LOW CARBON LIVING CRC

Carbon Value Engineering: Integrated Carbon and Cost Reduction Strategies for Building Design

Project: RP1034 ‘Carbon Value Engineering’

Authors	Mehdi Robati, Philip Oldfield, Ali Akbar Nezhad and David Carmichael
Title	Carbon Value Engineering: Integrated Carbon and Cost Reduction Strategies for Building Design
ISBN	
Date	24/04/19
Keywords	Value engineering, Embodied Carbon, Lifecycle Cost, Lifecycle Carbon, CO_2-e, Lifecycle Assessment
Publisher	Cooperative Research Centre for Low Carbon Living
Preferred citation	ROBATI, M., OLDFIELD, P., AKBAR NEZHAD, A. & CARMICHAEL, D. (2019). *Carbon Value Engineering: Integrated Carbon and Cost Reduction Strategies for Building Design*. CRC for Low Carbon Living, Sydney.

Edition/Revision Number	Description of Revision	Author	Date
1	First Draft	Mehdi Robati	13/03/19
2	Second Draft	Philip Oldfield	24/04/19
3	Third Draft	Mehdi Robati	3/5/2019

Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative. This project was undertaken by UNSW Sydney in collaboration with Multiplex Australasia on behalf of the CRC for Low Carbon Living (CRCLCL).

Disclaimer

Any opinions expressed in this document are those of the authors. They do not purport to reflect the opinions or views of the CRCLCL or its partners, agents or employees.

The CRCLCL gives no warranty or assurance, and makes no representation as to the accuracy or reliability of any information or advice contained in this document, or that it is suitable for any intended use. The CRCLCL, its partners, agents and employees, disclaim any and all liability for any errors or omissions or in respect of anything or the consequences of anything done or omitted to be done in reliance upon the whole or any part of this document.

Peer Review Statement

The CRCLCL recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The author(s) confirm that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007),

and provided constructive feedback which was considered and addressed by the author(s).

Contents

List of Tables

List of Figures

Acronyms

LCA	Lifecycle Assessment
VE	Value Engineering
EC	Embodied Caron emissions
CC	Capital Cost
GHG	Green House gasses

Executive Summary

The Carbon Value Engineering project aims to maximise the reduction of embodied carbon in the built environment. Rather than proposing a new process for these reductions, it adapts the industry-standard practice of value engineering (VE) for integrated carbon and cost minimisation.

The project set out to answer two research questions:

1. What is the impact of value engineering in its current form on building embodied carbon, and life-cycle carbon emissions?

2. To what extent can the process of value engineering be adapted to maximise the reduction of embodied and life-cycle carbon emissions early in the design phase while also securing economic value?

In the first stage of this research (*Embodied Carbon and Capital Cost Impact of Current Value Engineering Practices: A Case Study*) we determined that the traditional VE processes driven only by cost can reduce building embodied carbon emissions through dematerialisation. However, such reductions were small, with VE strategies applied to a case study building reducing material costs by 0.72%, and initial embodied carbon by 1.26% (6.67kgCO_2-e/m^2) within a cradle-to-gate framework.

In this final report, we demonstrate how considering cost and carbon *simultaneously* during VE can yield significant carbon and cost reductions at a late design stage, without fundamentally changing the building design (form, orientation, planning, etc)

The research presents a Carbon Value Engineering framework. This is a quantitative value analysis method, which not only estimates cost but also considers the carbon impact of alternative design solutions. It is primarily concerned with reducing cost and carbon impacts of *developed design projects*; that is, projects where the design is already a completed to a stage where a Bill of Quantity (BoQ) is available, material quantities are known, and technical understanding of the building is developed.

This framework is tested by exploring the same case study building as before. This time, a number of alternative design solutions are tested and their embodied carbon and capital cost calculated. This research demonstrates that adopting this integrated carbon and cost method was able to reduce embodied carbon emissions by 63-267kgCO_2-e/m^2 (8 – 36%) when maintaining a concrete frame, and 72-427 kgCO_2-e/m^2 (10 – 57%) when switching to a more novel whole timber frame. With a GFA of 43,229m^2 these savings equate to an overall reduction of embodied carbon in the order of 2,723 – 18,459 tonnes of CO_2-e.

Costs savings for both alternatives were in the order of \$127/m^2 which equates to a 10% reduction in capital cost.

For comparison purposes the case study was also tested with a high-performance façade. This reduced lifecycle carbon emissions in the order of 255 kgCO_2-e/m^2, over 50 years, but at an additional capital cost, due to the extra materials. What this means is strategies to reduce embodied carbon even late in the design stage can provide carbon savings comparable, and even greater than, more traditional strategies to reduce operational emissions over a building’s effective life.

1 Introduction

Conventionally, the success of a building project has been measured through the use of time, cost and quality management techniques. However, modern performance measurement tools are developing into more holistic approaches by considering client and stakeholder satisfaction and sustainability measures.

Sustainability in the building industry means ensuring that a building is ecologically friendly and economically feasible, as well as providing a healthy internal atmosphere for the occupants. Increasing sustainability awareness has sensitised building markets to go beyond traditional value analysis and consider the importance of sustainability features could have on property values in the short-term, medium-term and long-term (RICS 2013).

Despite increases in environmental awareness, the guidance currently available to the cost and value engineer on how to incorporate whole lifecycle CO_2-e emissions and cost is still limited. The earlier results of this study confirm the practices of Value Engineering (VE) can help reduce embodied carbon emissions, albeit to a minimal extent. It also highlighted the potential for considering both value engineering and embodied carbon analysis simultaneously.

This research seeks to move beyond conventional value engineering practices to integrate carbon reduction strategies alongside cost. The aim of this research then is to:

1. **Develop a framework for the integrated reduction of cost and carbon during the value engineering process**
2. **Determine the potential embodied and life cycle carbon savings possible using this framework**

2 Overview of Scope and Methodology

The Carbon VE framework is a quantitative value analysis method, which not only estimates cost but also considers the minimal impact on the environment for alternative design solutions. It is primarily concerned with reducing cost and carbon impacts of *developed design projects*; that is, projects where the design is already a completed to a stage where a Bill of Quantity (BoQ) is available, material quantities are known, and technical understanding of the building is developed. In the RIBA Plan of Works (2013), this relates to stages 3 and 4. The project is not concerned with changes to the initial or conceptual design of buildings for reduced carbon emissions (see Figure 1)

The research methodology was run over the following six stages:

Stage 1: Lifecycle Carbon and Cost Analysis

At the initial stage of the Carbon VE framework life cycle analysis was employed to estimate the cost and carbon emissions for a project (the 'base case' building). This is to determine the values against which design changes can be measured against.

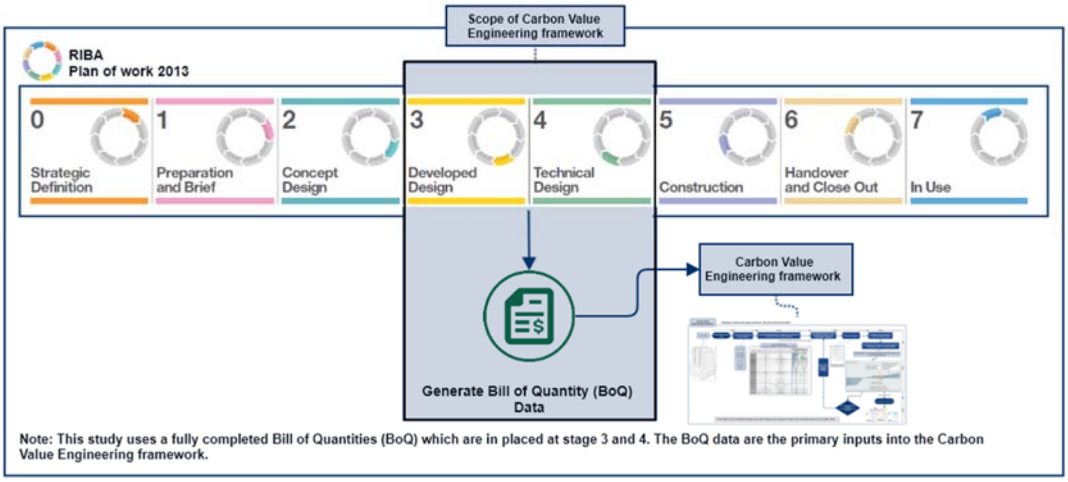


Figure 1 RIBA plan of work

Costs associated with building materials and construction activities were taken from the Australian construction handbook based on 2017 data (Rawlinsons 2017). The present value associated with replacement costs was estimated for all the BoQ items by considering their potential lifespan. Equation 1 is used to determine the present cost (NPV: Net Present Value) over a 50 years lifetime of a project.

$$PV(costs) = \sum_{year=1}^{year=50} \left(\frac{\mathbf{FC}}{(1+d)^n}\right) \qquad \text{(Equation 1)}$$

PV (cost): Present value of future cost

FC: Future cost (replacement)

d = discounted rate per year (discounted by 15% as a nominal per year)

n = the appropriate number of years (assumed as ≤50)

The carbon emissions associated with the product stage (Stages A1-A3) used material carbon coefficients from the CRCLCL database (Teh 2018). The carbon emissions associated with construction process stage (Stage A4-A5) was adapted from several studies (Hong, Ji et al. 2013, Nadoushani and Akbarnezha 2014, Kozlovská, Krajnak et al. 2015, Sandanayake, Zhang et al. 2016, Zhang, Sandanayake et al. 2017) by considering the machinery performance and usage during construction work (as shown in Table 8). Carbon emissions related to the replacement stage of the project was estimated by considering the lifespan of building materials. The average lifespan of the most popular construction materials is extracted from several resources (eTool 2014, Whitehead, Andrews et al. 2014, Robati, McCarthy et al. 2017). At the end of project (Stage C), carbon emissions associated with demolition, reuse and disposal of building materials was estimated by considering the machinery will be used at the end of life as suggested by several studies (Hong, Ji et al. 2013, Moussavi Nadoushani and Akbarnezhad 2015, Akbarnezhad and Xiao 2017). A summary of carbon emissions associated with equipment used in the construction and the end of life of a building is provided in Table 8. For the operational carbon emissions, a dynamic energy simulation was used to estimated operational carbon emission over lifetime of a building.

Figure 2 provides an overview of Carbon VE framework.

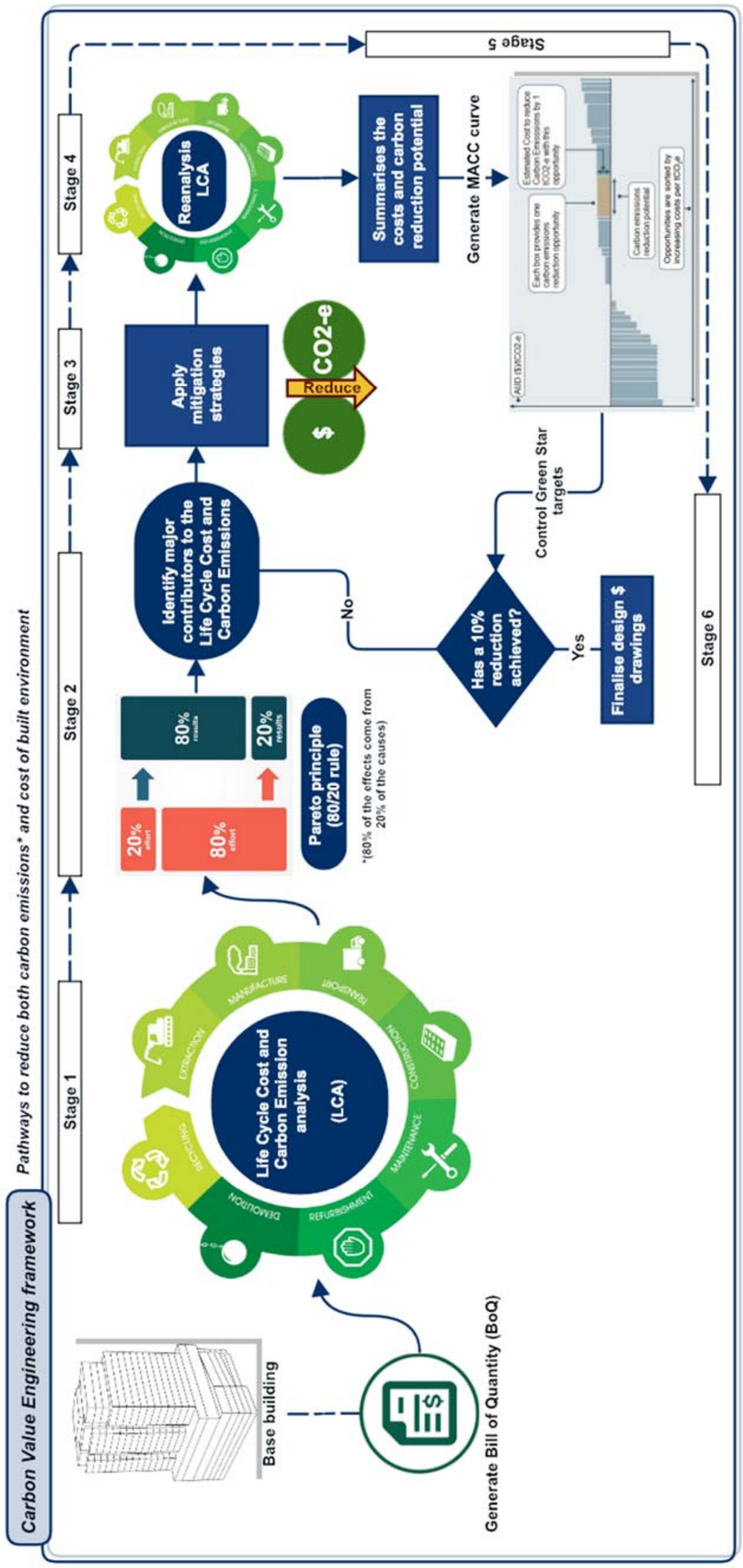


Figure 2 Carbon VE framework

Stage 2: Parento Principle (the 80:20 rule)

The second stage of Carbon VE employed Pareto principles (also known as the 80:20 rule) to identify significant contributors to the life cycle cost and carbon emissions of the base building. This primarily consists of identifying the 20% of materials that contribute to 80% of the carbon emissions and capital costs. The results of Pareto principles identify the materials which have the highest impacts on overall cost and carbon emissions of a building by ranking the magnitude impact of building materials (shown in Table 1). This allows decisions to be made as to what design and dematerialisation strategies are best placed to make the most significant cost and carbon reductions

Table 1 Typical Pareto principle table

Category	Item	Base case tCO_2-e
Superstructure	Concrete	
Internal finishes	Wall. AAC	
External finishes	Glazed façade- Block 1	
Fitting elements	Tiling	
Fitting elements	Flooring- Carpet	
Superstructure	Steel	
Superstructure	Concrete	
Fitting elements	Flooring- Timber	
Internal finishes	Plaster	
Internal finishes	Painting	
Internal finishes	Blockwork	
Superstructure	Formwork	
Superstructure	Concrete	
Internal finishes	Plasterboard	
Substructure	Concrete. 50MPa	
Fitting elements	Door	

Category	Item	Base case AUD ($)
Superstructure	Formwork	$
Superstructure	Steel	$
Internal finishes	Painting	$
External finishes	Glazed façade- Block 1	$
Superstructure	Concrete	$
Internal finishes	Wall. AAC	$
Fitting elements	Tiling	$
External finishes	Cladding	$
Superstructure	Steel	$
Internal finishes	Plaster	$
Fitting elements	Flooring- Timber	$
Fitting elements	Door	$
Superstructure	Concrete	$
Fitting elements	Door	$
Internal finishes	Waterproofing	$
Fitting elements	Flooring- Carpet	$ 657,502

Stage 3: Mitigation Strategies

This stage consists of applying integrated carbon and cost mitigation strategies based on the knowledge gleaned from the 80:20 analysis. For example, if concrete was determined to be a significant contributor to carbon and cost, alternative slab or frame strategies, and/or alternative materials could be investigated.

Stage 4: Reanalysis of Carbon and Cost

This stage involves re-calculating the carbon and cost totals for the building, based off the alternative design decisions.

Stage 5: MACC

This stage of the framework uses a marginal abatement cost curve (MACC) to present the findings from the mitigation strategies. Each bar in MACC curve represents a building material; the width of the bar represents the potential carbon emissions relative to a base case building (business as usual), and the height of the bar represents the abetment cost relative to a base building (as shown in Figure 3). The cost is revealed as Australian dollar per tonne carbon emissions. The MACC curve provides a graphical analysis tool, to explore both the direct and indirect impacts of mitigation strategies. This is because most strategies usually have both carbon and cost benefits and disadvantages.

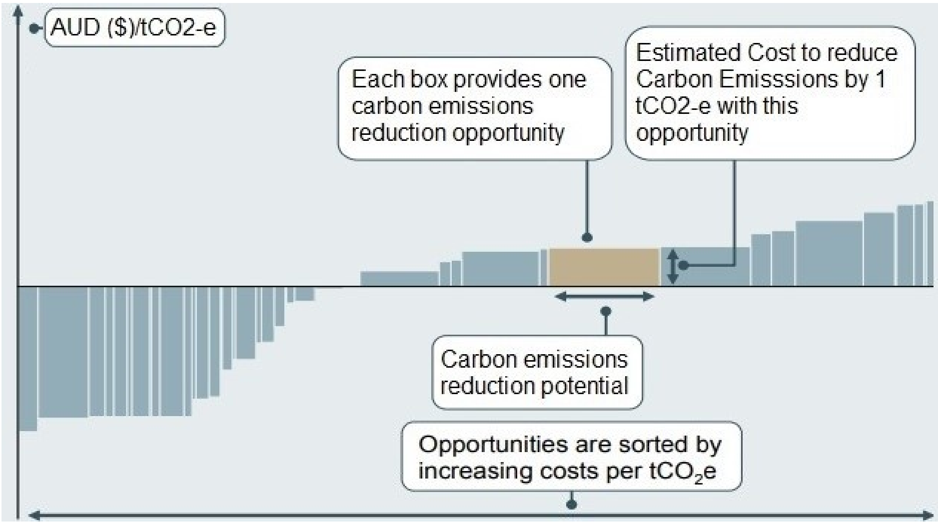


Figure 3 a typical marginal abatement cost curve (MACC)

Stage 6: Decision

The final stage of the framework determines which mitigation strategy will be implemented, or if further design changes are necessary. Targets can be set in terms of carbon and/or cost reduction. For example, the Green Building Council of Australia (GBCA) has announced proposed changes to the GreenStar rating system within the next two years, with the aim to reduce embodied carbon in buildings (GBCA 2018). They have revealed that all new buildings seeking a Green Star rating will be required to demonstrate that they have minimised embodied carbon emissions by at least 10% from 2020 and 20% after 2030.

In this case, a potential carbon target of 10% reductions could be considered a benchmark for suitable progress through Carbon Value Engineering.

3 Case Study

The following case study is presented to demonstrate the impact of following a Carbon Value Engineering methodology in practice.

An initial case study project was provided by our industry partner as a recent project in which had been through a traditional Value Engineering process. This project consists of two blocks of 18 (block 4) and 20 (Block 1) above ground storeys, with a shared 5-storey basement (Figure 4). The building consists of a mix of uses including offices, shops and residential units. The gross floor area for block 1 and 4 is 43,229m^2 and 41,228 m^2 respectively. Figure 4 and Table 2 provide a sketch and summary of the building.

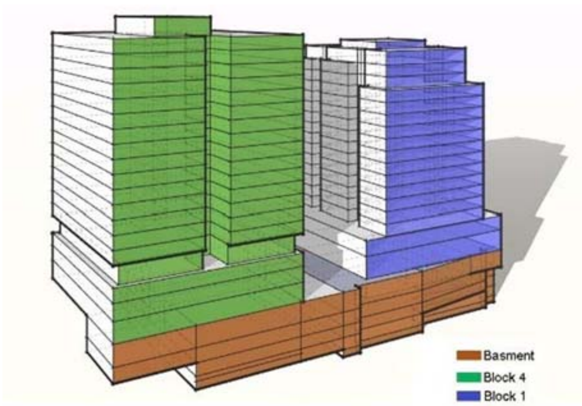


Figure 4 provided a case study building

The initial part of this project explored the carbon and cost impact of the traditional Value Engineering process on this building. Our results demonstrated that VE contributed to a reduction in cost of $396,000 (0.72%) and carbon of 6.67kgCO_2-e/m^2 (or 1.26% of total emissions in a cradle-to-gate framework). This demonstrated that the dematerialisation strategies employed did benefit from building carbon and cost. This next case study aims to explore how the alternative Carbon Value Engineering framework could improve these figures further.

Considering the complexity, the number of design variables and time constraints, we decided to focus on one block of the building for this stage. As such, we selected block 1 only. Therefore, the building was essential to cut in half, and only Block 1 was taken forward for further analysis. The base case building has been structurally re-designed to verify the structural integrity of this modified case study and a new BoQ generated.

The base case building in this study then is a mid-rise 18-storey mixed-use concrete structure; it has a rectangular plan shape with a gross area of 43,229 m^2 and consists of 3.3 m high storeys (on average) and 5 floors of basements. Figure 5 and Table 2 provide details of the base case building.

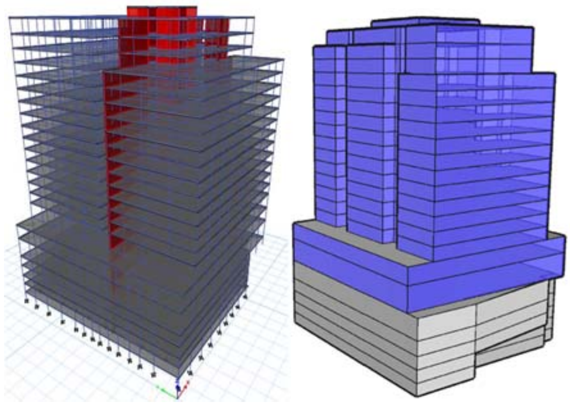


Figure 5 Base case building

Table 2 Overall characteristics of the Base case building

Parameters	Specifications
Number of stores	18
Number of stories above ground	13
Number of stories below ground	5
Average elevation per floor	3.3 m
Average concrete suspended slab thickness	180 mm
Total Gross Floor Area (GFA)	43,229 m^2

Following the carbon VE framework, the whole life carbon emissions and cost was estimated as 740 kgCO_2-e/m^2 and $1,266/m^2, respectively (discussed in section 9). We found that the substructure and superstructural components were the significant contributors to the life cycle cost and carbon emissions of the building. The Pareto Principle (80:20) results show that the structural concrete and formwork systems were the most significant contributors toward life cycle costs and carbon emissions (shown in Figure 6). So, several structural mitigation strategies were enacted to minimise carbon emissions and the cost of most intensive materials (discussed in section 4).

Life cycle carbon emissions		Base case
Category	**Item**	**tCO_2-e**
Superstructure	Concrete	20%
Internal finishes	Wall. AAC	14%
External finishes	Glazed façade- Block 1	13%
Fitting elements	Tiling	7%
Fitting elements	Flooring- Carpet	6%
Superstructure	Steel	5%

Life cycle cost		Base case
Category	**Item**	**AUD ($)**
Superstructure	Formwork	23%
Superstructure	Steel	9%
Internal finishes	Painting	9%
External finishes	Glazed façade- Block 1	8%
Superstructure	Concrete	8%
Internal finishes	Wall. AAC	6%

Figure 6 Pareto Principle results of the Base case building

4 Mitigation Strategies

Construction is not just about achieving the cheapest building possible, but about providing the best value for the owner, occupants and community. The best value includes the speed of construction, robustness, durability, sustainability as well as costs of the buildings. This study has analysed the potential impacts of various design strategies (conventional and non-conventional) on the lifetime carbon emissions and cost of the base case building. The overall results present the direct and indirect impacts associated with each strategy. The direct impacts are directly related to each alternative (changes of structural materials for instance), while indirect impact focuses on changes occurred *as a consequence* of the design change. For example, a change in structural material might result in deeper beams, and therefore a need for increased floor-to-floor heights. This, in turn, will increase the area of the cladding and exterior walls, and thus the embodied carbon.

All in all, we examined the effects of conventional and novel construction systems on the overall cost and carbon emissions of the building. It should be noted, due to the complexity and uncertainty in the estimation of carbon emissions, the impacts of services (mechanical and electrical), equipment and construction works were excluded from the scope of the study. The following building scenarios, determining carbon and cost for each (see also Table 3):

Base case building: The base case building was designed out of a flat plate, providing a uniform thickness of slab and flat soffit which requires a simple framework system.

Strategy 1 (ST.1): Strategy 1 has considered flat slab as the main flooring system. A flat slab is a two-way system (in this design) with thickenings in the slab at the vertical elements (columns and loadbearing walls) to increase shear capacity and the stiffness of the floor system under vertical loads. The flat slab is one of the most common forms of construction, with the average construction speed on site of approximately 500 m^2 per crane per week (CC 2016).

Strategy 2 (ST.2): Strategy 2 has considered a post-tensioned system in the floor. A Post-Tensioned (PT) floor provides the thinnest slab type and tends to be faster on site than a reinforced concrete slab due to a reduction in concrete and steel reinforcement quantities. A key advantage of PT systems is that they can reduce the number of columns, increase flexibility for internal planning and minimising the overall height of the building.

Strategy 3 (ST.3): Strategy 3 has explored the potential use of a steel deck floor. The steel deck acts as a permeant formwork requiring a minimum in scaffolding which speeds up the construction process as well as reducing the overall cost of the building (Priastiwi, Han et al. 2017). It does, however, increase the floor-to-floor height.

Strategy 4 (ST.4): Strategy 4 has explored the feasibility of a Cross Laminated Timber (CLT) floor slab with a steel frame and concrete core. CLT is a solid wood construction product consisting of several bonded timber boards (set at 90 degrees). Also, CLT is lighter than the reinforced concrete floor resulting in lower inertia response generated from lateral loads. Timber also absorbs carbon dioxide over its life as a tree, during photosynthesis, which can contribute to lower embodied carbon emissions using some methodologies.

Strategy 5 (ST.5): The growing interest in mass timber challenges conventional concrete and steel structural systems. Mass Timber (MT) buildings use innovative engineered products such as CLT and Glulam Timber as a main structural component. Strategy 5 has gone beyond the conventional practices by considering a MT alternative to investigate its potential benefits on cost and carbon emissions of the building. This strategy integrates a CLT and Glulam timber with a concrete core for lateral support.

Sub-strategies: in two scenarios (ST.2 and ST.5) a number of additional strategies were undertaken to explore the impact of design changes on carbon and cost in more detail. These were:

A: No changes

B: Testing potential impacts of an increasing lifetime of the building's materials (formwork, plaster and walls).

D: Testing potential impacts of sequestration on both timber and concrete elements.

E: Testing the potential impacts of using Geopolymer concrete on a building.

F: Testing potential impacts of selecting European engineered timer supplier, as oppose to Australian timber.

G: This case combines the lowest scenarios across case A to F, and it is named *"Ultimate case".* It is the effective lowest embodied carbon strategy.

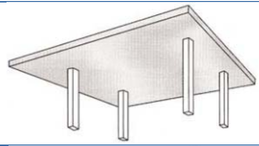
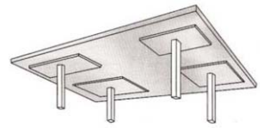
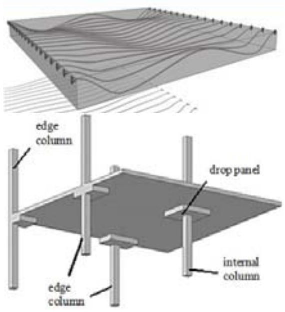
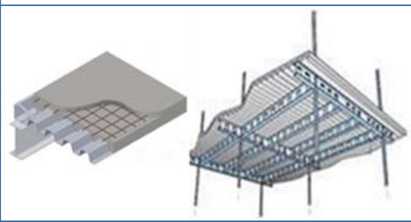
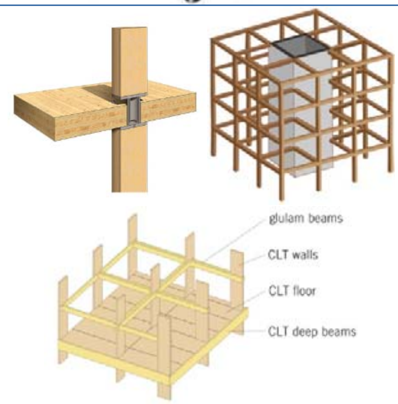
Strategy 6 (ST.6): Strategies 1 – 5 above have focussed on concepts that reduce initial cost and embodied carbon. However, three further scenarios were investigated that are designed to reduce *operational* carbon emissions and *operating* costs – such that these can be compared to the savings made in terms of capital cost and embodied carbon. This strategy investigates the potential impacts of three different Wall to Window Ration (WWR) on a base case building. Strategy 6 considers the following changes. The other building's characteristics are similar across all three cases.

ST.6a: WWR reduced from 65% to 50%.

ST.6b: WWR reduced from 65% to 30%.

ST.6c: This scenario considers "high-performance façade" by improving airtightness and insulation values of external walls, roof, internal floors and type of glazing. The other building's characteristics are similar to the base case.

Table 3 Summary of mitigation strategies

Strategy	Mitigation Strategy*	Detailed strategies (Sub-strategies)	Schematic
Base case building	Reinforced concrete structure with Flat plate floor	------	
ST.1	Reinforced concrete structure with Flat slab floor	------	
ST.2	Reinforced concrete structure with Post-tensioned floor	ST2.A: No changes ST2.B: Increased lifespan of the building's materials (formwork, plaster and walls) ST2.D: Testing impacts of sequestration (timber and concrete) ST2.E: Testing impacts of geopolymer concrete. ST2.F: Testing impacts of selecting timber from Europe. ST2.G: Combining all the lowest alternatives (Ultimate case)	
ST.3	Steel structure with Steel deck floor	------	
ST.4	Steel structure with Cross laminated timber floor (CLT)	------	
ST.5	Timber structure with Glulam and CLT elements- Mass Timber (MT) building	ST.5.A: No changes. ST5.B: Increase the lifetime of the building's materials (formwork, plaster and walls). ST.5.D: Testing impacts of sequestration (timber and concrete). ST.5.E: Testing impacts of geopolymer concrete. ST.5.G: Combining all the lowest alternatives (Ultimate case)	
ST.6	ST.6a: Window to Wall Ratio (WWR) reduced from 65% to 50%. ** ST.6.b: Window to Wall Ratio (WWR) reduced from 65% to 50%. ** ST.6.c: "high-performance façade"-Improving airtightness and insulation values of external walls, roof, internal floors and type of glazing. **		

*All the building structures designed with moment resisting frames and shear walls.
**The other building's characteristics are as per the base case.

5 Structural Analysis

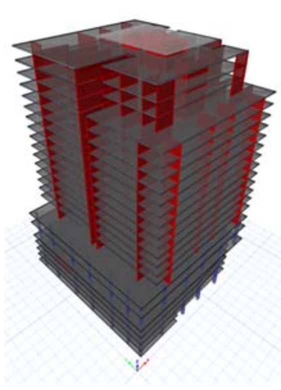
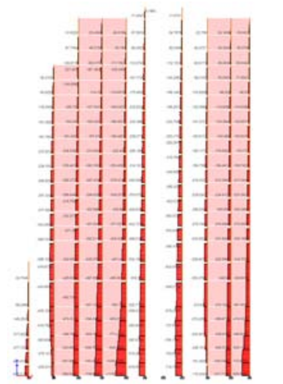
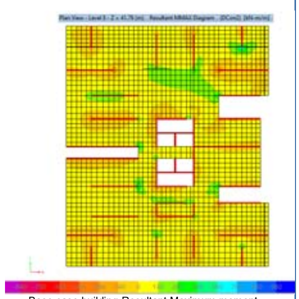
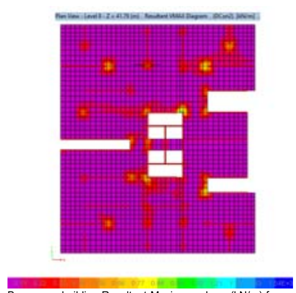
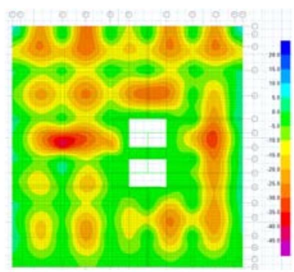
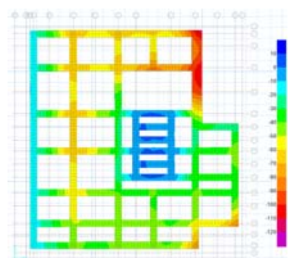
In this study, structural analysis was used to ensure rigidity and to validate the practicality of each mitigation strategy. The structure of these buildings (alternatives) were designed with a moment resisting frame and shear walls. The structure analysis first considered the flat plate (base case scenario) as a floor system by considering the proposed column arrangements (provided by our industry partner); the proposed building was then analysed for the various design alternatives outlined in section 4. For alternative designs, the floor systems were designed with slabs from 180 mm (ST.2) to 540 mm (ST.5) thick, depending on the type of floor system. These floor systems consist of the following (as also shown in Table 4):

- Flat plate,
- Flat slab,
- post-tensioned,
- Steel deck,
- CLT,
- Mass timber

In terms of structural design and analysis, a detailed structural design was considered by following Australian standards. Ultimate Limit State (ULS) and Serviceability Limit State (SLS) were taken into consideration during the structural design of these buildings. The Computer Aid Desing (CAD) packages Etabs, Safe and Microsoft Excel spreadsheets were utilised to verify the minimum requirements of the Australian standards and Building code of Australia (BCA). For the timber buildings (ST.4 and ST.5) fully 3D finite element models with ETABS and SAFE were used to predict structural response under the applied loads. Table 4 presents a typical structural analysis and design models with CAD packages.

Figure 7 and Table 5 shows ULS and SLS design procedure as well as loading conditions used in this study.

Table 4 typical finite element models with ETABS and SAFE

 3D representation of the base case building in ETABS	 Base case building- Axial force diagram under dead load (kN)- elevation view G1-10
 Base case building-Resultant Maximum moment (kN.m/m) for the floor level 8.	 Base case building-Resultant Maximum shear (kN/m) for the floor level 8.
 Base case building-Deformed shape- Displacements under maximum loading condition (mm) for the floor level 3	 Base case building-Deformed shape- Displacements under maximum loading condition (mm) for the foundation.

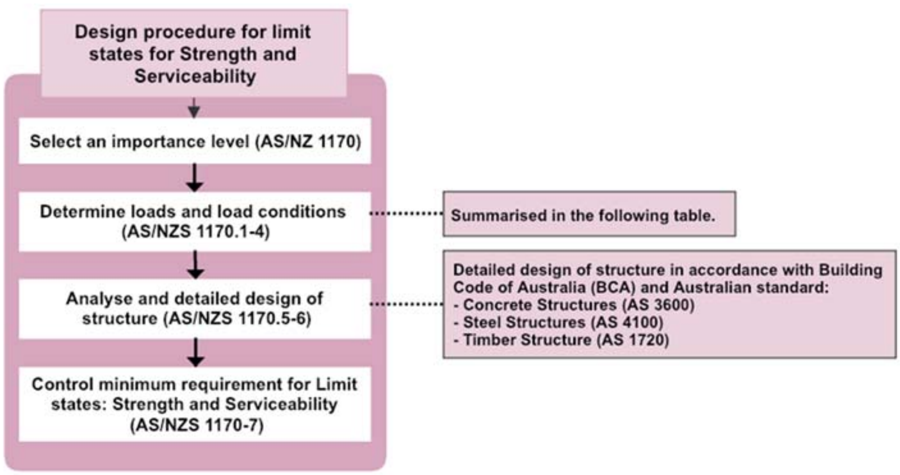


Figure 7 structural design procedure

Table 5 Loading conditions for designing the alternative buildings

Loading conditions		
Type of load		Load (kPa)
Live load-Office storage and parking area		5
Live load-Work rooms		3
Dead Load		4.3
Wind Load- Windward	Ultimate limit states	6.6
	Serviceability limit states	5.4
Wind Load- Leeward	Ultimate limit states	4.1
	Serviceability limit states	3.4
Wind Load- Sidewall	Ultimate limit states	1.3
	Serviceability limit states	1.1

Load combinations for Ultimate states design	Load combinations for serviceability states design
1.35G 1.25G+1.5Q 1.25G+1.5ΨlQ 1.2G+Wu+ΨcQ 0.9G+Wu	G+ Ψl Q G+ Ψs Q G+ ΨsQ + Ws

G: permanent action (dead load); Q: Imposed action (Live load);
Wu: ultimate load action; Ws: serviceability wind action;
Ψl: Factor for determining quasi-permanent values (long term) of actions; Ψs: Factor for determining quasi-permanent values (long term) of actions; Ψc: Combination factor for imposed action;

6 Operating Energy Analysis:

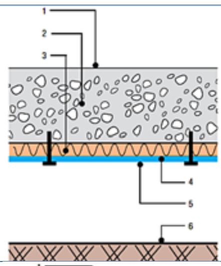
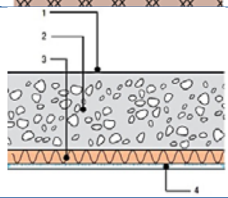
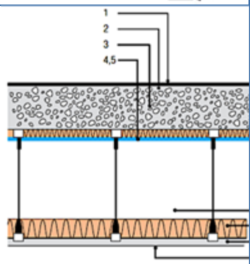
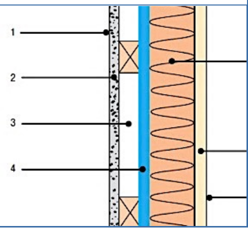
To understand the relative magnitude of any changes to embodied carbon, and to gain a perspective on the entire lifecycle carbon of the building, dynamic energy simulations were undertaken to determine operating carbon emissions.

- Base Case Building: base case building with 65% WWR and conventional envelope;
- ST.6a: base case building with 50% WWR and conventional envelope which is named.
- ST.6b: base case building with 30% WWR and conventional envelope which is named.
- ST. 6c: base case building with 65% WWR and high-performance façade which is named.

In all other scenarios (ST.1 – ST.5), the building systems and fabric remain the same. As such, it is estimated that operating carbon emissions remain the same as the base case scenario.

The modelling results revealed the total energy usage as well as the heating and cooling loads. The total energy consumption was compared to national and state averages determined from real-world data from Australian residential buildings to ensure the results are within acceptable ranges of the available energy consumption values (Pitt&Sherry 2012). Table 6 summarises the Physical properties informing the operating energy analysis.

Table 6 Physical properties of four alternative buildings

Thermal resistance requirements and values and thermal mass values				
Elements	**R-values (m²K/W)**	**Item description**		**References**
External floor	a: 2.00 b: 7.10		1.Indoor air film 2.Solid concrete 3(a).Air gap 3(b).blanket (120mm reflective PRP) 4.Memberance 5.Subfloor air film 6. Ground Thermal Resistance	Based on BCA (ABCB 2016) requirments and ICANZ (2016) suggestions
Internal floor	a: 0.21 b: 3.70		1.Indoor air film 2.Solid concrete 3(a). None 3(b).blanket (120mm reflective PIR) 4.Indoor air film	Based on BCA (ABCB 2016) requirments and ICANZ (2016) suggestions
Roof	a: 4.00 b: 4.00		1.Outdoor air film 2. Roof Water Proofing Membrane 3.150mm Concrete Slab 4,5. Reflective Insulation Material 6. Reflective Air Space 7. Ceiling Insulation 8. 10mm Plasterboard 9. Indoor Air-Film	Based on BCA (ABCB 2016) requirments and ICANZ (2016) suggestions
External Wall	a: 3.00 b: 4.70		1.Outdoor air film 2. Lightweight Cladding 3. Air Space 4. Reflective Insulation Material 5. Reflective 90mm Air Space 6. Bulk Insulation Wall Batt 7. 10mm Plasterboard 8. Indoor Air-Film	Based on BCA (ABCB 2016) requirments and ICANZ (2016) suggestions
Window	(a) based on façade performance specification provided by our industry partner: U=1.65 W/m²K and SHGC= 0.35. (b) Based on Criteria for the Passive House (PHI 2016), U=1.25 W/m²K and SHGC= 0.54 (triple glazing).			

a: address the characterises associated with base case, ST.6a (50% WWR) and ST.6b (30% WWR).
b: address the characterises associated with ST.6c (high-performance façade)
BCA: Building Code of Australia; ABCB: Australian Building Codes Boards; ICANZ: Insulation Council of Australia and New Zealand; PIR: Polyisocyanurate.

A detailed energy simulation analysis via DesignBuilder was used to quantify the operating energy consumption, energy cost and carbon emissions of the base building. DesignBuilder is a third-party graphical user interface for EnergyPlus that has been used in many studies in Australia (Chowdhury, Rasul et al. 2008, Rahman, Rasul et al. 2010, Rahman, Rasul et al. 2011, Daly 2015). The weather data used for this study was extracted from the EnergyPlus weather database (EnergyPlus 2017). The weather data are in RMY format, and they are a set of weather files developed to comply with the Building Code of Australia (EnergyPlus 2017). The equipment and occupancy schedules were sourced from the Building Code of Australia (ABCB 2016). The HVAC system was modelled by using DesignBuilder's "simple" HVAC description which considers a variable air volume system (VAV) with auto size routine. Table 7 provides a summary of the assumption made for the energy simulations.

Table 7 Simulated assumptions for the energy analysis

Parameters	Key variables	References
Lighting power density	3 (W/m^2)	(Bannister, Robinson et al. 2018)
Occupancy density	5 (m^2/person)	(ABCB 2016)
Equipment load	5 (W/m^2)	(ABCB 2016)
Domestic hot water	50 (L/person)	(ABCB 2016)
Air infiltration for the base case, ST.2, ST.3	1 (ACH)	(Ambrose and Syme 2017)
Air infiltration for ST.8	0.6 (ACH)	(Ambrose and Syme 2017)
HVAC set point	20°C (heating) - 24°C (cooling)	(Daly, Cooper et al. 2014)

*The schedules were extracted from Building Code of Australia (ABCB 2016)

7 Lifecycle Carbon Analysis

The life cycle carbon emissions of a building can be divided into the following four phases: production, use, end of life, and beyond life (as shown in Figure 8).

Figure 8 shows the different stages of environmental impact assessment over a building's lifecycle as per EN 15978. The cradle-to-gate stage covers the supply of raw materials (A1), the transportation of materials from extraction to manufacturing plant (A2), and the manufacturing process (A3). The cradle-to-site phase includes A1–A3 and transportation from the manufacturer's gate to the construction site (A4), as well as the construction processes (A5). The cradle to grave phase includes A1–A5 along with the day-to-day building use, which includes the impacts arising from the use of components (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5) and the energy (B6) and water (B7) used by the building during its operational lifetime. Cradle to grave also includes the end of the building's life, consisting of deconstruction and demolition (C1), transport from site to landfills or recycling facilities (C2), and waste processing (C3) and disposal (C4). Beyond this, stage D represents the benefits and impacts of components for reuse, materials for recycling, and energy recovery for future use.

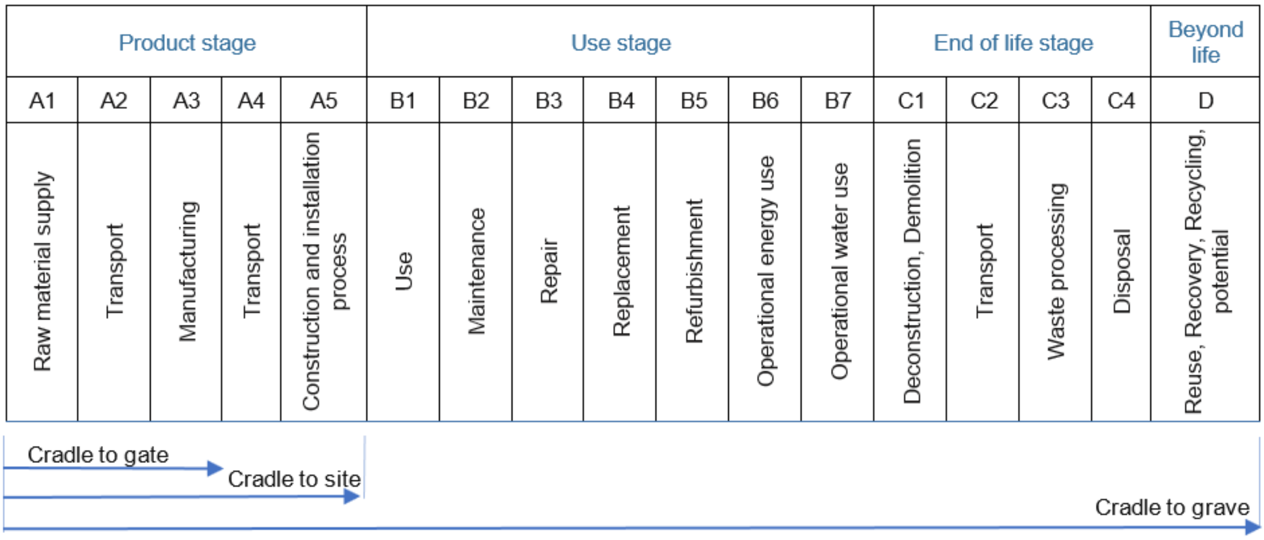


Figure 8 Building lifetime stages (Cradle to Grave) defined by EN 15978 (EN15978 2011)

The life cycle carbon emissions (LCCE) of each stage was calculated (Equation 2) by adding the magnitude of each parameter incurred in extraction and manufacturing (E_{em}), transportation to site (E_{tr}), Construction (E_{cn}), Replacement (E_{rp}), Operation (E_{op}) and End of life (E_{el}).

$$LCCE = E_{em} + E_{tr} + E_{cn} + E_{rp} + E_{op} + E_{el}$$

(Equation 2)

Module A1-A3 (Cradle-to-gate):

This project integrated the LCA material database developed by 'RP2007: Integrated Carbon Metrics - A Multi-Scale Lifecycle Approach for the Built Environment' into the embodied carbon analysis. RP2007's database provides comprehensive information on carbon emissions associated with various construction materials used in Australia (Teh 2018).

Module A4 (gate to site):

This module covers the transport of construction materials to the construction site. The mean travel distance value from the potential manufacturing companies to the site was measured using online mapping tools (Poinssot, Bourg et al. 2014, Robati, McCarthy et al. 2018). The defined starting point for the journey was the gate at the boundary of the last manufacturing to delivery to the construction site. The defined endpoint for the journey was the construction site in the central business district (CBD) located in Sydney, Australia. For overseas product (Subcategory "F"), transport truck in the country of origin was not included; therefore the shiliping and transport in Australia was consided in the embodied carbon emissions analysis. It was assumed that manufacturers are close to a port. The transport between suppliers and the last manufacturing company is covered in module A2, as such it was excluded from stage A4. Equation (3) represents Cradle to Site (A1-A4) CO_2-e emissions associated with selection of the building materials which was adopted from previous studies (Crawford 2011, Akbarnezhad and Xiao 2017, Chiniforush, Akbarnezhad et al. 2018).

$$E_{em} + E_{tr} = \sum_{i=1}^{n=47} \left(\begin{array}{c} (Q_i \times E_i) + \\ \left(\frac{Q_i \times D_{i.truck} \times E_{truck}}{C_{truck}} + D_{i.ship} \times E_{i.ship} \right) \times \frac{L_t}{L_i} \\ + E_{cn} + E_{rp} + E_{op} + E_{el} \end{array} \right)$$

(Equation 3)

Where:

- $E_{em} + E_{tr}$ is the cradle to site embodied carbon emissions of the building (kg.CO_2-e emissions);

- This study considers the impacts of 47 materials used in the building (n=47). Q_i presents the quantity of the i[th] building material (based on Appendix 1, Table A.1-1);
- E_i is the carbon emissions related to the i[th] building material (kg.CO_2-e /unit of material);The embodied carbon emissions were extracted from the CRCLCL database (Teh 2018).
- $D_{i.truck}$ is the travelling distance the i[th] building material was transported from the supplier to the construction site (km);
- E_{truck} is the embodied CO_2-e emissions associated with the machine used to transport materials as shown in Table 8;
- C_{truck} is related to the truck capacity (2 ways transport) as shown in Table 8;
- $D_{i.ship}$ is the travelling distance (km) the imported timber materials from Europe to Sydney's port (Port Botany). It was estimated as 25,335 km (SEA-DISTANCES 2019). The distance from Port Botany to the construction site was estimated as 13.3 km and considered in $D_{i.truck}$.
- $E_{i.ship}$ is the embodied CO_2-e emissions associated with the ship used to ship materials, suggested as 8.4 g.CO_2/ton-km (ECTA 2011).
- L_i is the lifetime related to the i[th] building material (number of years); for a material's lifetime more than 50 years (such as concrete, steel reinforcement, timber), the lifetime ratio $\left(\frac{L_t}{L_i}\right)$ is equal to 1;
- L_t represents the total lifetime of the building, assumed to be 50 years (AS3600 2009);

Module A5 (Construction):

This module considers embodied emissions associated with construction and installation process. Construction of mid-rise and high-rise structures usually involves the use of a tower crane to transfer materials from different loading locations to the loading platform of each storey. The total amount of work per equipment was calculated by considering the capacity and activity of each machine (as shown in Table 8). The calculated hours of work were used to determine the embodied carbon emissions for the main construction equipment by considering Australian National Greenhouse Account (NGA) factors (DEE 2018). The equipment hourly energy consumptions is based on Hong, Ji et al. (2013) study.

For the purpose of this study, the total hours of work per equipment were calculated, and the all equipment used in the construction phase was taken into consideration. The characteristics include the type of equipment used for each activity and the efficiency of each machinery. Table 8 summarises the unit emissions of the required equipment.

Waste rates were excluded from the scope of stage A5. Waste management on mid-rise construction sites varies according to waste management plans and the processes used by the various trades that operate on a site over its duration; opportunities for waste minimisation on construction sites is mainly dependent on choices made by all stakeholders during the construction process.

Table 8 Carbon emissions factor for different Vehicle/Equipment used in the construction of the case study building

Equipment	Capacity		carbon emission
concrete mixer truck	m^3	6	0.1493 (kgCO_2-e/ton.km)
Trailer 20t	ton	20	0.067803(kgCO_2-e/ton.km)
Truck crane 25t	ton	25	15.04947 (kgCO_2-e/hr)
Truck crane 50t	ton	50	24.6747 (kgCO_2-e/hr)
Tower crane	m^3/h	17.05	62.25 (kgCO_2-e/hr)
Excavator	m^3	0.7	28.62 (kgCO_2-e/hr)
Truck – Earthwork	ton	25	0.051726 (kgCO_2-e/ton.km)
Truck – Earthwork	m^3	20	0.051726 (kgCO_2-e/ton.km)
Crawler crane 50-80	ton	50-80	45.23 (kgCO_2-e/hr)
Concrete pump car 80	m^3/hr	80	81.37 (kgCO_2-e/hr)
Concrete vibrator 2.5	m^3/hr	2.5	2.59 (kgCO_2-e/hr)
Air compressor	m^3/hr	425	37.77 (kgCO_2-e/hr)
Loading hopper	ton	1.77	37.07 (kgCO_2-e/hr)
Conveying	ton/hr	400	37.77 (kgCO_2-e/hr)
primary crushing	ton/hr	350	80.94 (kgCO_2-e/hr)
Sieving and conveying	ton/hr	500	26.98 (kgCO_2-e/hr)
separation	ton/hr	350	0.61 (kgCO_2-e/hr)

Source: (Hong, Ji et al. 2013, Moussavi Nadoushani and Akbarnezhad 2015, Akbarnezhad and Xiao 2017)

Module B1 to B7 (Use stage):

These modules consider the carbon emissions associated with the operation of the building over its entire life cycle. In the absence of data from facilities management strategy report stages B1-B3 and B6 were excluded from this study. While, module B4 was taken into account to estimate any carbon emissions associated with the anticipated replacement of building components, including any emissions from the replacement process. All emissions arising from the production, transportation to site, installation of the replacement components have been included. Table 9 provides assumptions made on lifespans for the components listed.

Table 9 Building's Component lifespan

Category	Item	Materials	Lifetime	Unit
Substructure	Concrete. 50MPa	Padding & foundation 50Mpa	110	years
	Reinforcing Steel	Padding & foundation. Steel Reinforcing	110	years
Superstructure	Formwork	Formwork. Timber	3 to 10	times
		Formwork. Steel	81	years
	Concrete	(32 MPa; 40 MPa, 50 MPa, 65 MPa)	81	years
	Steel	Steel Reinforcing	83	years
		Post Tensioning	81	years
		Steelwork	83	years
	Precast Concrete	Precast concrete	81	years
	Timber	Timber CLT	+50*	years
		Timber (Glulam and LVL)	+50*	years
External finishes	Glazed façade	Glazed façade- Block 1	30	years
	Cladding	Aluminium	35	years
	Cladding	Stone	30	years
	Cladding	Timber	30	years
	Roof	Concrete Pavers	30	years
	Roof	Ballast	30	years
	Roof	Waterproofing membrane	30	years
	Roof	ALPOLIC	30	years
Internal finishes	Blockwork	Blockwork & Brickwork	50	years
	Insulation	Acoustic & Thermal Insulation	30	years
	Plasterboard	Suspended Ceilings Plasterboard	20	years
	Cement Fiber	Suspended Ceilings Cement Fiber	20	years
Internal finishes	Veneer timber	Suspended Ceilings Veneer Timber	20	years
	Partitions	Partitions - Framed & Lined. Plaster	30 to 50	years
	Partitions	Partitions - Framed & Lined. Wall. AAC	30 to 50	years
	Rendering	Plastering/ Rendering	50	years
	Waterproofing	Internal Waterproofing	50	years
	Cementitious	Cementitious Topping	50	years
	Painting	Painting	10	years
	Resilient Finishes	Resilient Finishes	30	years
Fitting elements	Screens	Screens	30	years
	Door	Aluminium frame	30	years
	Door	Timber Frame	30	years
	Galvanised	Metalwork Galvanised	30	years
	Metalwork	Metalwork- Shower screens	30	years
	Handrails	Metalwork- Balustrades and Handrails	50	years
	Flooring- Carpet	Carpet Flooring	10	years
	Flooring- Timber	Timber Flooring	30	years
	Tiling	Tiling	30	years
	Glazing	Mirrors and Glazing	30	years
External works	External Waterproofing	External Waterproofing	30	years

"Glued-laminated (Glulam) and CLT timber have demonstrated excellent long term performance in the field in excess of 50 years in plywood and glued-laminated timber" (Bolden and Greaves 2008)
Source: (Bolden and Greaves 2008, RICS 2017, Robati, McCarthy et al. 2018)

Module B6 covers any emissions arising from the energy use of the operation of technical systems in the building over the lifetime of the project. At the operational stage of a building, energy conversion results in the release of greenhouse gas emissions which was estimated by using the national emissions factor proposed by the Australian

National Greenhouse Accounts (DEE 2018). The emissions factor used to convert the consumption of operational energy into CO_2-e emissions is a function of the electricity purchased and consumed over 50 years lifetime of a building (the base year 2018). Due to lack of estimates for the carbon intensity of electricty after 2030, it is assumed as constant after this time. Figure 9 illustrates carbon emissions intensity of Australia electricity from 2018 to 2067 used in this study. Section 6 provides detailed information on the dynamic simulations used to estimate operational energy emissions across the various alternatives.

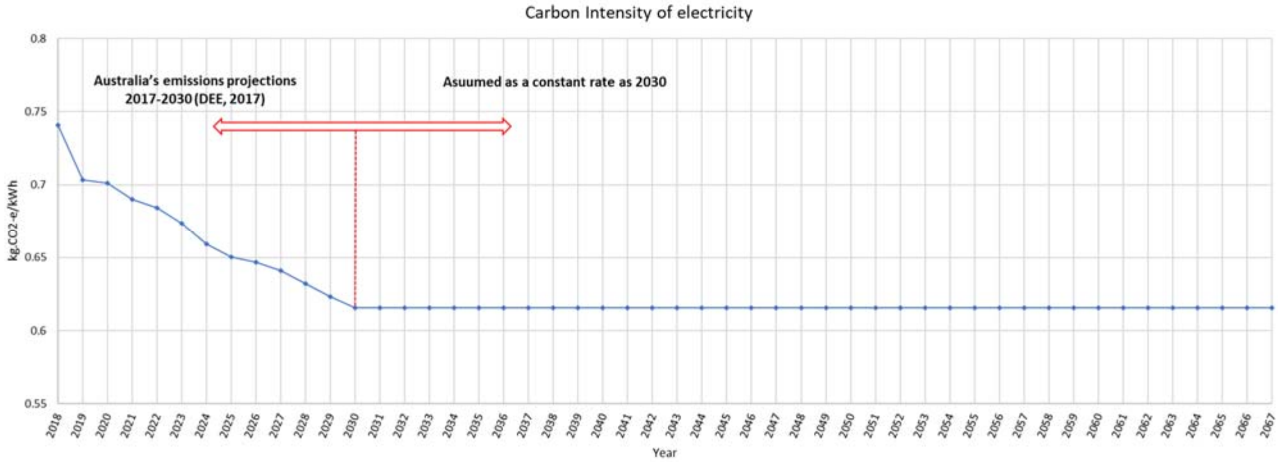


Figure 9 Carbon emissions intensity of Australian electricity over 50 years (adapted from (DEE 2016))

Module C (EoL - End of Life):

This module considers any emissions arising from demolition, reuse and disposal of building materials at the end of the project. For the purpose of this study, Table 8 (module A5) was used to estimate carbon emissions arising from demolitions, transportation at the end lifetime of projects. In the absence of specific information, this study analysed the carbon emissions associated with the machinery which are commonly used at the end of life to demolish and transport materials to the recycling or disposal point. The transport carbon emissions for the discarded items were calculated based on the following formula as suggested by RICS (2017). For this study mass of waste to be transported was assumed as same as materials used in the building. The transport distance to the disposal site (Sydney Recycling point) was assumed as 4 km.

$$Transport\ carbon\ emissions = Mass\ of\ waste\ to\ be\ transported\ \times transport\ coefficients \times\ distance\ to\ disposal\ site$$

The positive impacts of sequestration for both timber and concrete products were investigated in sub-strategy "F" for the selected design solutions (ST.2 and ST.5).

8 Lifecycle Cost Analysis

Life cycle cost assessment defines all the cost associated with the lifetime of a building, including owning and operating a facility over a period of time, as shown in Figure 10 (Mearig, Coffee et al. 1999, Hunkeler, Lichtenvort et al. 2008). For the purpose of this study, the initial cost includes the expenses associated with the manufacturing materials and construction of the building. The operating and maintenance cost includes the running energy and material replacement cost during the lifetime of the building. The disposal cost includes demolition cost.

The initial cost associated with building materials and construction activities were taken from the Australian construction handbook based on 2017 data (Rawlinsons 2017). The operating energy cost was estimated based on the annual energy consumption (based on energy simulation results) and estimated future Australian energy prices (Economics 2015, Jacobs 2016) for the cost of energy up to 2040. A future cost analysis was then used to extend the energy cost from 2040 to 2068 (50-year lifetime of the building- the base year 2016). The Present Value (PV) of operational cost was estimated based on Equation 4 with a 15% discount as a nominal rate per year (Carmichael 2017).

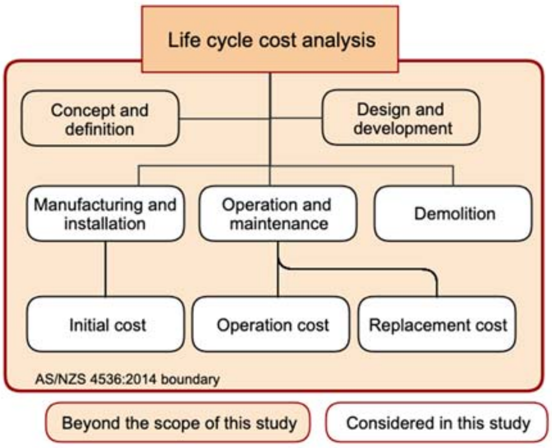


Figure 10 Life cycle cost of building

$$PV\ of\ operating\ cost = \sum_{y=1}^{building\ lifetime=50\ year} \frac{future\ cost}{(1 + discounted\ rate)^{occuring\ year}}$$

(Equation 4)

The PV replacement cost for the building materials was estimated as having a shorter lifetime than the buildings (50 years) (Rauf and Crawford 2012). The replacement cost was calculated based on the current price of the materials and an escalation (inflation) rate of 3% (RBA 2016). Equation 5 was used to represent the present value for replacement cost (Fuller 2010).

$$PV\ of\ maintenance\ cost = \sum_{y=1}^{building\ lifetime=50\ year} \frac{Current\ material\ price\ \times\ (1 + escalation\ rate)}{(1 + discounted\ rate)^{occuring\ year}}$$

(Equation 5)

The cost associated with demolition at the end of life was estimated based on the future cost analysis (shown in Equation 6). The future cost was estimated based on the national average cost of demolition per square metre ($690.74/m^2) for a mid-rise building in Sydney (Rawlinsons 2017) over a 50 year lifetime of buildings. The expenses associated with refurbishment and development of the external site were not included in this study.

$$PV\ of\ demolition\ cost = \frac{current\ demolition\ cost\ \times\ (1 + escalation\ rate)^{50}}{(1 + discounted\ rate)^{50}}$$

(Equation 6)

For the operational cost, the operating energy over life cycle of the building was calculated based on the dynamic energy simulations. The estimated annual energy consumptions were multiplied by the relative market forecasts as shown by Robati, McCarthy et al. (2018). Equation 4 was used to determine the present operational cost over 50 years of life of the building. Figure 11 compares the potential energy price up to 2067 across several studies (Jacobs 2016).

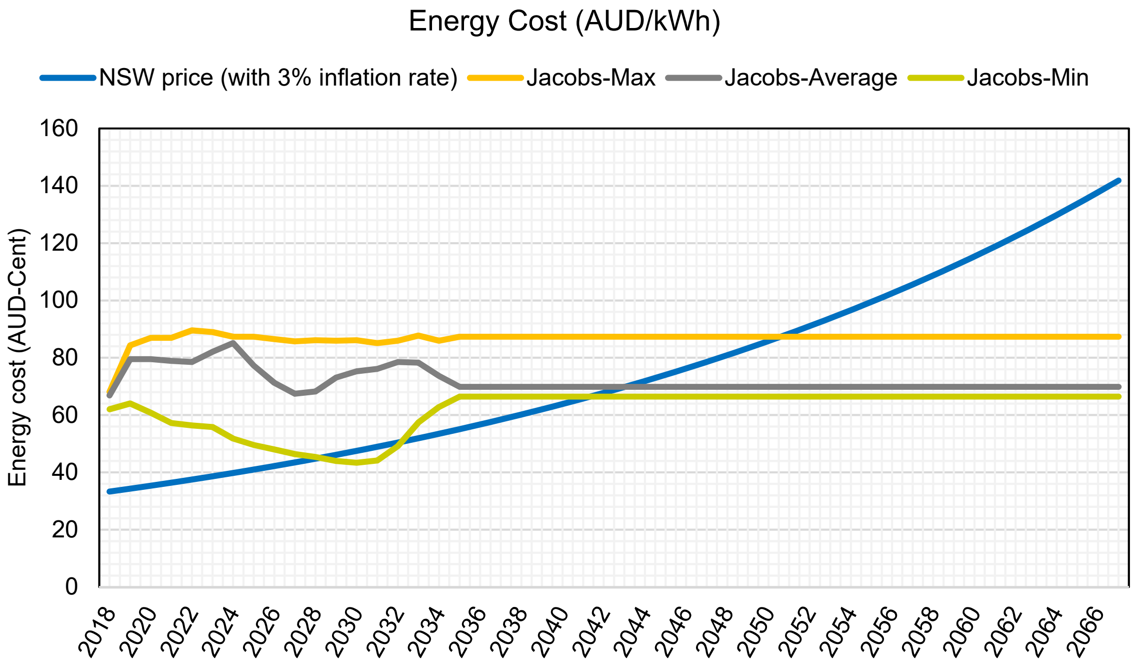


Figure 11 Energy cost forecast over 50 years (adapted from (Jacobs 2016))

9 Results and Discussion

The project findings are outlined below:

9.1 life cycle cost and carbon emissions of the base case building

Figure 12 presents the life cycle cost and carbon emissions associated with the base case building over a 50-year lifespan. The base case building total lifecycle carbon was 2,500kgCO_2-e/m^2. Of this, 740kgCO_2-e/m^2 was embodied carbon, equivalent to 27% of total emissions. Its whole lifecycle cost was $1,266/m^2. Of this, $1,000 was capital costs (materials and construction), making up 86% of total costs. For the embodied carbon emissions, the estimated value us within suggested literature which ranges from the studies, as outlined in Figures 13. For the overall cost, the estimated value is lower than suggested range by the cost data (as shown in Figure 14); this is mainly due to assumptions and amount of details considered in compiling each cost data. Commonly cost data are taken from previous projects data, which inherent materials waste; Such materials waste can be in vary quantities due to the nature of each project (Hanid, Siriwardena et al. 2011).

Operating energy consumption was simulated as 64.38 kWh/m^2/annum. This is consistent with similar residential baseline energy use (69.2 kWh/m^2/annum) as identified in ASBEC & ClimateWorks 2018. The carbon emissions associated with operational energy usage are determined as 2,024 kg.CO_2-e/m^2 or 73% of the whole carbon emissions of the building.

Its present cost value associated with future energy consumption was estimated as $204.80/m^2 or 14% of the whole cost of the building. It is interesting to note that future operational carbon emissions are the greatest contributor to total carbon footprint, yet future operation energy costs are a relatively minor lifecycle cost. With increasingly moving toward energy efficient building, the operational phase of a life cycle assessment will make a gradually smaller contribution to the total environmental impact, while material selection will become relatively more important.

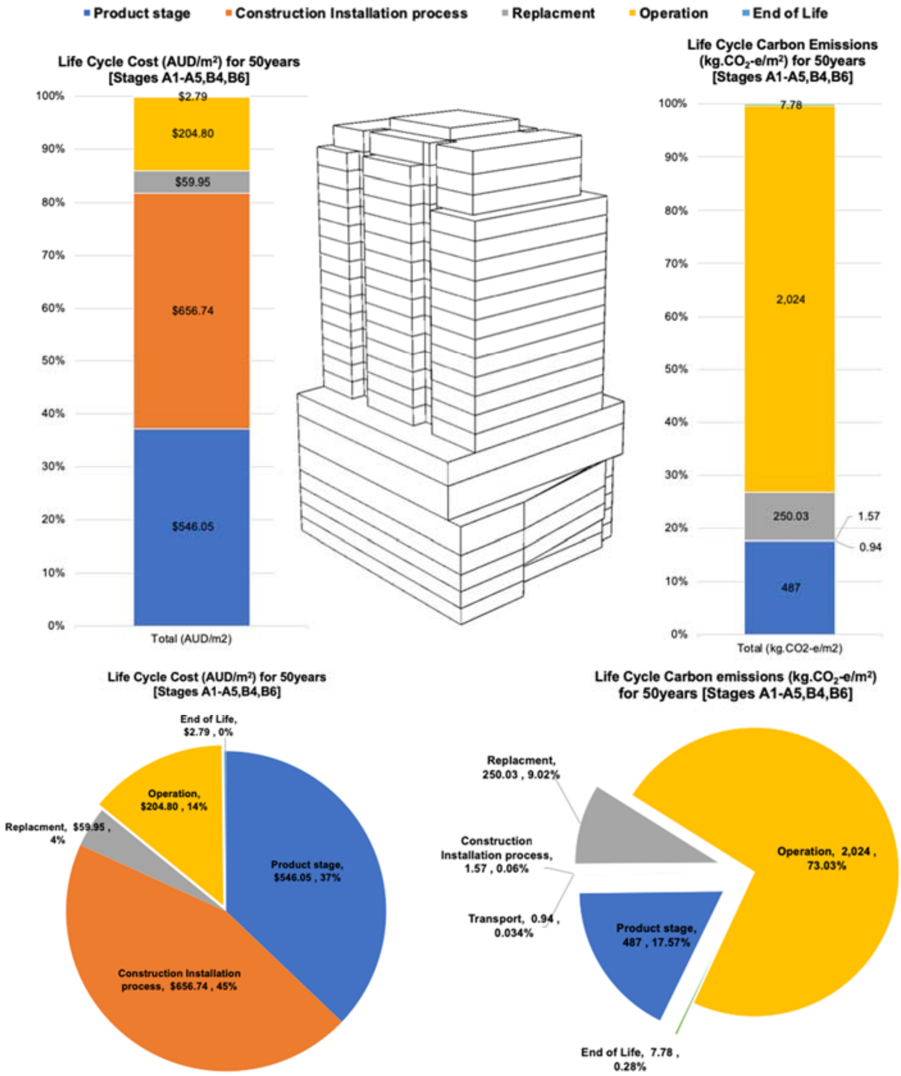


Figure 12 life cycle cost and carbon emissions associated with the base case building

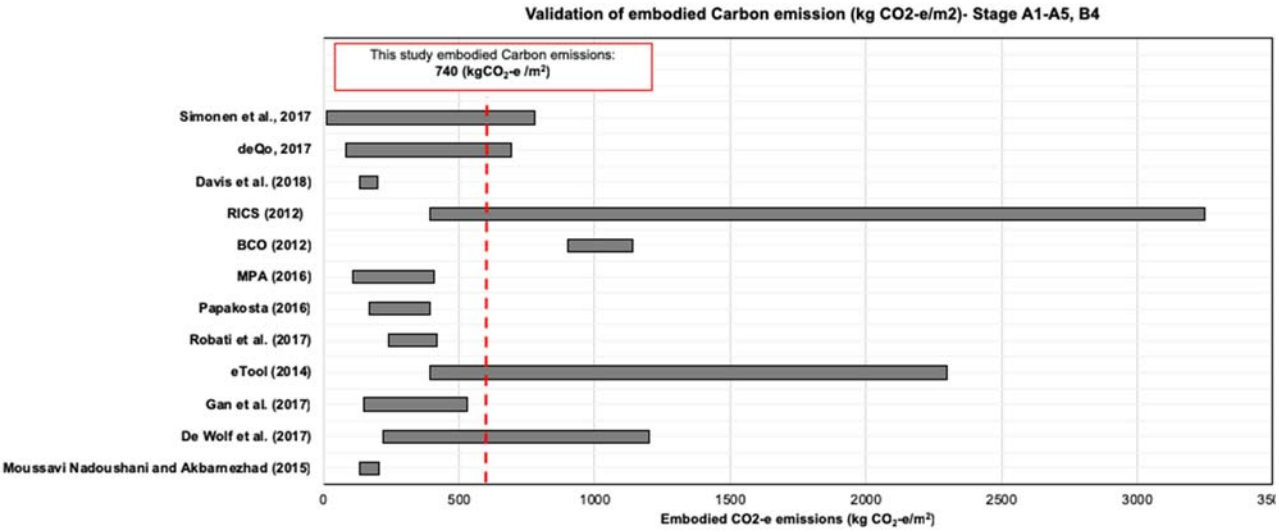


Figure 13: Comparison of this project embodied carbon with other studies

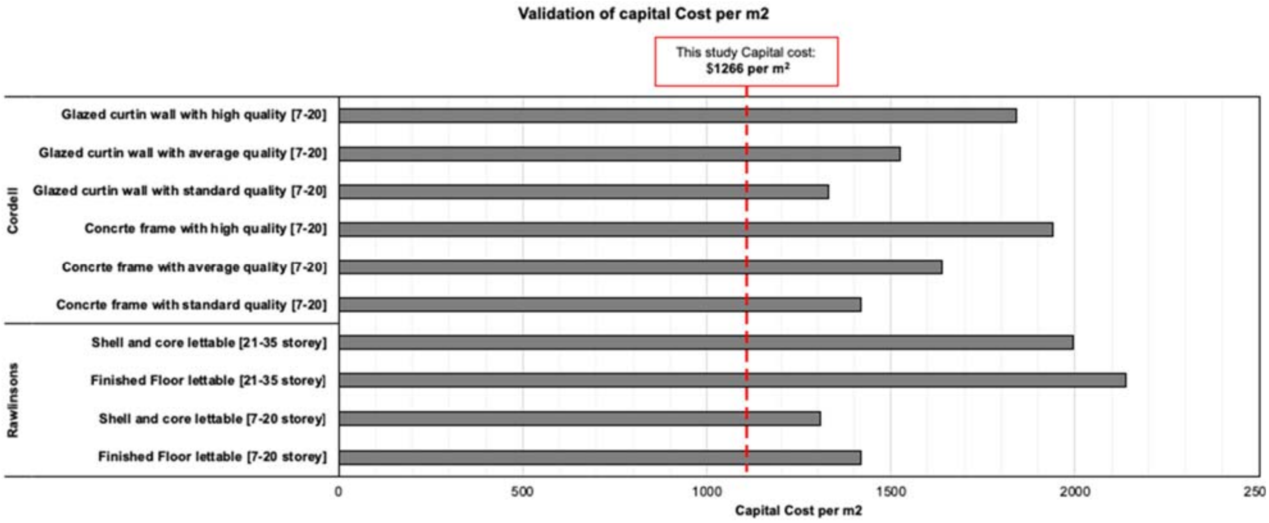


Figure 14: Comparison of this project capital cost with other studies

The relative importance of building elements in terms of overal cost and embodied carbon emissions are shown in Figure 15. It can be seen that the sub-structure and superstructure together represent 52% of the total cost and 37% carbon emissions of the base case building. The following section compares life cycle cost and carbon emissions across alternative solutions.

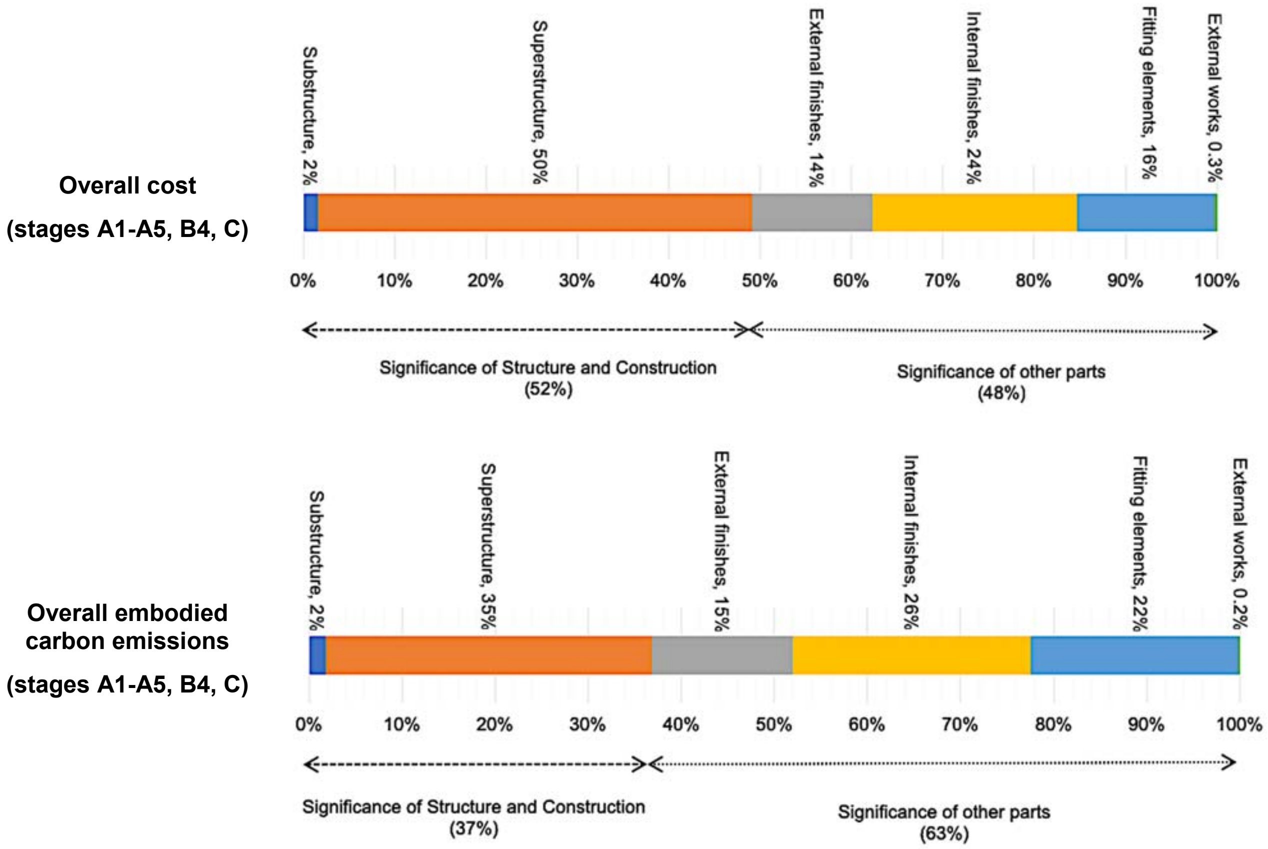


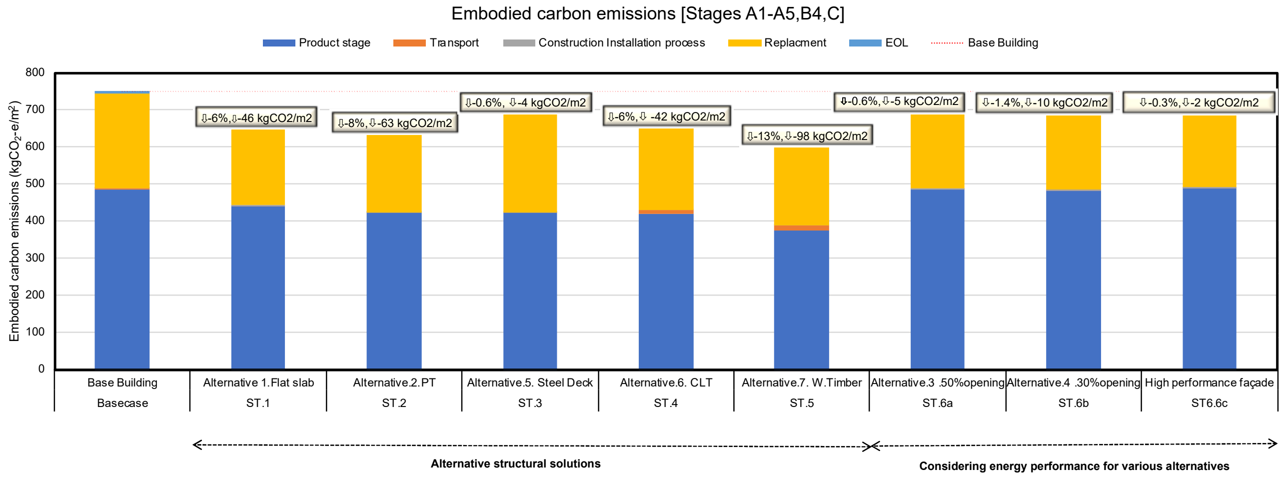
Figure 15 importance of building parts in terms of cost and embodied carbon emissions

9.2 Carbon and Cost impact of alternative design scenarios

Figure 16 compares the embodied carbon emissions and cost of different scenarios considered in this study. As can be seen, the type of structural systems can have considerable effects on both cost and carbon emissions of the building. The results highlighted that the use of timber as a main structural material (Alternative 7.W.Timber) could save up 13% or 98 kg.CO_2-e/m^2 in embodied carbon emissions of the building and its lifecycle cost was reduced by 5% or $66/$m^2$ (equivalent to $ 2,853,114 saving in cost). Similarly, Post-tensioned and flat slab structures (Alternative.2. PT and Alternative.1.FS) have reduced embodied carbon emissions by 8% and 6%, respectively. Saving in cost was estimated as high as 15% for the Flat slab, due to reducing in quantities of steel reinforcement and concrete.

Beside the base case building, the result shows that steel deck which is commonly used in steel structure has the highest embodied carbon emissions (747 kg.CO_2-e/m^2) among the other solutions, whilst it has a second lowest cost among the other alternatives. This high value in embodied carbon emission was attained due to the increase in quantities of steel as a carbon intensive material in the building. Considering the obtained result, we found that ST.2 (PT building) and ST.5 (Mass timber buildings) are the most cost-effective and low embodied carbon emissions alternatives. These two-design alternatives are considered for future sensitivity analysis (as shown in Table 3) to have more insight understanding on impacts of design alternative have on whole-life carbon emissions of the building. The following sections (section 9.3) was planned to explore the potential impacts of carbon sequestrations, procurement strategy, and materials lifespan on two selected alternatives (PT and Mass timber). Furthermore, the indirect impacts related to changes in design alternatives have been discussed in section 9.4.

In section 9.5, we have considered a detailed energy simulation analysis (via DesignBuilder) to quantify the potential impacts of operational energy on whole-life carbon emissions of the building. We examined the impacts of typical operational improvements such as changing WWR and implementing high-performance façade on both operational and embodied carbon emissions



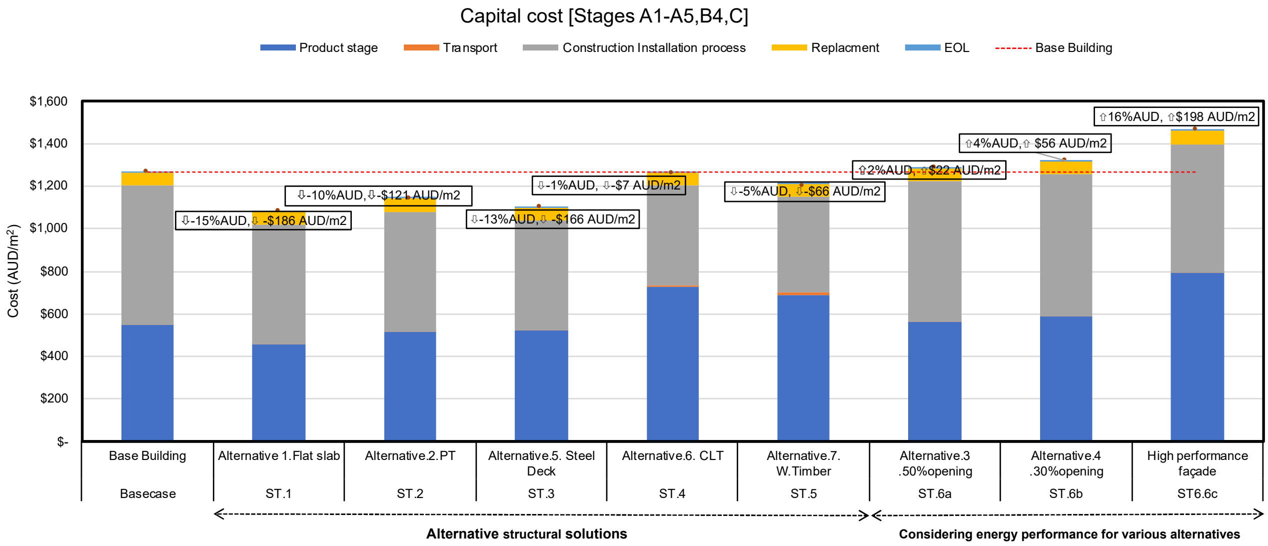


Figure 16 Embodied carbon emissions and cost savings across different alternatives

9.3 Sensitivity analysis:

The analysis of embodied carbon emission comprises estimations with various uncertain factors associated with each building components. Sensitivity analysis offers a way of investigating the uncertainty surrounding each chosen parameter. In another word, sensitivity analysis provides a better understanding of the impacts of design solutions have on lifetime of the building. As such, we employed sensitivity analysis to determine the potential range of figures for scenarios designed out of mass timber (alternative 7) and post-tensioned concrete (alternative 2).

In relation to testing the sensitivity of the design alternatives on cost and carbon emissions of the building, the following strategies were implemented.

I. Sensitivity analysis on the mass timber and post-tensioned structures:

The resulting sensitivity analysis for two selected buildings is shown in Figures 17 and 18. For the Mass timber structure (ST.5), the reduction in embodied carbon emissions is ranged from -72 $kgCO_2$-e/m^2 (-10%) to -427 $kgCO_2$-e/m^2 (-57%). For the post-tensioned buildings, the saving in carbon emissions is ranged from -63 $kgCO_2$-e/m^2 (-8%) to -267 $kgCO_2$-e/m^2 (-36%). The maximum reductions in cost appeared as \$127/m^2 (10% reduction) for both alternatives, compare with the based case building. The ultimate strategy for which combined all other studied strategies have the highest contribution in terms of embodied carbon emissions and cost saving.

These variations in the results show the significant impacts of considering alternative strategies (incl. procurement strategy, sequestration analysis, utilising a novel concrete and using materials with longer lifespan) through embodied carbon emissions analysis of the building. The significance of each strategy is discussed separately in the following sections.

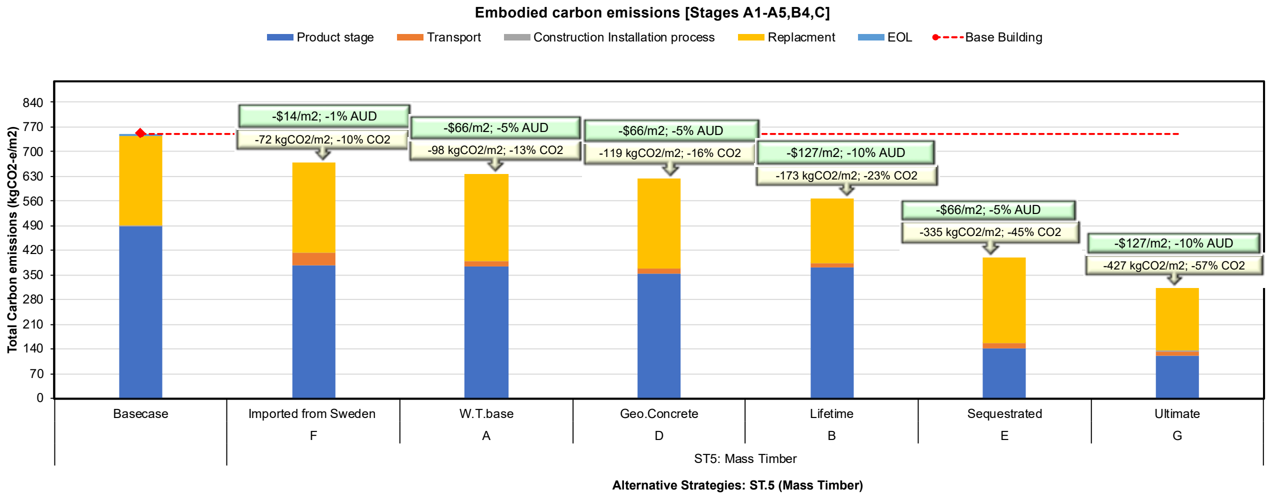


Figure 17 results of sensitivity analysis for the mass timber building

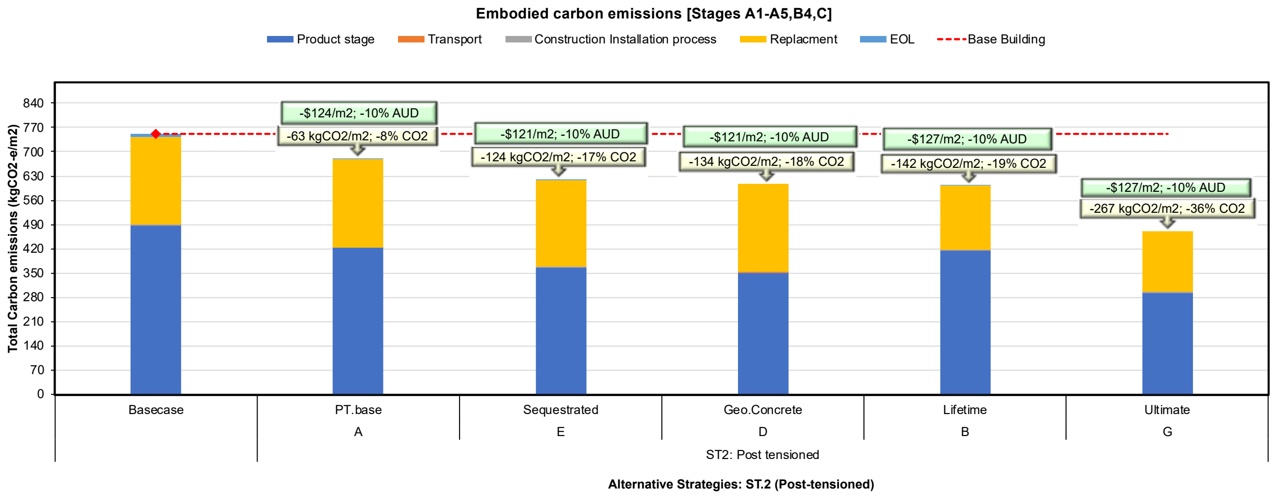


Figure 18 results of sensitivity analysis for the post-tensioned building

II. Impacts of procurement strategy:

This section presents the strategy considered to determine the "gate to site" cost and carbon emissions for the mass timber building. In the mass timber building, a new generation of structural timber (Glulam:glue-laminated timber, CLT: Cross-laminated timber) is being used to construct mid-rise timber building. With the growing popularity of mass timber in building constriction, most of the manufacturing and production of Glulam and CLT is undertaken in Europe. Australian timber manufacturers are following this development to produce engineering timber for mid-rise buildings. As such, it is vital to understand the potential impacts of procurement strategy on carbon emissions and cost at the initial stage of the decision-making process. Hence, this strategy studies the potential impacts of sourcing structural timber from a European supplier (F: Sweden) on cost and carbon emissions of the mass timber building in compare with sourcing the materials from Australia (A). The strategy shares the same assumptions for the other building materials and activities to the base case building.

Figure 19 shows that importing the structural timber (alternative 5.F) have increased the material cost (incl. shipping) and embodied carbon emissions by 195 AUD/m^2 and 35.3 kgCO_2-e/m^2, respectively. The result revealed the necessity of using local materials not only to reduce the building cost but also to minimise carbon emissions associated with the transportation of the materials.

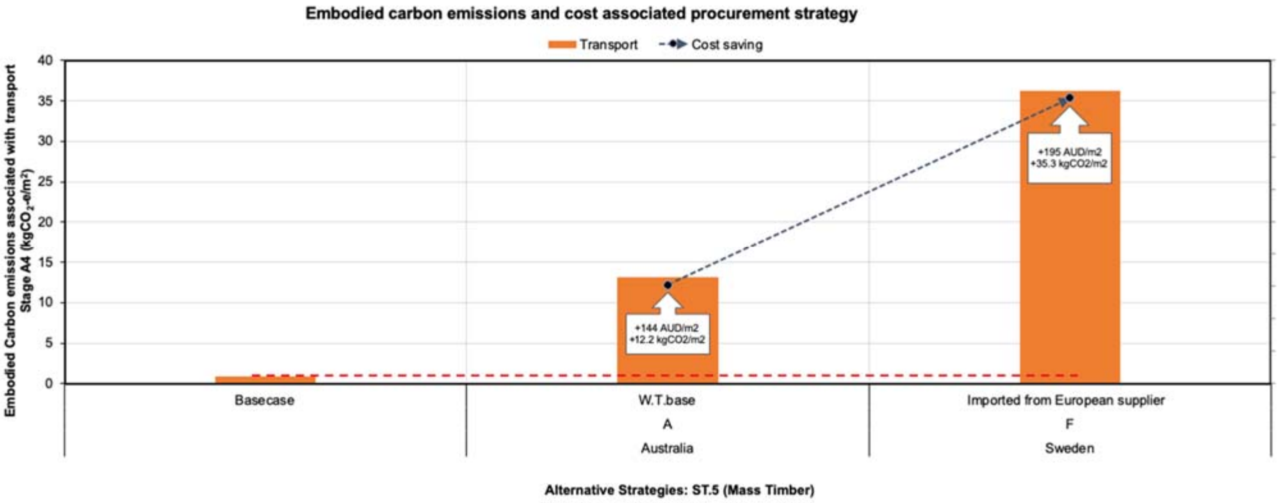


Figure 19 Impacts of procurement strategy on cost and carbon emissions

III. Impacts of sequestration of carbon emissions analysis:

Carbon sequestration is the process of capturing carbon from the atmosphere through natural processes (such as photosynthesis in trees) and storing it for a long-time to mitigate or defer global warming (Kumar and Nair 2011). Carbon sequestration is a vital impact to consider when determining life cycle carbon emissions of buildings. Timber manufactures typically include a negative value on the embodied carbon emissions of timber to incorporate carbon sequestrations benefit for the timber materials (Kremer and Symmons 2015, De Wolf 2017). However, there is a debate about whether carbon sequestrated should be credited to timber through life cycle assessment (De Wolf, Pomponi et al. 2017).

Additionally, recent studies have considered carbonation data to estimates carbon sequestrated by exposed concrete elements (Souto-Martinez, Arehart et al. 2018). Carbonation in concrete is a chemical reaction between hydrated cement paste and atmospheric carbon dioxide which also provides a way to sequester carbon. However, several studies believe that the long-term carbon sequestration for concrete is negligible. Meanwhile, other studies have claimed that 15.5%-17% (Yang, Seo et al. 2014), 13-48% (Collins 2010) or 20-47% (García-Segura, Yepes et al. 2014) of the initial carbon emissions of concrete elements can be recovered through carbonation of exposed components. However, there is not an agreement on the degree of importance of carbon sequestration in exposed concrete elements. Hence, this part of study was designed to account carbon sequestration associated with both structural timber and concrete materials used in the mass timber and post-tensioned buildings.

Figure 20 shows the impacts of carbon sequestration carbon emissions analysis of the buildings. As expected, higher embodied carbon saving was estimated for mass timber (ST.5) as -355 kgCO_2-e/m^2 or -45% reduction in carbon emissions as compared to the non-timber base case. For the post-tensioned building (ST.2), the total embodied carbon emissions saving due to carbon sequestration was estimated as -124 kgCO_2-e/m^2 or -17% in compare with the base building. This is on the basis of 100% carbon sequestration for engineered timber and concrete. The sequestration of carbon was assumed as 972 kgCO_2-e/m^3 (ABARES 2013) for timber, 14.6 kgCO_2-e/m^3 (ABARES 2013, WoodSolutions 2017) for plywood which has a very short carbon storage period (up to 3 years) (Ximenes 2006),and 130.79 kgCO_2-e/m^3 (Souto-Martinez, Arehart et al. 2018) for concrete.

It should be mentioned that these numbers are only valid if the engineered timber materials are sustainably sourced (Weight 2011). Also, the selection of treatment at the end of life could have a considerable effect of carbon emissions of mass timber building (Darby, Elmualim et al. 2013). Darby, Elmualim et al. (2013) found that the carbon emissions associated with the different treatments for a building can be ranged from -1021 tCO_2-e (for reuse) to 126 tCO_2-e (for incinerate), however, timber structure resulted in overall lower carbon emission among other alternatives.

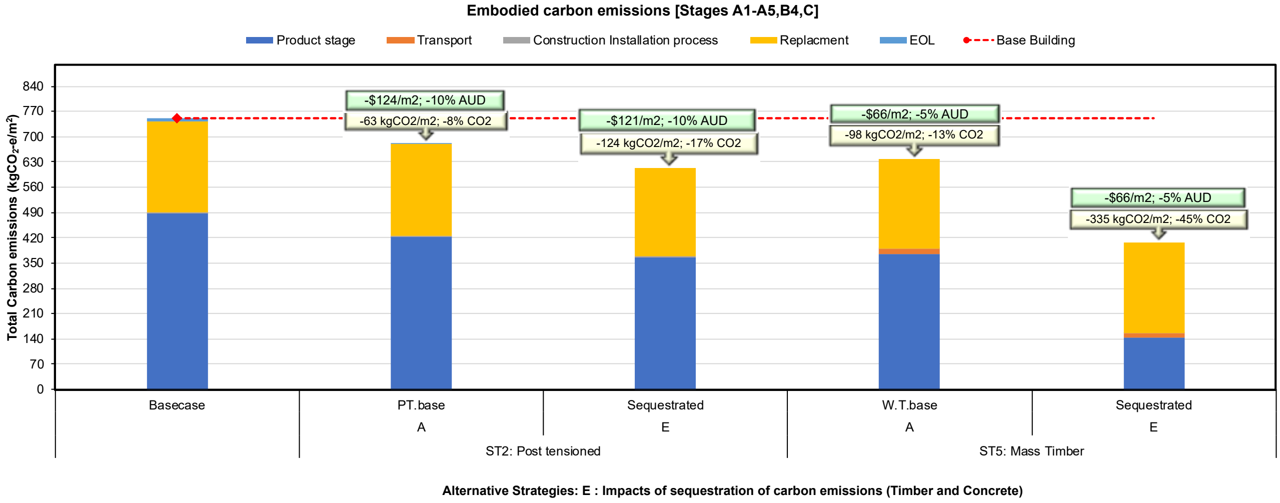


Figure 20 Impacts of carbon sequestration analysis

IV. Impacts of utilising a novel concrete:

Concrete is the most widely used construction material in the building industry and as such consumes the second highest amount of natural resources (ISO15673 2005). A report released by the United States Geological Survey shows that the global production of cement increased by 100 million tonnes in one year to 4.18 billion tonnes in 2014 (Survey 2015). The American Portland Cement Association (PCA) estimates that the consumption of cement will continue to increase into the future (PCA 2015). This situation raises the question on how to design a most efficient concrete building with respect to the concrete strength, thermal properties, environmental impact, and CO_2-e emissions intensity. The concrete industry is addressing some of the worries about environmental issues by supplementing or replacing the use of cement and other components associated with high embodied CO_2-e emissions. Several researchers have studied the possibility of replacing cement in concrete with recycled materials (de Castro and de Brito 2013, Ingrao, Giudice et al. 2014, Jacoby and Pelisser 2015). The use of alternative cementitious materials remains the main path to reducing embodied CO_2-e emissions in the concrete industry (Mehta 2002, Le, Tam et al. 2018). The supplementary cementitious material replacement proportion in concrete can be ranged from 10% to 60%, though more than 60% replacement is unrealistic (Illankoon, Tam et al. 2018). Hence, this study examines the implication of using a geopolymer concrete which consists of 50% GGBFS (Ground Granulated Blast Furnace Slag) in overall carbon emissions and cost of buildings. This type of concrete is available in the market (BORAL 2011, Keyte, Lloyd et al. 2017).

Figure 21 shows cost and carbon emission associated with employing geopolymer concrete in the post-tensioned and mass timber building. For the mass timber building, the first five stories (parking) were designed out of geopolymer concrete. It can be seen that the geopolymer concrete can save up to 16% or -119 $kgCO_2$-e/m^2 in embodied carbon emissions and 5% or 66$/$m^2$ in cost of mass timber building. For the post-tensioned system, saving in carbon emissions was estimated as -134 $kgCO_2$-e/m^2 of -18%, and saving in cost was estimated as 10% or 121$ /m^2. Saving in cost mainly affected by quantities of materials used in the building rather than the type of concrete. A recent study found that the higher cost saving can be achieved by replacing higher percentage of supplementary cementitious materials (in the Australian context), and it is suggested that the fly ash and blast furnice slag are the most economical alternative compared with silica fume (Illankoon, Tam et al. 2018).

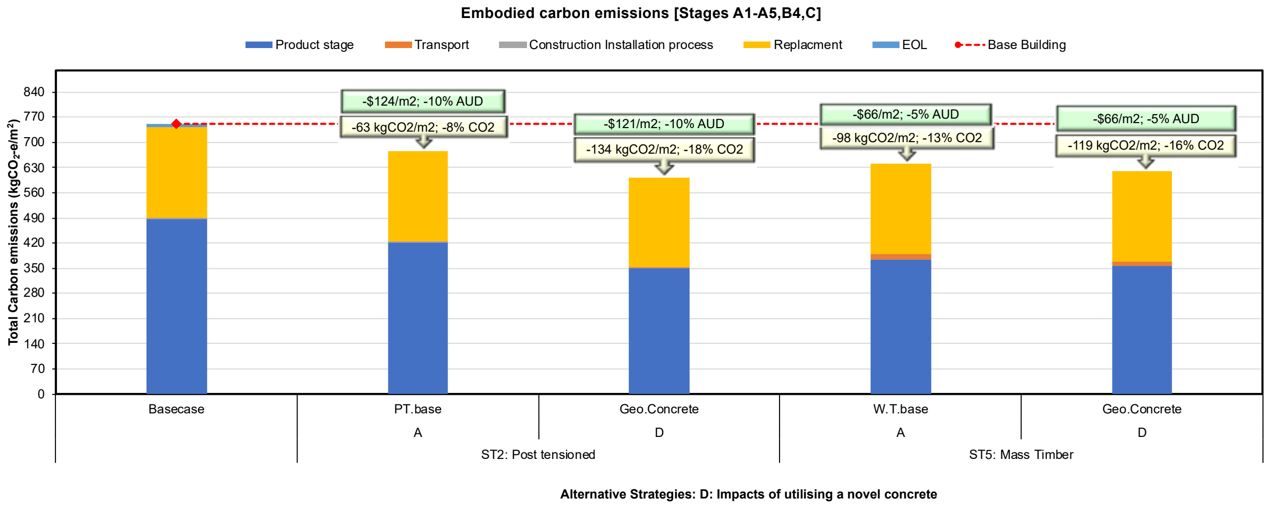


Figure 21 Impacts of utilising a novel concrete

V. Impacts of using materials with a longer lifespan:

Technology and selection of building materials have different impacts on cost and carbon emissions of buildings. Several studies have been made to determine the effects of materials lifespan on the cost of buildings (Ashworth and Perera 2016, Oh, Park et al. 2016, Eleftheriadis, Schwartz et al. 2018). Eleftheriadis, Schwartz et al. (2018) found that concrete formwork is almost as important as the cost of the concrete in structural components. The formwork is one of the largest cost contributors in the columns. The primary results of analysis for the base case building also shows that the formwork and walls (as a non-structural component) have the highest on cost and carbon emissions, respectively (as shown in Figure 22). Despite the important role materials lifespan play in life cycle assessment, limited studies have looked into the impact of building lifespan on carbon emissions and cost of a building.

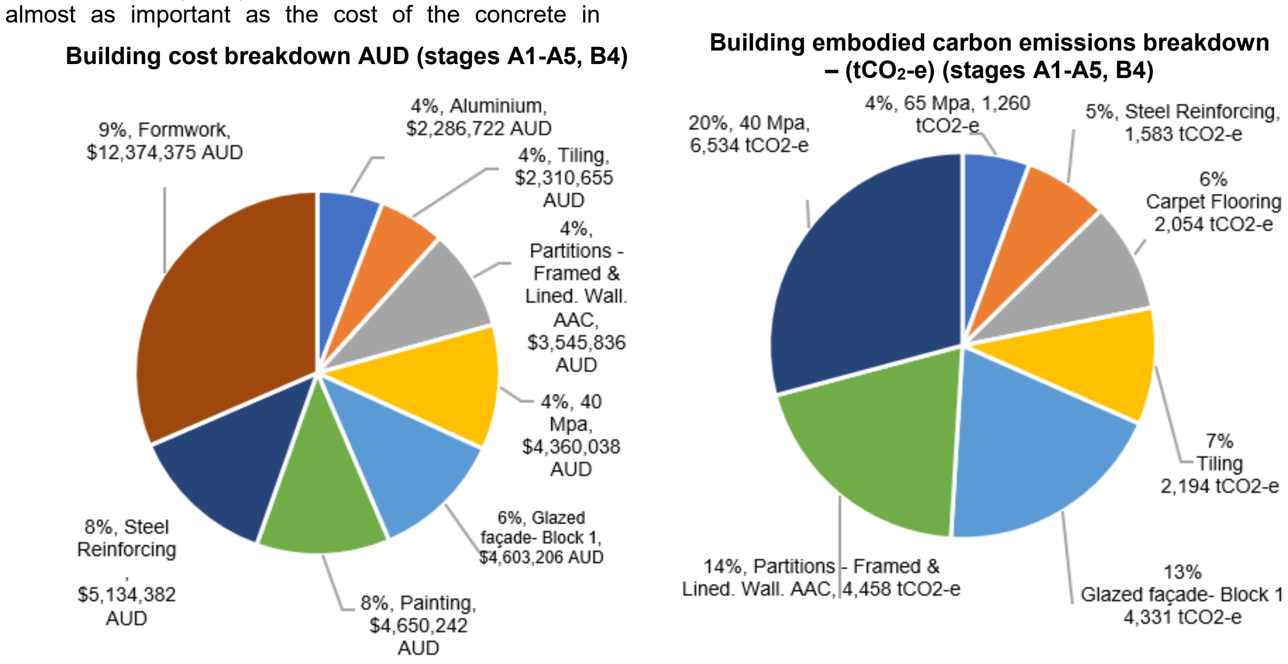


Figure 22 magnitude impacts of building materials on carbon emissions and cost of the base case.

As such, it was decided to examine the potential impacts of longer service life for both formwork (number of times used) and wall components. For the formwork materials, the number of reuses was increased from three as used in the base case (Nadoushani and Akbarnezha 2014) to ten (eTool 2014). For the plaster and Autoclaved aerated concrete lifespan was increased from 30 years in the base case to 50 years (eTool 2014, RICS 2017). Figure 23 compares the impacts of these longer lifespans on embodied carbon emissions.

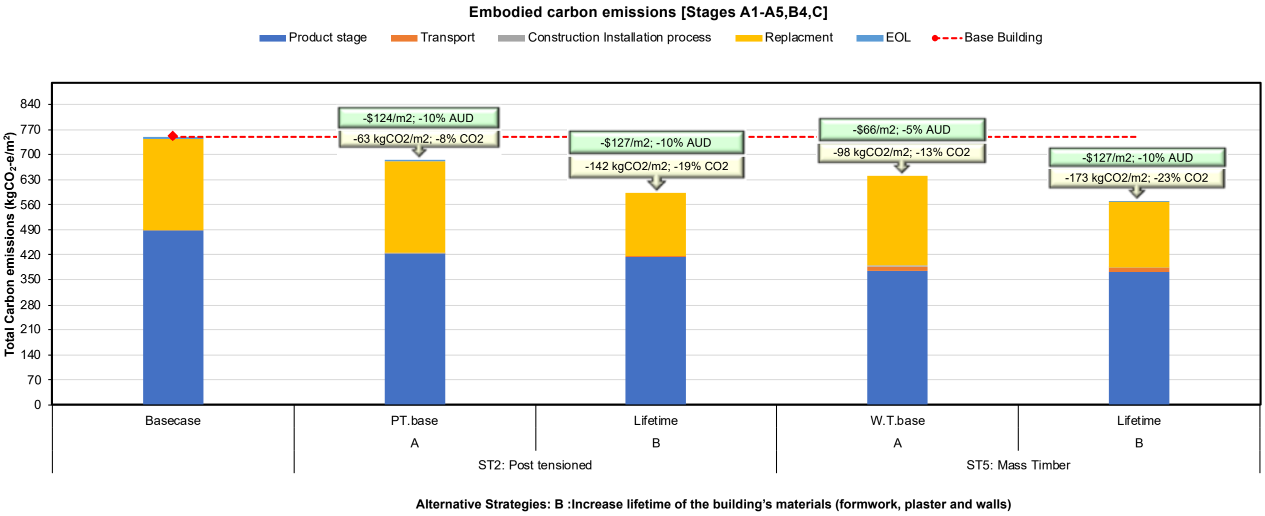


Figure 23 Impacts of using materials with a longer lifespan

The results show that the increasing the material's lifetime (formwork and walls) can save up to 173 $kgCO_2$-e/m^2 (-23%) and 142 $kgCO_2$-e/m^2 (-19%) in carbon emission of the mass timber and post-tensioned scenario, respectively. Additionally, the overall cost was reduced by 10% or 127\$/m^2 in both buildings. The results illustrate that increased material lifespan can be an effective strategy to reduce cost and carbon emissions of buildings. Additionally, it points out the importance of having a holistic approach in the selection of potentially green and cost-effective materials.

VI. Ultimate strategy: most cost-effective and carbon friendly alternatives

This part of study combines all the previous findings with the aim of achieving the most cost-effective and carbon reducing alternative. Specifically, the impacts of a longer lifetime, carbon sequestration for timber and concrete and using geopolymer concrete were combined. Figure 24 provides a summary of the integration of these alternatives on cost and carbon emissions of the two selected structures (mass timber and post-tensioned concrete).

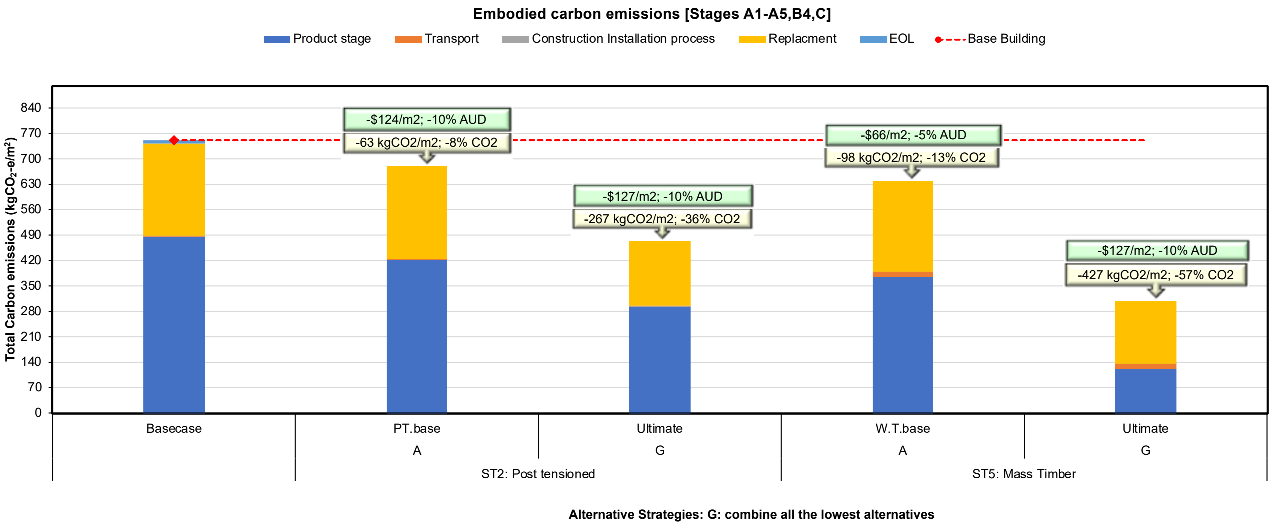


Figure 24 Ultimate strategy: most cost effective and carbon friendly alternatives

The highest saving in embodied carbon emissions was estimated in mass timber building by saving -427 kg.CO2-e/m2 or -57% overall. The combination of strategies in the post-tensioned building has reduced the embodied carbon emission by -267kg.CO_2-e/m^2 or -36%. In addition to the carbon emissions, the overall cost of the buildings was reduced by 10% or 127$/m² in both instances. These results revealed that the embodied carbon and capital cost of a building is systematically influenced by the selection of building materials and construction systems. And in particular, that changes to the building structure and construction made later in the design process, without impacting the overall design, can contribute to very significant carbon reductions while simultaneously reducing cost.

9.4 Measuring indirect impacts: the role of the MACC

The selection of an ideal alternative in terms of economic and environmental performance needs a holist decision-making method. This study investigates the ability of Marginal Abetment Cost Curves (MACC) to capture the impacts of alternative design solutions on capital cost and embodied carbon emissions of a building. The novelty of this MACC analysis lies in the application of cost and carbon emissions at the initial stage of decision-making. The results of the MACC curve not only identify the lowest cost and highest carbon benefits but also indicate the indirect impacts of design changes by plotting where saving or extra cost and carbon emissions occur. Results of the overall carbon emissions reductions and cost vary from case to case across alternative design solutions. The Following section provides the results of MACC associated with two design alternatives.

Figure 25 shows a MACC for the post-tensioned concrete scenario, as compared to the base case. Boxes on the y-axis below zero show cost benefits, while those above zero show increased costs. The x-axis scale shows embodied carbon emissions associated with each product (savings, or additional embodied carbon emissions).

It can be seen that the highest saving obtained by reducing the size of structural components and reducing quantities of formwork, but the greatest embodied carbon emissions saving was for structural concrete (32 MPa, 40MPa and 50MPa). Changing the structural systems introduced extra materials in the building as shown in a positive cost measure. Post-tensioning was a cost addition item, while internal finishes (insulation, plater and painting) was the most significant carbon addition in the building.

For the post-tensioned building, rectangular columns replaced the structural sheer walls in the upper floors. This changes in design have led to the additional building materials for the interior walls in order to meet the architectural requirements of the building. As such, it can be seen extra cost and carbon emissions occur for insulation, painting, plasterboard (to the right-hand side of the MACC)

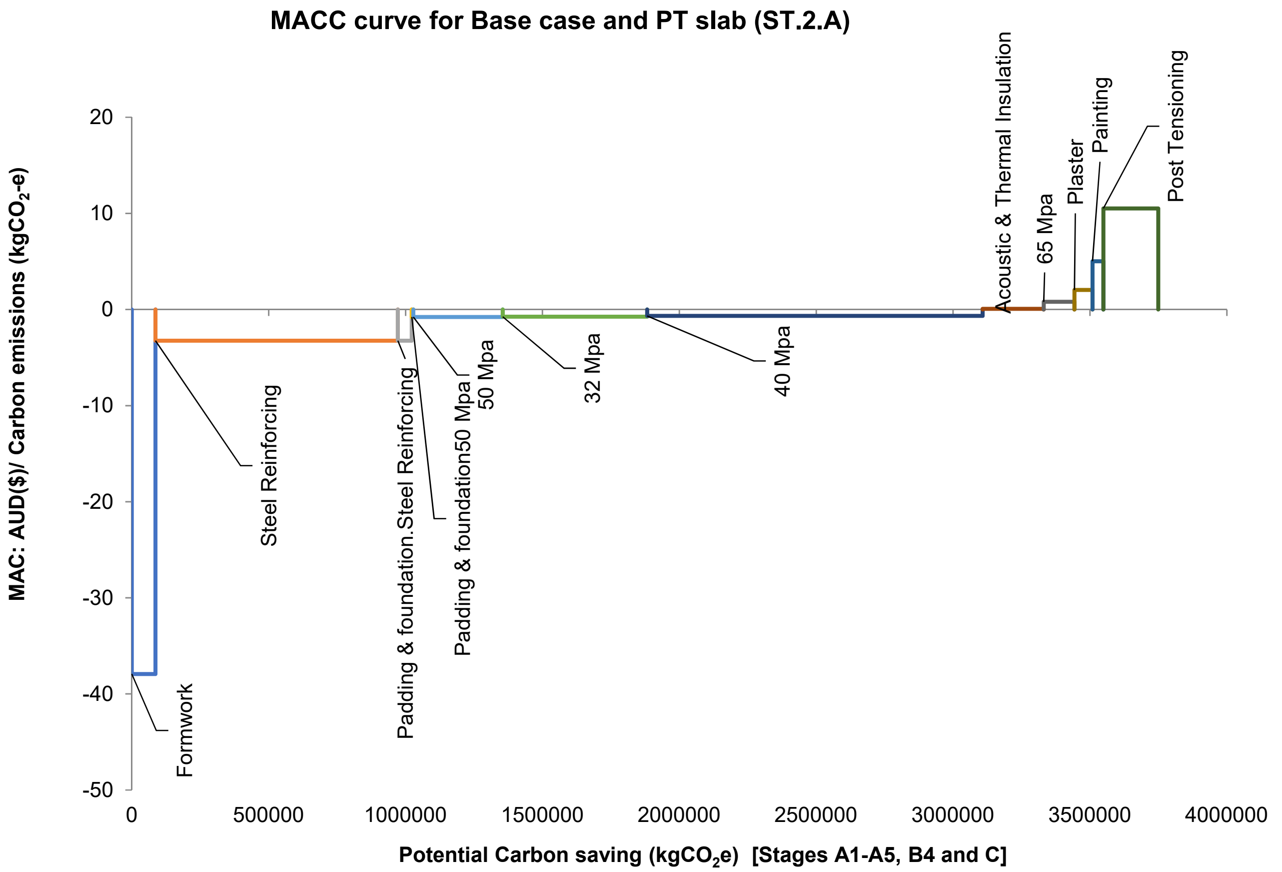


Figure 25 MACC curve for Base case and Post-tensioned (ST2.A)

For the mass timber building, Figure 26 shows that the positive and negative impacts across cost and carbon through changing the main structural materials from concrete and steel to engineered timer material (CLT and glulam). The use of timber structure increased floor to floor height (on average 336 mm), which consequently caused indirect impacts. The indirect impacts captured the additional material required in the façade and exterior wall to meet the minimum requirement of each floor.

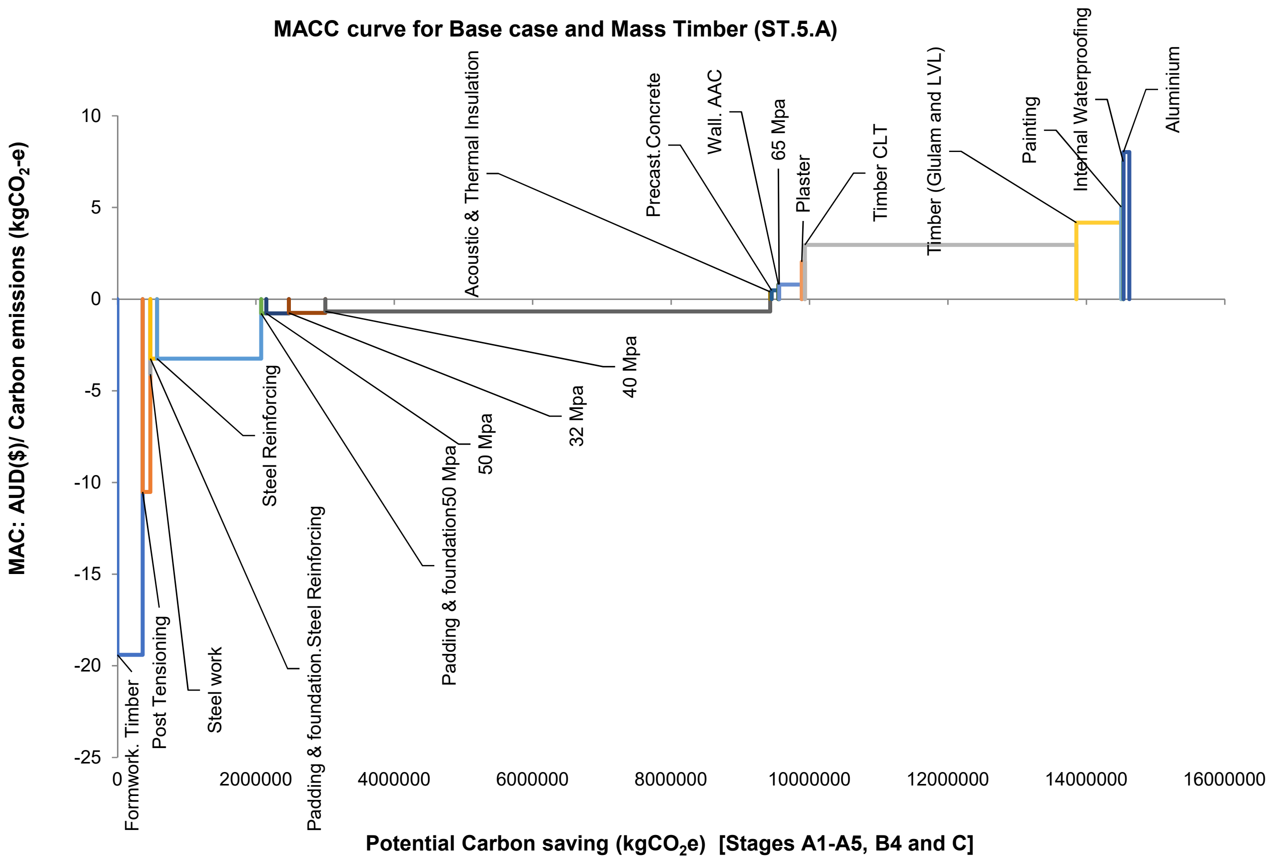


Figure 26 MACC curve for Base case and Whole Timber (ST5.A)

So, while a move to timber fuelled significant embodied carbon savings from a reduction in 40MPA concrete, it also increased embodied carbon through additional timber, plaster, paint and aluminium (see right hand side above) due to an increase in floor-to-floor heights. A typical cross-section, as well as minimum requirements for each floor, is shown in Figure 27.

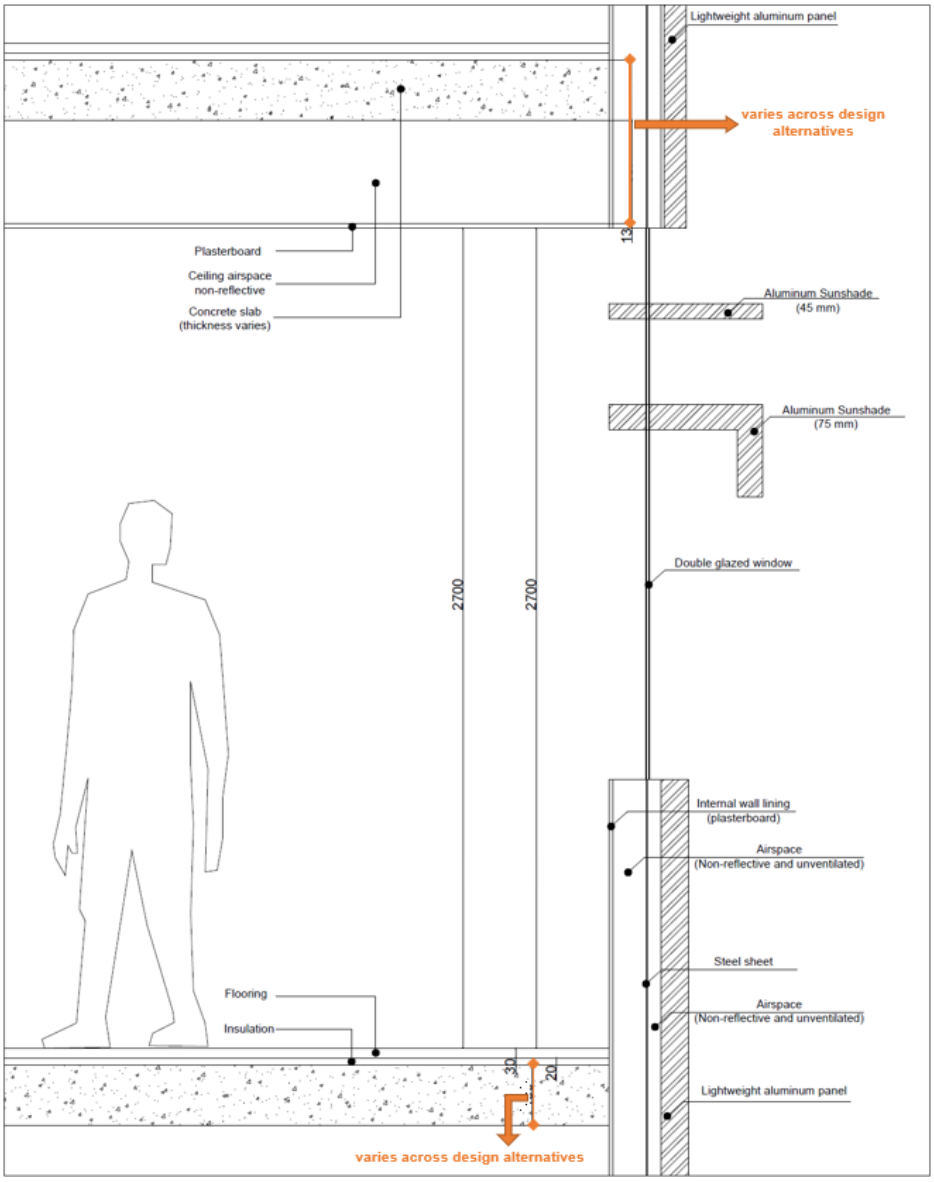


Figure 27 A typical cross-section for each floor. Changes in structural system impact floor-to-floor heights which have indirect impacts on embodied carbon as demonstrating on the MACCs.

The direct and indirect impacts can be easily determined by using the MACC method. The MACC results of the other design alternatives are provided in Appendix 3.

9.5 Lifecycle Carbon: Comparison with strategies to reduce operational emissions

Operational energy over the lifetime of a project is expressed as the annual operating energy multiplied by the lifetime of the project. The operational energy is generally greater than the embodied energy over the lifetime of a building (Torgal and Jalali 2011). Many studies suggest different passive and active technology to reduce the amount of operational energy (Kestner, Goupil et al. 2010). With passive design, the amount and type of insulation in the external walls and roofs, the building's orientation, the use of shading and glazing for windows, passive solar heating and thermal mass, contribute to improving the overall energy usage of a building (Kestner, Goupil et al. 2010). Therefore, this part of study employs dynamic energy simulation method to determine the impacts of design decisions on operational energy and carbon emissions of the building – and compares these strategies to savings in embodied carbon explored in the scenarios above. Detailed information about the assumptions, building properties as well as the method used to estimate cost are shown in section 6 and section 7, respectivly.

The simulated annual energy consumption compared the baseline energy usage with changes in the window to wall ratio (WWR65%, WWR 50% and 30%) and envelope performance (HPF-WWR65%). These results are shown in Figure 28. The baseline energy use based on national construction code (ABCB 2016) was estimated as 69.2 kWh/m^2 (ASBEC and ClimateWorks 2018), and the estimated results for this study are with this range. As would be expected, show operating energy can be reduced by reducing WWR, and most significantly, can be reduced by including a high-performance façade. The scenario with the high-performance façade benefits from a 12% operating energy saving (56.35kWh/m2 as opposed to 64.38kWh/m2).

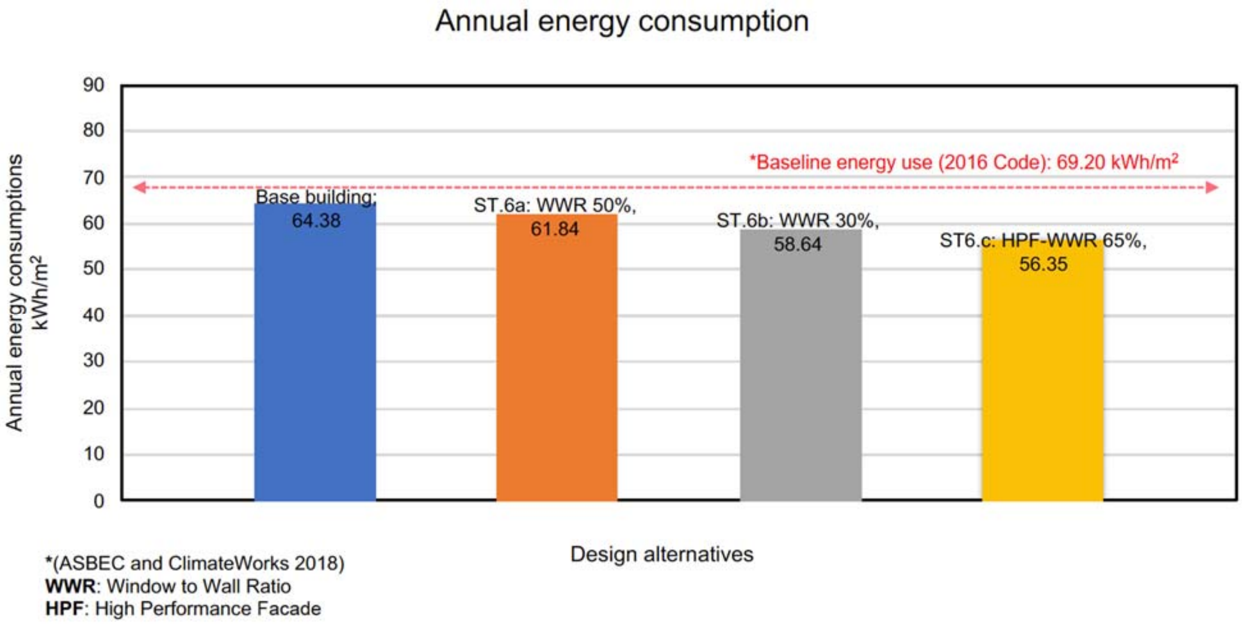


Figure 28 Annual energy consumptions

Figure 29 presents the relative magnitude impacts of the change in the design alternatives to the overall carbon emissions of the buildings across its lifecycle. For example, incorporating a high-performance façade with high-levels of insulation causes embodied carbon to rise, but also reduces operational carbon – the greatest contributor to the carbon footprint.

The embodied carbon emissions comprise 27% for the base case scenario and 30% for the high-performance façade scenario. Yet, overall the high-performance façade scenario has the lowest lifecycle carbon emissions, saving 255kgCO2-e/m2 over a 50 year lifecycle.

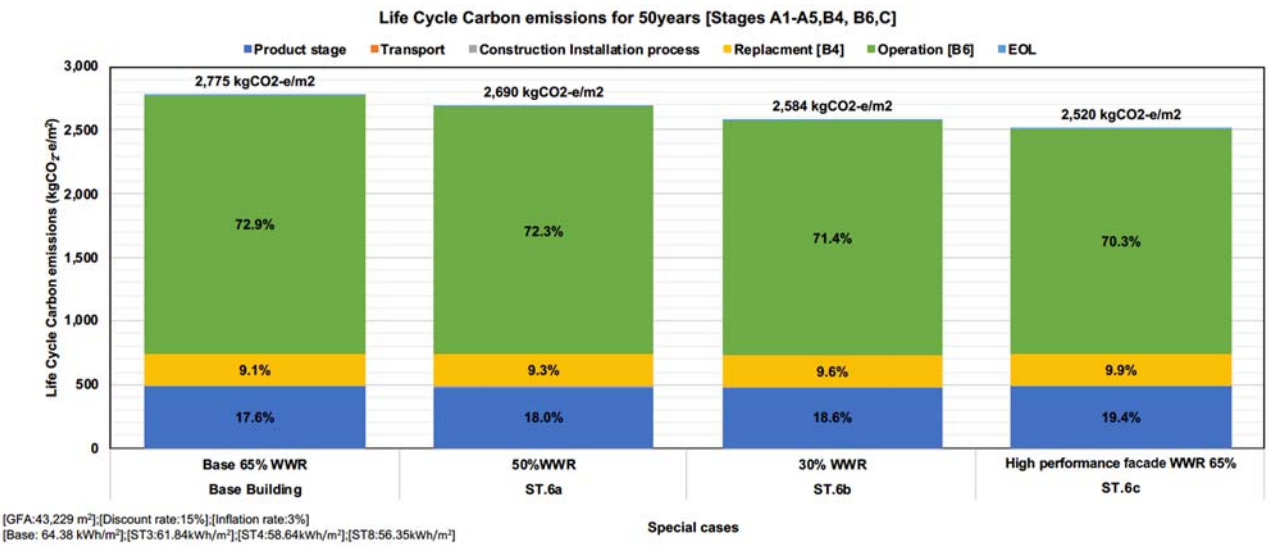


Figure 29 magnitude impacts of the changes in the building envelope on life cycle carbon emissions

In contrast, the results of life cycle cost analysis show that the cost of a building with the high-performance façade is higher than the other alternatives. For instance, high-performance façade building increases the life cycle cost by 11% of 173 AUD/m^2 in comparison with the base case building as shown in Figure 30. This is mostly due to upfront capital costs required for the façade materials and construction. In terms of energy saving, the lower discount rate can increase the significant impacts of energy saving over lifetime of the high-performance façade building. It should be acknowledged that the variation in the discount rate can influence the estimated present money value.

It is also worth comparing the lifecycle carbon savings possible through a high-performance façade, with those explored through changes in materials and structural systems. The high-performance façade contributes to a lifecycle carbon saving of 255 $kgCO_2$-e/m^2. In comparison, the PT concrete strategy (ST.2) provided potential carbon savings of between 63-267 $kgCO_2$-e/m^2, and the whole timber structure of between 72-427 $kgCO_2$-e/m^2. What this means is strategies to reduce embodied carbon even late in the design stage, as demonstrated here, can provide carbon savings comparable and even greater than traditional strategies to reduce operational emissions over a building's effective life. While the high-performance façade example was found to require an increased capital and lifecycle cost, the strategies to reduce embodied carbon emissions also generated cost savings *in addition* to carbon benefits.

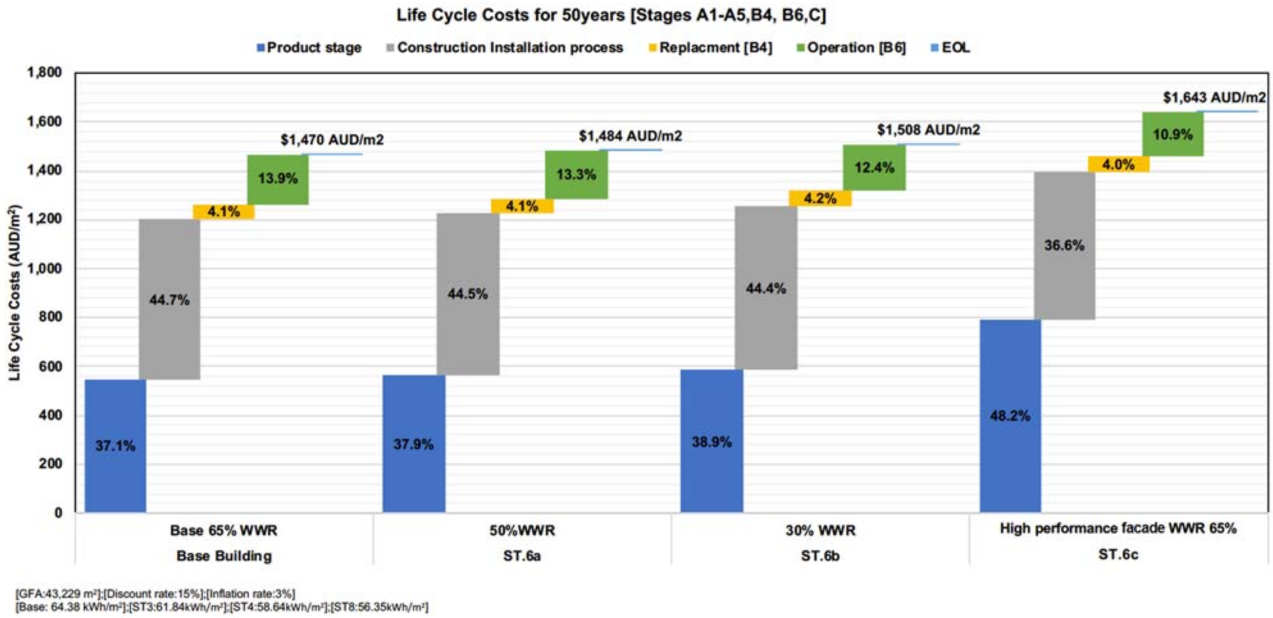


Figure 30 magnitude impacts of the changes in the building envelope on life cycle cost

9.6 Time value of carbon emissions

The previous sections show the economic and environmental impacts of alternative design solutions over the lifetime of a building by focusing on life cycle carbon emissions and cost. The results show as we implement energy efficiency measures, such as improved building façade (ST.6c), operating emissions have reduced, while embodied carbon emissions increase. Most embodied carbon emissions occur at the product stage of a building before it commences to operate. At this stage, embodied carbon emissions are responsible for 13,975 tCO_2-e to 20,902 tCO_2-e for two most carbon friendly design alternatives, namely mass timber (ST5.G) and post-tensioned concrete (ST2.G), respectively.

The operating emissions are cumulative and happen over the lifespan of the building. For instance, Figure 31 compares the amount of saved embodied carbon emissions against the operational carbon emissions by considering the examined (section 9.5) energy strategies. For the mass timber (ST5.G), the embodied carbon saving equates to more than eight years of cumulative operational carbon emissions. For the post-tensioned (ST2.G) building, the amount of carbon saving was approximated as nearly four years of operational emissions of the building. Combination of mass timber building with high-performance façade could potential have the lowest lifecycle carbon cumulatively.

Besides the cumulative carbon emissions over the building's lifetime, it is essential to consider when these emissions happen. Once a building has been built, the embodied carbon emissions have already been released into the atmosphere, and we cannot do anything to reduce it. However, the operational carbon emissions can potentially be reduced through continuing development in renewable energy generation plant and retrofitting buildings. While such saving in an individual building might seem to have a limited influence, expanding these savings into growing Australia's building market (Kelly (2018) estimated 4.8% annual growth by 2024) could potentially save up to 5.97 $MtCO_2$-e by 2024 or 0.95 $MtCO_2$-e per year (Considering 2017 Australian residential building stock which estimated by Bannister, Moffitt et al. (2018)). This trend highlights the significant impacts of decision-making process can have not only on project cost but also on the overall sustainability of buildings in Australia.

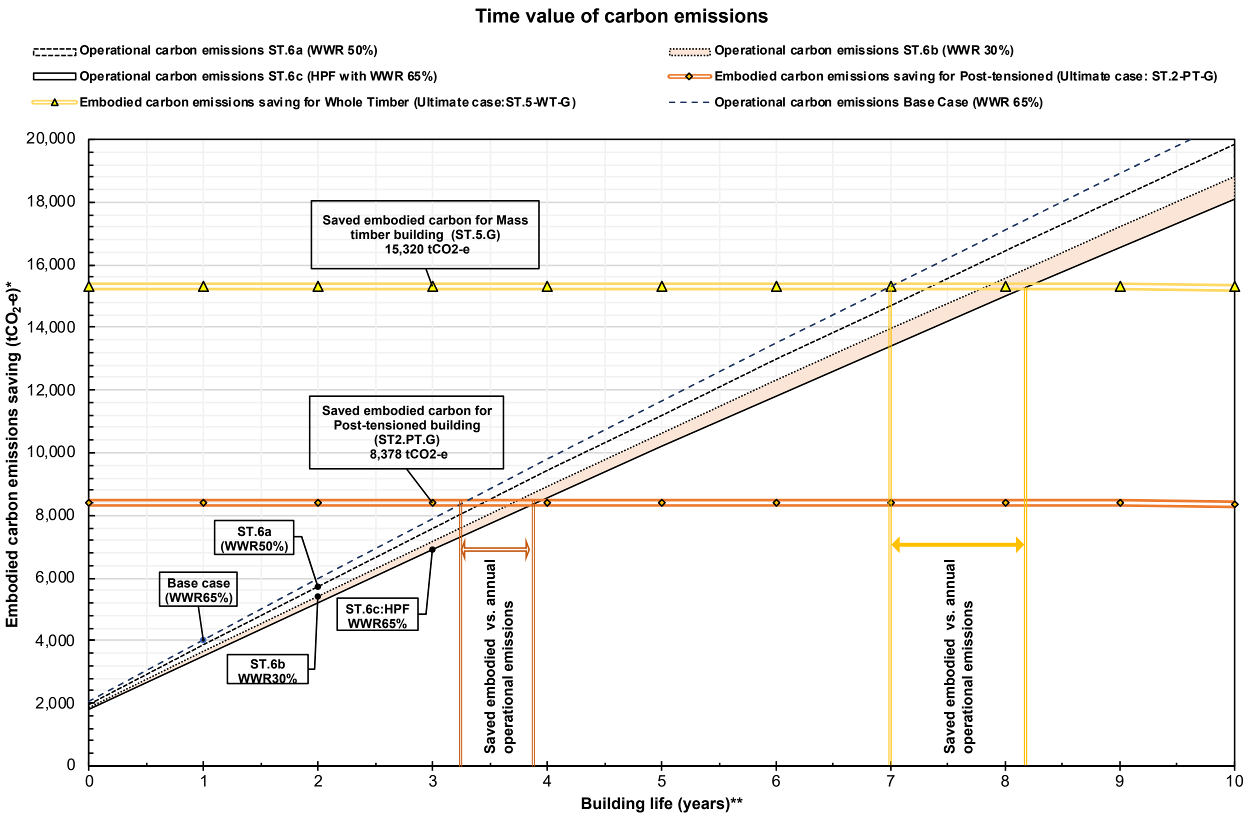


Figure 31 amount of saved embodied carbon emissions against the operational carbon emissions

Conclusion

Traditionally, a cost-effective strategy focused on several key variables and their implications on the capital cost of a project. While increasing environmental awareness raises a necessity for integration of carbon mitigation mechanism during the early stage of design.

The initial results of this study found that conventional Value Engineering (VE) practices as driven by cost savings can also contribute to carbon reduction through dematerialisation. However, this carbon saving was insignificant.

So, this research developed a holist Carbon Value Engineering (CVE) framework to evaluate cost and carbon emissions of alternative solutions at the early stage of the decision-making process. The obtained results of this study revealed a significant saving in the carbon emissions could be made through VE process without significantly affecting the building design. For a 22- storey building, the results show embodied carbon emissions saving in the order of 63-427 $kgCO_2$-e/m^2 while also obtaining 10% saving in the capital cost.

The develop CVE framework provides a potential mechanism to meet GreenStar's target to reduce embodied carbon emissions by 10% (from 2020) and 20% (after 2030), as embodied carbon emissions saving in this study found to be up 57%. This amount of saving in embodied carbon emissions equivalents to the several year's operation carbon emissions in a traditional passive design mechanism such as a high-performance façade building. In this study, building with a high-performance façade generates saving of 255 $kgCO_2$-e/m^2, while carbon value engineering demonstrated savings of up to 427 $kgCO_2/m^2$. It should be noticed once a building is built, there will find no way to reduce the emitted embodied carbon emissions. However, this will not be a case for operational carbon emissions due to continue development in power generations plant and retrofitting buildings. However, to truly reduce carbon emissions in buildings, it is vital to demonstrate holistic savings across all areas of a building's lifecycle, including both operational and embodied.

Taken together, these findings point out the important role for value engineering through lifetime cost and carbon emissions of a building. The sustainability of buildings is influenced by the unique features of each building and it is required a better understanding of the relation between material choice and lifetime performance of a building.

Reference

ABARES (2013). Australia's State of the Forests Report. Criterion 5 Maintenance of forest contribution to global carbon cycles.

ABCB (2016). National construction code. Canberra, Australian Building Codes Board.

Akbarnezhad, A. and J. Xiao (2017). "Estimation and minimization of embodied carbon of buildings: A review." Buildings **7**(1): 5.

Ambrose, M. and M. Syme (2017). "Air tightness of new Australian residential buildings." Procedia Engineering **180**: 33-40.

AS3600 (2009). Concrete structures. Sydney, Australia, Standards Australia International Ltd.

ASBEC and ClimateWorks (2018). Built to Perform, An industry led pathway to a zero carbon ready building code, Australian Sustainable Built Environment Council (ASBEC).

Ashworth, A. and S. Perera (2016). Cost studies of buildings. New York, Routledge.

Bannister, P., S. Moffitt, H. Zhang, D. Johnston, D. Shen, D. Robinson, P. Cooper, Z. Ma, L. Ledo, L. Green, L. Reedman and P. Harrington (2018). Building Code Energy Performance Trajectory project - Final Technical Report.

Bannister, P., D. Robinson, L. Reedman, P. Harrington, S. Moffitt, H. Zhang, D. Johnston, D. Shen, P. Cooper, Z. Ma, L. Ledo and L. Green (2018). Title Building Code Energy Performance Trajectory project - Final Technical Report.

Bolden, S. and H. Greaves (2008). Guide to the specification, installation and use of preservative treated engineered wood products Melbourne.

BORAL (2011). ENVISIA- Technical Data. B. CONCRETE, BORAL CONCRETE.

Carmichael, D. G. (2017). "Adjustments within discount rates to cater for uncertainty—Guidelines." The Engineering Economist **62**(4): 322-335.

CC (2016). Concrete framed buildings: a guide to design and construction. London, Concrete Centre.

Chiniforush, A. A., A. Akbarnezhad, H. Valipour and J. Xiao (2018). "Energy implications of using steel-timber composite (STC) elements in buildings." Energy and Buildings **176**: 203-215.

Chowdhury, A. A., M. Rasul and M. M. K. Khan (2008). "Thermal-comfort analysis and simulation for various low-energy cooling-technologies applied to an office building in a subtropical climate." Applied Energy **85**(6): 449-462.

Collins, F. (2010). "Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint." The International Journal of Life Cycle Assessment **15**(6): 549-556.

Crawford, R. (2011). Life cycle assessment in the built environment. New York, Spon Press.

Daly, D. (2015). Improving energy efficiency in lower quality commercial buildings: Simulation, retrofit optimisation and uncertainty. Doctor of Philosophy, University of Wollongong.

Daly, D., P. Cooper and Z. Ma (2014). "Implications of global warming for commercial building retrofitting in Australian cities." Building and Environment **74**: 86-95.

Darby, H., A. A. Elmualim and F. Kelly (2013). "A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building." SB13 Implementing Sustainability-Barriers and Chances.

de Castro, S. and J. de Brito (2013). "Evaluation of the durability of concrete made with crushed glass aggregates." Journal of Cleaner Production **41**: 7-14.

De Wolf, C., F. Pomponi and A. Moncaster (2017). "Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice." Energy and Buildings **140**: 68-80.

De Wolf, C. C. E. L. (2017). Low carbon pathways for structural design: embodied life cycle impacts of building structures, Massachusetts Institute of Technology.

DEE (2016). Australia's emissions projections 2016. Canberra, Australia, Department of the Environment and Energy.

DEE (2018). National greenhouse accounts factors. Canberra, Australia, Department of the Environment and Energy.

Economics, F. (2015). Electricity market forecasts: 2015. Sydney, Frontier Economics.

ECTA (2011). Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations.

Eleftheriadis, S., Y. Schwartz, R. Raslan, P. Duffour, D. J. B. S. Mumovic and Optimization (2018). "Integrated building life cycle carbon and cost analysis embedding multiple optimisation levels."

EN15978 (2011). Sustainability of construction works : assessment of environmental performance of buildings : calculation method. United Kingdom, British Standards Institution.

EnergyPlus. (2017). "Weather data sources." Retrieved 1/02/2017, from https://energyplus.net/weather/sources#RMY.

eTool. (2014). "Life cycle assessment online tool." Retrieved 23/6/2015, from http://etoolglobal.com/.

Fuller, S. (2010). "Life-cycle cost analysis (LCCA)." National Institute of Building Sciences, An Authoritative Source of Innovative Solutions for the Built Environment **1090**.

García-Segura, T., V. Yepes and J. Alcalá (2014). "Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability." The International Journal of Life Cycle Assessment **19**(1): 3-12.

GBCA (2008). Green star multi-unit residential energy calculator benchmarking methodology Green Building Council of Australia (GBCA)

GBCA (2018). A Carbon Positive Roadmap for the built environment, Stage 1: Commercial, institutional, and government buildings and fitouts, Green Building Council of Australia.

Hanid, M., M. Siriwardena and L. Koskela (2011). What are the big issues in cost management? RICS Construction and Property Conference.

Hong, T., C. Ji, M. Jang and H. Park (2013). "Assessment model for energy consumption and greenhouse gas emissions during building

construction." Journal of Management in Engineering **30**(2): 226-235.
Hunkeler, D., K. Lichtenvort and G. Rebitzer (2008). Environmental life cycle costing. Boca Raton, CRC Press.
ICANZ (2016). Insulation handbook part 1: Thermal Performance- version 3, Insulation Council of Australia and New Zealand**:** 32.
Illankoon, I. M. C. S., V. W. Y. Tam, K. N. Le and J. Y. Wang (2018). "Life cycle costing for obtaining concrete credits in green star rating system in Australia." Journal of Cleaner Production **172**: 4212-4219.
Ingrao, C., A. L. Giudice, C. Tricase, C. Mbohwa and R. Rana (2014). "The use of basalt aggregates in the production of concrete for the prefabrication industry: Environmental impact assessment, interpretation and improvement." Journal of Cleaner Production **75**: 195-204.
ISO15673 (2005). Guidelines for the simplified design of structural reinforced concrete for buildings. Switzerland, The International Organization for Standardization.
Jacobs (2016). Retail electricity price history and projections - Public. Melbourne, Australia, Jacobs Australia Pty Limited.
Jacoby, P. C. and F. Pelisser (2015). "Pozzolanic effect of porcelain polishing residue in Portland cement." Journal of Cleaner Production **100**: 84-88.
Kelly, A. (2018). Multi-Unit Apartment and Townhouse Construction in Australia. IBISWorld Industry Report E3019.
Kestner, D. M., J. Goupil and E. Lorenz (2010). Sustainability guidelines for the structural engineer, American Society of Civil Engineers (ASCE).
Keyte, L., R. Lloyd, C. Holt, J. Chandler, D. Hocking and T. Thomas (2017). Low-Carbon Post-Tensioned Concrete. 28th Biennial National Conference of the Australia 2017, . 22-25 October 2017., At Adelaide, Australia, Concrete Institute of Australia.
Kozlovská, M., M. Krajnak, L. Sirochmanova, R. Baskova and Z. Strukova (2015). "New approaches to specifying performance of construction machinery." Građevinar **67**(07.): 673-680.
Kremer, P. and M. Symmons (2015). "Mass timber construction as an alternative to concrete and steel in the Australia building industry: a PESTEL evaluation of the potential." International Wood Products Journal **6**(3): 138-147.
Kumar, B. M. and P. R. Nair (2011). Carbon sequestration potential of agroforestry systems: opportunities and challenges, Springer Science & Business Media.
Le, K. N., V. W. Tam, C. N. Tran, J. Wang and B. J. I. T. o. E. M. Goggins (2018). "Life-Cycle Greenhouse Gas Emission Analyses for Green Star's Concrete Credits in Australia." (99): 1-13.
Mearig, T., N. Coffee and M. Morgan (1999). Life cycle cost analysis handbook:Draft. Juneau, State of Alaska, Department of Education and Early Development, Education Support Services/Facilities.
Mehta, P. K. (2002). "Greeningof the Concrete Industry for Sustainable Development." Concrete international **23**.
Moussavi Nadoushani, Z. S. and A. Akbarnezhad (2015). "Effects of structural system on the life cycle carbon footprint of buildings." Energy and Buildings **102**: 337-346.
Nadoushani, Z. M. and A. Akbarnezha (2014). A computational framework for estimating the carbon footprint of construction. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, IAARC Publications.
Oh, B. K., J. S. Park, S. W. Choi and H. S. Park (2016). "Design model for analysis of relationships among CO2 emissions, cost, and structural parameters in green building construction with composite columns." Energy and Buildings **118**: 301-315.
PCA. (2015). "Global cement consumption on the rise." from http://www.cement.org/newsroom/2015/06/03/global-cement-consumption-on-the-rise.
PHI (2016). **Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard**. Germany.
Pitt&Sherry (2012). Baseline energy consumption and greenhouse gas emissions In commercial buildings in Australia. Part 1 - Report. Council of Australian Governments (COAG) National Strategy on Energy Efficiency.
Poinssot, C., S. Bourg, N. Ouvrier, N. Combernoux, C. Rostaing, M. Vargas-Gonzalez and J. Bruno (2014). "Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles." Energy **69**: 199-211.
Priastiwi, Y., A. Han, A. Maryoto and E. Noor (2017). Experimental study on the use of steel-decks for prefabricated reinforced concrete beams. IOP Conference Series: Materials Science and Engineering, IOP Publishing.
Rahman, M. M., M. Rasul and M. M. K. Khan (2010). "Energy conservation measures in an institutional building in sub-tropical climate in Australia." Applied Energy **87**(10): 2994-3004.
Rahman, M. M., M. Rasul and M. M. K. Khan (2011). "Feasibility of thermal energy storage systems in an institutional building in subtropical climates in Australia." Applied Thermal Engineering **31**(14): 2943-2950.
Rauf, A. and R. H. Crawford (2012). The effect of material service life on the life cycle energy of residential buildings. ASA2012: The 46th Annual Conference of the Architectural Science Association (formerly ANZAScA)–Building on Knowledge: Theory and Practice, Department of Architecture, Griffith University Gold Coast.
Rawlinsons (2017). Rawlinsons construction cost guide 2017. Perth, Rawlinsons Group.
RBA. (2016). "Reserve Bank of Australia—Inflation target." Retrieved 20/20/2017, from http://www.rba.gov.au/monetary-policy/inflation-target.html.
RICS (2013). Sustainability and commercial property valuation. London.
RICS (2017). Whole life carbon assessment for the built environment. London.
Robati, M., T. J. McCarthy and G. Kokogiannakis (2017). A method of uncertainty analysis for life cycle embodied CO2-e of building and structural materials in Australia. 28th Biennial National Conference of the

Concrete Institute of Australia. Adelaide, Concrete Institute of Australia (CIA).
Robati, M., T. J. McCarthy and G. Kokogiannakis (2018). "Integrated life cycle cost method for sustainable structural design by focusing on a benchmark office building in Australia." Energy and Buildings.
Sandanayake, M., G. Zhang and S. Setunge (2016). "Environmental emissions at foundation construction stage of buildings–Two case studies." Building and Environment **95**: 189-198.
SEA-DISTANCES. (2019). "port distances." Retrieved 17/2/2019, from https://sea-distances.org/.
Souto-Martinez, A., J. H. Arehart and W. V. Srubar (2018). "Cradle-to-gate CO2e emissions vs. in situ CO2 sequestration of structural concrete elements." Energy and Buildings **167**: 301-311.
Survey, U. S. G. (2015). Mineral commodity summaries 2015. Washington, U.S. Geological Survey.
Teh, S. H. (2018). Integrated carbon metrics and assessment for the built environment. Sydney, Environmental Engineering, Faculty of Engineering Unsw.
Torgal, F. P. and S. Jalali (2011). Eco-efficient construction and building materials. Philadelphia, Woodhead Publishing.
Weight, D. H. (2011). "Embodied through-life carbon dioxide equivalent assessment for timber products." Proceedings of the Institution of Civil Engineers - Energy **164**(4): 167-182.
Whitehead, B., D. Andrews, A. Shah and G. Maidment (2014). "Assessing the environmental impact of data centres part 1: Background, energy use and metrics." Building and Environment **82**: 151-159.
WoodSolutions (2017). Environmental Product Declaration Plywood. Australia, Forest and Wood Products Australia.
Ximenes, F. (2006). "Carbon storage in wood products in Australia: a review of the current state of knowledge." Report prepared by Forest and Wood Products Research and Development Corporation. Accessible online at: http://fwprdc. org. au/asp.
Yang, K.-H., E.-A. Seo and S.-H. Tae (2014). "Carbonation and CO2 uptake of concrete." Environmental Impact Assessment Review **46**: 43-52.
Zhang, G., M. Sandanayake, S. Setunge, C. Li and J. Fang (2017). "Selection of emission factor standards for estimating emissions from diesel construction equipment in building construction in the Australian context." Journal of environmental management **187**: 527-536.

Appendix 1: Summary of building materials and quantities

This appendix summarises the materials lifespan and quantities across various design solutions.

Table A.1- 1 Summary of material quantities and lifespans across alternative solutions (Base case, ST.1-ST.6)

						ST1		ADDED	ST2			ST3			ST4			ST5			ST6a			ST6b			ST6c		
				Base case		Flat Slab	REMOVED	REDUCED	PT Slab			Metal deck			CLT			Timber			50%			30%			65%		
Category	Materials	RICS Lifetime	Unit	Quantities	Unit	Quantities	%	Variables	Quantities	%	Variables	Quantities	%	Variables	Quantities	%	Variables	Quantities	%	Variables	Quantities	%	Variables	Quantities	%	Variables	Quantities	%	Variables
Substructure	Excavation and Eathworks.rock	0	years	330	m3	330	0%	---	330	0%	---	330	0%		330	0%		330	0%		330	0%		330	0%		0	0%	
	Disposal.rock	0	years	24	m3	24	0%	---	24	0%	---	24	0%		24	0%		24	0%		24	0%		24	0%		0	0%	
	Padding & foundation50 Mpa	110	years	903	m3	891.68	-1%	REDUCED	892	-1%	REDUCED	867	-4%	REDUCED	684	-24%	REDUCED	760	-16%	REDUCED	903	0%		903	0%		0	0%	
	Padding & foundation.Steel Reinforcing	110	years	170	t	109.69	-35%	REDUCED	100	-41%	REDUCED	57	-67%	REDUCED	38	-78%	REDUCED	39	-77%	REDUCED	170	0%		170	0%		0	0%	
Superstructure	Formwork. Timber	3	times	86,939	m2	63969.63	-26%	REDUCED	63,890	-27%	REDUCED	18,928	-78%	REDUCED	18,557	-79%	REDUCED	37,278	-57%	REDUCED	86,939	0%		86,939	0%		0	0%	
	32 Mpa	81	years	1,026	m3	0.00	-100%	REMOVED	0	-100%	REMOVED	-	-100%	REMOVED	-	-100%	REMOVED	-	-100%	REMOVED	1,026	0%		1,026	0%		0	0%	
	40 Mpa	81	years	12,710	m3	12234.74	-4%	REDUCED	10,326	-19%	REDUCED	4,323	-66%	REDUCED	961	-92%	REDUCED	208	-98%	REDUCED	12,710	0%		12,710	0%		0	0%	
	50 Mpa	81	years	635	m3	0.00	-100%	REMOVED	0	-100%	REMOVED	-	-100%	REMOVED	-	-100%	REMOVED	-	-100%	REMOVED	635	0%		635	0%		0	0%	
	65 Mpa	81	years	2,451	m3	2544.08	4%	ADDED	2,670	9%	ADDED	2,471	1%	ADDED	2,471	1%	REDUCED	3,087	26%	ADDED	2,451	0%		2,451	0%		0	0%	
	Steel Reinforcing	83	years	2,165	t	1429.27	-34%	REDUCED	954	-56%	REDUCED	473	-78%	REDUCED	266	-88%	REMOVED	106	-95%	REDUCED	2,165	0%		2,165	0%		0	0%	
	Post Tensioning	81	years	275	t	0.00	-100%	REMOVED	549	100%	ADDED	-	-100%	REMOVED	-	-100%	REMOVED	122	-56%	REDUCED	275	0%		275	0%		0	0%	
	Steel work	83	years	59	t	59	0%	---	59	0%	---	2,173		ADDED	2,345		ADDED	59	0%	---	59	0%		59	0%		0	0%	
	Precast.Concrete	81	years	656	m3	656	0%	---	656	0%	---	819	25%	ADDED	946	44%	ADDED	922	41%	ADDED	656	0%		656	0%		0	0%	
External finishes	Glazed façade- Block 1	30	years	13,806	m2	13,806	0%	---	13,806	0%	---	13,806	0%	---	13,806	0%	---	13,806	0%	---	12,342	-11%	REDUCED	10389.3	-25%	REDUCED	0	0%	
Superstructure	Formwork. Steel	81	years	0	m2	0	0%	---	0	0%	---	43,229		ADDED	9,606		ADDED	0	0%	---	0	0%		0	0%		0	0%	
External finishes	Aluminium	35	years	2,715	m2	2,715	0%	---	2,715	0%	---	3,211	18%	ADDED	3,597	32%	ADDED	3,525	30%	ADDED	4,179	54%	ADDED	6131.702	126%	ADDED	0	0%	
	Stone	30	years	556	m2	556	0%	---	556	0%	---	556	0%	---	556	0%	---	556	0%	---	556	0%		556	0%		0	0%	
	Timber	30	years	6	m3	6	0%	---	6	0%	---	6	0%	---	6	0%	---	6	0%	---	6	0%		6	0%		0	0%	
	Roof.Concrete Pavers	30	years	649	m2	649	0%	---	649	0%	---	649	0%	---	649	0%	---	649	0%	---	649	0%		649	0%		0	0%	
	Roof.Ballast	30	years	1,894	m2	1,894	0%	---	1,894	0%	---	1,894	0%	---	1,894	0%	---	1,894	0%	---	1,894	0%		1,894	0%		0	0%	
	Roof.Waterproofing membrane	30	years	259	m2	259	0%	---	259	0%	---	259	0%	---	259	0%	---	259	0%	---	259	0%		259	0%		0	0%	
	Roof.Alpolic	30	years	1,422	m2	1,422	0%	---	1,422	0%	---	1,422	0%	---	1,422	0%	---	1,422	0%	---	1,422	0%		1,422	0%		0	0%	
Superstructure	Timber CLT	81	years	0	m2	0	0%	---	0	0%	---	-	0%	---	8,070		ADDED	8,070	0%	---	0	0%		0	0%		0	0%	
Internal finishes	Blockwork & Brickwork	50	years	5,298	m2	5,298	0%	---	5,298	0%	---	5,298	0%	---	5,298	0%	---	5,298	0%	---	5,298	0%		5,298	0%		0	0%	
	Acoustic & Thermal Insulation	30	years	11,048	m2	11,048	0%	ADDED	12,816	16%	ADDED	11,632	5%	ADDED	11,473	4%	ADDED	11,858	7%	ADDED	12,513	13%	ADDED	14464.96	31%	ADDED	6336.696	43%	ADDED
	Suspended Ceilings.Plasterboard	20	years	24,084	m2	24,084	0%	---	24,084	0%	---	24,084	0%	---	24,084	0%	---	24,084	0%	---	24,084	0%		24,084	0%		0	0%	
	Suspended Ceilings.cement fiber	20	years	112	m2	112	0%	---	112	0%	---	112	0%	---	112	0%	---	112	0%	---	112	0%		112	0%		0	0%	
Superstructure	Timber (Glulam and LVL)	81	years	0	m2	0	0%	---	0	0%	---	-	0%	---	0	0%	---	1,196	0%	---	0	0%		0	0%		0	0%	
Internal finishes	Suspended Ceilings.VeneerTimber	20	years	369	m2	369	0%	---	369	0%	---	369	0%	---	369	0%	---	369	0%	---	369	0%		369	0%		0	0%	
	Partitions - Framed & Lined. Plaster	30	years	52,719	m2	52,719	0%	ADDED	56,254	7%	ADDED	54,382	3%	ADDED	54,451	3%	ADDED	55,148	5%	ADDED	54,184	3%	ADDED	56135.9	6%	ADDED	0	0%	
	Partitions - Framed & Lined. Wall. AAC	30	years	29,813	m2	29,813	0%	---	29,813	0%	---	29,857	0.15%	ADDED	29,891	0.26%	ADDED	29,884	0%	---	29,813	0%		29,813	0%		0	0%	
	Plastering/ Rendering	30	years	1,410	m2	1,410	0%	---	1,410	0%	---	1,410	0%	---	1,410	0%	---	1,410	0%	---	1,410	0%		1,410	0%		0	0%	
	Internal Waterproofing	50	years	21,489	m2	21,489	0%	---	21,489	0%	---	22,029	3%	ADDED	22,448	4%	ADDED	22,369	4%	ADDED	22,953	7%	ADDED	24905.26	16%	ADDED	0	0%	
	Cementitious Topping	50	years	4,054	m2	4,054	0%	---	4,054	0%	---	4,054	0%	---	4,054	0%		4,054	0%	---	4,054	0%		4,054	0%		0	0%	
	Painting	10	years	82,532	m2	82,532	0%	ADDED	86,067	4%	ADDED	84,239	2%	ADDED	84,341	2%	ADDED	85,032	3%	ADDED	83,997	2%	ADDED	89365.6	8%	ADDED	0	0%	
	Resilent Finishes	30	years	75	m2	75	0%	---	75	0%	---	75	0%	---	75	0%	---	75	0%	---	75	0%		75	0%		0	0%	
Fitting elements	Screens	30	years	2,376	m	2,376	0%	---	2,376	0%	---	2,376	0%	---	2,376	0%	---	2,376	0%	---	2,376	0%		2,376	0%		0	0%	
	Aluminium frame	30	years	3,021	m2	3,021	0%	---	3,021	0%	---	3,021	0%	---	3,021	0%	---	3,021	0%	---	3,021	0%		3,021	0%		0	0%	
	Timber Frame	30	years	4,902	m2	4,902	0%	---	4,902	0%	---	4,902	0%	---	4,902	0%	---	4,902	0%	---	4,902	0%		4,902	0%		0	0%	
	vork- General (Gates, Bollards, Sundry Metalwork). Galv	30	years	3,114	m2	3,114	0%	---	3,114	0%	---	3,114	0%	---	3,114	0%	---	3,114	0%	---	3,114	0%		3,114	0%		0	0%	
	Metalwork- Shower screens	30	years	883	m2	883	0%	---	883	0%	---	883	0%	---	883	0%	---	883	0%	---	883	0%		883	0%		0	0%	
	Metalwork- Balustrades and Handrails	50	years	965	m	965	0%	---	965	0%	---	965	0%	---	965	0%	---	965	0%	---	965	0%		965	0%		0	0%	
	Carpet Flooring	10	years	7,449	m2	7,449	0%	---	7,449	0%	---	7,449	0%	---	7,449	0%	---	7,449	0%	---	7,449	0%		7,449	0%		0	0%	
	Timber Flooring	30	years	10,375	m2	10,375	0%	---	10,375	0%	---	10,375	0%	---	10,375	0%	---	10,375	0%	---	10,375	0%		10,375	0%		0	0%	
	Tiling	30	years	22,314	m2	22,314	0%	---	22,314	0%	---	22,314	0%	---	22,314	0%	---	22,314	0%	---	22,314	0%		22,314	0%		0	0%	
	Mirrors and Glazing	30	years	1,149	m2	1,149	0%	---	1,149	0%	---	1,149	0%	---	1,149	0%	---	1,149	0%	---	1,149	0%		1,149	0%		0	0%	
External works	External Waterproofing	30	years	4,626	m2	4,626	0%	---	4,626	0%	---	4,626	0%	---	4,626	0%	---	4,626	0%	---	4,626	0%		4,626	0%		0	0%	

Appendix 2: Operational Carbon emissions

The following table summarises an average annual energy consumption across various type of building in Australia.

Table A.2- 1 summary of annual energy consumption across various type of building in Australia

Type of building	Energy consumptions (kWh/m^2 per year)	source
Single Apartment	69.2	(ASBEC and ClimateWorks 2018)
Attached House	44.8	(ASBEC and ClimateWorks 2018)
Detached house	42.7	(ASBEC and ClimateWorks 2018)
Office	93.2	(ASBEC and ClimateWorks 2018)
Retail	116.3	(ASBEC and ClimateWorks 2018)
Hotel	114.7	(ASBEC and ClimateWorks 2018)
Hospital ward	137.9	(ASBEC and ClimateWorks 2018)
School building	84.6	(ASBEC and ClimateWorks 2018)
Carpark	55.47	(GBCA 2008)
Foyers, hallways, corridors	8.76	(GBCA 2008)

Appendix 3: MACC results

The following figures provide MACC results for the alternative strategies which was named as ST.1 to ST.6c.

Figure A.3-1 shows the MACC for the flat slab concrete scenarios, as compared with the the base case. It can be seen that the highest saving was achieved by reducing the size of structural elements and quantities of formwork. However, the greatest embodied carbon emission saving was for structural concrete (32MPa) which has been used for slabs. Changing structural systems also introduced extra cost and carbon emissions through used high strength concrete (65 MPa).

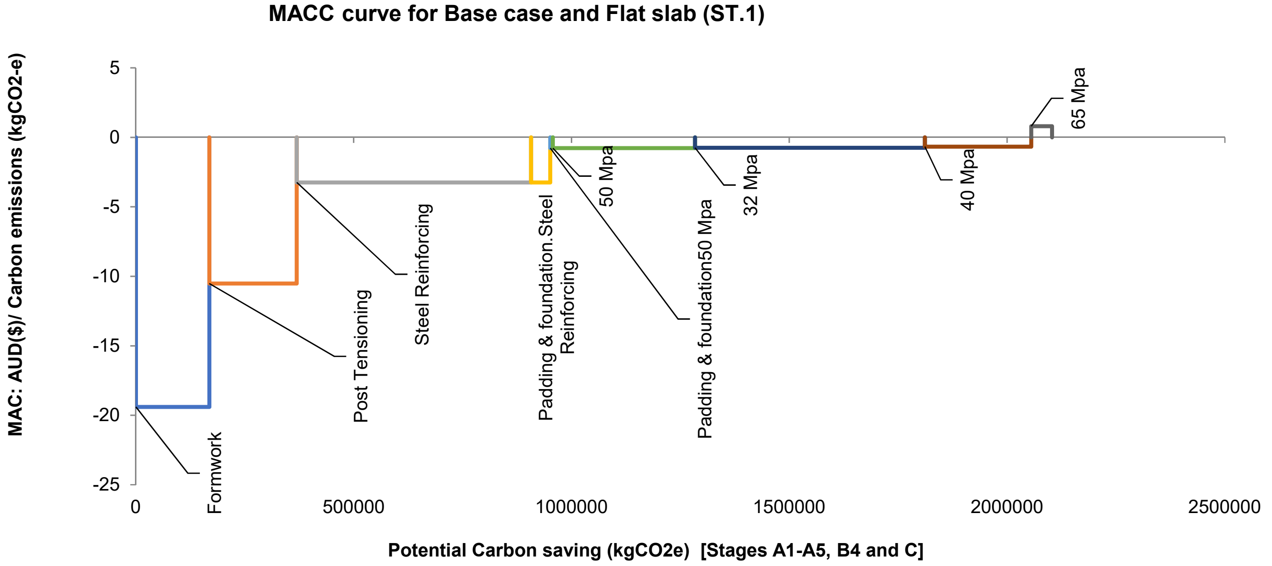


Figure A.3-1 MACC curve for Base case and Flat slab (ST.1)

Figure A.3-2 to A.3-7 show the MACC for the Post-tensioned concrete scenarios, as compared with the base case. These figures provide the direct and indirect changes associated with various strategies (sensitivity analysis results). It can be seen that the highest cost saving was dominantly achieved by reducing the size of structural elements (slabs, columns and footing) and quantities of formwork. However, changing the structural systems has an indirect impact on the internal finishes due to changes into the structural wall and columns configurations. The changes in the structural systems have led to the additional cost and carbon for the post-tensioning and the internal finishes. However, the longer life span (Figure A.3-3) and considering carbon sequestrations (Figure A.3-4) have reduced their potential impacts on carbon and cost of the building. Also, considering geopolymer concrete in the design of the building could significantly reduce carbon emissions associated with the structural concrete (Figure A.3-5). Despite the extra cost and carbon emissions due to sourcing timber products from Europe, the highest saving in cost still achieved in the formwork component (Figure A.3-6). In the case of the ultimate scenario (Figure A.3-7), the highest carbon and cost saving occurred in the structural materials and formwork, respectively.

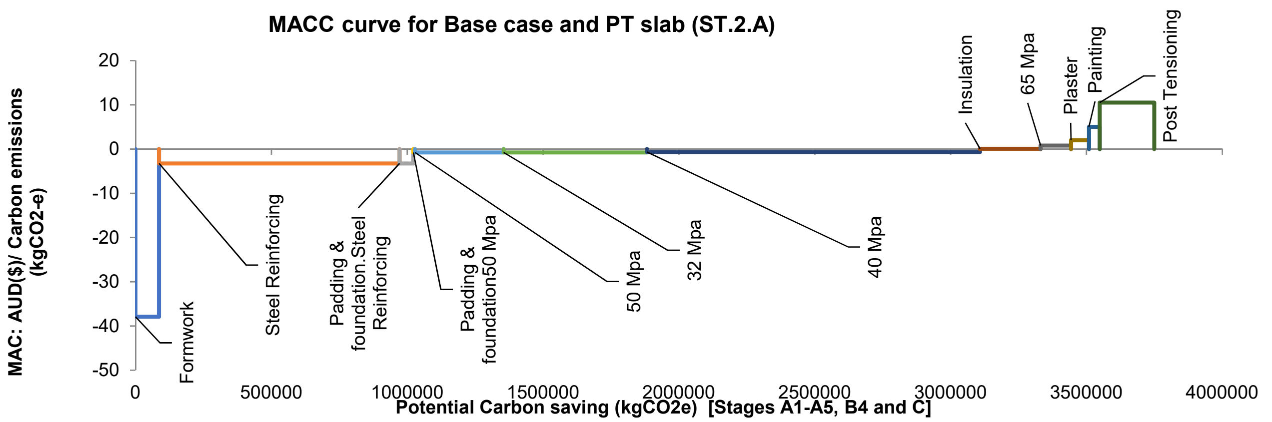


Figure A.3-2 MACC curve for Base case and Post- tensioned (ST.2.A)

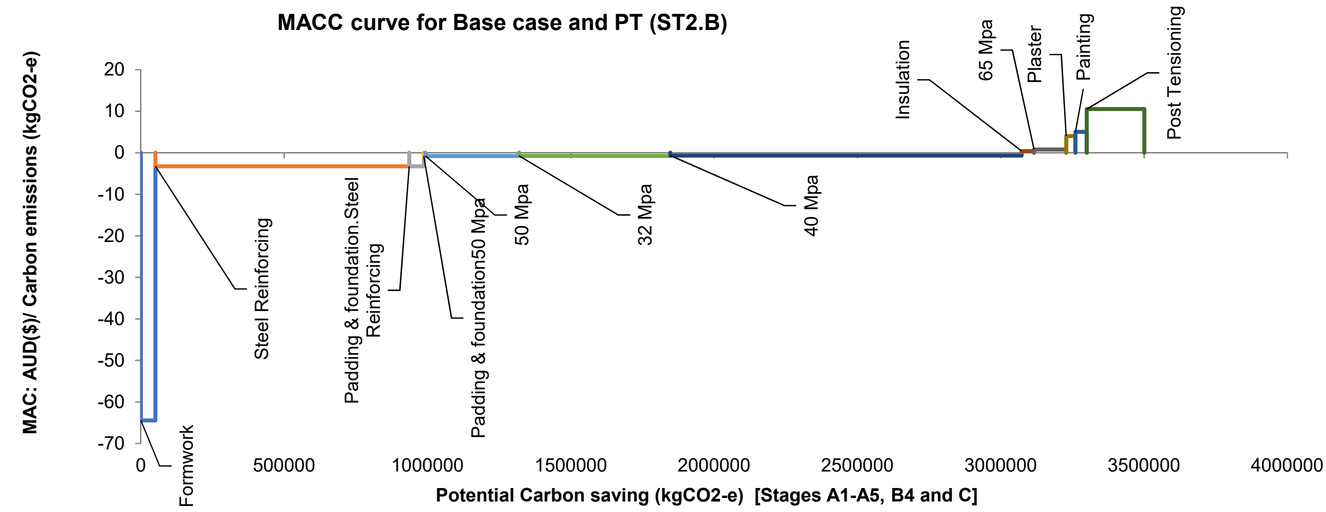


Figure A.3-3 MACC curve for Base case and Post- tensioned (ST.2.B)

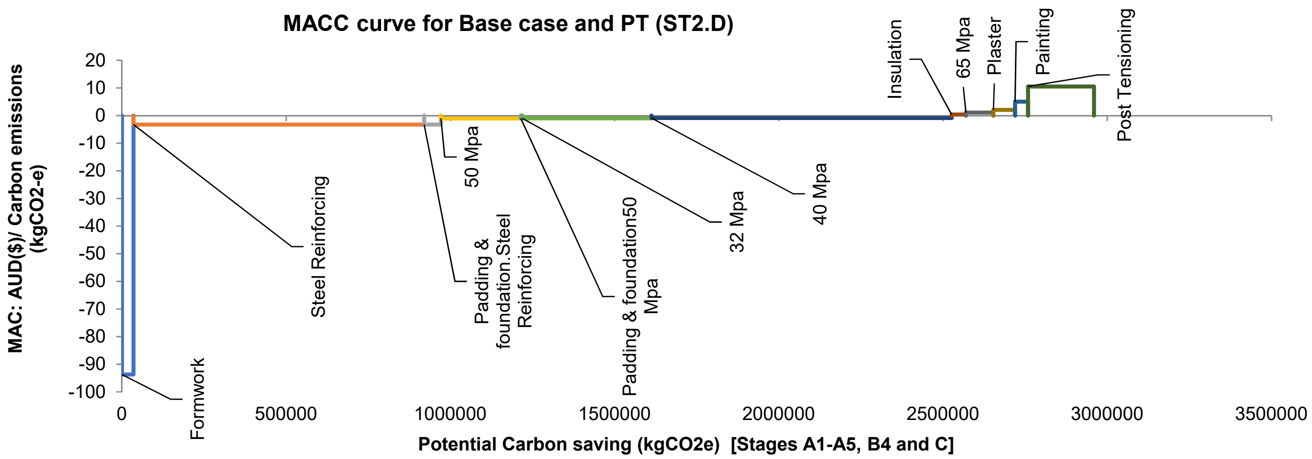


Figure A.3-4 MACC curve for Base case and Post- tensioned (ST.2.D)

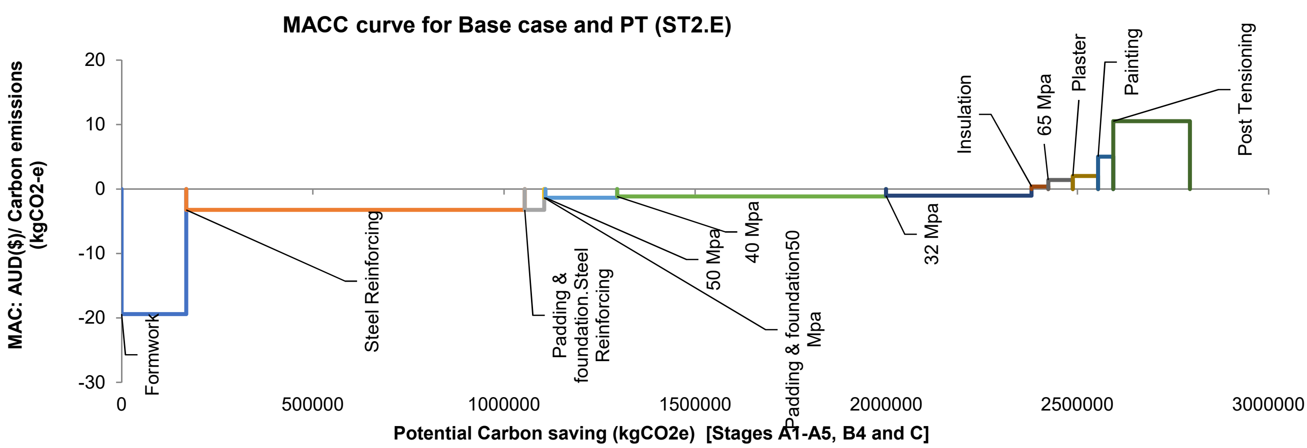


Figure A.3-5 MACC curve for Base case and Post- tensioned (ST.2.E)

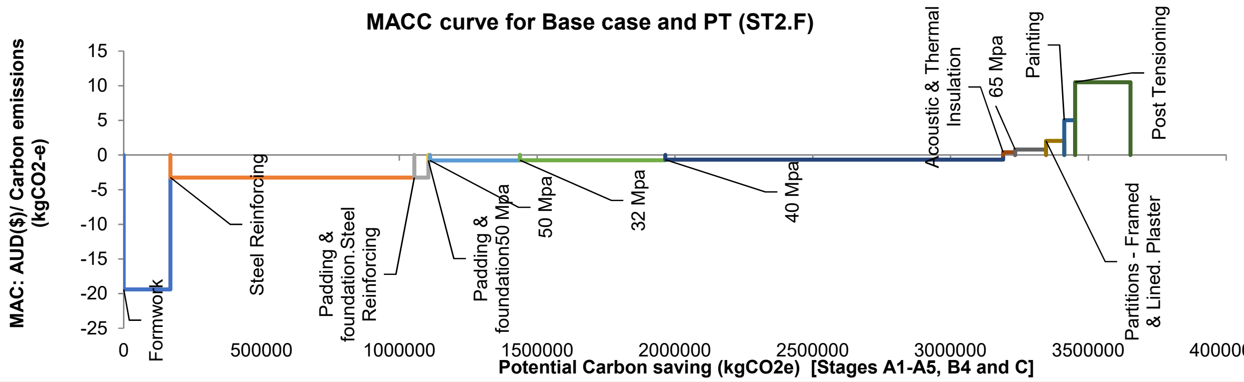


Figure A.3-6 MACC curve for Base case and Post- tensioned (ST.2.F)

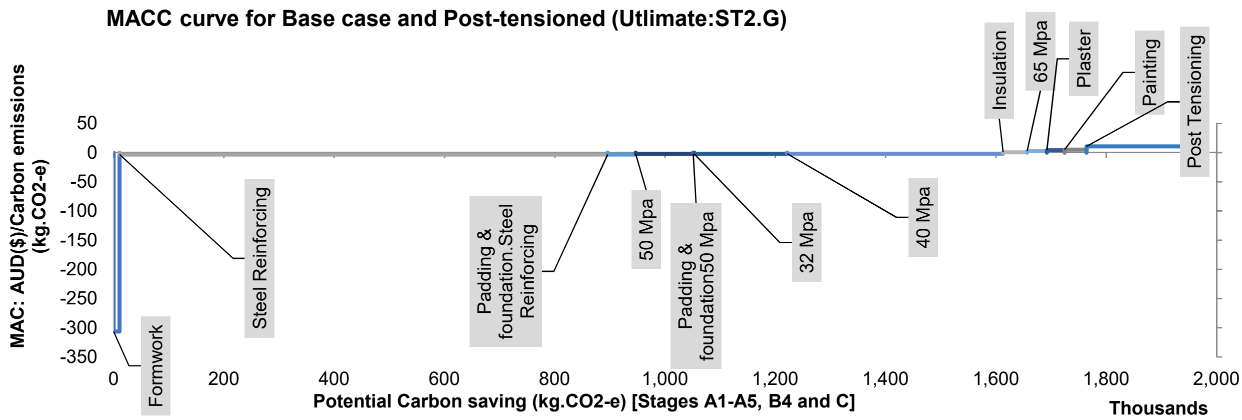


Figure A.3-7 MACC curve for Base case and Post-tensioned (Utlimate: ST2.G)

Figure A.3-8 shows MACC curve for the building comprises a steel deck in compare with the base case. As mentioned above, formwork and structural concrete (32 MPa, 40 MPa and 50MPa) have the highest cost and carbon saving, respectively. However, changing construction systems to Steel deck introduced extra cost and carbon emissions in the external and internal finishes. It can be seen that the aluminium component (external finishes) and added steel formwork have the highest added cost and carbon emissions, respectively.

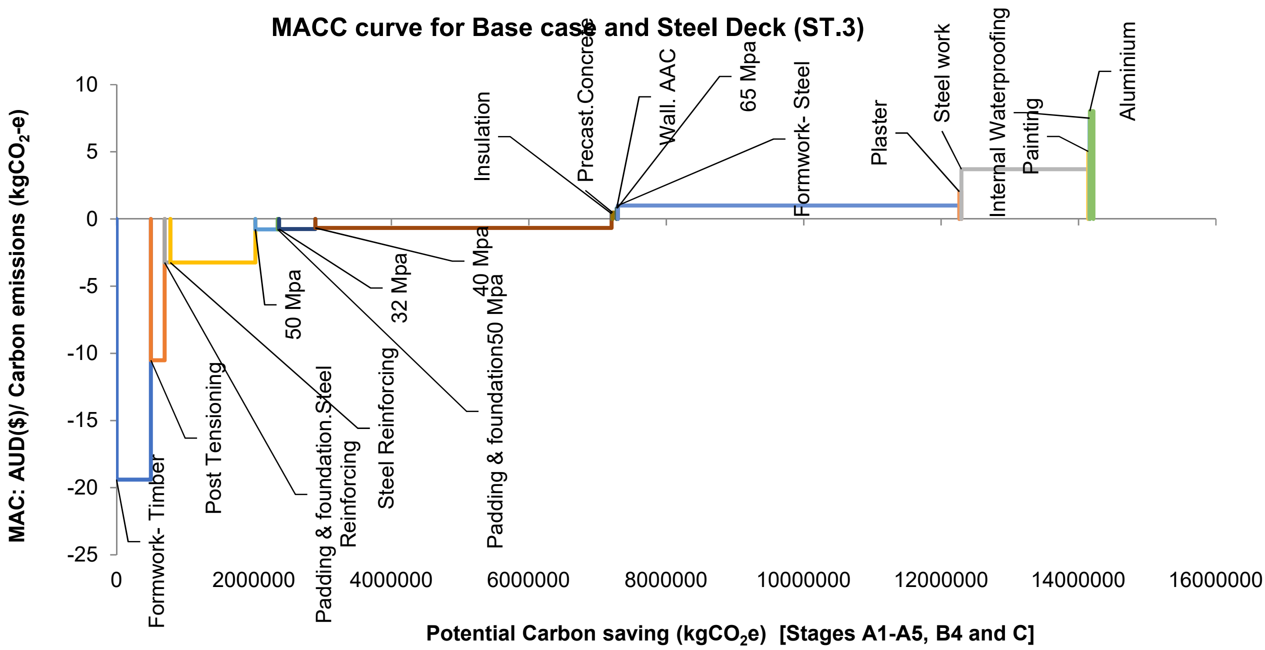


Figure A.3-8 MACC curve for Base case and steel deck (ST.3)

Figure A.3-9 provides a MACC curve for the building contains CLT elements in the steel structure (ST.4) and the base case. Similar to the previous cases, formwork and structural concrete (32 MPa, 40 MPa and 50MPa) have the highest cost and carbon saving, respectively. However, changing construction systems to CLT introduced extra cost and carbon emissions in the external and internal finishes. It can be seen that the aluminium component (external finishes) and added CLT components have the highest added cost and carbon emissions, respectively.

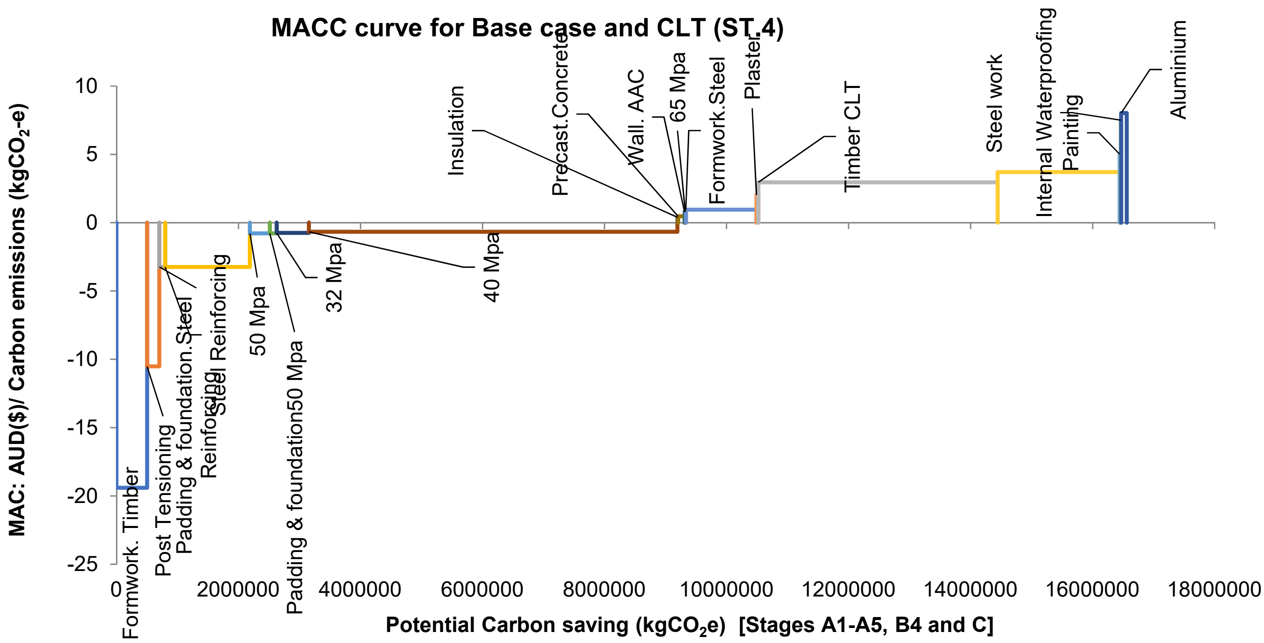


Figure A.3-9 MACC curve for Base case and CLT (ST.4)

Figure A.3-10 to A.3-15 show the MACC for the Mass timber scenarios (ST.5), as compared with the base case. These figures provide the direct and indirect changes associated with various strategies (sensitivity analysis results). Similar to the previous cases, it can be seen that the highest cost saving was dominantly achieved by reducing the size of structural elements (slabs, columns and footing) and quantities of formwork. However, changing the structural systems has an indirect impact on the internal finishes due to changes into the structural wall and columns configurations. The changes in the structural systems have led to the additional cost and carbon for the aluminium as an external component and the internal finishes. These changes in the external and internal finishes are mainly due to the increased slab thickness in the timber. The results show that the longer life span (Figure A.3-11) and considering carbon sequestrations (Figure A.3-12) have reduced the potential impacts of building materials on carbon and cost of the building. Also, considering geopolymer concrete in the design of the building could significantly reduce carbon emissions associated with the structural concrete (Figure A.3-13). Sourcing timber products from Europe added to the overall carbon emissions and cost of the building. However, the highest saving in cost still achieved in the formwork component (Figure A.3-14). In the case of the ultimate scenario (Figure A.3-15), the highest carbon and cost saving occurred in the structural materials and formwork, respectively. Also, the flooring system (timber CLT) and external materials (aluminium) are the most carbon and cost-intensive components.

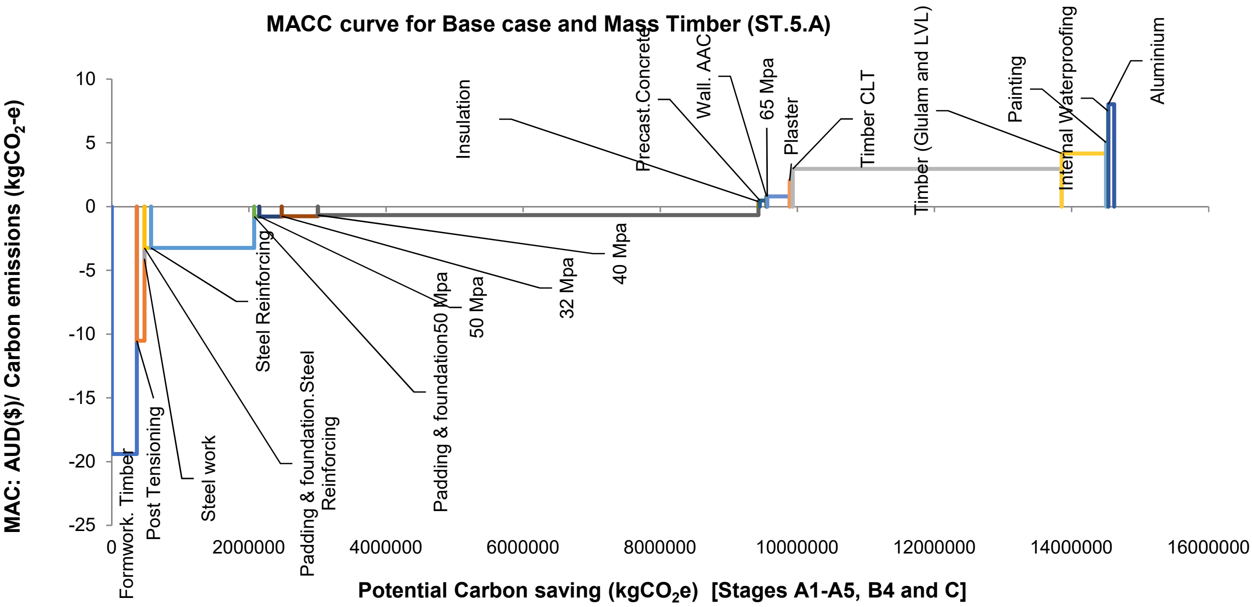


Figure A.3-10 MACC curve for Base case and Mass Timber (ST.5.A)

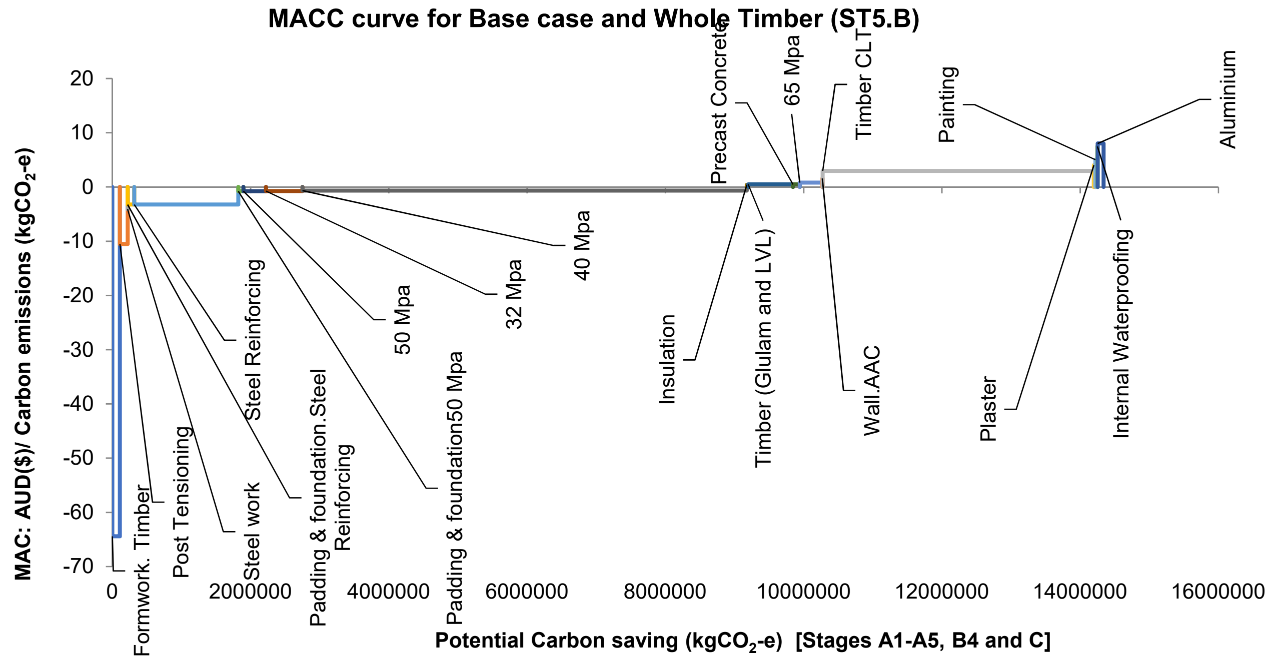


Figure A.3-11 MACC curve for Base case and Mass Timber (ST.5.B)

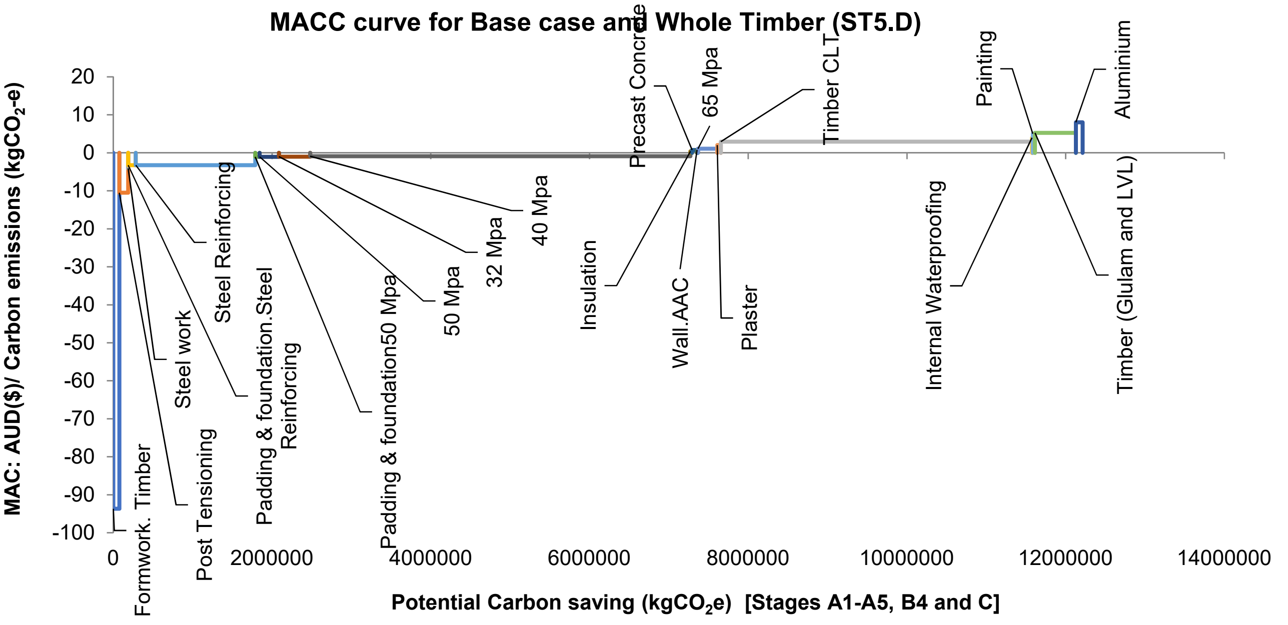


Figure A.3-12 MACC curve for Base case and Mass Timber (ST5.D)

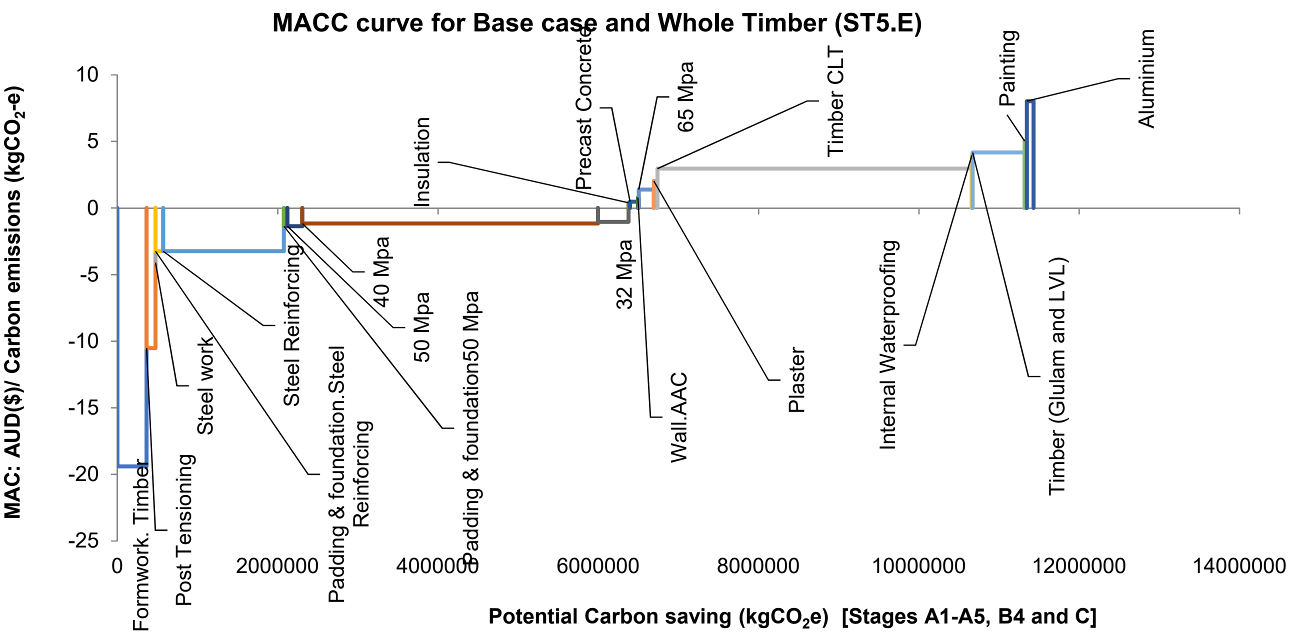


Figure A.3-13 MACC curve for Base case and Mass Timber (ST.5.E)

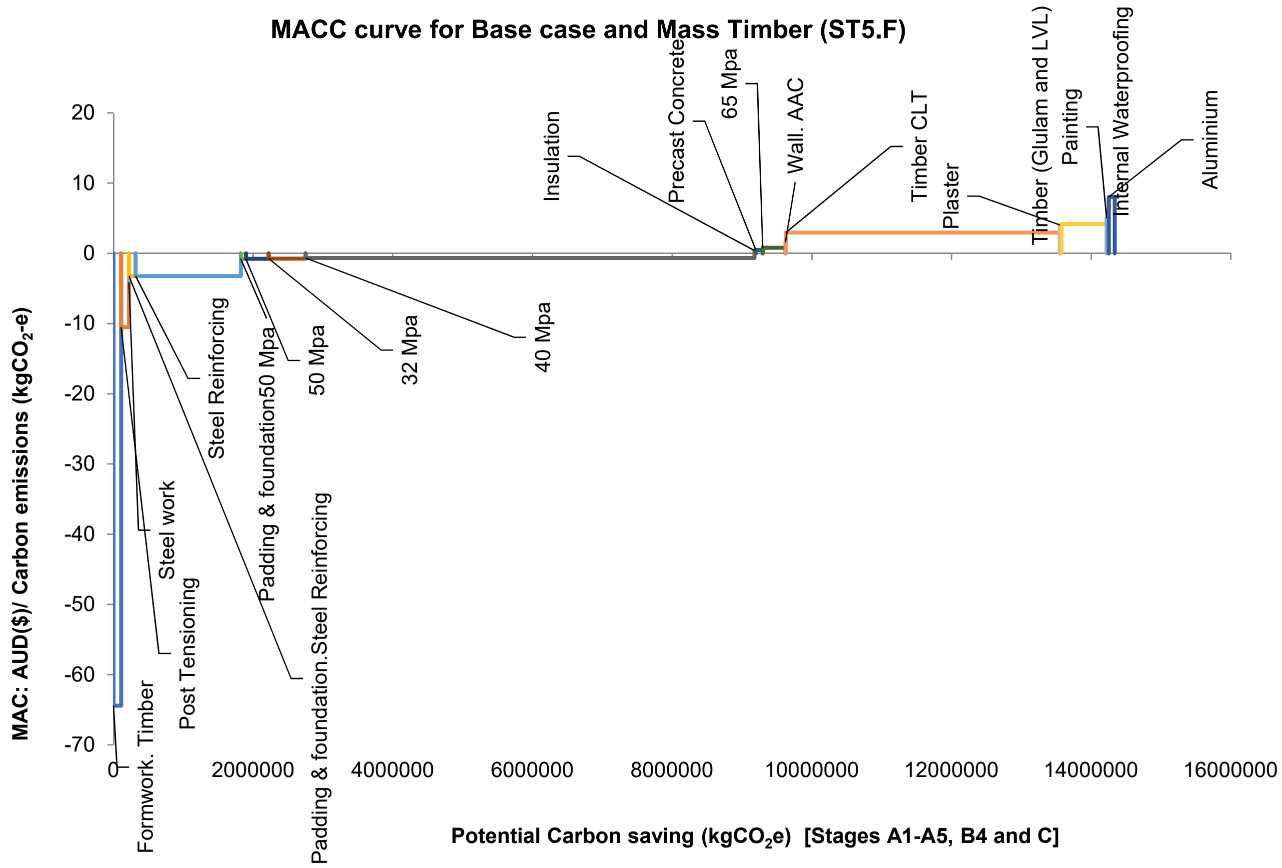


Figure A.3-14 MACC curve for Base case and Mass Timber (ST5.F)

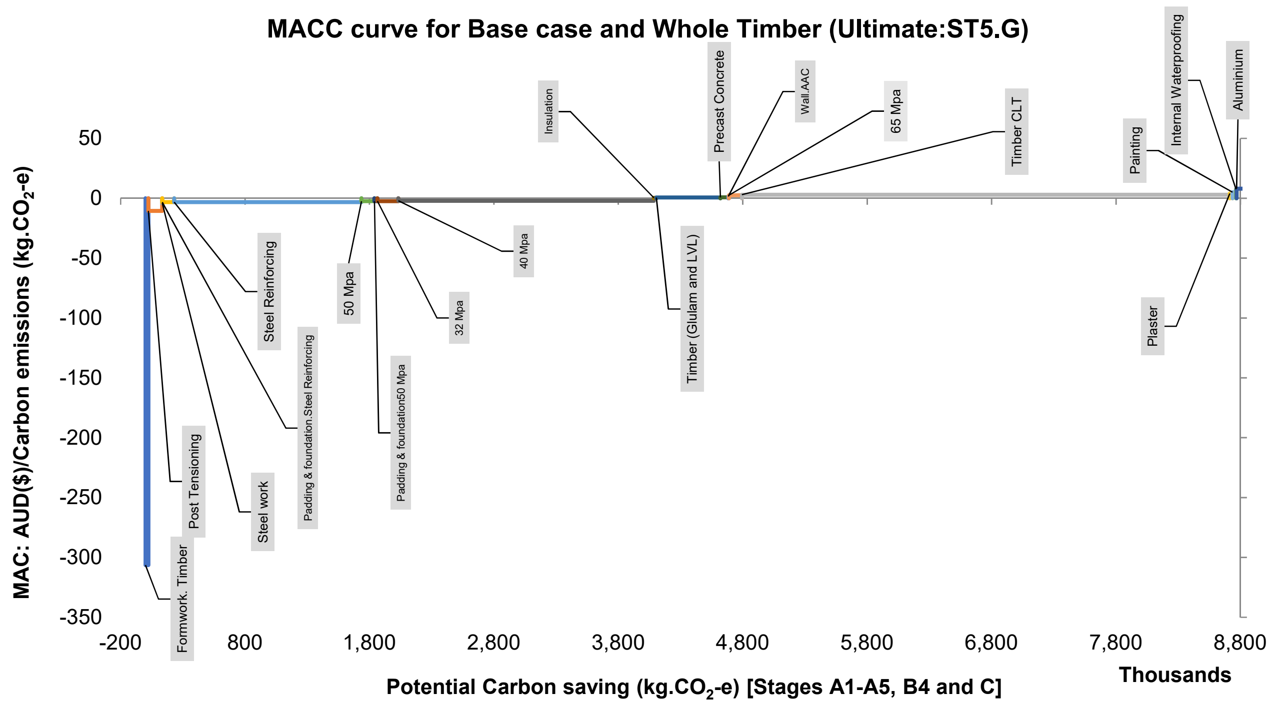


Figure A.3-15 MACC curve for Base case and Mass Timber (Ultimate: ST5.G)

Figures A.3-16 to A.3-18 provides a MACC curve for three strategies which focused on two 50% and 30% WWRs and a high-performance façade. It can be seen that lower WWR can reduce the building glazing cost and carbon emissions while increasing the cost and carbon emissions associated with the external finishes. In the case of 50% (Figure A.3-16) and 30% WWR (Figure A.3-17), the highest cost and carbon emissions were estimated for the aluminium which have been used as cladding in the building. Figure A.3-18 shows that adding extra insulation materials in the high-performance façade significantly the overall cost and carbon emissions of the building.

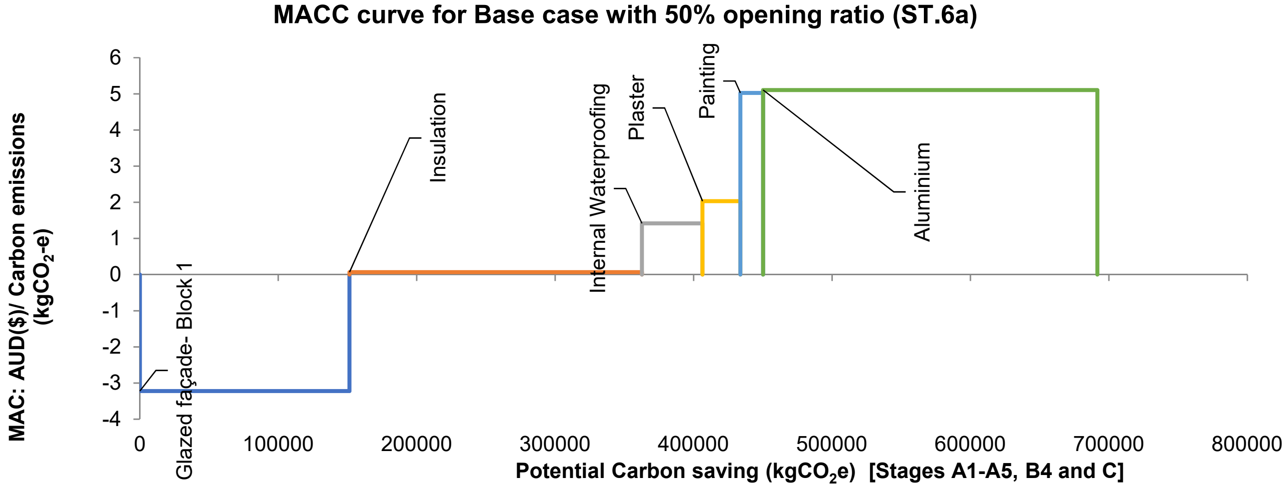


Figure A.3-16 MACC curve for Base case and 50% WWR with conventional envelope (ST.6a)

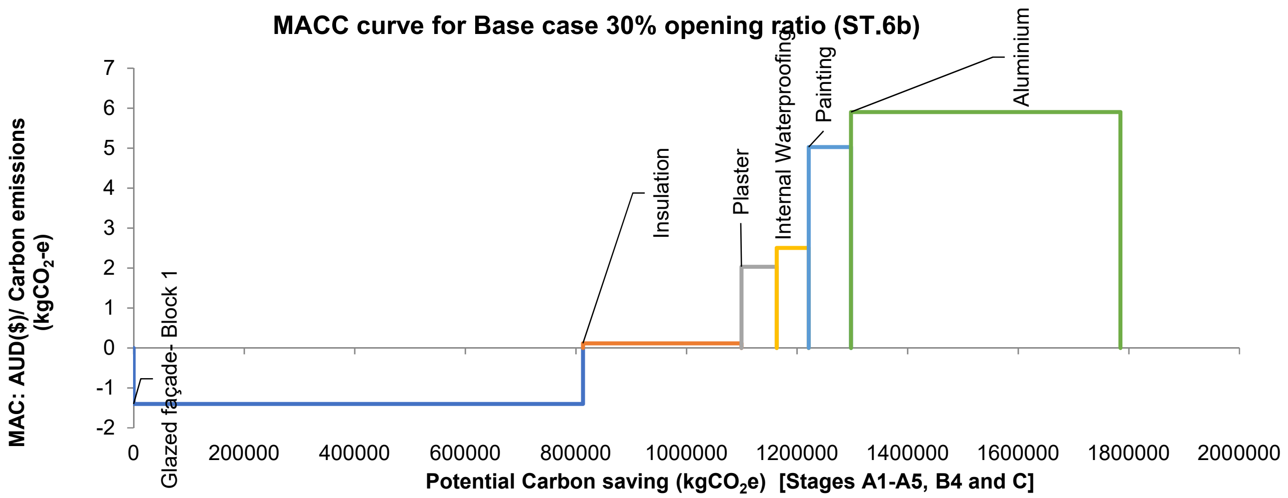


Figure A.3-17 MACC curve for Base case and 50% WWR with conventional envelope (ST.6b)

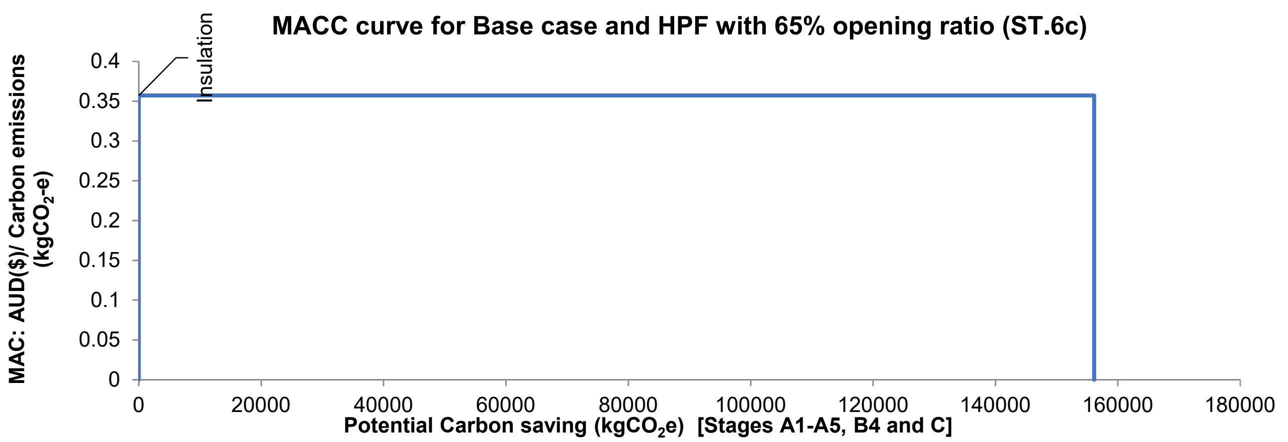


Figure A.3-18 MACC curve for Base case and 65% WWR with high-performance façade (ST.6c)