Embodied Carbon and Capital Cost Impact of Current Value Engineering Practices: A Case Study

Project: RP1034 ‘Carbon Value Engineering’

Authors	Mehdi Robati, Philip Oldfield, Ali Akbar Nezhad and David Carmichael
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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).

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Acronyms

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

Executive Summary

The drive towards the green economy means there is a growing interest in building design that balances economic, social and environmental factors. Yet, despite improvements in low-carbon design, the guidance currently available on how to improve both economic and environmental performance in building design is limited. One opportunity is to adapt the established industry practice of Value Engineering (VE). Value engineering is a process where cost reduction and constructability are optimised prior to building construction. It is a mandatory practice for all NSW government projects with a value exceeding AUD $5million. This research explores the carbon impact of current VE practices in Australia. To accomplish this goal, a complex mixed-use building in Sydney is modelled to determine the capital material costs and initial embodied carbon emissions before and after the VE process. The results support the suggestion of a positive relationship between embodied carbon and capital cost, as outlined in the literature. In this case study, conventional VE strategies not only reduce the building material costs, as would be expected, (by 0.72%, or $396,000 in this instance), but also reduce the initial embodied carbon of the building by 563 tonnes (6.67kgCO_2-e/m^2 or 1.26% of total emissions in a cradle-to-gate framework). While such savings might seem slight in an individual scenario, expanding these findings across all future non-residential buildings in Australia could to lead to savings in the order of 18,769 tonnes of CO_2-e per year, demonstrating the potential positive impact efficiency and dematerialisation can have on Australia's built environment. The report's findings will be of specific value to cost consultants and quantity surveyors, as it reveals the potential impact of the current VE practices on embodied carbon and capital cost of a building.

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 a more holistic approach by considering client and stakeholder satisfaction and sustainability measures. Value management provides a framework for performance measurement to analyse the cost incurred and benefits delivered by a construction project. From a practical point of view, value tends to rise by improving benefits without increasing cost, or by providing the same benefits at a lower expense (Oke and Aigbavboa, 2017). Table 1 is a value management framework that guides the process of analysis through the various stages of a project. This framework enables the development of number of feasible economical and functional alternatives to meet modern performance requirements (client and stakeholder satisfaction as well as sustainability measures). Both the evaluation and development phases of value management are mainly derived by value engineering (VE) practices. Value engineering identifies the design strategies that will be most effective in delivering the value desired by through the client's requirements. Essentially, the basic activities in the evaluation phase consider eliminating, pruning, modifying and combining first design ideas to create meaningful and practical ones. Based on the outcome of this phase, the development stage evaluates alternative design and cost strategies, so that a justification can be provided on feasibility and viability for the new proposal (Robinson et al., 2015, Oke and Aigbavboa, 2017). The final proposal comprises design alternatives that meet the stakeholder and client's needs with a reduced project cost.

Table 1: Value management process plan. Adapted from Olanrewaju (2013) and Oke and Aigbavboa (2017)

Activities	Value management phases	Tasks	Questions	Techniques
Pre-Study	Planning value management	Select area to be studied, train members, arranged venue, commission team briefing,	What is to be studied? Why must it be studied?	Identify area of potential improvements
Value study	Information	Obtain latest information	What is to be studied?	Request for fact
	Functional analysis	To identify, classify and document functions	What must it do?	Identify main functions, cost and allocate worth
	Analytical	Create alternative ideas	What else will perform the functions?	Simplify and classified functions, use creativity
	Evaluate	Evaluate by comparison alternative ideas	What is the cost and worth of the alternative? Is that the cheapest?	Established standard for evaluation, developed cost and worth model
	Development	Developed alternatives	Will it work? Will it meet client's requirements?	Collect facts, translate fact and consider other alternatives
	Presentation	Method of presentation, present workable alternatives	List benefits and constraints	Method of presentation, prepare reports
Post study	Implementation	Implement presented ideas	Who will implement it? What contractual changes are needed?	Eliminate barriers, actualise plan, implement ideas
	Follow up	Control results	Ideas successful or not; what are the benefits and setbacks?	Final feedback and feedforward

In other words, in the value engineering process any unnecessary costs to meet the client's and stakeholders' functional needs are eliminated from the proposed design. That is, it provides best value. Unnecessary cost is defined as expenses which provide neither use, nor life, quality, appearance or client features (Kelly et al., 2014). Unnecessary costs occur as a result of unnecessary design components, materials and poor buildability (Robinson et al., 2015). Shen and Liu (2004) have mentioned that it is an essential part of the approach that the cost of an element should match the importance of its realised function. A set of questions have been suggested in the examination of functions in the value engineering process (Robinson et al., 2015, Kelly et al., 2014):

- What is it? (Description of element)
- What does it do? (Functional definition of element)

- What does it cost? (Exploration of cost)
- What else will do it? (Innovative alternatives)
- What does that cost? (Comparison of functions given and relative costs)
- What is its value? (Exploration of value associated with design alternatives)

In addition to the cost of an element, an increase in environmental awareness has also highlighted the need to include potential environmental benefits into the VE process, but so far this has received limited attention in academia and industry. Environmental benefits can be made through the VE process through the efficient use of materials and utilisation of buildings to minimise the carbon emissions associated with different stages of buildings. The trade-off between cost and environmental impacts is critical in the decision making process. Additionally, the increasing trend of carbon financing, with carbon prices established in several developed countries, reflects the increasing demand to establish a trade-off between carbon emissions and cost in design alternatives (Oke and Aigbavboa, 2017, Robinson et al., 2015, Robati et al., 2018). As such, the main aim of this study is to examine the relationship between environmental impacts and building costs associated with current VE practices. It is suggested within the literature that cost reductions, the primary driver of VE, can in turn reduce building material quantities (known as 'dematerialisation'), and thus potentially reduce embodied carbon (Langston and Langston, 2008). What is not clear though is to what extent can VE reduce embodied carbon. As such, this report seeks to answer the following research question:

What is the impact of value engineering (VE), in its current form, on building initial embodied carbon and cost?

The findings of this report will be of interest to policy makers, design team, developers and more specifically to cost consultants and quantity surveys. This report is structured as follows. The next section provides the background of study by summarising the current studies that have utilised both cost and carbon emissions analysis into the decision-making process of buildings. This is followed by the methodology used to examine the potential impact of current value engineering on embodied carbon emissions and cost of a case study building. Lastly, the key findings of this study are given.

2. Background

2.1 Value Engineering and Carbon Mitigation

A building is responsible for the release of a considerable amount of CO_2-e emissions over the several phases of its lifecycle. These lifecycle CO_2-e emissions can be categorised as emissions relating to the running of the building (operational emissions) and the emissions relating to the manufacturing, construction, maintenance and end of life demolition of the building. According to Yu et al. (2017), the embodied carbon emissions of residential and non-residential buildings was estimated as 40.6 Mt CO_2-e in Australia in 2013. The emission associated with building materials and construction activities was estimated as 12 Mt CO_2-e (8 Mt CO_2-e for residential buildings, 4 Mt CO_2-e for non-residential). This situation has become more critical due to the increasing size of the construction industry in Australia. The value of work done by the building industry was $104.7 billion for residential (67%) and non-residential (33%) in 2016, excluding the funding allocated to smaller renovation works (ABS, 2016). The IBIS World Industry report predicted an overall 2.5% growth over the next five years (2018 to 2023) in the Australian construction industry (Kelly, 2017). As such, a reduction in Greenhouse gases is a vital need for Australia to cope with the Paris (UN Climate Conference) carbon reduction agreement by decreasing emissions 26-28% below the 2005 level by 2030 (DEE, 2015).

These growing pressures for environmental accountability have led to greater efforts to improve the sustainability of the building industry in Australia (Ding and Forsythe, 2013, Crawford, 2011, Moussavi Nadoushani and Akbarnezhad, 2015, Akbarnezhad et al., 2014, Miller et al., 2013, Robati et al., 2018). However, the sustainable design of buildings still encounters several impediments and barriers. Gou et al. (2013) summarised some of key topics in building sustainability market and cost related obstacles. They mentioned that the sustainable design of buildings is facing higher capital costs (initial design, construction, and procurement costs), a long payback time (of 20 years) and difficulty in defining measurable requirements during the procurement procedure. Other studies have also shown that the real cost and benefits are a major impediment to the development of green buildings (Khoshbakht et al., 2017, Hwang and Tan, 2012).

Environmental value engineering is a quantitative value analysis method, which not only estimates profitability and return on investment but also considers minimal impact with the natural environment for alternative design options (Ashworth and Perera, 2016). Similar to conventional financial strategies and performance measurements, environmental value engineering examines the relationship between sustainable strategies and performance to explore relationships between costs and benefits for decision making at the initial stage of design (Ashworth and Perera, 2016, Khoshbakht et al., 2017, DFA, 2006). In other words, the cost of building design alternatives are evaluated against their environmental impact over the many lifecycle stages of the building.

2.2 Building Environmental Impact Analysis

The European standards technical committee (CEN) TC350 has published a series of standards to define the cradle-to-grave environmental impact of buildings (Moncaster and Symons, 2013) and construction work (De Wolf et al., 2017). These are shown in Table 2.

Table 2: Building lifetime stages (Cradle to Grave) defined by EN 15978 (EN15978, 2011)

Product stage					Use stage							End of life stage				Beyond life
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction and installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction, Demolition	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling, potential

Table 2 shows the different stages of environmental impact assessment over a building's lifecycle. 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.

2.3 Relationship Between Building's Cost and Initial Carbon Emissions

There are a number of publications that attempt to relate the CO_2-e emissions and costs in buildings. These studies can be classified into three categories: building scale, building components, and building materials.

2.3.1 The Building Scale

In term of building scale, as an example, Langston and Langston (2008) evaluated the initial embodied energy and capital cost of thirty completed buildings in Melbourne, Australia. These case studies are a mix across a broad range of functional purposes, including office workplaces, health facilities, residential and educational buildings, as well as commercial and hotel accommodation. The embodied energy of a building is calculated based on the Input-Output based hybrid analysis and by considering the process analysis data with Input-Output data available from Australian government statistics (1996-1997). The results indicate that initial embodied energy and capital cost has a very strong correlation (r^2 = 0.9542). That is, initial embodied energy tends to increase with capital cost, meaning less expensive buildings often have reduced embodied emissions (as shown in Figure 1).

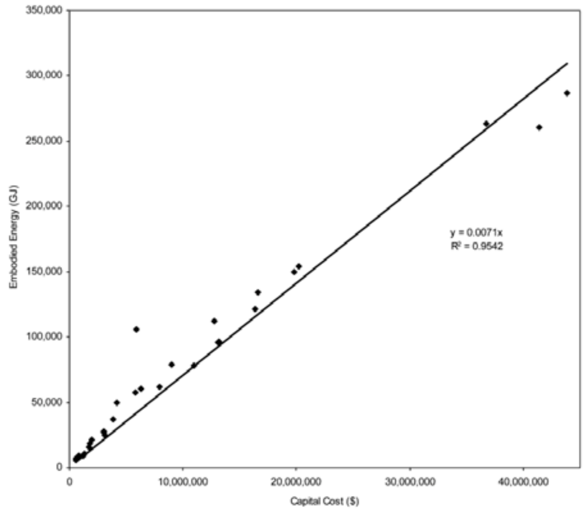


Figure 1: Embodied energy vs capital cost relation (Langston & Langston 2008)

2.3.2 Building Components

In terms of building components, several investigations have been undertaken. For example, Takano et al. (2014) demonstrated the impact of building material selection on the embodied CO_2-e emissions and cost of a building in the Finnish context. The authors studied three building component categorises including structural frame, inner wall components (insulation and sheathing) and surface components (exterior cladding and flooring). The results of the study show that the selection of the structural frame material has a greater influence on the embodied CO_2-e emissions and cost than the other two categories.

Figure 2 shows the relation between the capital cost and GHG emissions for six alternative structural frames. The LWT (lightweight timber panel) frame has the lowest capital cost and embodied CO_2-e emissions. The steel frame has the second lowest GHG emissions (kg CO_2-e/m^2) and capital cost (€/m^2). In contrast, by changing the frame type from LWT to CLT (cross-laminated timber) and RC (reinforced concrete panel) both cost and embodied CO_2-e increased up to 80% and 51%, respectively. The use of brick as an alternative to the LWT in the frame structure increased GHG emissions by 53% and capital cost by 19%. In the structural frame category, the envelope of the building (foundation, exterior walls and roof) is the critical building element (as shown in Figure 3).

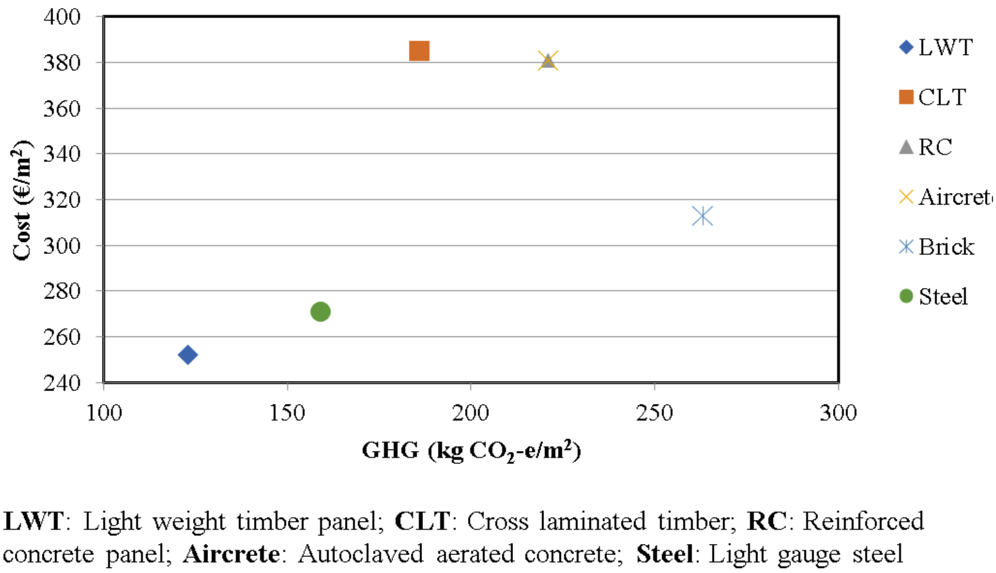


Figure 2: Embodied CO_2-e emissions vs capital cost relation. Adapted from Takano et al. (2014)

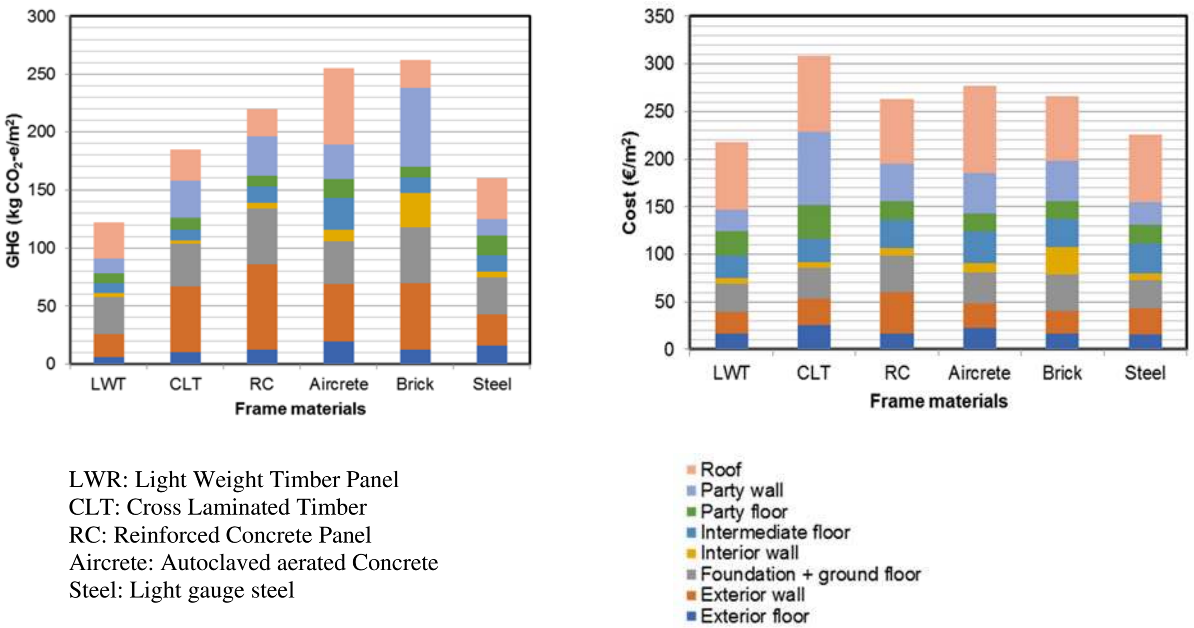


Figure 3: GHG and capital cost associated with six alternative frame materials. Adapted from Takano et al. (2014)

A comparison study across the variables shows that the external wall and roof are responsible for 41% of GHG emissions and 52% of the building capital cost as shown in Figure 4. In other words, an appropriate selection of material and design in the external wall and roof systems contributes to significant savings in the cost and GHG emissions of buildings.

Takano et al. (2014) concluded that the sustainability of the building is influenced by the unique features of each case study and there is not a single solution for selecting optimum materials and systems for cost and carbon. They also recommended lifecycle assessment analysis for achieving a better understanding of the relation between material choice and lifetime performance of a building.

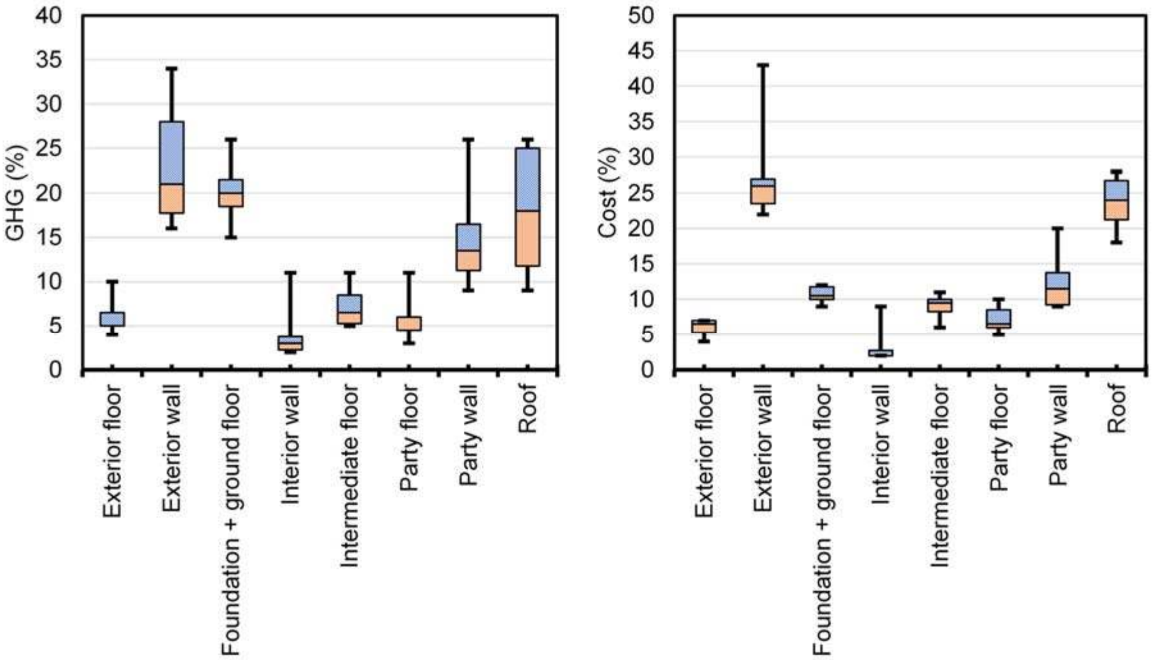


Figure 4: GHG and Capital cost variation across the buildings components - Adapted from Takano et al. (2014)

2.3.3 Building Materials

In terms of building materials, a number of studies have tried to optimise the design of buildings by proposing a conceptual framework (called the "eco-efficiency method") to measure the sustainability of buildings by simultaneously selecting the optimal product design and considering the environmental and cost characteristics (Cha et al., 2008, Ji et al., 2014, Saling et al., 2002, Hahn et al., 2010). Park et al. (2014) conducted a study to optimise the cost and embodied CO_2-e emissions associated with reinforced concrete (RC) as a structural material. The study shows that increasing the strength and steel reinforcement ratio provides optimum embodied CO_2-e emissions in a RC column. The optimum cost was achieved through increasing the strength of the concrete and steel reinforcement, while increasing the amount of steel reinforcement was the least effective approach. In another study, Park et al. (2013) found that reducing the amount of steel, but increasing the amount of concrete, can be an effective way to reduce the structural costs and CO_2-e emissions for steel reinforced concrete columns (SRC).

In summary, the relationship between capital cost and embodied CO_2-e emissions is influenced by the characteristics of each building. For low-rise buildings, embodied CO_2-e emissions are dominated by external walls, slabs and foundations (Oldfield, 2012; Sansom and Pope, 2012). For medium to high-rise buildings, embodied CO_2-e emissions are dominated by floors and building frames (Sansom and Pope, 2012). From a cost and CO_2-e emissions point of view, it is recommended to consider a holistic approach by using Lifecycle Assessment (LCA) methods to achieve a better understanding on the relationship between design alternative costs and their potential CO_2-e emission impacts over the life span of buildings.

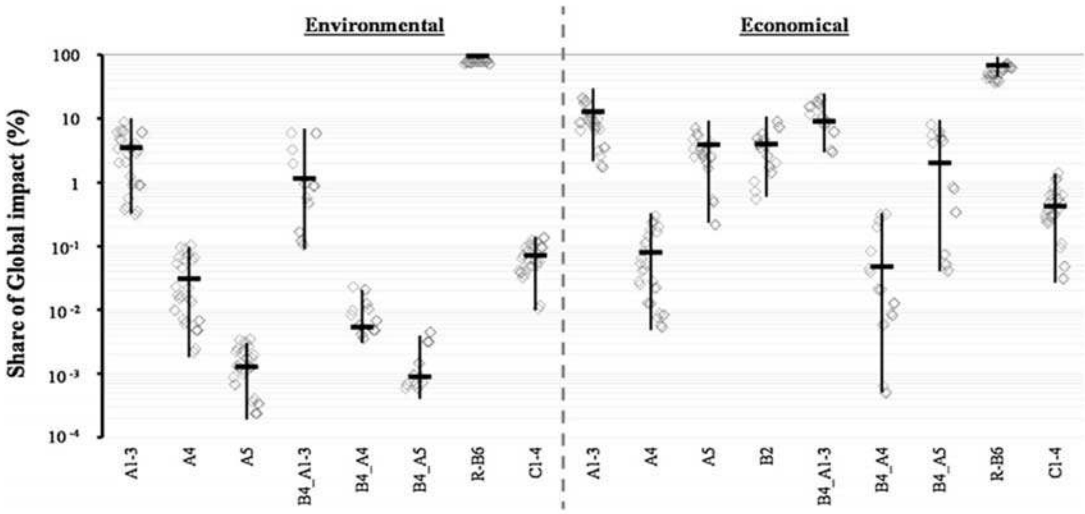
2.4 The Relationship Between Buildings' Whole Lifecycle Cost and Lifecycle CO_2-e Emissions

Many researchers have attempted to explore links between CO_2-e emissions and the costs associated with the lifetime performance of buildings. Lifecycle CO_2-e emissions of a building are the sum of all the CO_2-e emissions over its effective life, including the initial embodied CO_2-e emissions, the recurrent embodied CO_2-e emissions, and the operational CO_2-e emissions (Cabeza et al., 2014). Referring to Table 2, this covers stages A – D. Lifecycle cost assessment defines all the costs associated with the lifetime of a building, including owning and operating a facility over a period of time (Hunkeler et al., 2008, Mearig et al., 1999). In the building industry, a number of studies have quantified the effect that the structural materials have on the whole life energy performance of buildings (Torgal and Jalali, 2011, Appleby, 2012, Anderson and Silman, 2009, Lemay and Leed, 2011, DIIS, 2013). These studies have shown that basic decisions about structural components (type of floor, shape of core servers, arrangements of columns, and heights of beams) have a direct impact on the energy consumption of buildings.

Others have proposed methods to evaluate environmental impact and economics by converting embodied CO_2-e into a monetary term (Ji et al., 2014, Gu et al., 2008, Kim et al., 2012, Itsubo and Inaba, 2003, Hong et al., 2013). For example, several studies on structures and construction materials have evaluated the environmental impact and cost over various stages of the lifecycle (Silvestre et al., 2014, Chou and Yeh, 2015, Huang et al., 2009). According to Cabeza et al. (2014), a combination of lifecycle cost analysis with lifecycle environmental impact provides a better understanding of the total impact of a proposed project or policy (Cabeza et al., 2014).

Similarly, Oregi et al. (2017) conducted a study to quantify the impact of each lifecycle stage in relation to the overall cost and environmental impact on residential building refurbishment projects. The results of the study are shown in Figure 5. It is clear, that for both environmental and economic impacts, stage B6: Operational Energy, is the largest contribtuor. However, in addition, it can be seen that stage A1 – 3 the product stage, also plays a significant role.

Taken together, these studies show a general relation between capital cost and initial embodied carbon emission of buildings. However, when considering the whole lifecycle, links between lifecycle cost and lifecycle carbon emissions of buildings are less clear. This could potentially change in the future, as several studies have been reporting a gradual decline in contributions of operation stages due to ongoing development toward net zero energy alternatives (Thormark, 2006, Cole and Fedoruk, 2015), meaning capital cost and initial embodied carbon may play a more significant role in future building lifecycles.



Product stage (A1-A3)	Construction stage (A4-A5)	Use stage (B1-B7)	End of life stage (C1-C4)
A1. Raw materials supply A2. Transport A3. Manufacturing	A4. Transport A5. On-site process	B1. Use B2. Maintenance B3. Repair B4. Replacement B5. Refurbishment B6. Operational energy B7. Operational water	C1. Deconstruction and demolition C2. Transport C3. Waste processing C4. Disposal

Figure 5: Environmental and cost analysis for each stage of a building's lifecycle (Oregi et al. 2017)

3. Case Study: Methodology

This study seeks to identify the embodied carbon impact of current VE practices. A multi-storey building in a central Sydney location is used as the case study to this research. The scope of the study considers the CO_2-e emissions associated with the extraction of raw materials, manufacturing and processing, or stages A1 – A3 in Table 2. This is often known as ‘cradle-to-gate’. The carbon emissions associated with the transportation and end of life stage of buildings were excluded due to limited availability of data. For the operational carbon emissions, the value engineering schedules (provided by the contractor) show that the fabric of the building has not been changed through VE practices, and, as such, the operational performance of the building would be the same in both the before and after VE scenarios. As such, operational emissions are excluded from the study.

This study employed Australian building material emissions factors which have been developed by the CRC for Low Carbon Living (Wiedmann, 2017). The carbon unit of measurement used in this study is $kgCO_2$-e/m^2 where m^2 refers to the building floor area.

Costs are the initial costs associated with the building materials, with a unit of measurement of \$/m^2. Costs associated with building materials are taken from the Australian construction handbook based on 2017 data (Rawlinsons, 2017).

3.1 Building Characteristics

The case study building consists of two blocks of 18 and 20 above ground storeys, with a shared 5-storey basement (Figure 6). The building consists of a mix of uses including offices, shops and residential units. The gross floor area for block 1 and 4 is 43,229 m^2 and 41,228 m^2 respectively. Figure 6 and Table 3 provide a sketch and summary of the building.

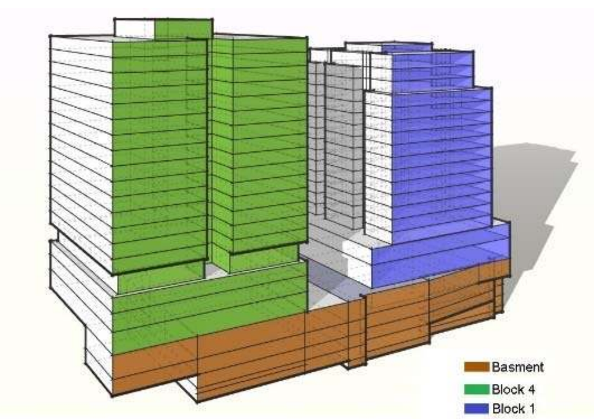


Figure 6: Case study building

Table 3: Case study building details

Parameter	Unit	Block 1	Block 4
Ground floor dimensions	m	41.0 × 32.8*a*	23.26×20.93*a*
Average floor-to-floor height	m	3.41	3.25
Total floor Area *b*	m²	43,229	41,228
Total height	m	64.89	68.30
Number of floors above ground level	---	18	20
Number of floors below ground level (basement area)	---	5 (12,442 m²)	5 (9,009 m²)

a Estimated value.

b Total area of floors (above and below ground level).

3.2 Value Engineering Process

Initial value engineering proposed a total of 201 items for design and/or material changes across the building. Of these, 94% were approved, and 6% rejected. Figure 7 provides a breakdown of where these value engineering changes took place. The top frequently value engineered categories are façade (22%), electrical (22%), finishes (19%) and structure (14%), with each having more than 29 VE items. The least often value engineered categories are elevator and building management/automation system components (BMS, BAS, EMS and IHD), in each of these categories there were less than 5 and 7 VE items, respectively. In this study, the embodied carbon and cost analysis focusses on building materials in the substructure and superstructure, external finishes and internal finishes and fittings and this follows from the availability of information (see also Figure 7)

The following bullet points summarise the key value engineering changes which were undertaken.

Substructure and Superstructure

- Rationalise the structural design to accommodate lightweight façade loads
- Deletion and substitution of non-load bearing concrete walls
- Increased mesh or post tensioning for exposed slabs

External finishes

- Rationalisation of external façade specification.

Internal finishes and fitting

- Rationalisation of basement blockwork detailing
- Rationalisation of where walls can become non-load bearing

- Rationalisation of all core walls
- Removal of all concrete pavers to roofs and replacement with ballast materials
- Rationalise all metalwork
- Remove sandstone blocks and replace with a concrete finish
- Removal of all timber wall panels and replacement with a plasterboard finish
- Alterative carpet finish (for block 4)
- Removal of hard floor finishes and replacement with carpet (block 4)
- Use of a tile finish for balcony areas
- Removal of all internal apartment glazing (for block1)
- Removal of sandstone finish and replacement with a concrete finish
- Removal of mirrored screens in showers and replacement with tiles

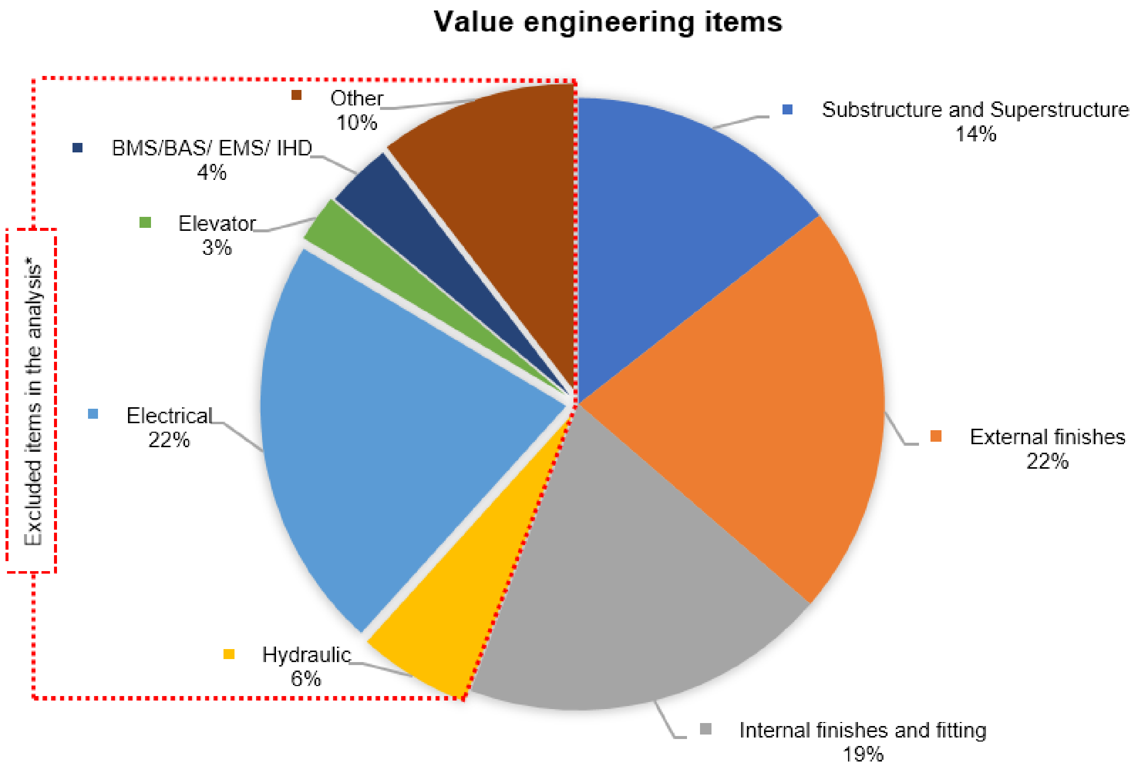
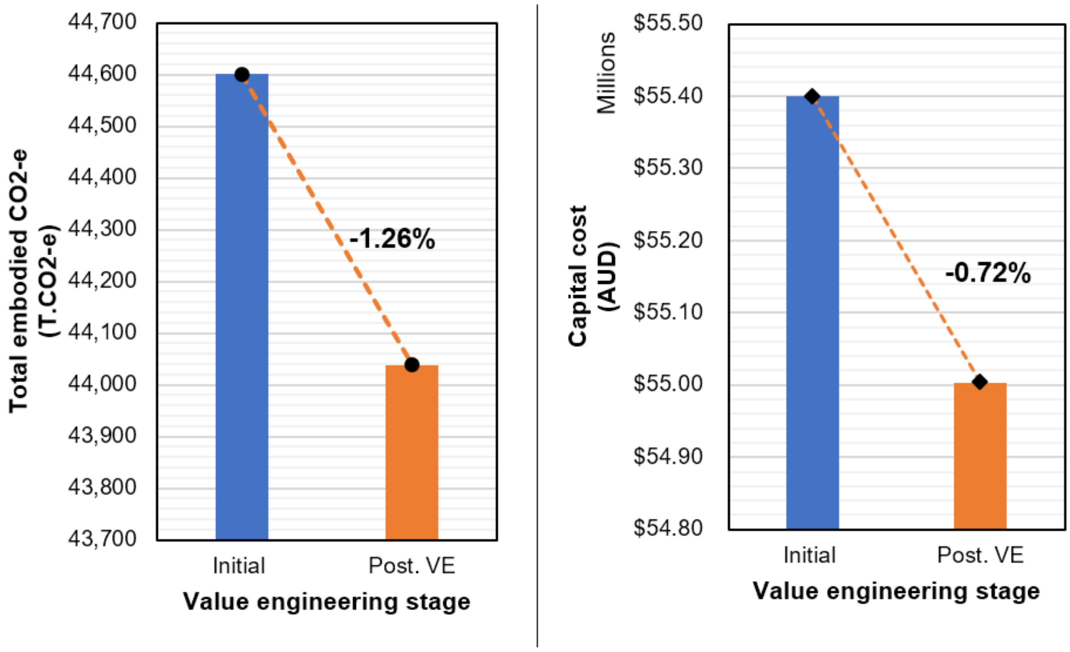


Figure 7: Breakdown of value engineering items by category

4. Case Study: Results and Discussion

The case study building, prior to VE, had an initial embodied carbon of 44,601tCO_2-e, or 528kgCO_2-e/m². Its material cost was $55.4million, or $655.95/m². After VE, the initial embodied carbon was 44,038tCO_2-e, or 521kgCO_2-e/m² and costs were $55.0 million and $651.26/m². This equates to a 1.26% saving of embodied carbon and a 0.72% saving of material costs, as outlined in Figure 8. This trend indicates the potential positive impact of conventional VE strategies on the embodied carbon emissions (cradle to gate) and added value to the building. The saving of 6.67kgCO_2-e/m² may seem small, but when multiplied across the Australian built environment, its impact can be significant. According to COAG (2012) 2,814,000m² of new non-residential floor area is predicted to be constructed in 2019. If this was subject to a 6.67kgCO_2-e/m² saving, the result would be a reduction in 18,769 tonnes of CO_2-e/year.

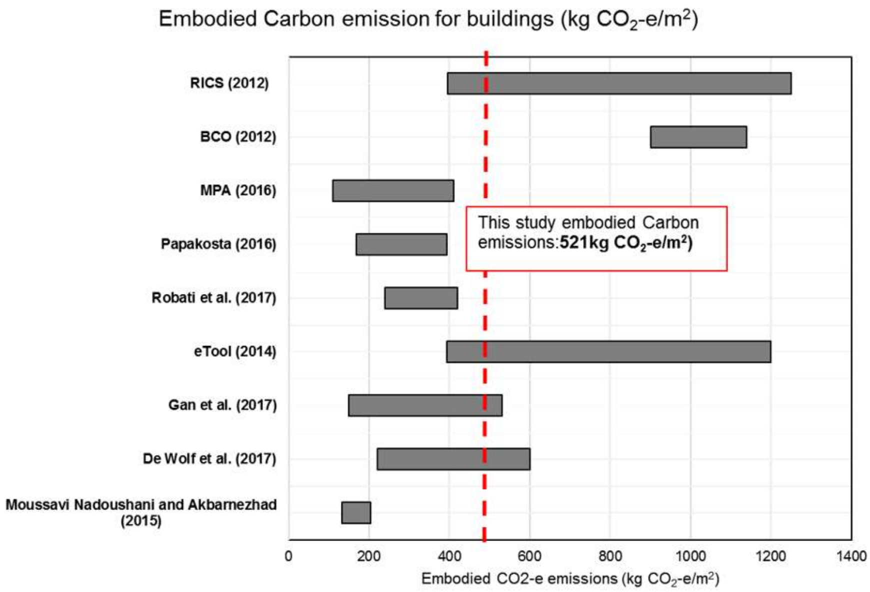
Figure 9 shows that the obtained results of this study fall within ranges and findings of previous studies (Moussavi Nadoushani and Akbarnezhad, 2015, De Wolf et al., 2017, Gan et al., 2017, eTool, 2014, Papakosta, 2016, MPA, 2016, BCO, 2012, RICS, 2012, Robati et al., 2017).The earlier studies found that the embodied CO_2-e emissions (cradle to gate) can vary from 131 to 1,200 kg.CO_2-e/m² across various mid-rise buildings. These variations in embodied CO_2-e emissions are due to different methods of analysis used for each assessment, the different system boundaries, the sources of data, and quality of input used to calculate the energy consumptions of upstream manufacturing process (Buchanan and Honey, 1994, Dixit et al., 2010, Crawford, 2013, Huang et al., 2010, Langston and Langston, 2008).



Summary	EC			CC		
	T.CO_2-e	kg.CO_2-e/m²	%	AUD $	AUD $/m²	%
Initial	44,601	528	0	$55,399,301	$655.95	0
Post. VE	44,038	521	1.26%	$55,003,133	$651.26	0.72%

EC: Embodied CO_2-e emissions (Tonne CO_2-e emissions)
CC: Capital Cost (Australian Dollar)
VE: Value Engineering

Figure 8: Impacts of value engineering practices on the total carbon emissions and costs



Source: (Moussavi Nadoushani and Akbarnezhad, 2015, De Wolf et al., 2017, Gan et al., 2017, eTool, 2014, Robati et al., 2017, MPA, 2016, Papakosta, 2016, BCO, 2012, RICS, 2012)

Figure 9: Embodied carbon emissions of buildings per m^2 across different studies

The magnitude of the impacts of the building components on the overall embodied CO_2-e emissions and capital cost of the building at the post-VE stage is shown in Figure 11. The result indicates that the superstructure category has the major impacts on both capital cost (58.82%) and embodied CO_2-e emission (63.68%) of the case study building. While, the other categories have a less than 36% and 41% share on overall embodied CO_2-e emissions and capital cost of the building, respectively.

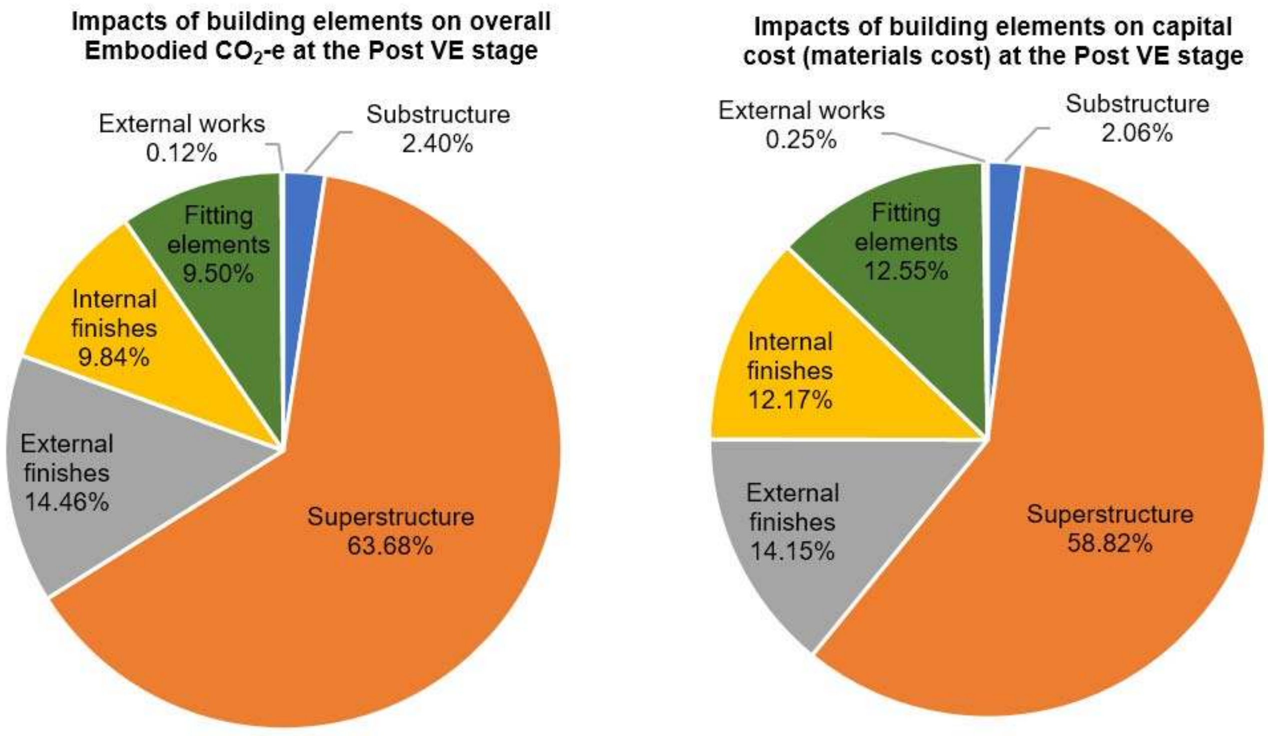


Figure 10: Impacts of building components on embodied CO2-e emissions and Cost at Post VE stage

The significance of the major VE strategies on cost and embodied carbon emissions cam also be identified. Figure 11 and the following section summarise the key value engineering strategies and their impact:

- For the superstructure, differences between initial and final tender prices demonstrate savings in the amount of concrete, steel reinforcement and formwork of the building, reducing the total carbon emissions and costs of the building.
- For the external finishes, changes in the roof result in higher material quantities (concrete, ballast, waterproofing membrane). Through this value engineering strategy, the external finishes cost reduced by $33,000 although the embodied carbon emissions increased by 176t.CO_2-e. This demonstrates that at the building element level, reductions in cost do not always equate to a reduction in embodied carbon (even if such trends are more apparent at the building level)
- For the Internal finishes, increases in the length of internal walls have led to an increase in the total cost ($29,000) and an increase in embodied carbon emissions (71t.CO_2-e). In this category, autoclaved aerated concrete (AAC), plaster and plasterboard have the highest impacts on embodied CO_2-e emissions of internal finishes (up to 86%).
- For the fitting components, replacing glazing and hardwood timber floors with tilling in the bathrooms and balcony areas have led to a decrease in embodied carbon emissions (156t.CO_2-e). These changes reduced the materials costs by $19,051.

However, as shown in Figure 11, it is the reduction of concrete and dematerialisation of the superstructure that has had by far the most significant saving in terms of both cost and initial embodied carbon.

Figure 12 breakdowns the main embodied CO_2-e emissions and costs for the building components which have been affected by VE. By considering whole building components, the value engineering strategies associated with the following components have the highest impacts on overall carbon and cost of the building:

- Superstructure components - item 5 (concrete): saving of 646t.CO_2-e of embodied carbon emissions and $327,902 in material costs
- Fitting components - item 40 (glazing): saving of 198t.CO_2-e carbon emissions and $128,984 in material costs
- External finishes - item 17 (roof): addition of 170t.CO_2-e carbon emissions and $92,761 material costs
- Fitting components - item 36 (tiling): addition of 66t.CO_2-e carbon emissions and $309,552 in material costs

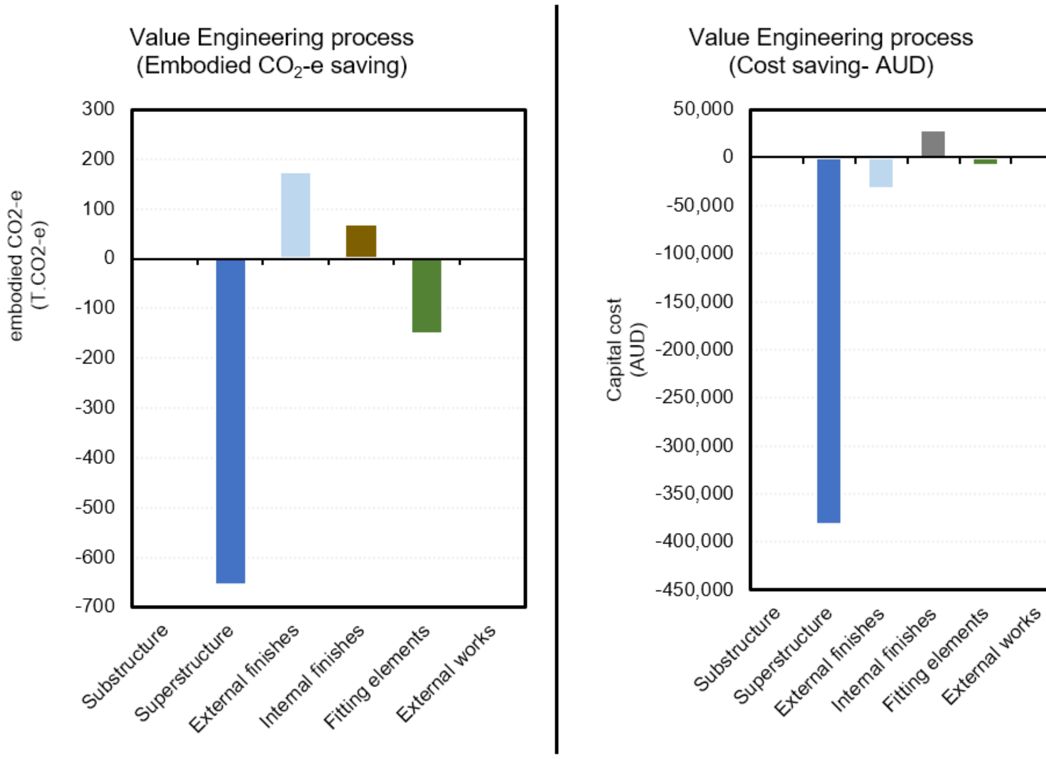
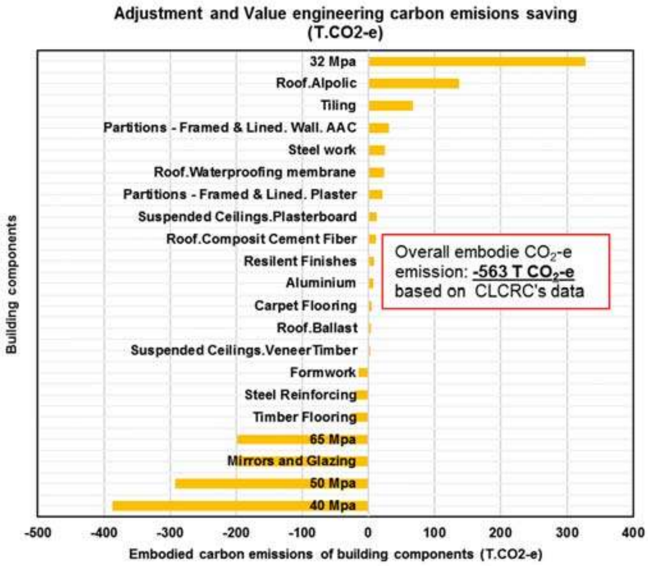
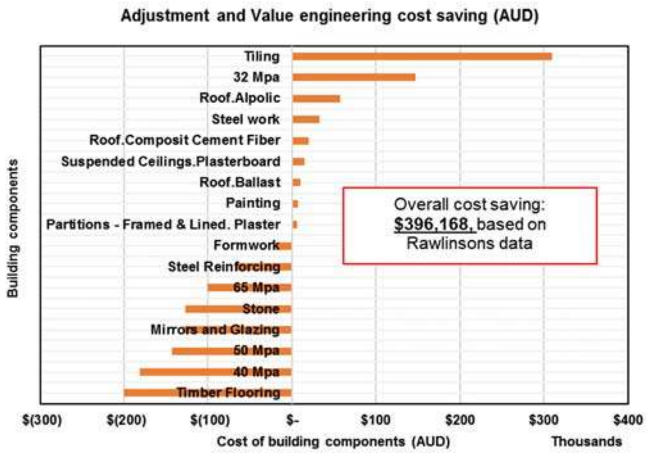


Figure 11: Carbon and cost saving across the building components



*Due to qunatities of building componenets, items with less than 1 tonne embodied CO_2-e emissions were excluded from the graph.



*Due to qunatities of building componenets, items with less than $6000 (AUD) were excluded from the graph.

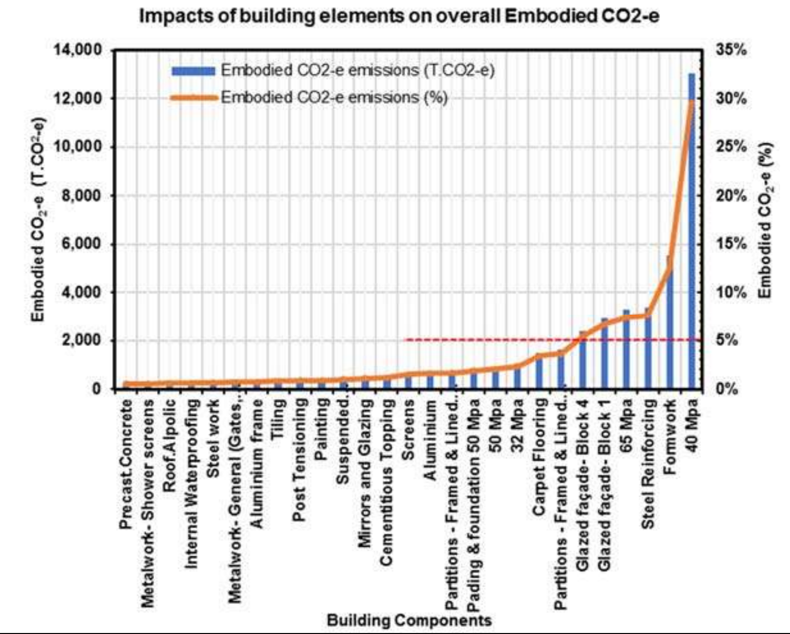
Building Parts	BoQ code	Building component
Sub-structure	5.5	Padding and foundation.50 Mpa
	6.2	Padding and foundation. Steel Reinforcing
Superstructure	3	Formwork
	5.1	32 Mpa
	5.2	40 Mpa
	5.3	50 Mpa
	5.4	65 Mpa
	6.1	Steel Reinforcing
	8	Post Tensioning
	11	Steel work
	9, 10	Precast. Concrete
External finishes	15	Glazed façade- Block 1
	16	Glazed façade- Block 4
	12	Aluminium
	13	Stone
	14	Timber
	17.1	Roof. Concrete Pavers
	17.2a	Roof. Ballast
	17.2b	Roof. Waterproofing membrane
	17.3	Roof. Alpolic
	17.4	Roof. Composite Cement Fiber
Internal finishes	20	Blockwork
	25	Cement Fiber
	26.1	Cementitious Topping
	26.2	Insulation
	26.3	Mineral tiels
	26.4	Painting
	27.1	Plaster
	27.2	Plasterboard
	32	Rendering
	33	Resilient Finishes
	37	Veneer timber
	38	Wall. AAC
	39	Waterproofing
Fitting components	4	Screens
	34	Carpet
	35	Timber
	28.1	Galvanised
	30	Handrails
	29	Shower screens
	36	Tiling
	40	Glazing
	21.1	Aluminium frame
	21.2	Timber Frame
External works	18	External Waterproofing

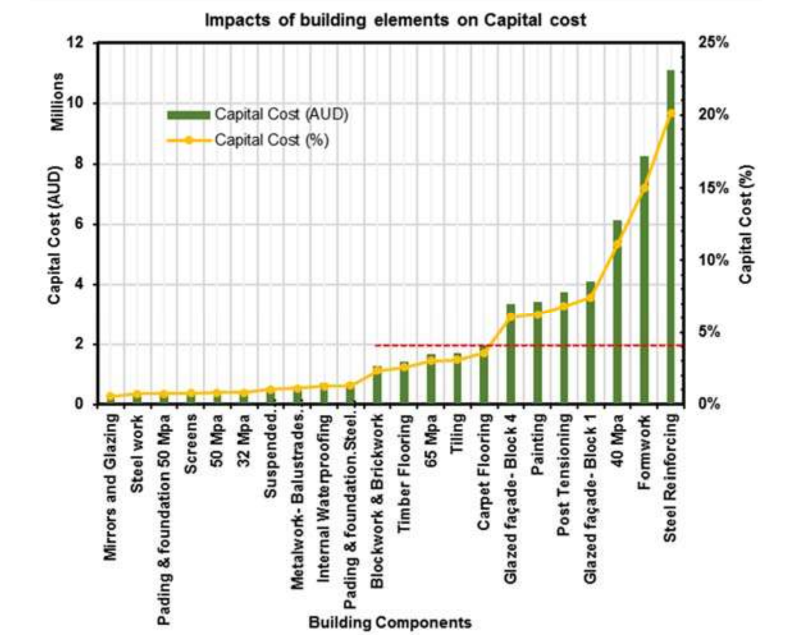
Figure 12: Magnitude impacts of value engineering strategies on the capital cost and initial embodied CO_2-e emissions

The results reveal the significance that each building component has on the capital cost and CO_2-e emissions of the whole building at the post VE stage (as shown in Figure 13). The results show that the concrete (item 5), formwork (item 3), steel reinforcing (item 6) and façade (items 15 and 16) have the highest impacts on embodied CO_2-e emissions of the building at the post-VE stage. The embodied emissions associated with the superstructure including concrete, formwork and steel reinforcement are estimated as high as 42% (18,466t.CO_2-e), 13% (5,534t.CO_2-e) and 8% (3,363t.CO_2-e) of the building overall embodied CO_2-e emissions. These findings confirm previous studies showing that the superstructure materials have a significant impact on the embodied CO_2-e emissions. The façade glazing (items 5 and 6) forms up to 12% (5,355 t.CO_2-e) of total carbon emissions.

In terms of the capital material costs, structural materials (concrete, steel and formwork) are the predominant cost components (59% of total cost, $32.3 million dollar). External finishes (façade), fittings (carpet and timber flooring, tilling) and Internal finishes (painting, blockworks) contribute up to 13% ($7.4 million dollar), 10% ($5 million dollar) and 8% ($4.7 million dollar) toward the cost of the building, respectively.

The findings of this study highlight the potential impacts of value engineering practices on both cost and carbon emissions of the building. However, the most expensive components do not totally relate with the highest embodied carbon. This situation raises the question about how best to integrate both cost and carbon emissions into conventional value engineering practices.





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	26.4	Painting
	27.1	Plaster
	27.2	Plasterboard
	32	Rendering
	33	Resilient Finishes
	37	Veneer timber
	38	Wall. AAC
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Fitting components	4	Screens
	34	Carpet
	35	Timber
	28.1	Galvanised
	30	Handrails
	29	Shower screens
	36	Tiling
	40	Glazing
	21.1	Aluminium frame
	21.2	Timber Frame
External works	18	External Waterproofing

Figure 13: Impact of each building component on the capital cost and initial CO_2-e emissions at post-VE stage

In summary, the results of this study confirm the potential impact of value engineering practices on the carbon emissions of the case study building. It also highlighted the potential for considering both value engineering and embodied carbon analysis at the same time in the process of evaluating design alternatives. Failure to address them simultaneously exposes the concern of choosing solutions that while satisfying clients' needs, at a closer scrutiny, are revealed not to be environmentally friendly.

Future Studies

While this study identifies the impact of VE in its current form on building embodied carbon, the next stage of the project seeks to explore to what extent can VE be adapted to maximise the reduction of embodied and life-cycle carbon emissions early in the design phase while also securing economic value? To complete this, the case study building above will be adapted and redesigned to explore alternative design and structural strategies that optimise the building for reduced cost and life-cycle carbon emissions (including operational emissions) simultaneously. The aim is to develop a new framework of 'Carbon Value Engineering' (CVE) – VE that integrates both carbon (kgCO_2-e) and cost ($) metrics.

Reference

ABS 2016. Construction work done :Preliminary March, Jun, Sep, Dec 2016. Canberra, Australia: Australian Bureau of Statistics.

AKBARNEZHAD, A., ONG, K. C. G. & CHANDRA, L. R. 2014. Economic and environmental assessment of deconstruction strategies using building information modeling. *Automation in Construction,* 37**,** 131-144.

ANDERSON, J. E. & SILMAN, R. 2009. A lifecycle inventory of structural engineering design strategies for greenhouse gas reduction. *Structural Engineering International,* 19**,** 283-288.

APPLEBY, P. 2012. *Integrated sustainable design of buildings,* London, Routledge.

ASHWORTH, A. & PERERA, S. 2016. *Cost studies of buildings,* New York, Routledge.

BCO 2012. Whole-Life Carbon Footprint Measurement and Offices. *British Council for Offices*.

BUCHANAN, A. H. & HONEY, B. G. 1994. Energy and carbon dioxide implications of building construction. *Energy and Buildings,* 20**,** 205-217.

CABEZA, L. F., RINCÓN, L., VILARIÑO, V., PÉREZ, G. & CASTELL, A. 2014. Lifecycle assessment (LCA) and lifecycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews,* 29**,** 394-416.

CHA, K., LIM, S. & HUR, T. 2008. Eco-efficiency approach for global warming in the context of Kyoto Mechanism. *Ecological Economics,* 67**,** 274-280.

CHOU, J.-S. & YEH, K.-C. 2015. Lifecycle carbon dioxide emissions simulation and environmental cost analysis for building construction. *Journal of Cleaner Production,* 101**,** 137-147.

COAG 2012. Baseline Energy Consumption and Greenhouse Gas Emissions In Commercial Buildings in Australia. National Strategy on Energy Efficiency.

COLE, R. J. & FEDORUK, L. 2015. Shifting from net-zero to net-positive energy buildings. *Building Research & Information,* 43**,** 111-120.

CRAWFORD, R. 2011. *Lifecycle assessment in the built environment,* New York, Spon Press.

CRAWFORD, R. H. 2013. Post-occupancy lifecycle energy assessment of a residential building in Australia. *Architectural Science Review,* 57**,** 114-124.

DE WOLF, C., POMPONI, F. & MONCASTER, A. 2017. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings,* 140**,** 68-80.

DEE 2015. Australia's 2030 emissions reduction target. Canberra, Australia: Department of Environment and Energy.

DFA 2006. Introduction to Cost-Benefi t Analysis and Alternative Evaluation Methodologies. ACT: Financial Management Group.

DIIS 2013. *Your home : Australia's guide to environmentally sustainable homes,* Canberra, Australia, Department of Industry, Innovation and Science.

DING, G. & FORSYTHE, P. J. 2013. Sustainable construction: lifecycle energy analysis of construction on sloping sites for residential buildings. *Construction Management and Economics,* 31**,** 254-265.

DIXIT, M. K., FERNÁNDEZ-SOLÍS, J. L., LAVY, S. & CULP, C. H. 2010. Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings,* 42**,** 1238-1247.

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

ETOOL. 2014. *Lifecycle assessment online tool* [Online]. Available: http://etoolglobal.com/ [Accessed 23/6/2015].

GAN, V. J., CHENG, J. C., LO, I. M. & CHAN, C. M. 2017. Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. *Journal of cleaner production,* 141**,** 825-836.

GOU, Z., LAU, S. S.-Y. & PRASAD, D. 2013. MARKET READINESS AND POLICY IMPLICATIONS FOR GREEN BUILDINGS: CASE STUDY FROM HONG KONG. *Journal of Green Building,* 8**,** 162-173.

GU, L., LIN, B., ZHU, Y., GU, D., HUANG, M. & GAI, J. 2008. Integrated assessment method for building lifecycle environmental and economic performance. *Building Simulation,* 1**,** 169-177.

HAHN, T., FIGGE, F., LIESEN, A. & BARKEMEYER, R. 2010. Opportunity cost based analysis of corporate eco-efficiency: A methodology and its application to the CO2-efficiency of German companies. *Journal of Environmental Management,* 91**,** 1997-2007.

HONG, T., KOO, C. & KWAK, T. 2013. Framework for the implementation of a new renewable energy system in an educational facility. *Applied Energy,* 103**,** 539-551.

HUANG, Y., BIRD, R. & HEIDRICH, O. 2009. Development of a lifecycle assessment tool for construction and maintenance of asphalt pavements. *Journal of Cleaner Production,* 17**,** 283-296.

HUANG, Z., DING, X., SUN, H. & LIU, S. 2010. Identification of main influencing factors of lifecycle CO2 emissions from the integrated steelworks using sensitivity analysis. *Journal of Cleaner Production,* 18**,** 1052-1058.

HUNKELER, D., LICHTENVORT, K. & REBITZER, G. 2008. *Environmental lifecycle costing,* Boca Raton, CRC Press.

HWANG, B. G. & TAN, J. S. 2012. Green building project management: obstacles and solutions for sustainable development. *Sustainable development,* 20**,** 335-349.

ITSUBO, N. & INABA, A. 2003. A new LCIA method: LIME has been completed. *The International Journal of Lifecycle Assessment,* 8**,** 305.

JI, C., HONG, T. & PARK, H. S. 2014. Comparative analysis of decision-making methods for integrating cost and CO2 emission – focus on building structural design –. *Energy and Buildings,* 72**,** 186-194.

KELLY, A. 2017. On shaky ground: Divergent industry demand trends have led to division revenue fluctuations. IBISWorld Industry Report E: Construction in Australia: IBISWorld.

KELLY, J., MALE, S. & GRAHAM, D. 2014. *Value management of construction projects,* Hoboken, John Wiley & Sons.

KHOSHBAKHT, M., GOU, Z. & DUPRE, K. 2017. Cost-benefit Prediction of Green Buildings: SWOT Analysis of Research Methods and Recent Applications. *Procedia Engineering,* 180**,** 167-178.

KIM, J., HONG, T. & KOO, C.-W. 2012. Economic and environmental evaluation model for selecting the optimum design of green roof systems in elementary schools. *Environmental science & technology,* 46**,** 8475-8483.

LANGSTON, Y. L. & LANGSTON, C. A. 2008. Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies. *Construction Management and Economics,* 26**,** 147-160.

LEMAY, L. & LEED, A. 2011. *Lifecycle assessment of concrete buildings,* Silver Spring, US, National Ready Mixed Concrete Association.

MEARIG, T., COFFEE, N. & MORGAN, M. 1999. *Lifecycle cost analysis handbook:Draft,* Juneau, State of Alaska, Department of Education and Early Development, Education Support Services/Facilities.

MILLER, D., DOH, J.-H., GUAN, H., MULVEY, M., FRAGOMENI, S., MCCARTHY, T. & PETERS, T. 2013. *Environmental impact assessment of post tensioned and reinforced concrete slab construction,* London, Taylor & Francis Group.

MONCASTER, A. M. & SYMONS, K. E. 2013. A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy and Buildings,* 66**,** 514-523.

MOUSSAVI NADOUSHANI, Z. S. & AKBARNEZHAD, A. 2015. Effects of structural system on the lifecycle carbon footprint of buildings. *Energy and Buildings,* 102**,** 337-346.

MPA 2016. *Whole-Life Carbon and Buildings: Concrete solutions for reducing embodied and operational CO2,* London, The Concrete Centre.

OKE, A. E. & AIGBAVBOA, C. O. 2017. *Sustainable Value Management for Construction Projects,* Cham, Springer.

OLDFIELD, P. (2012). Embodied Carbon and High-Rise. *Proceedings of the CTBUH 9th World Congress "Asia Ascending: Age of the Sustainable Skyscraper City",* Shanghai, China, 19th – 21st September, 2012. pp. 614 – 622.

OREGI, X., HERNANDEZ, P. & HERNANDEZ, R. 2017. Analysis of life-cycle boundaries for environmental and economic assessment of building energy refurbishment projects. *Energy and Buildings,* 136**,** 12-25.

PAPAKOSTA, A. 2016. *Whole life carbon: Structural systems* [Online]. Building. Available: https://www.building.co.uk/whole%C2%ADlife%C2%ADcarbon%C2%ADstructural%C2%ADsystems/5081262.article?adredir=1 [Accessed 1/02/2018].

PARK, H. S., KWON, B., SHIN, Y., KIM, Y., HONG, T. & CHOI, S. W. 2013. Cost and CO2 emission optimization of steel reinforced concrete columns in high-rise buildings. *Energies,* 6**,** 5609-5624.

PARK, H. S., LEE, H., KIM, Y., HONG, T. & CHOI, S. W. 2014. Evaluation of the influence of design factors on the CO 2 emissions and costs of reinforced concrete columns. *Energy and Buildings,* 82**,** 378-384.

RAWLINSONS 2017. *Rawlinsons construction cost guide 2017,* Perth, Rawlinsons Group.

RICS 2012. *Methodology to calculate embodied carbon of materials,* London, Royal Institution of Chartered Surveyors.

ROBATI, M., MCCARTHY, T. J. & KOKOGIANNAKIS, G. 2017. A method of uncertainty analysis for lifecycle 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., MCCARTHY, T. J. & KOKOGIANNAKIS, G. 2018. Integrated lifecycle cost method for sustainable structural design by focusing on a benchmark office building in Australia. *Energy and Buildings*.

ROBINSON, H., SYMONDS, B., GILBERTSON, B. & ILOZOR, B. 2015. *Design Economics for the Built Environment: Impact of Sustainability on Project Evaluation,* West Sussex, John Wiley & Sons.

SALING, P., KICHERER, A., DITTRICH-KRÄMER, B., WITTLINGER, R., ZOMBIK, W., SCHMIDT, I., SCHROTT, W. & SCHMIDT, S. 2002. Eco-efficiency analysis by BASF: the method. *The International Journal of Lifecycle Assessment,* 7**,** 203-218.

SANSOM, M. & POPE, R. J. 2012. A comparative embodied carbon assessment of commercial buildings. *The Structural Engineer***,** 38-49.

SHEN, Q. & LIU, G. 2004. Applications of value management in the construction industry in China. *Engineering, Construction and Architectural Management,* 11**,** 9-19.

SILVESTRE, J., DE BRITO, J. & PINHEIRO, M. D. 2014. Environmental impacts and benefits of the end-of-life of building materials–calculation rules, results and contribution to a "cradle to cradle" lifecycle. *Journal of Cleaner Production,* 66**,** 37-45.

TAKANO, A., HUGHES, M. & WINTER, S. 2014. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. *Building and Environment,* 82**,** 526-535.

THORMARK, C. 2006. The effect of material choice on the total energy need and recycling potential of a building. *Building and Environment,* 41**,** 1019-1026.

TORGAL, F. P. & JALALI, S. 2011. *Eco-efficient construction and building materials,* Philadelphia, Woodhead Publishing.

WIEDMANN, T. 2017. *RP2007: Integrated Carbon Metrics – A Multi-Scale Lifecycle Approach to Assessing, Mapping and Tracking Carbon Outcomes for the Built Environment* [Online]. CRC for Low Carbon Living. Available: http://www.lowcarbonlivingcrc.com.au/research/program-2-low-carbon-precincts/rp2007-integrated-carbon-metrics-%E2%80%93-multi-scale-life-cycle [Accessed 19/10/2017].

YU, M., WIEDMANN, T., CRAWFORD, R. & TAIT, C. 2017. The carbon footprint of Australia's construction sector. *Procedia engineering,* 180**,** 211-220.