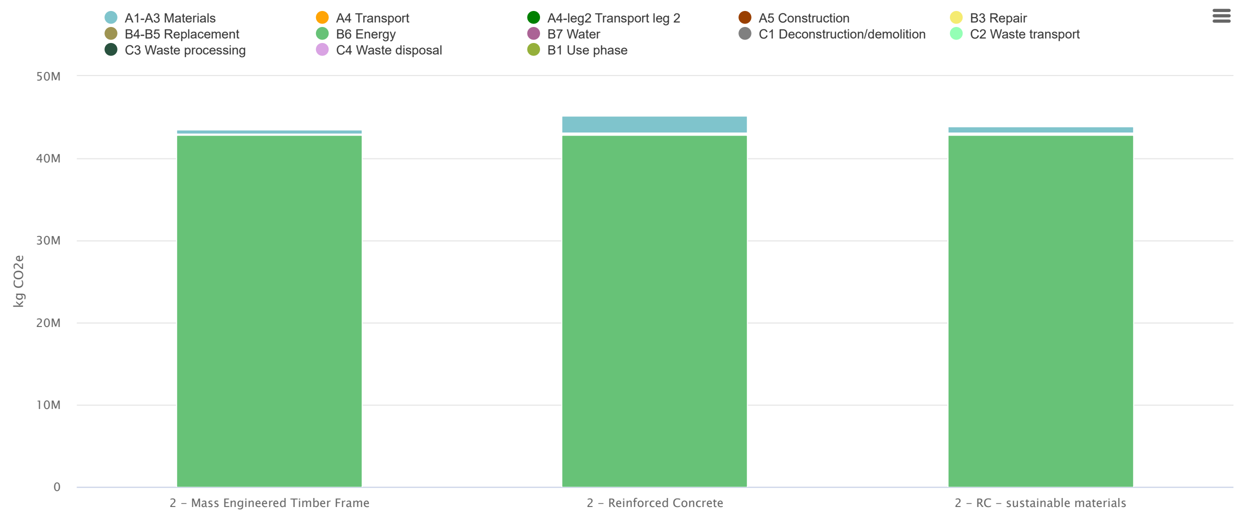
All impact categories | Life-cycle stages | Elements | Compare elements | Elements and life-cycle stages | **All graphs**

How can we help?

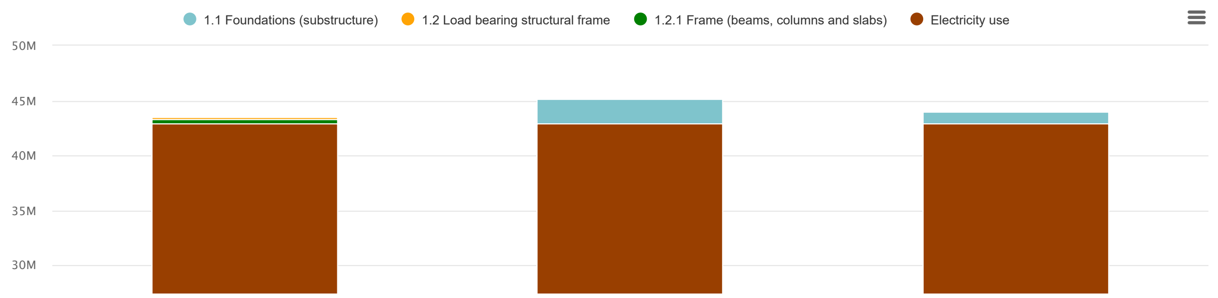
Level(s) life-cycle assessment (EN15804 +A1) - All impact categories

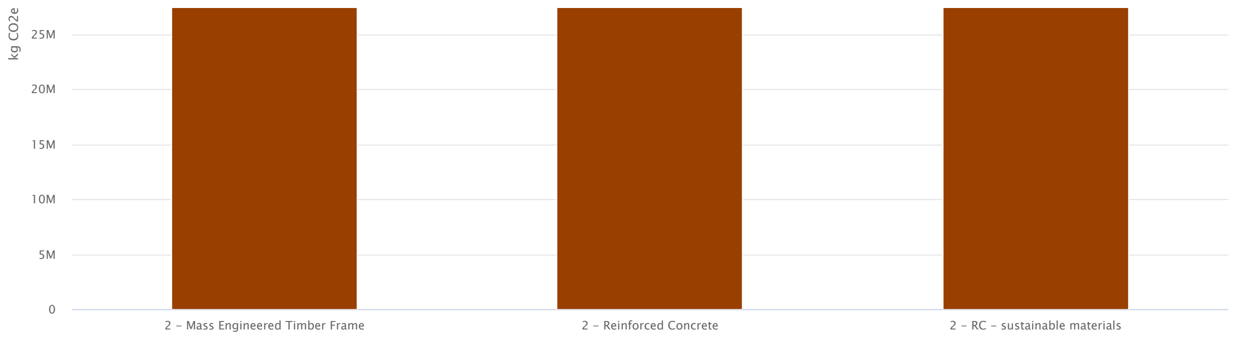


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Life-cycle stages



Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements

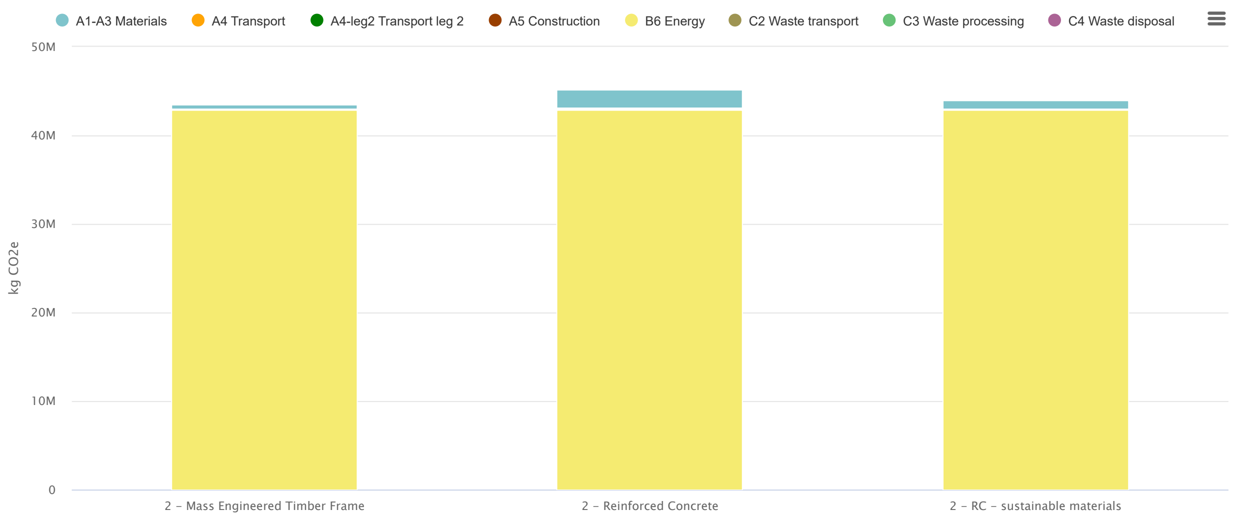




Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Compare elements

Select groupings

Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements and life-cycle stages



Main > Decarbonisation of the built environment (South African building)

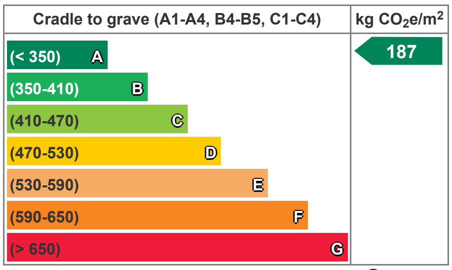
Decarbonisation of the built environment (South African building)

General information

Results and benchmarking - Design: 2 - RC - sustainable materials

Select design

Embodied carbon benchmark



Global apartment building - 2023 Q3

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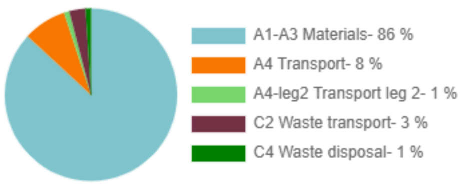
Embodied carbon by life-cycle stage



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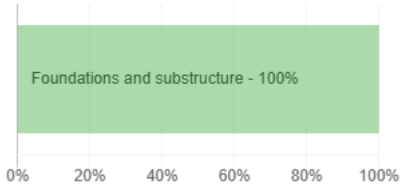
Embodied carbon by structure - A1-A3



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Project level parameters are not defined. Set them under the Parameters menu. Changing them later on will lead to results being recalculated.

Design phase: 3 designs

Parameters | Add a design | Compare data | Carbon Designer 3D | Tools

Tool	Unit	2 - Mass Engineered Timber Frame	2 - Reinforced Concrete	2 - RC - sustainable
Level(s) life-cycle assessment (EN15804 +A1) ? Help	kg CO_2e	43 542 822	45 135 790	43 935 05
Level(s) life-cycle assessment (EN15804 +A2) (new version available) ? Help	kg CO_2e	Ready	Ready	Reac
Building Circularity (unsupported - new version available) ? Help	%	33	3	5

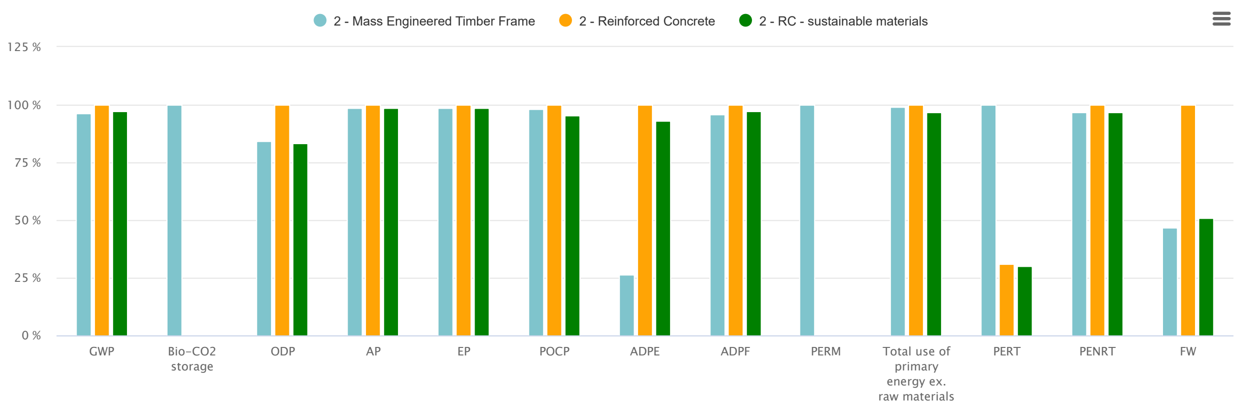
Graphs Level(s) life-cycle assessment (EN15804 +A1), Glob...

Showing: 3 / 3 Designs | Classification | Change tool and impact category

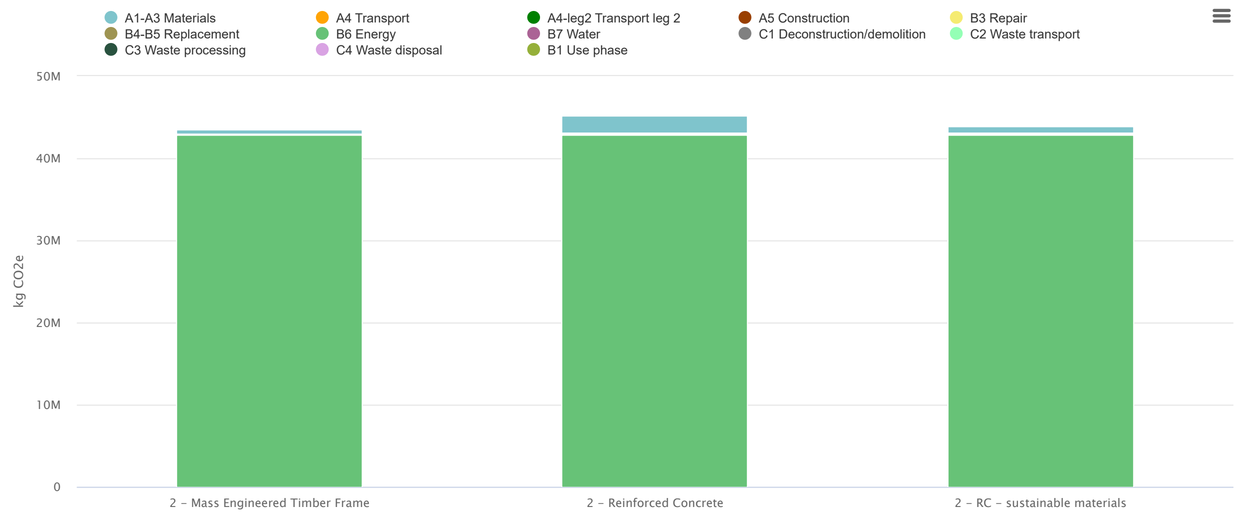
All impact categories | Life-cycle stages | Elements | Compare elements | Elements and life-cycle stages | **All graphs**

How can we help?

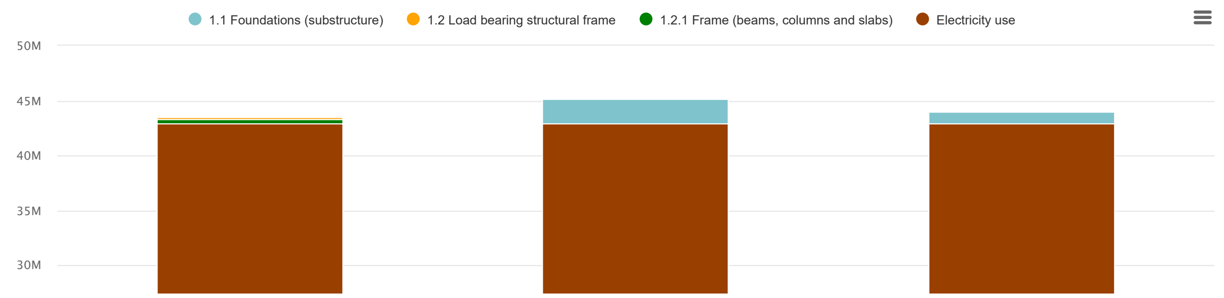
Level(s) life-cycle assessment (EN15804 +A1) - All impact categories

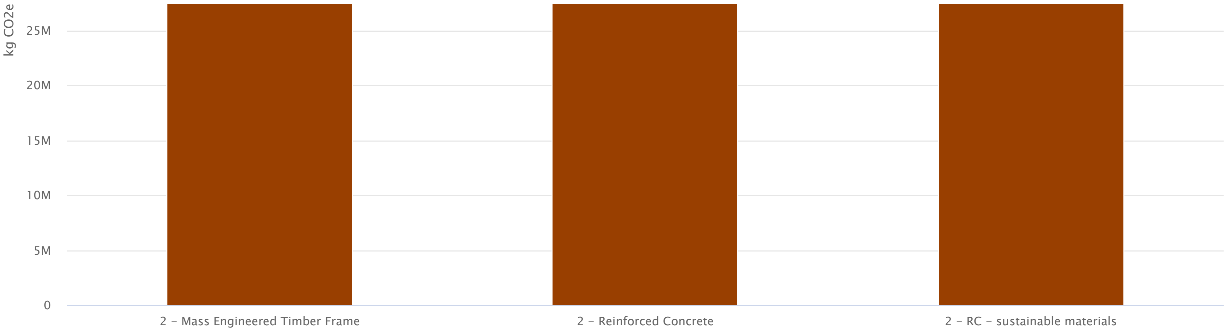


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Life-cycle stages



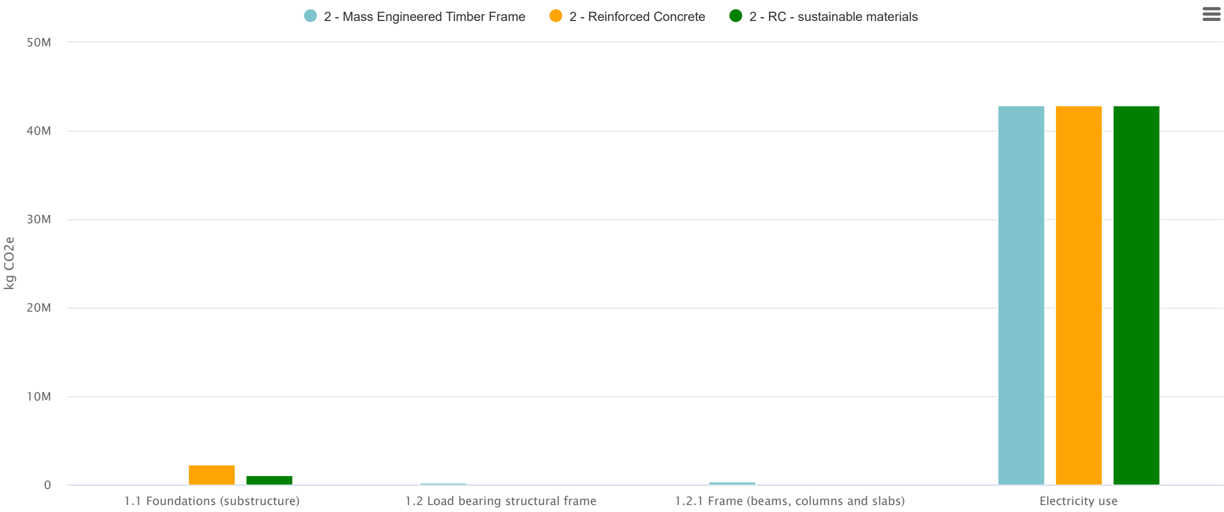
Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements



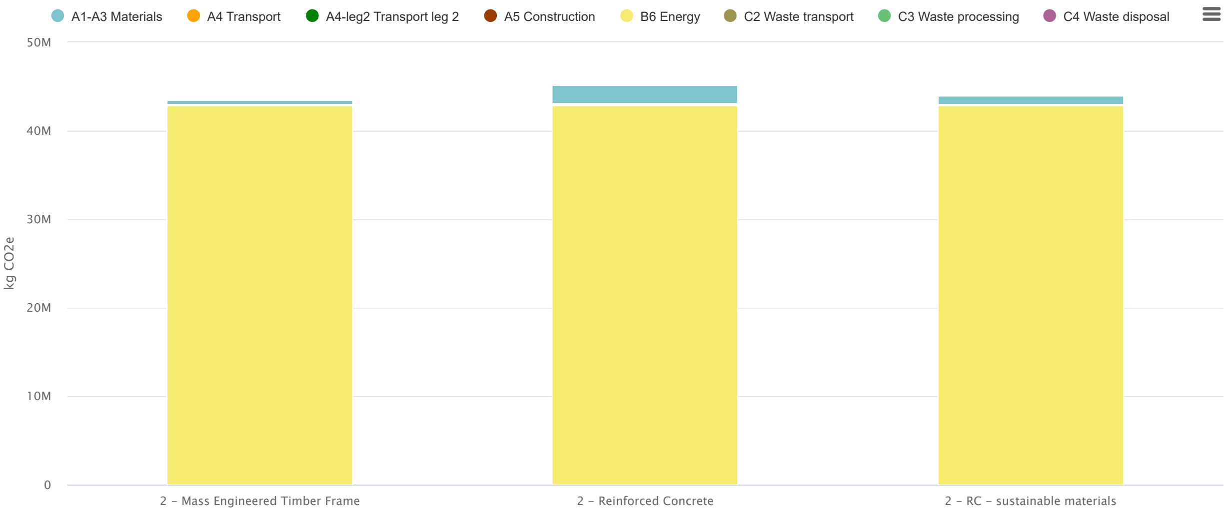


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Compare elements

Select groupings



Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements and life-cycle stages



Main > Decarbonisation of the built environment (Australian building)

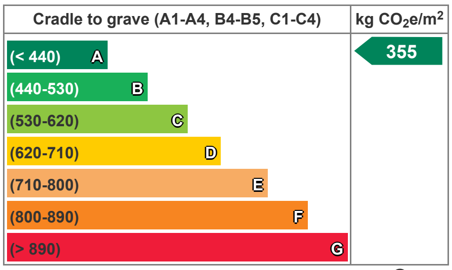
Decarbonisation of the built environment (Australian building)

General information

Results and benchmarking - Design: 2 - Australian Reinforced Concrete Frame

Select design

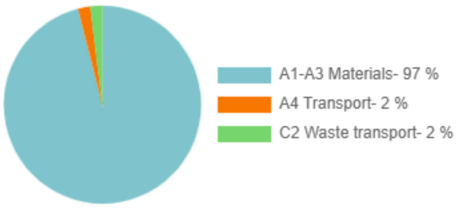
Embodied carbon benchmark



Australia all building types excl. MEP - 2023

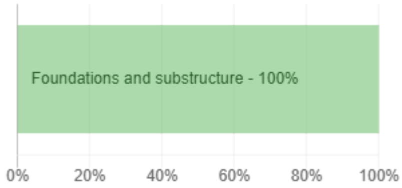
Download as image

Embodied carbon by life-cycle stage



Download as image

Embodied carbon by structure - A1-A3



Download as image

Project level parameters are not defined. Set them under the Parameters menu. Changing them later on will lead to results being recalculated.

Design phase: 3 designs

Parameters | Add a design | Compare data | Carbon Designer 3D | Tools

Tool	Unit	2 - Australian Mass Timber Building	2 - Australian Reinforced Concrete Frame
Level(s) life-cycle assessment (EN15804 +A1) ? Help	kg CO_2e	30 779 222	32 302 504
Level(s) life-cycle assessment (EN15804 +A2) (new version available) ? Help	kg CO_2e	Ready	Ready
Building Circularity (unsupported - new version available) ? Help	%	65	27

Graphs Level(s) life-cycle assessment (EN15804 +A1), Glob...

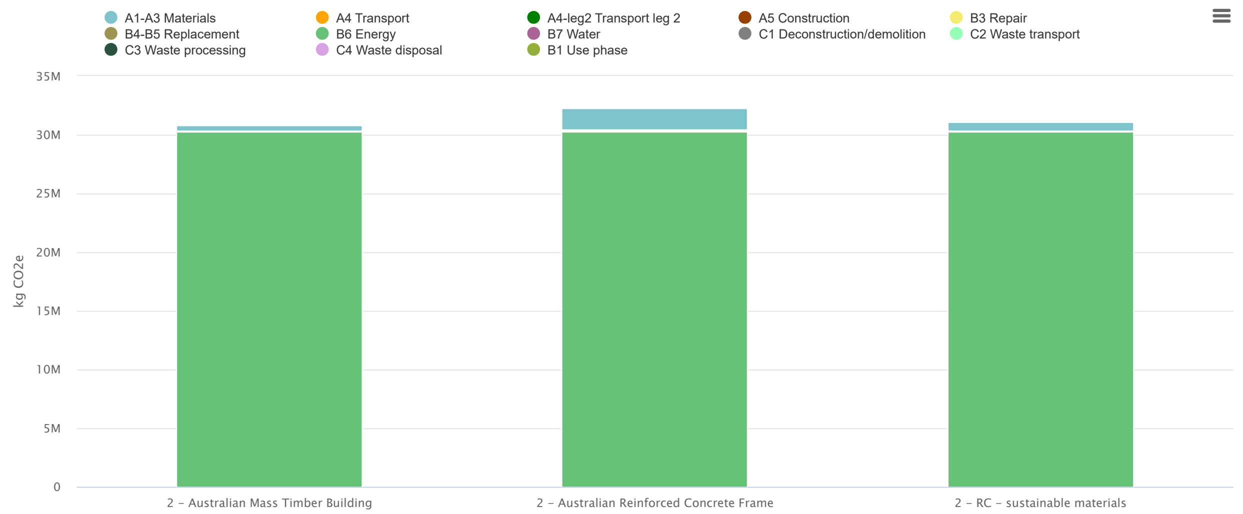
Showing: 3 / 3 Designs | Classification | Change tool and impact category

All impact categories | Life-cycle stages | Elements | Compare elements | Elements and life-cycle stages | **All graphs**

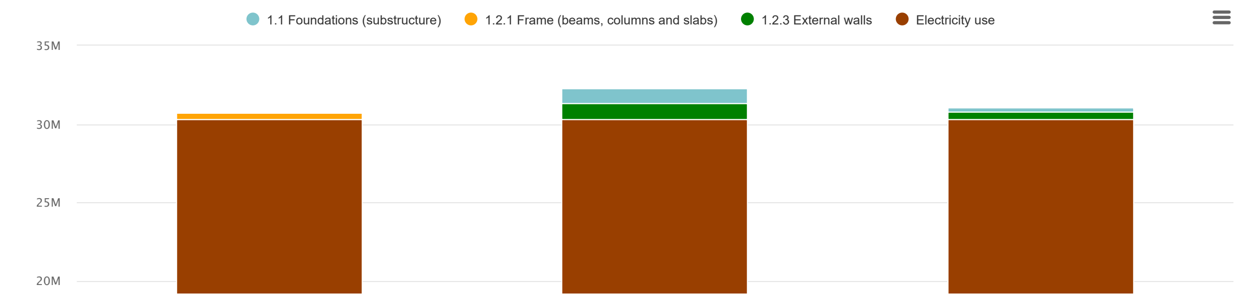
How can we help?

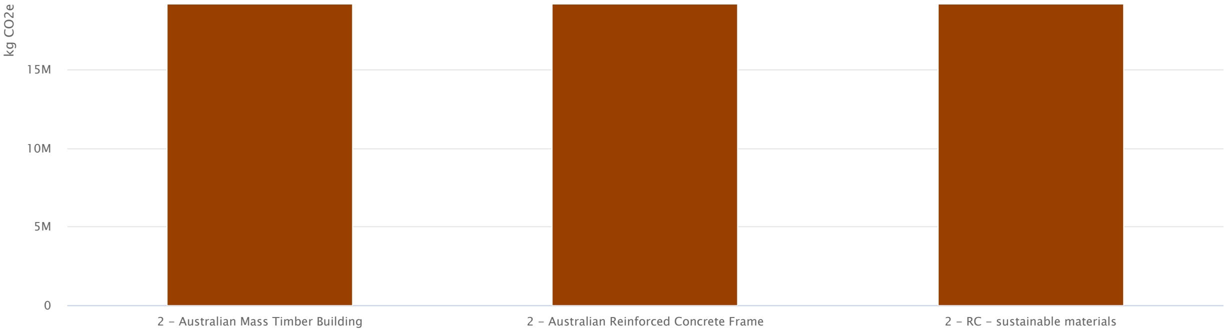
Level(s) life-cycle assessment (EN15804 +A1) - All impact categories

Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Life-cycle stages



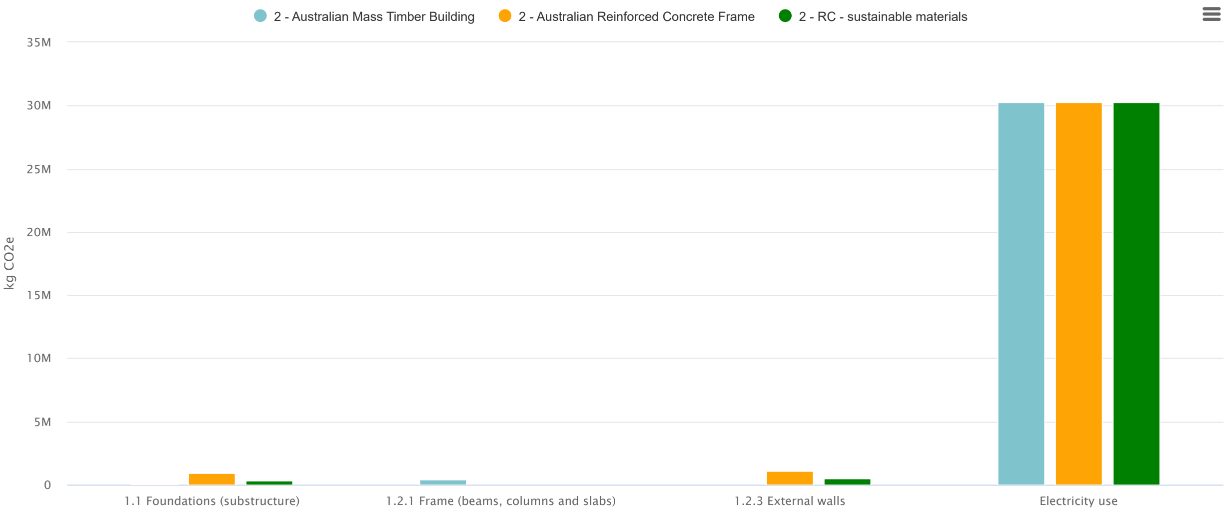
Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements



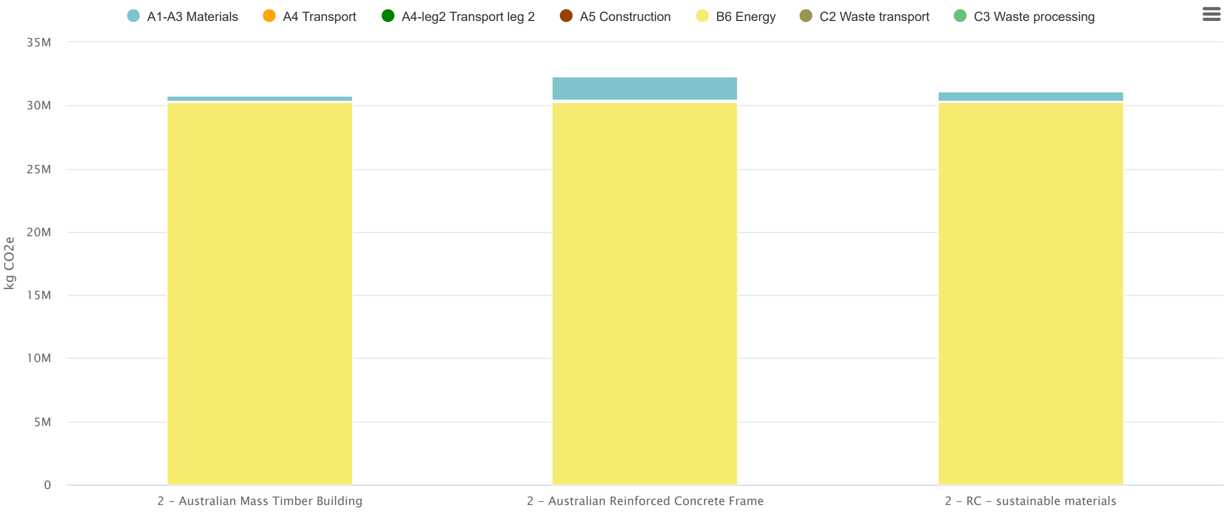


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Compare elements

Select groupings



Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements and life-cycle stages



Main > Decarbonisation of the built environment (Australian building)

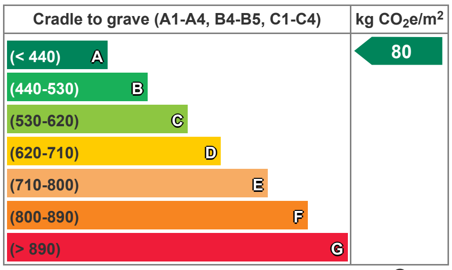
Decarbonisation of the built environment (Australian building)

General information

Results and benchmarking - Design: 2 - Australian Mass Timber Building

Select design

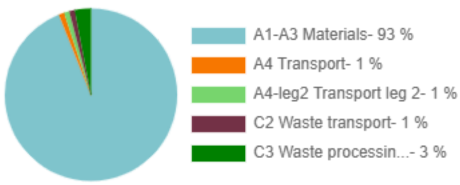
Embodied carbon benchmark



Australia all building types excl. MEP - 2023

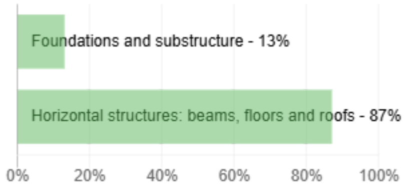
Download as image

Embodied carbon by life-cycle stage



Download as image

Embodied carbon by structure - A1-A3



Download as image

Project level parameters are not defined. Set them under the Parameters menu. Changing them later on will lead to results being recalculated.

Design phase: 3 designs

Parameters | Add a design | Compare data | Carbon Designer 3D | Tools

Tool	Unit	2 - Australian Mass Timber Building	2 - Australian Reinforced Concrete Frame
Level(s) life-cycle assessment (EN15804 +A1) ? Help	kg CO_2e	30 779 222	32 302 504
Level(s) life-cycle assessment (EN15804 +A2) (new version available) ? Help	kg CO_2e	Ready	Ready
Building Circularity (unsupported - new version available) ? Help	%	65	27

Graphs Level(s) life-cycle assessment (EN15804 +A1), Glob...

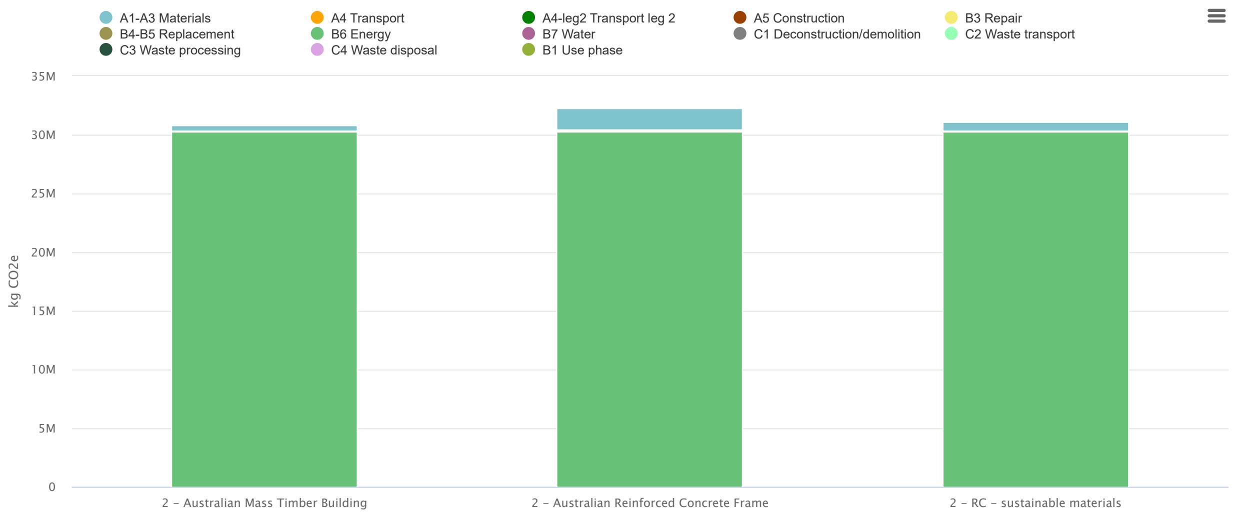
Showing: 3 / 3 Designs | Classification | Change tool and impact category

All impact categories | Life-cycle stages | Elements | Compare elements | Elements and life-cycle stages | **All graphs**

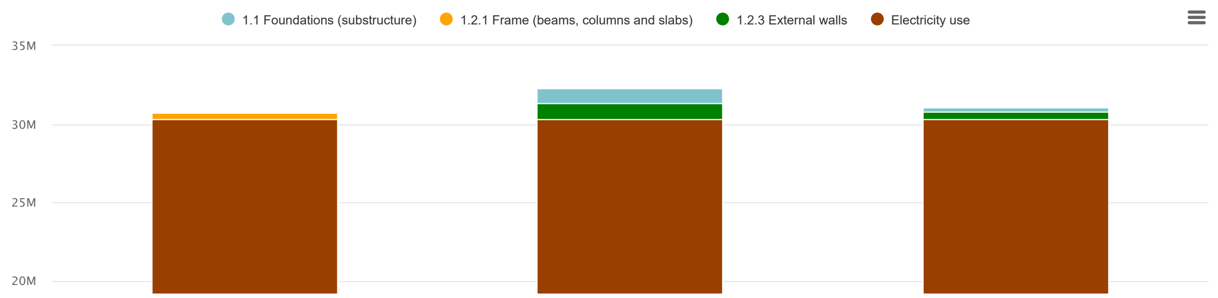
How can we help?

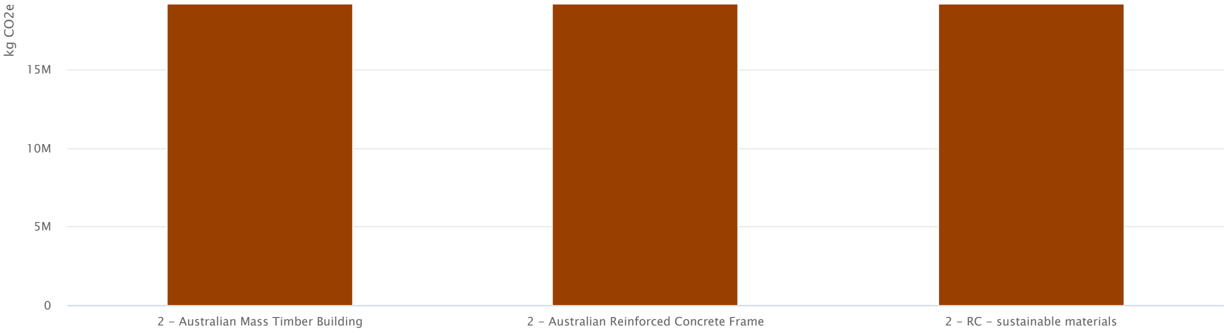
Level(s) life-cycle assessment (EN15804 +A1) - All impact categories

Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Life-cycle stages



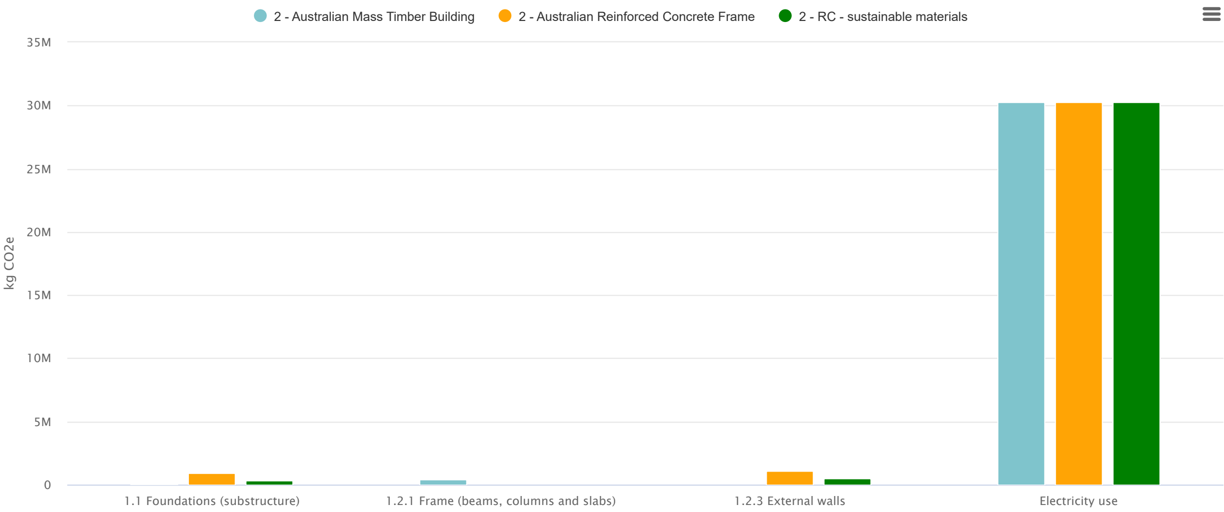
Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements



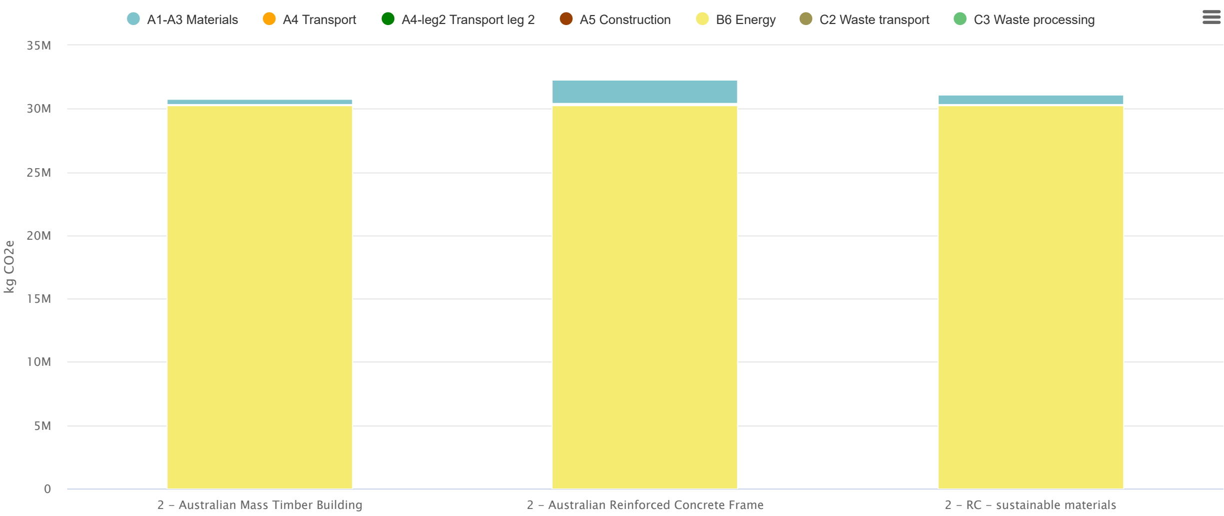


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Compare elements

Select groupings



Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements and life-cycle stages



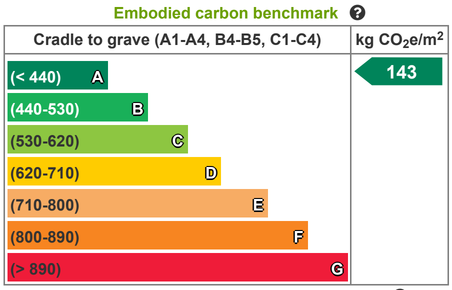
Main > Decarbonisation of the built environment (Australian building)

Decarbonisation of the built environment (Australian building)

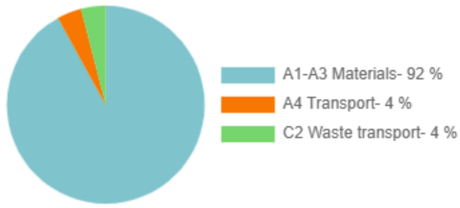
General information

Results and benchmarking - Design: 2 - RC - sustainable materials

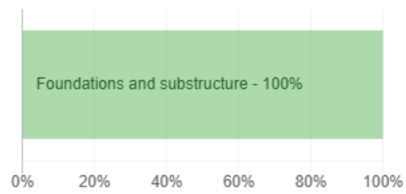
Select design



Download as image



Download as image



Download as image

Project level parameters are not defined. Set them under the Parameters menu. Changing them later on will lead to results being recalculated.

Design phase: 3 designs

Parameters | Add a design | Compare data | Carbon Designer 3D | Tools

Tool	Unit	2 - Australian Mass Timber Building	2 - Australian Reinforced Concrete Frame
Level(s) life-cycle assessment (EN15804 +A1) ? Help	kg CO_2e	30 779 222	32 302 504
Level(s) life-cycle assessment (EN15804 +A2) (new version available) ? Help	kg CO_2e	Ready	Ready
Building Circularity (unsupported - new version available) ? Help	%	65	27

Graphs Level(s) life-cycle assessment (EN15804 +A1), Glob...

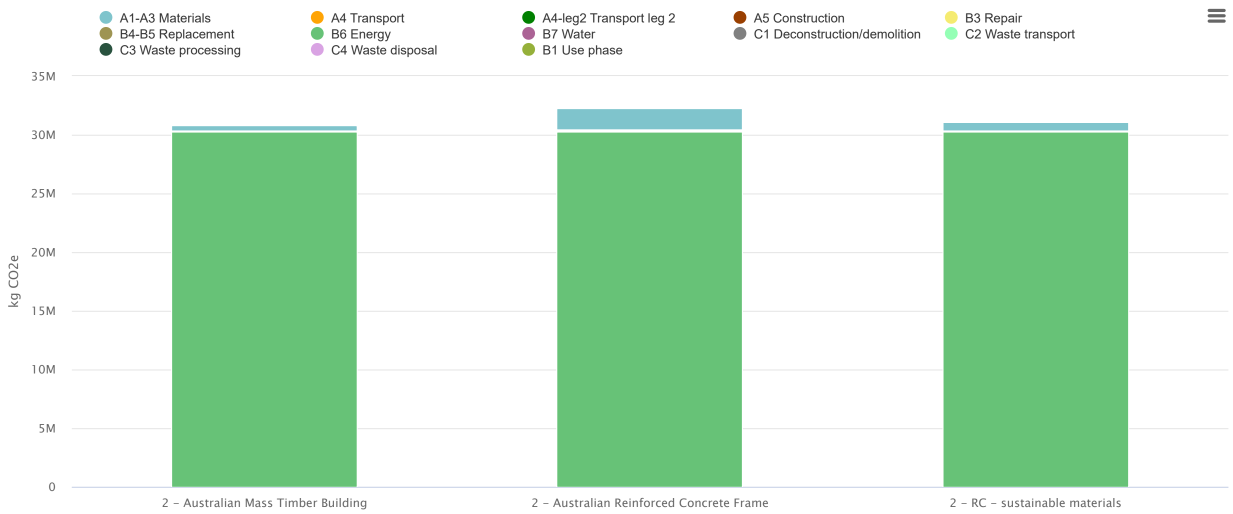
Showing: 3 / 3 Designs | Classification | Change tool and impact category

All impact categories | Life-cycle stages | Elements | Compare elements | Elements and life-cycle stages | **All graphs**

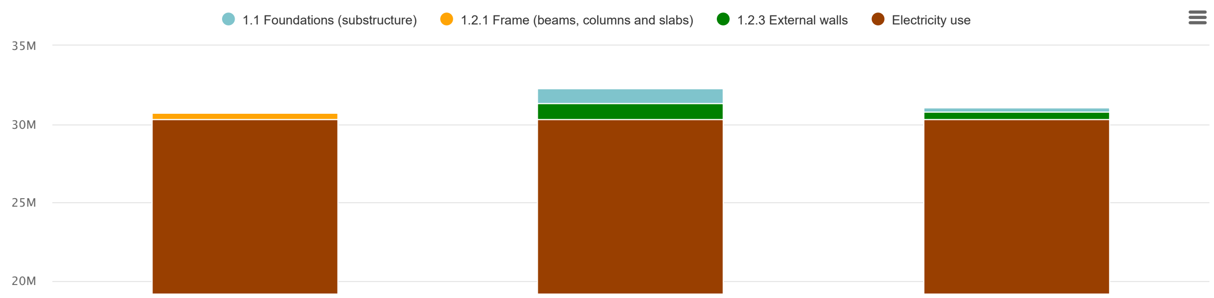
How can we help?

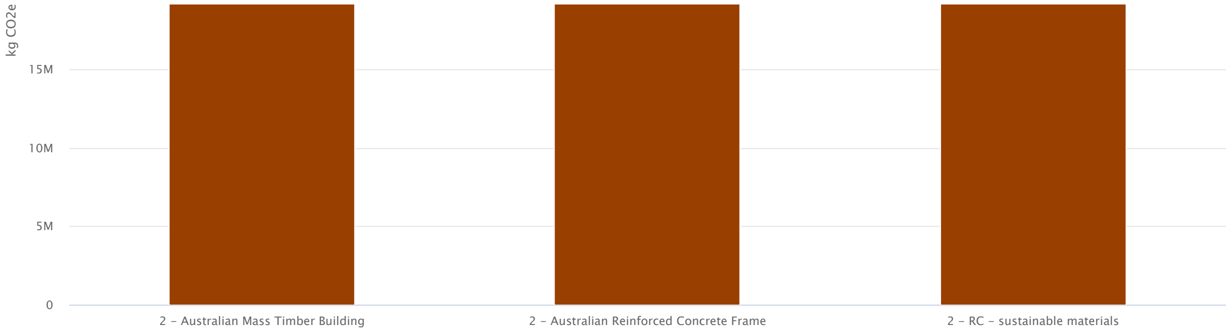
Level(s) life-cycle assessment (EN15804 +A1) - All impact categories

Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Life-cycle stages



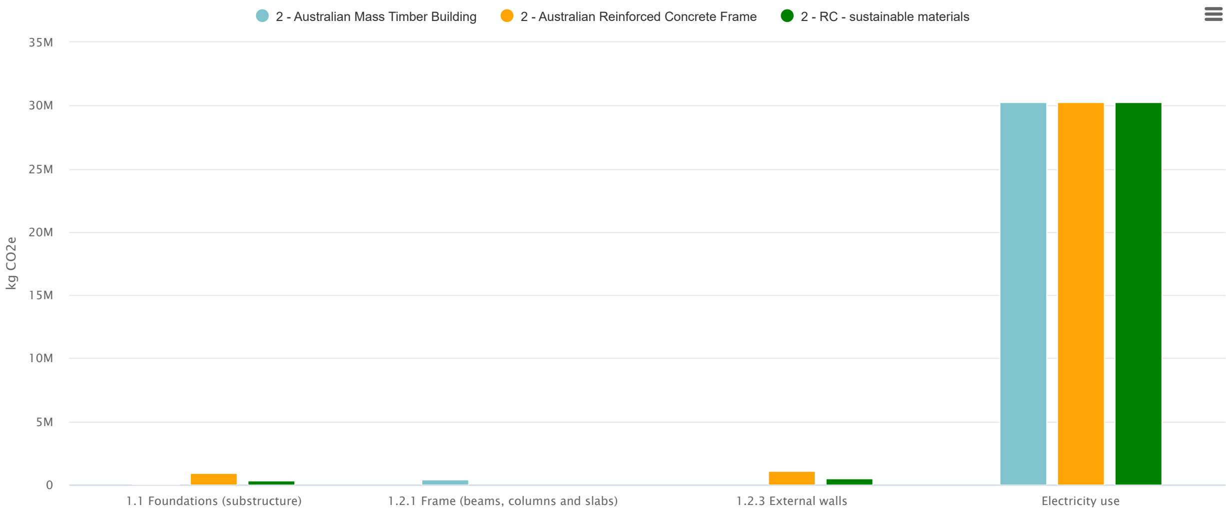
Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements



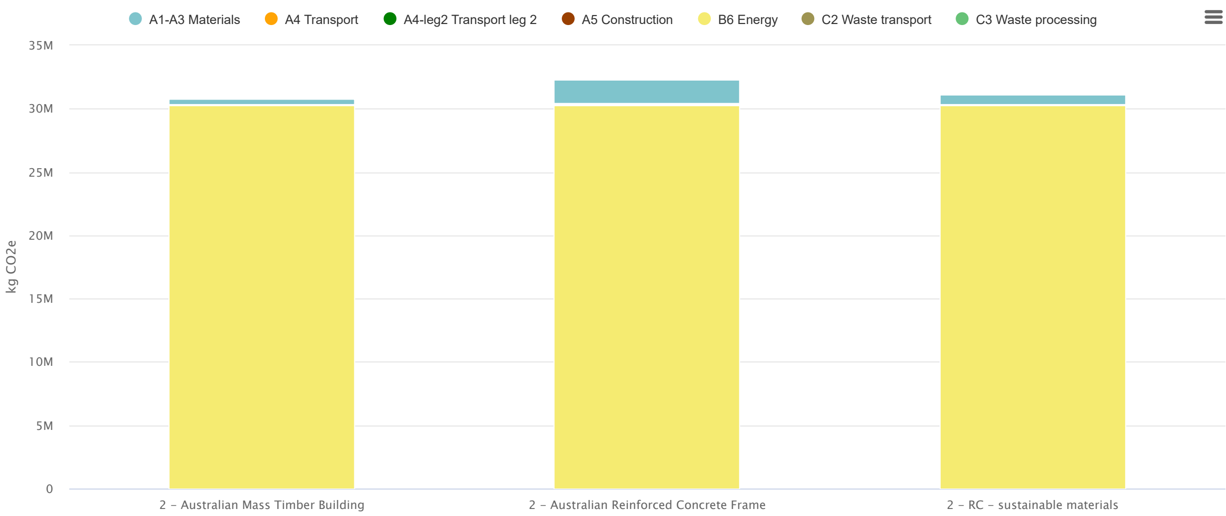


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Compare elements

Select groupings



Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements and life-cycle stages



Appendix B: Ethics Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG | SCHOOL OF ARCHITECTURE & PLANNING

20 November 2023

Dear Jan Erasmus (2416094)

This letter confirms that your clearance/waiver application has been approved. Your protocol/clearance number is: SOAP075/07/2023

Yours sincerely

Lerato Nkosi

Lerato Nkosi

School of Architecture and Planning, Faculty of Engineering and Built Environment, John Moffat Building, Wits, 2050, South Africa
Tel: +27 11 717 7692 Email: lerato.nkosi2@wits.ac.za | **www.wits.ac.za**